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Broadband Access Networks

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Editorial

LEIF AARTHUN IMS

1999 is in many respects the first year of broadband access introduction on a reasonably large scale. The number of cable modem installations world-wide will probably exceed one million this year. Deutsche Telekom, Tele Denmark and Telenor are now offering ADSL (asymmetric digital subscriber line) services, as the first operators in Europe. Interactive broadband services and broadband portals are now emerging, following the recent dramatic growth in Internet and mobile services. Simultaneously, the rapidly increasing competitiveness in the telecommunications market forces the actors in the field to minimise costs and to maximise revenues. Broadband services are widely recognised as potentially decisive for the capability of the actors to defend and eventually expand the current revenue base as they position for the future service battle.

The access network is the part of the telecommunications network most closely related to service demand, but also the most cost sensitive network segment. Providing an access network with interactive broadband service capability requires infrastructure investment levels expected to be comparable to the investments associated with the establishment of the current access network for telephony. Moreover, the future interactive broadband arena, and in particular the residential market, is characterised by a high uncertainty both with respect to service take rates and willingness to pay. Accordingly, high risks are associated with upgrading this cost sensitive network segment. Hence, developing a positive business case for reaching the customers with interactive broadband access is probably one of the most challenging tasks for the actors in the industry at the threshold of a new millennium.

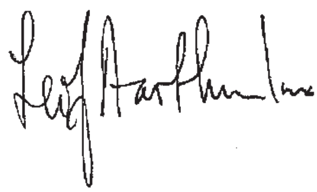
The vision of a multiservice broadband access network dates back at least to the early eighties, when the first “optical fibre fever” spread. In fact, around 1990 most of the experts expected an evolution toward fibre to the home (FTTH) connections in the access network. A lot of different field trials were launched and so-called “killer-applications” have been singled out, but very little has happened when it comes to commercial broadband access products for the mass market. So, what are the main reasons for this? The main inhibitors have obviously been the high risks associated with placing the significant upgrade investments in a market in which future services and revenues are highly uncertain. There simply has been no business case built so far for broadband access.

So – why should broadband delivery happen now? First of all, the explosive growth in Internet subscriptions and the likely evolution of the current Internet services capacity requirements into a demand for higher bandwidth has fuelled the broadband market vision with substance. Secondly, the recent technology developments, in particular of high speed copper transmission systems and digital compression technologies enable the provision of broadband as an overlay on the existing copper access plant at a reasonable cost. Thirdly, new broadband services are now gaining momentum as the prerequisite for maintaining margins with an increased competition.

In this feature section we will cover a range of broadband access network related aspects, hopefully providing a valuable insight into the main challenges of broadband access delivery. We start with an introductory chapter for the reader not too familiar with the material. Initially, surveys of market development and analyses of future regulatory environments are presented. This set of papers addresses the crucial questions of what will be the future demand for broadband services and how much are the customers willing to pay for these services.

The future broadband access network will be different from the existing narrowband copper based network in three respects, namely technology variety, open provisioning and service integration. The second section of the feature issue gives a comprehensive coverage of the key issues related to architectures, starting with the impact of the IP development on the access network evolution. The section includes an overview of wireline, terrestrial wireless, mobile, satellite and stratospheric platform concepts and architecture options, including currently available technologies, emerging technologies and migration paths towards the future broadband access networks. Separate contributions are devoted to some concepts of particular interest, like the passive optical network, wavelength division multiplexing, inverse multiplexing and power cable transmission. The crucial issue of access network management is addressed, as well as concepts for broadband home networks.

As we move towards actual deployment of broadband access technologies, implementation issues and operational aspects get increasingly important. We address these issues through some of the operator’s current access network strategies. Finally, in view of the underlying fundamentals of where and when to invest in order to create a positive business case for broadband services, the last section gives a comprehensive coverage of techno-economic methodology and application results, with the focus on work carried out within ACTS and EURESCOM.



Introduction to broadband access networks

LEIF AARTHUN IMS

Currently the evolution of the access network towards broadband (capacity per customer ≥ 2 Mbit/s) is one of the most crucial and demanding challenges in the battle between the actors in the telecommunications industry. The issue of establishing access networks for broadband services is complex, both in terms of the broadband service market, which is highly uncertain at present, and in terms of the future regulation of the customer access to telecommunications infrastructure. Moreover, there is a wide range of technologies available for broadband access, which further complicates the issue of broadband access. Starting from sometimes very different existing networks the access network providers have to select the appropriate migration paths and broadband architectures and ensure a successful deployment, management and operation of the new access network infrastructure. And of course, the bottom line is that the shareholders require return on investments, which at present probably is the most challenging aspect of upgrading the very cost sensitive access network to broadband. In this article these main issues related to broadband access networks are presented and discussed, primarily in the context of providing broadband service connectivity to the residential market and small and medium enterprises. The intention is first and foremost to introduce the major concepts of broadband access networks to readers not too familiar with the topic, through an overview with a modest level of detail.

1 Introduction

Telecommunication networks and services constitute the backbone in the emerging information society. Indeed, almost all recent technological and organisational innovations are dependent on and sensitised by easy access to services provided by telecommunication networks. The *information superhighways*, like the motorways in the fifties, electricity at the beginning of the century, railways in the nineteenth century, are becoming the vital and prerequisite instruments for economic growth in a modern society.

The telecommunications sector has experienced dramatic technology changes during the last two decades. New technologies like the Internet, the explosion in mobile communications, the introduction of optical fibres, development of satellite personal services are revolutionising the whole field of telecommunication services. The market has recently seen a great impact from new services and technologies coupled with the extensive market deregulation, for new and even the traditional voice services. The explosive evolution of the Internet in particular during the last years has a great impact on the telecommunications market in general. Both the traffic and the number of subscribers are now increasing exponentially. In addition, the number of applications on the Internet are increasing, and the functionality and content of the applications are under continuous development. New service providers entering into the marketplace are challenging the established service providers and threatening even the core business of traditional public network operators (PNOs) as they emphasise meeting customers' needs as the key to success and survival.

The customers are connected to the telecommunications network and the *information superhighways* via the access network, which is the network infrastructure between the customer premises and the nearest local exchange (LEX), point of presence (POP) or cable network hub. The access network is often called the last mile or the local loop, as well. The dominating access networks today are:

- Twisted pair based networks, initially built for telephony services;
- Cable networks, intended for broadcast services;
- Cellular radio networks for mobile telephony;
- Satellite networks for broadcasting.

Figure 1 gives a simplistic rendition of these four types of access networks.

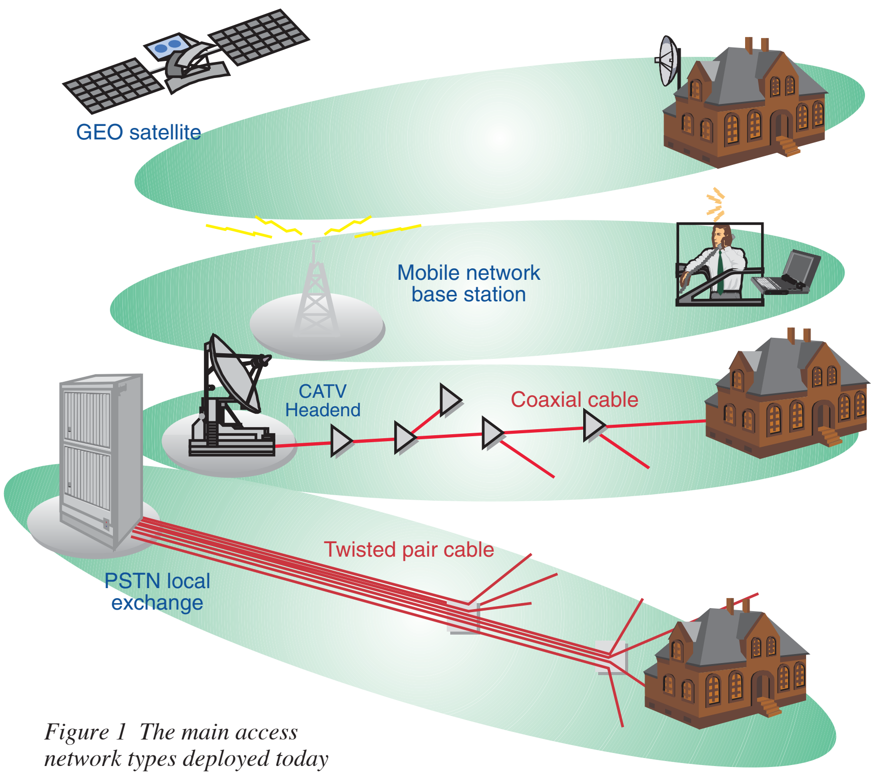


Figure 1 The main access network types deployed today

Interactive broadband services are now emerging, and none of the mentioned access network types have the capability of providing interactive broadband connectivity without a network upgrade. Thus all the access network providers with the intention of offering broadband services in some way or another must prepare their network infrastructures for these new interactive broadband services. The access network is the most cost sensitive part of the telecommunications network, and in addition the one most closely related to service demand. Thus, the access network operators of today are faced with the challenge of how to develop the existing network infrastructure into a broadband access network. Simultaneously, a rapidly increasing competitiveness in the telecommunications market forces the actors in the field to minimise costs and to maximise revenues, most likely through a simultaneous defence and expansion of the current revenue base.

Ten years ago most of the experts expected an evolution towards fibre to the home (FTTH). However, economic analyses indicated that the overall project values of network architectures for the residential market are reduced significantly when the fibre is installed close to the customer premises. FTTH solutions have proved very expensive, due to the high cost of civil works and the low customer share of optics and electronics equipment (in general, the cost of network elements decreases during time, whilst there is no reduction in civil works costs). Even Nippon Telegraph and Telephone Corporation (NTT) last year dropped their plan for fibre to every Japanese home by the year 2010, a project estimated at a total cost of USD 240 billion [1]. So, why then the current increasing interest in broadband access? Much of this increase in interest is due to the recent development of cable modems and digital subscriber line (DSL) modems. These new technology developments enable the utilisation of the existing twisted pair and coaxial cable base for high capacity transmission to the customer as alternatives to the FTTH solutions. The costs of cable modems and DSL modems have already decreased significantly compared to a couple of years back, and the price reduction is expected to continue over the next years due to mass production. This will impact the broadband service prices, which accordingly will fall to a level close to the current narrowband connection tariffs and give the opportunity to extend the present narrowband applications on Internet to broadband applications.

Cost effective, future proof broadband access networks accommodating a wide range of demographic diversity for a set of services with different bandwidth requirements will be required. Hence, strategies for developing the access network, along a cost effective path, flexible enough to serve a complex set of customer demands are crucial for the operators, service providers and equipment manufacturers. In this introductory article we will address the main areas involved in the evolution of the access network towards broadband. The article is sectioned into eight main chapters, of which the second one briefly sketches the scene of what is happening right now with respect to broadband access – the most aggressive actors, some of the hypes and rumours heard through the grapevine. This initial status report will hopefully enable the reader to more easily relate the following, more general chapters to the current situation.

Chapter 3 addresses the main driver for broadband network deployment, namely the demand for new services. Provisioning of new, advanced services through the introduction of modern technology is commonly expected to be a crucial prerequisite as the operators position for the future service battle. However, at present the telecommunications arena, and in particular the residential domain, is characterised by a high degree of uncertainty with respect to the rapid technology evolution, market development and regulatory environment. Uncertainties in service take rates, willingness to pay, future technology capabilities, cost levels and technology and market convergence introduce new and significant risk elements into telecommunications investment projects. The key question is: how will the market for residential broadband services evolve? The policy of regulatory bodies will to a large extent impact the evolution of the broadband access delivery to the residential and small and medium enterprise market. The regulatory environment as such is not addressed in this introductory chapter. The topic is treated in more detail in [2].

The broadband access network evolution must be considered in view of the current trends in network evolution. Some of these trends even suggest that the old local exchange network structure is a part of the past and is fading into oblivion. What are the major trend projections, and how might they eventually impact the evolution of the access network? Chapter 4 briefly summarises the aspects related to network evolution which impact the evolution towards broadband access networks.

The future broadband access network infrastructure will largely have to be developed from the existing infrastructure, such as the twisted pair based telephone network, the coaxial cable network and satellite networks for television distribution and the cellular network for mobile telephony. In particular the existing twisted pair based local loop represents a significant asset for telecommunication operators, and is regarded as the key enabler for provisioning of new advanced services. In chapter 5 the existing access network infrastructure is described.

A large variety of access network architectures are available for the operators and must be rigorously examined in order to determine the most appropriate ones for the different area types and service demands. Chapter 6 gives a brief introduction to the access network technologies and architectures that enable broadband service delivery, including wireline, wireless and satellite alternatives.

The main inhibitors for the roll-out of broadband access networks have obviously been the high capital investments required in order to upgrade the existing, cost-sensitive access infrastructure or build new access networks, and the high risks associated with placing these significant investments in a market in which future services and revenues are highly uncertain. No business case has simply been built so far for broadband access. In chapter 7 the economics and corresponding financial risks of delivering broadband access are discussed. Access network upgrade strategies for emerging new broadband services have been evaluated in several studies, with technological options ranging from enhanced copper to hybrid fibre coax and broadband passive optical networks. The main issues of broadband access economics are summarised in this chapter.

And finally, having taken the major aspects of broadband access into account, the challenge for the operators is to derive suitable minimum-risk strategies for either a migration of existing network infrastructures or for deployment of a completely new access network infrastructure. Chapter 8 introduces the main criteria on which an access network strategy for broadband migration is devised.

The intention of this introductory chapter is neither to provide a complete overview of the complex aspects of broadband access, nor to give a thorough description of the respective fields of market, regulation and technology addressed herein.

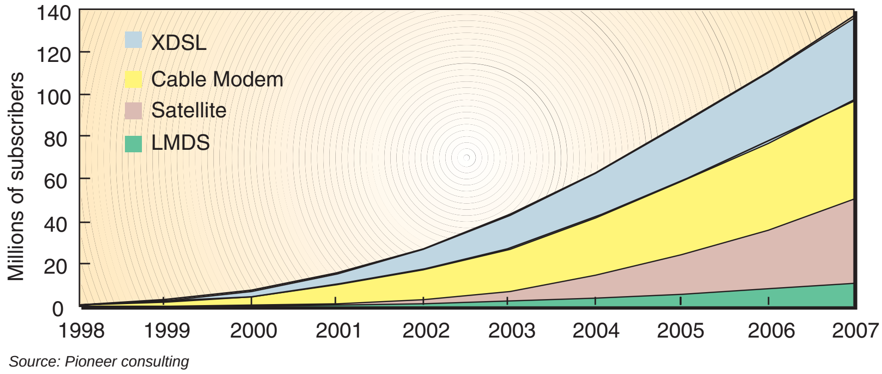


Figure 2 Global broadband access subscribers by technology, 1998 – 2007

The main objective is to provide a brief introduction to broadband access, at the level of detail considered sufficient for the reader unfamiliar with the subject or for the reader in need of a condensed synopsis on the matter. For a more detailed treatment of the aspects, we refer to the articles in the remainder of this special issue of *Telektronikk* on broadband access networks.

2 Broadband access right now

This year – 1999 – is pretty much set to be the first year of broadband access introduction on a reasonably large scale in some developed markets throughout the world. In the United States in particular the number of installed cable modems will reach really significant volumes this year, already an estimated 650,000 to 750,000 such modems have now been installed in North America, mainly for Internet Access services [3]. Several of the larger telephone companies in the US have plans for large-scale DSL (digital subscriber line) roll-outs, and this year we will for the first time see broadband connections being offered via ADSL (Asymmetric Digital Subscriber Line) on a commercial basis in Europe, after years of unfulfilled promises of broadband service delivery by the incumbent operators [4, 5].

This happens after years of marketing of broadband technologies and services – without any significant materialisation in terms of service offerings in the residential and SME markets. And one should bear in mind that even if new broadband technologies are expected to be installed in relatively large volumes during 1999, it will of course still be at rather modest penetration levels compared to traditional services such as POTS (plain old telephony services) and CATV (community antenna television). At the end of 1998 there were approximately 800,000 subscribers globally with a broadband access connection [6], with 570,000 cable modem subscribers, 200,000 DSL subscribers and approximately 30,000 broadband customers with satellite access. One forecast for broadband access connections for the next ten years is shown in Figure 2. According to this forecast, by the year 2007 the number of broadband access subscribers world-wide on XDSL, cable modems, LMDS (Local Multipoint Distribution System) or satellite will be around 140 million.

Of the many forces and incidents impacting the broadband access market, probably four of the most influential ones right now are:

- AT&T's acquisition of TCI (Telecommunications Inc.), MediaOne and joint venture with Time Warner;
- ADSL offerings on a commercial basis in North America and Europe;
- Personal computers with factory installed DSL modems;
- Broadband portals emerging on the Internet, offering broadband content.

Also the access arena has lately been dominated by the general trend in the telecommunications industry of rather frenetic merger and acquisition activities. During the last year AT&T through mergers and acquisitions has grown to become the largest cable operator in the US [7, 8]. In May this year AT&T bought MediaOne, almost doubling its number of cable customers, to reach approximately 25 millions. MediaOne was bought following the acquisition announced in the summer of 1998 of TCI, then the largest cable operator in the US. This is now known as *AT&T Broadband and Internet Services*. The cable networks of TCI and its affiliates pass 33 million homes in the US. In February this year AT&T and Time Warner announced a joint venture, which will enable AT&T to reach directly into another 20 million US homes [9, 10]. This additional joint venture with Time Warner will give AT&T access to cable networks which in total pass over 70 million homes in the US, that is around 60 % of the households in the country. Over the past few years, up until AT&T's seemingly determined entrance into the local loop market by the use of HFC, the interest worldwide in HFC technology has decreased. These moves by AT&T are expected to re-fuel the development of the HFC technology (hybrid fibre-coaxial) and may prove decisively important for the cable operator and manufacturer industry's capability to enter the residential broadband markets on a large scale.

Simultaneously, the DSL market in the US continues to develop with rapid pace. Currently US West has by far the largest base of installed DSL connections in the US, probably more than 80 % of the total number of lines [11]. In March this year Covad Communications announced the first US nation-wide DSL network, offering services in the range from 144 kbit/s to 1.1 Mbit/s symmetric access [12]. SBC Communications Corp. plans to offer high-speed Internet access to 9.5 million potential customers across most of the operating region by the end of this year [13]. Microsoft recently began trials of their high-speed digital subscriber line in four large US cities, providing consumers with speeds of up to 8 Mbit/s [14]. The DSL roll-out in Europe has been somewhat slower than in the US, but this year ADSL offerings on a commercial basis in Europe are expected by some of the major incumbent operators [15]. Telenor, Tele Denmark and Deutsche Telekom are already offering commercial ADSL services. BT plans to install ADSL equipment in 400 of their exchanges within the next year [16]. On July 6 this year Oftel, the UK telecommunications regulator, proposed to open up BT's twisted pair local loop network by the year 2001, implying that BT is to provide other operators with high capacity access via a point-to-point data service between the end user and the service provider [17, 18, 19]. In Australia, the operator TransAct in a field trial already uses the next-generation DSL, VDSL, to offer telephone, data and video services to some hundred users with connection capacities of up to 36 Mbit/s [20].

The integration of broadband capacity modems into end-user equipment such as PCs, is likely to boost the broadband access market. The Universal ADSL consortium was formed in January 1998, led by Intel, Microsoft and Compaq Computer [21, 22]. The consortium developed the G.Lite specification, which trades transmission capacity for splitterless installation and thus enables plug-and-play solutions in terms of eg. PCs with factory installed DSL modems. PCs with DSL modems are expected to reach the market in significant numbers this year. Dell Computers now markets a new personal computer with a pre-installed ADSL modem, capable of speeds of up to 768 kbit/s [23]. The Bell companies project the number of installed DSL lines this year to be 200,000 [24]. But also other actors are now making their moves into broadband tailored end-user equipment. In May this year Microsoft bought a 2 % stake in AT&T, simultaneously reaching an agreement with AT&T on the use of Windows CE software in up to ten million of the set-top boxes to be installed in connection with the broadband upgrade of AT&T's cable networks [25].

And finally, the content providers are now seemingly at the entrance into the broadband era. Broadband portals such as *broadcast.com* and *Snap!* stream live and on-demand audio and video programs over the Internet [26, 27] amongst delivery of other content (Figure 3). They even offer dedicated services to users with connection speeds of 128 kbit/s or higher [28]. A next likely move is partnerships between such portals, including the dominating ones like *Yahoo!* and access network operators with broadband access roll-out plans [29, 30]. It may be worth noting that one of the owners of *Snap!*, NBC, entered into an agreement with AT&T Broadband and Internet Services in June, paving the way for distribution on NCB's programming properties on AT&T's cable networks [31].

3 The market evolution

Even if the accelerated development of broadband applications is the most important factor for the evolution of a broadband market, and the current status of broadband access seems to indicate that the somewhat turbulent market is developing rather fast, the future market evolution is still quite uncertain. In the mid-nineties there was a strong belief in the need for one killer application, and in particular video on demand (VOD) was focused as a potential killer application. However, the market, including the residential broadband market, has proved to be more sophisticated than earlier assumed. It is obviously difficult to predict the killer application(s). Moreover, there are reasons to believe that in the future the demand for residential broadband connections will be created by a wide range of applications rather than a single one. In this chapter, we will discuss three main issues related to the broadband access market evolution, namely the future *consumption* or *usage patterns*, the application *demand* and *willingness to pay* for new broadband application and services.

The future *consumption patterns* are likely to have a great impact on the evolution of broadband applications and services and correspondingly the need for broadband access. But where can we get indications on the future behaviour of the consumers? The recent Internet and mobile communication developments have shown that the early adopters of the new ways of communication and the enabling technologies typically are people characterised by a high acceptance of new solutions combined with a strong desire and need to get rid of constraints caused by limitations in space and time [32]. And in the last years developments indicate that the impacts and benefits of new services for the larger, general public market in turn are identified by these somewhat entrepreneurial consumers. The general development, including enabling technologies, in the information and communications industry is likely to have a large impact on how, when and where broadband services are applied [33]. Very soon the content and distribution are expected to become all-digital. The exponential growth in microprocessor power, memory size and storage capacity will probably continue for the

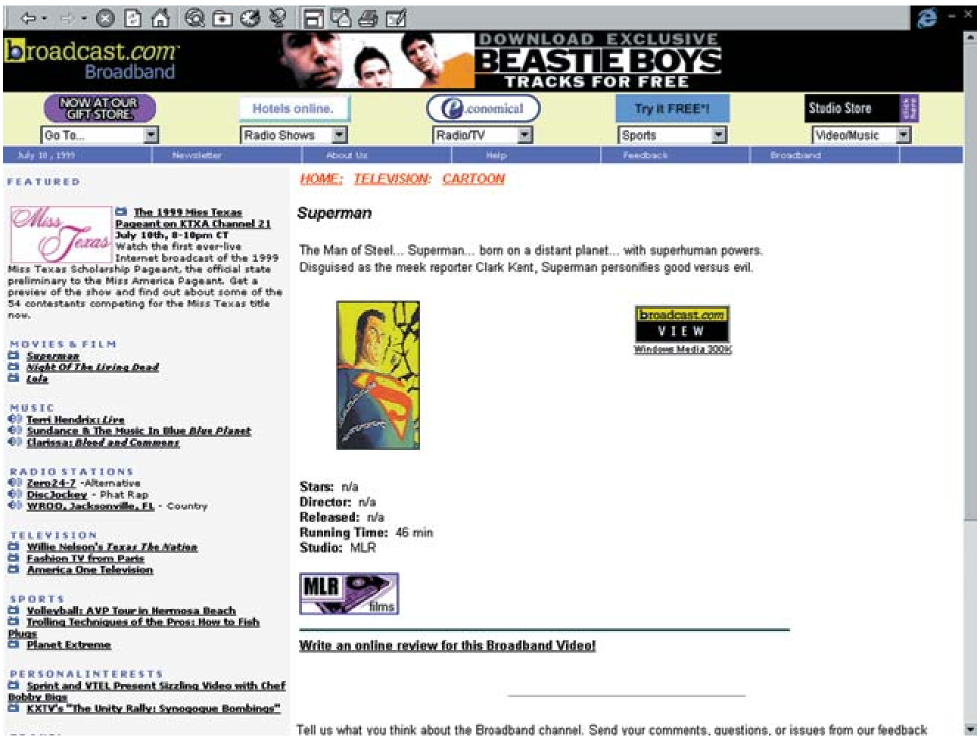


Figure 3 Broadband portals such as broadcast.com *are now emerging on the Internet*

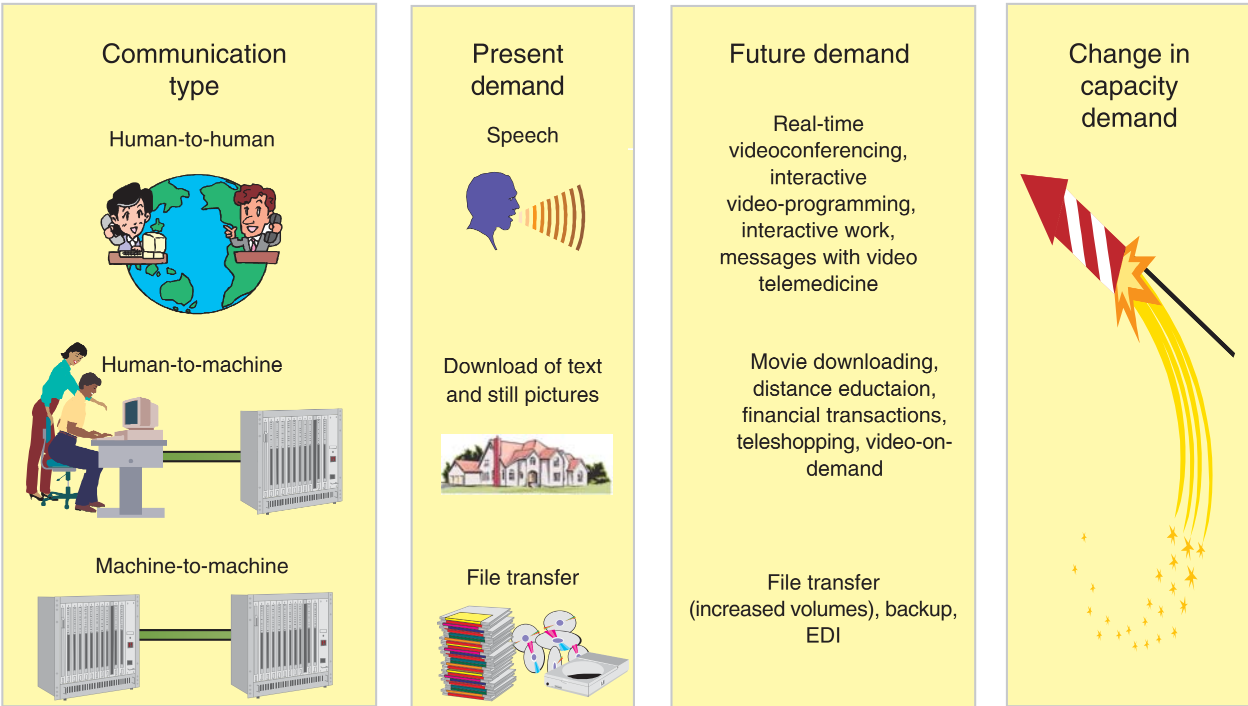


Figure 4 The development towards a demand for higher access capacity

next ten years. This implies that the performance of the end-user systems will continue to increase, possibly to 100 times the performance of the current systems. Resulting new consumption patterns and needs are thus likely to be seen, driving a demand for new services and applications.

However, forecasting the new broadband services with respect to both application type and demand is very difficult, mainly due to the lack of historical data. In addition most of the applications are new and it is difficult to predict growth directly. Nevertheless, some surveys have in a systematic way aimed at identifying the new applications [34, 35]. Despite such market surveys, the current market status and recent field trials, the new broadband customer applications, in particular in the residential and small business markets, remain ill-defined. Nevertheless, some trends can be recognised:

1. The integration of telecommunications and information processing is escalating.
2. The use of interactive video services, such as videoconferences, is growing.
3. Entertainment services are increasingly important.

Figure 4 illustrates a possible development from the present towards the future demand for applications. The types of communication are classified as *human-to-human*, *human-to-machine* and *machine-to-machine*. The present application demands and usage patterns are different for these three types of communication, and so might also the future application demands be. However, they all have that in common that expected evolution of applications leads to a demand for higher access capacity, even if the differences in usage patterns are likely to remain also in the future.

The different usage patterns will imply variations in bandwidth requirements of the future services, as illustrated in Figure 5 for residential services [36]. Some applications and services are likely to be highly asymmetric in nature, whilst others will require a more symmetric set-up of capacity between consumer and network provider, and vice versa. Furthermore, this might to some extent govern which infrastructure platform the services are provided on.

Given these indications of future application and access capacity requirements, the key question is *how large a growth* in demand for transmission capacity can be expected within the next five to ten years? New service forecasting and demand projections have recently been reported, derived from current spending patterns of households or from market surveys. According to several studies, like the RACE/TITAN and ACTS OPTIMUM Delphi surveys [35, 34], the work by the Bureau of Transport & Communications Economics, Canberra [37] or the FSAN initiative [38], and several consulting reports [30, 39] there will be a significant future demand for asymmetric and symmetric broadband services in the residential and small business market segments. These findings are supported by main findings in several other reports, which conclude that broadband services will reach the mass market soon after the turn of the century with cable modems as the dominant access method (at least in North America) at the same time as content and service providers will create new services for the broadband customers [40]. Forrester Research in a recent report estimates that almost one third of all on-line subscribers in the US will have cable modem or ADSL access in 2003 [30].

The third main market issue is *the willingness to pay* for new broadband applications and services, and the crucial question of *is there any incremental willingness to pay for new broadband, multimedia services?* In this context multimedia services comprise voice, video and data services. The demand level will to a large extent depend on the price and the pricing schemes, in particular in the very important mass market, which mainly is discussed here. Some studies indicate that the incremental willingness to pay compared to current services may be very limited, particularly in the consumer market [34, 41, 42]. This is probably the main challenge in the access operator's strife for achieving returns on the huge investments required in network upgrades for broadband access delivery. In addition, not only the price level, but also the pricing structures are likely to be very important. Based on a reasonably large scale experiment measuring the demand for Internet as a function of bandwidth, applications and pricing structure, the Internet Demand Experiment (INDEX) confirms that Internet users are sensitive towards different pricing structures. The INDEX project proposes usage-based pricing as a fair way to charge customers [43].

The future Internet market, including an eventual emergence of wide-scale offered broadband Internet connections, is also expected to be segmented into quality-differentiated service portfolios, implying a mixed set of price structures for the segments. Customer group segmentation and segmentation into geographic areas are the two other important segmentation aspects related to broadband access delivery.

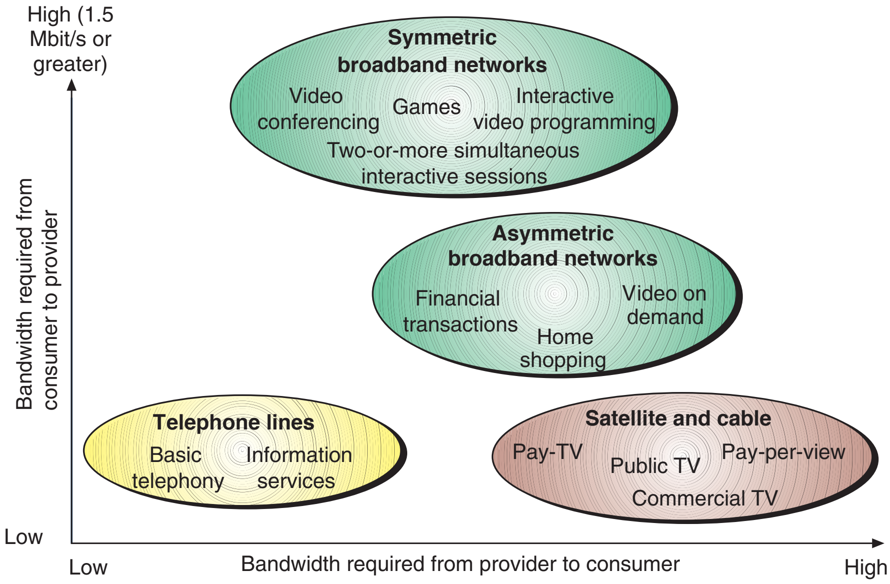


Figure 5 Bandwidth requirements of current and future residential services [36]

4 Network evolution

This telecommunications network development in general obviously impacts the evolution towards broadband access networks. Thus, some of the major trends in network evolution will need to be briefly introduced here. Many complex and interacting factors have an impact on the demand for new services and accordingly the network evolution. Figure 6 gives a brief overview of the complexity [44]. The main factors, as illustrated in the figure, may be considered to be:

- applications;
- technology;
- network platform;
- service quality;
- cost evolution;
- demand;
- price;
- environment;
- strategy/policy.

The *strategy* of the network operator is governed by *revenue estimates* and the targeted and expected *return on his investments*. In general, the introduction of new applications, new technology, new network platforms, new architectures, etc. are likely to depend on the long term revenue prospects. However, with increasing competition strategic decisions play an important role also in the near term positioning. Figure 6 illustrates the network platform options for introduction of new applications, namely *further utilisation* of the existing network platform, *expansion* of the network platform or by introduction of *new network technology*.

The preferred alternative will among other factors depend on the cost of network components and the expected future cost evolution. The price paid by the users for the given applications and services in turn depends on investment costs, operation and maintenance costs and the revenue considerations of the network operator. The application demand is determined by factors such as the expected competition, the market potential for the applications, expected market shares, substitution effects between applications, penetration as a function of time and the price the service quality. In addition there are interactions between the main factors, as shown in the figure.

The current network trends towards multimedia broadband are influenced by the general technology evolution, which typically characterised by digitalisation, miniaturisation, high capacity and mobility, the latter both in terms of terminal, user and service mobility. And indeed, we are currently witnessing a change in network technology with respect to price and functionality, for instance through the introduction of WDM (wavelength division multiplexing) ATM (asynchronous transfer mode) and IP technology, often considered as key enabling technologies for the future full service integrated network, which is a vision that dates several years back. Furthermore,

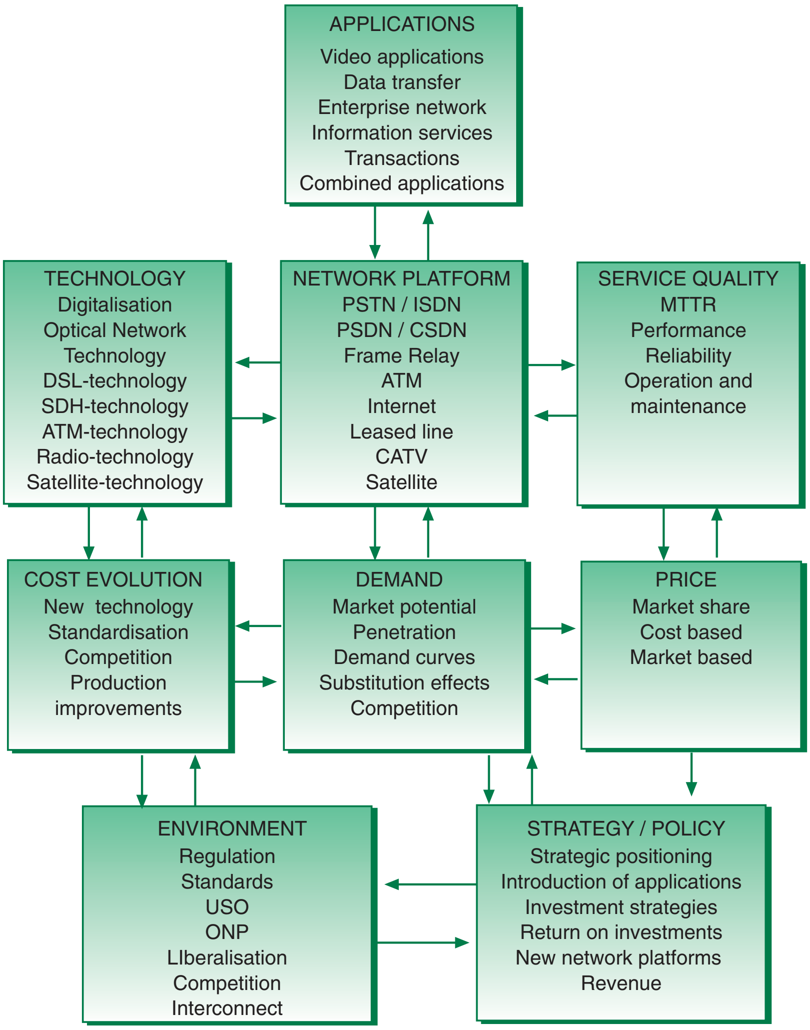


Figure 6 Key factors for demand and network evolution [44]

the network evolution towards multimedia broadband is influenced by the ongoing convergence of the traditional markets for broadband services, namely the data communications market, the broadcast/video market and the telecommunications market. The rigid boundaries between these traditionally separated service markets are already blurred, and look set to disappear over the next few years. Thus, both the technology evolution and the service market evolution may be taken as indicators of networks evolving into integrated broadband services networks.

The telecommunications network operators have already integrated the traffic from the different platforms in the transport network at long distance and junction level and also in parts of the access network. The technology used today is mainly fibre and plesiochronous digital hierarchy (PDH) or synchronous digital hierarchy (SDH) transmission systems in addition to radio links in rural areas. But still, network operators commonly introduce new services by means of a new service network with dedicated equipment. This may very well be the case for several years to come, resulting in an incoherent mixture of technologies remaining also in the future [45, 46].

However, in this paper the evolution towards broadband access will be discussed in view of a development towards the future telecommunications network which may be considered as representing a paradigm shift from dedicated service networks towards a common service production platform utilising a set of parallel access network technologies, such as twisted pair, coaxial cable, cellular, radio and satellite. This is illustrated in Figure 7. This evolution represents a shift towards network independent service production, mainly based on software. The result will most likely be a fundamental change of roles within telecommunication, in which product development and customer relations will be taken over by other than today's suppliers and operators.

Thus, given this shift towards a common service production platform utilising a set of parallel access network technologies, the future broadband access network will be different from the existing narrowband copper based network in three respects, namely *technology variety, openness and service integration* [47]. Hence, the architectural requirements of the access network are likely to change along these three dimensions. This will most likely lead to the end of a single access network architecture in terms of underlying technologies. Future broadband multiservice access networks will probably be built on combinations of systems and technologies, including fibre

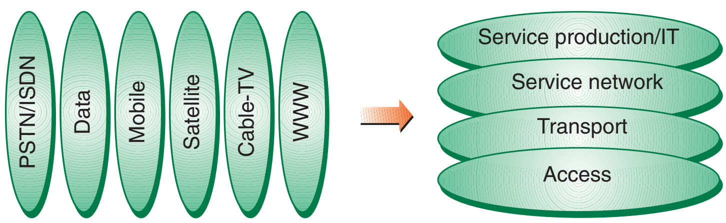


Figure 7 The shift towards a common service production platform utilising a set of parallel access network technologies

solutions, satellite systems, cable-TV networks, broadband radio systems and DSL systems on the existing copper network. However, in a competitive environment with a variety of network operators the access operators will be required to establish open network architectures. And lastly, the vision of the integrated multiservice access network requires service integration in terms of introduction of statistical multiplexing in the access part of the network.

Before we briefly introduce the different broadband access technology options, we will in the next chapter address one of the most influential aspects with respect to selection of the future broadband access architecture, namely the existing infrastructure.

In summary, the access network operator will be faced with a bewildering choice of alternatives. The preferred architecture will depend on considerations of several factors, of which the key ones are:

- The regulatory regime;
- The competitive environment (commoditisation, price reduction;
- The services to be provided;
- Market segmentation;
- The existing plant;
- Replacement strategy;
- System costs;
- Financial strength in terms of cash flow and capital funding.

5 The existing access network infrastructure

The future broadband access network infrastructure will to a large extent have to be developed from the existing infrastructure such as the twisted pair based telephone network, the coaxial cable network and satellite networks for television distribution, and the cellular network for mobile telephony. The dominant telecommunication access network infrastructure is still based on twisted pair copper cables for telephony services and Internet access. Coaxial cable networks and direct to the home (DTH) satellites support the residential market with distributive broadband applications. Recently some cable operators have upgraded their coaxial cable networks with return capabilities in order to provide Internet access. Cellular networks for mobile services have been deployed in large numbers over the past years, and constitutes a powerful starting point for the development towards broadband access. In summary, the main access network platforms applied today are:

- Twisted pair networks for PSTN, ISDN and leased lines services;
- Coaxial cable networks for digital and analogue broadcasting;
- Geostationary satellite networks for digital and analogue broadcasting and business communications;
- Cellular radio networks for mobile services;
- Wireless networks for PSTN.

The above network infrastructure types are either broadband access networks without interactive capabilities at present (eg. the coaxial cable networks and satellite networks), or narrowband networks with interactive capabilities (eg. twisted pair networks or cellular radio networks). That is, the cable operators usually have a starting situation for a migration towards interactive broadband access which is significantly different from the situation of the telephone operator. The twisted pair network of the telephone operator has a point-to-point topology and the coaxial cable network has a distributive topology. Nevertheless, interactive broadband services may not be implemented in any of the current access networks without an upgrade of the infrastructure. However, the differences in existing access networks may call for quite different upgrade strategies. In this chapter the main features and differences in existing access networks will be outlined.

5.1 Twisted pair access networks

The telecommunication access network connects the telephone set at the customer premises to the local exchange (LEX) physically through a pair of copper cables, referred to as a twisted pair. Approximately 600 million twisted pair access lines have been installed worldwide [48]. A typical structure of the existing twisted pair access network is illustrated in Figure 8.

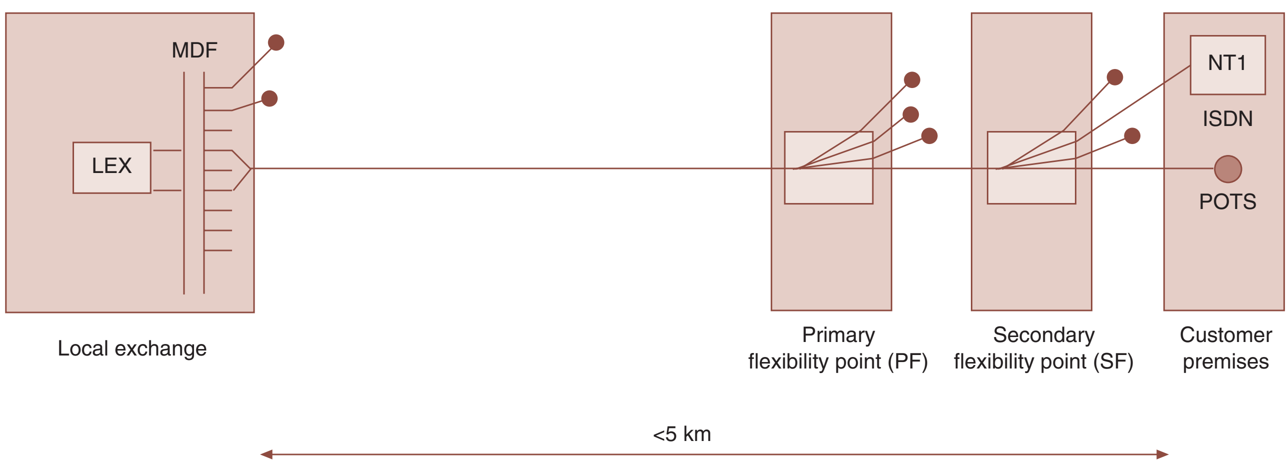


Figure 8 Existing twisted pair access network

The twisted pair based access network consists of a main distribution frame (MDF), a primary distribution cable, secondary distribution cable and drop cable. Flexibility points (connection points), often located in street cabinets, are introduced in the network in order to provide flexibility in network evolution. The drop cable (usually two or more pairs) is installed between the customer premises and is terminated in a flexibility point, or distribution point. The flexibility point is located in a small cabinet installed either at street corners, on poles, or in the basement of building blocks. Usually between ten and 30 customers are connected to this flexibility point. Also terminated in this flexibility point is a larger single cable with a cable pair size dependent on the number of customers connected to the flexibility point. This larger cable, secondary distribution cable, connects the secondary flexibility point to a primary flexibility point closer to the local exchange. Several secondary distribution points (in the order of tens) are terminated in this primary flexibility point. The primary flexibility points are terminated in the local exchange via primary distribution cables, with cable pair sizes dependent on the number of flexibility points connected to each primary flexibility point. In the local exchange, the primary cable pairs are terminated in the main distribution frame, which is a rack connecting the primary cables to the local exchange equipment. The customer is connected to subscriber equipment such as a line card through a cross connection between the cable side and the exchange side. Thus, from the customer premises to the exchange, each customer has his own pair of copper cables dedicated for his usage.

At present several access network operators have completed their digitalisation of the exchanges. However, the access network infrastructure which connects the customers to the local exchanges has not changed significantly during the digitalisation process. In the original roll-out of the network the reach of the network was typically set to between four and six kilometres, with allowances for longer distances in more sparsely populated areas, using thicker cables. In urban areas today fibres are deployed not only in the junction networks but also in parts of the access network. Fibre loops with service access points (SAPs), transmission equipment and remote subscriber units are established in order to increase reliability and flexibility. The SAP refers to the localisation of the concentrator and/or add and drop multiplexers in the network, as commonly used in European countries with advanced access network infrastructures. The development of the new architecture is advancing by the introduction of SDH technology and add and drop multiplexers in the local loop. Shown in Figure 9 is a typical public switched telephone network (PSTN) access network infrastructure with service access points. In addition, many business customers are now connected to the access network with multiples of 2 Mbit/s provided on optical fibres. This is mainly due to the digitalisation and the high demand for primary rate integrated services digital network (ISDN), leased lines and data communication services.

5.2 Coaxial cable networks

The cable operators typically have a coaxial cable distribution network which distributes television and radio programmes from a central receiver location, often referred to as CATV (community antenna television) networks. The signals are fed from a receiver station, called headend, which passes some tens of thousands of homes, to the distribution network. The headend may serve several hubs which typically pass some thousands of homes. The distribution network is usually a coaxial cable network, but more and more often fibreoptic cables and combinations of coaxial and fibreoptic cables are used. Optical fibres are usually used for the transmission of signals from the headend to the hubs, whilst the network between the hub and the subscriber is a coaxial cable distribution network, with bandwidths of 300 MHz, 450 MHz, 606 MHz, 750 MHz or 860 MHz. Figure 10 shows a coaxial cable network for distribution of television services. In the coaxial cable part of the network the signals are amplified, selected and frequency converted by the use of coaxial amplifiers. All of the customers on the coaxial cable branch receive the same signal.

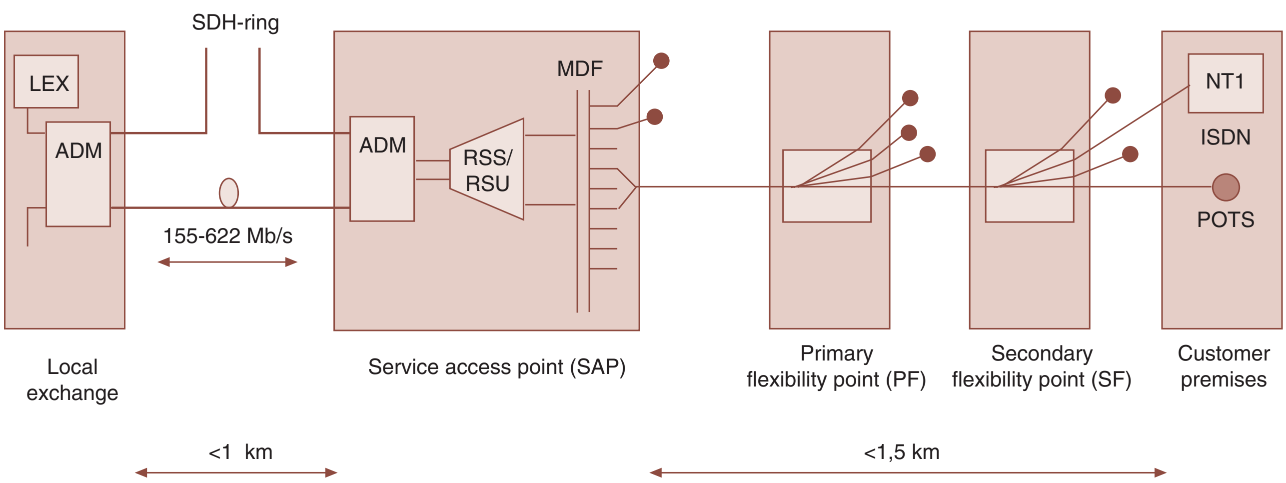


Figure 9 A typical public switched telephone network (PSTN) access network infrastructure with service access points

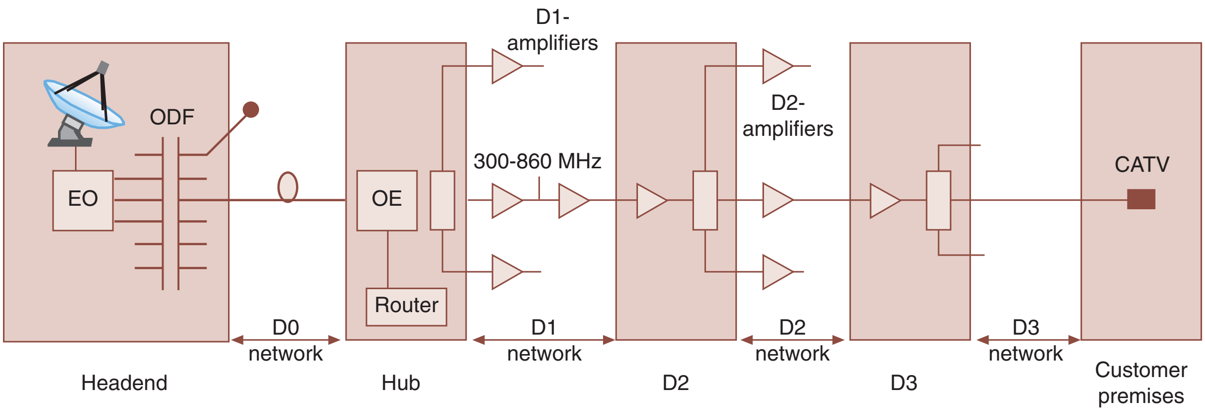


Figure 10 Existing coaxial cable network for distributive services

The distribution network depicted in Figure 10 consists of four segments, the D0-D3. The D0 network distributes the optical signals from the headend, typically over long distances, to the network hubs. The D1 network consists of coaxial cables and amplifiers and may be considered as corresponding to the primary network in the twisted pair based access network infrastructure. The number of amplifiers in this network segment is determined from the distance in the D1 segment. The D2 network, which similar to the D1 segment contains coaxial cable amplifiers, may be compared to the secondary network in the twisted pair based access network. The D3 segment often consists of individual coaxial cables, connecting the customer premises to the distribution point. The D3 distribution point serves in the order of ten to 30 customers. The D3 segment may be looked upon as corresponding to the drop cable in the twisted pair network. Today an increasing number of cable operators are offering Internet access over their coaxial cable networks. This requires an upgrade of the described coaxial cable network in order to enable return channel signalling, as described in [49].

5.3 Satellite networks

Geostationary communication satellite networks at present include fixed service satellites (eg. for television distribution, distance learning and data communications), DTH broadcast service satellites and mobile service satellites (voice services and digital communications) [50]. The geostationary communication satellites are located at the geostationary earth orbit (GEO), approximately 42,000 km from the earth's centre, and normally function as analogue transponders [51].

The main application so far has been broadcasting. The satellite systems are very different from cable based access networks, since they offer coverage over very large geographical areas and may operate without any terrestrial infrastructure [52]. Each satellite typically has some hundred MHz of available spectrum, with cell sizes of commonly some hundreds to thousands of kilometres in diameter. Thus, the average individual channel user density supported is low compared to terrestrial access networks. Furthermore, the two-way delay in satellite systems is about 0.25 seconds, caused by the long transmission distance. In addition there is a significant propagation path loss. By the use of very small aperture terminals (VSAT) geostationary satellite networks may be established for wideband access, point-to-point communications or for star or mesh type of networks. However, the user terminals are expensive and high bitrates require very large antennas. Satellites can be launched into orbits that are closer to the earth in order to overcome these problems. These systems are described in more detail in [52].

5.4 Mobile access networks

The cellular networks deployed over the past years for mobile services, such as the GSM networks, comprise access network infrastructures which may constitute a good starting point for the development towards broadband access service delivery. Figure 11 shows a common access network infrastructure established for GSM and NMT networks. The base station controller (BSC) depicted on the left-hand side may be co-located with the PSTN local exchange. The traffic between the base station controller and the base station (BS) may be transmitted by the use of fixed lines (twisted pairs or fibreoptic cables) of capacities in the range of up to 2 Mbit/s, or alternatively by the use of radio links. Several base stations may be connected to the same multiplexer (DXX), which is typically located at a network level comparable to the primary or secondary flexibility point of the twisted pair access network. Present cell sizes in GSM 900 networks in densely populated areas are typically some few hundred metres. The development of the current mobile networks towards broadband is described in more detail in [53].

5.5 Wireless local loops

Today wireless local loop (WLL) and radio in the local loop (RLL) systems are deployed for the provision of narrowband or broadband services intended as a replacement for the conventional copper loop. In countries with a developed twisted pair infrastructure point-to-multipoint radio access systems are mainly used where network rehabilitation or extension by the use of twisted pair cable based solutions require high investments. However, in terms of installed systems in developed countries, wireless local loop alternatives are very few compared to

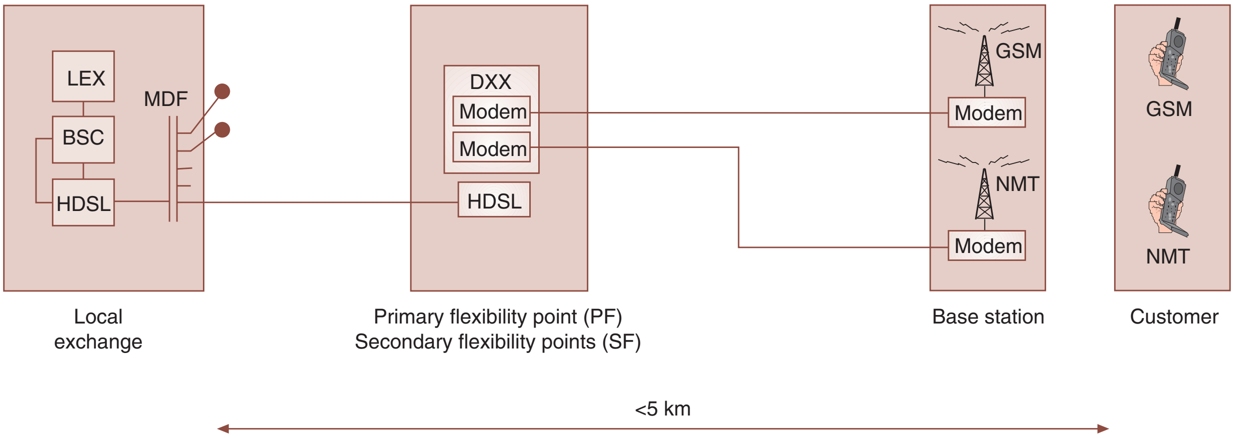


Figure 11 Access network infrastructure for mobile networks

twisted pair copper lines. In developing countries wireless local loop systems are often the preferred alternative for establishing a telecommunications access network.

The present radio access systems are either point-to-point or point-to-multipoint radio access systems. In point-to-multipoint systems the central radio station (CS) communicates with a number of customer terminals in a multipoint structure. Figure 12 shows a point-to-multipoint radio system for telephony. All communication between the central radio station and the customer terminals is based on radio links between one or more base stations and the customer terminals. The total system capacity is a shared resource, dedicated on demand to the customer terminals. The central radio station is usually co-located with a local exchange. The base station may by line of sight have a reach of around 40 kilometres. The base stations may serve in the order of 200 telephony customers, and are connected to the central radio station by the use of fixed line connections.

6 Broadband access technologies

Both the technological and the economic aspects related to the establishment of the access network segment of a broadband network platform for multimedia services will be of particular importance for the telecommunication operators and other actors. Today there is a wide variety of technologies available for interactive broadband access [54]. The technology is under rapid development and associated with some degree of uncertainty, both with respect to performance in existing networks and price evolution. At an overall level the technology choice in the access network is concerned with mobility and capacity, and the choice of transmission medium, ie. twisted pair copper cable, coaxial cable, fibreoptic cable, radio systems (fixed and mobile) or satellite. For each medium there are several options with respect to topology, configuration of network nodes and system technology. Today the cable based alternatives (twisted pair copper cable, coaxial cable and fibreoptic cable) are probably most mature with regard to technology – these systems have been

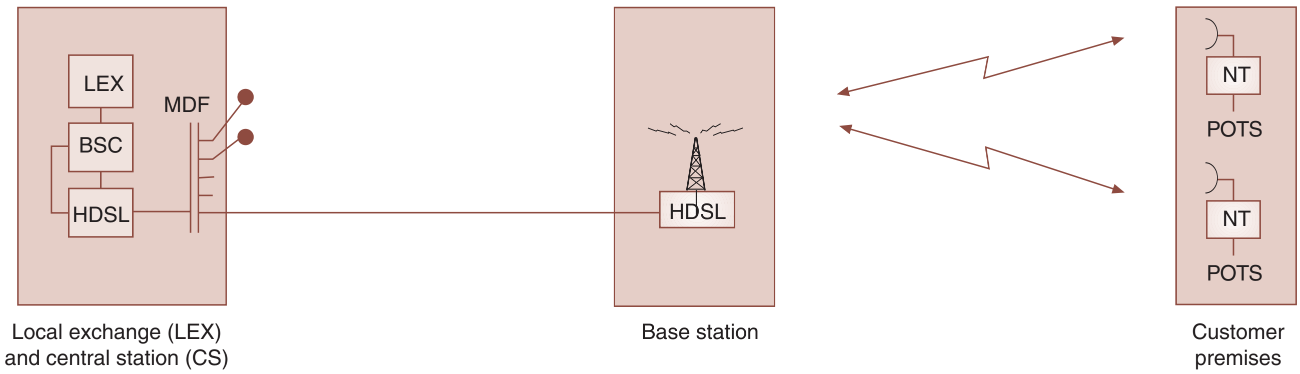


Figure 12 Point-to-multipoint radio systems for telephony

commercially available for some time already.

The technology variety is illustrated in Figure 13 in which some of the relevant technologies are sorted by transmission medium. The five main wireline upgrade alternatives are shown in the figure, namely power line modems to the far left, coaxial cable modems and HFC technology, digital subscriber line (DSL) modems and fibreoptic systems. As we move further up into the air there are several terrestrial wireless alternatives, such as local multipoint distribution system (LMDS) and mobile systems such as UMTS. Several satellite systems and concepts have been presented, including geostationary satellites (GEO), mid earth orbit (MEO) systems and low earth orbit (LEO) systems. The so-called stratospheric platforms such as HALO and SkyStation are based on high altitude balloons or aeroplanes.

The assessment of the different access network architecture alternatives must be based on a consistent evaluation of a set of criteria, among other things including performance, cost effectiveness (installed first costs and running costs), technological maturity and flexibility. The transmission capacity is probably the most important aspect regarding the performance evaluation, ie. which capacity in Mbit/s may or will be provided to the customer on the chosen architecture? Some of the architecture alternatives, such as the satellite systems, coaxial cable modem systems and some broadband radio systems, are based on a sharing of the transmission capacity between the customers. For other alternatives, however, such as ADSL (asymmetric digital subscriber line) and VDSL (very high-speed digital subscriber line), the specified transmission capacity is exclusively available to each simultaneous user. The maximum available capacity per user under ideal circumstances may be very high for eg. satellite systems and coaxial cable modem systems, with up to several tens of Mbit/s. The costs associated with a network dimensioning which guarantees this maximum available capacity per simultaneous user are likely to be prohibitively high. Thus, the network is likely to be dimensioned for available capacities per simultaneous user which are significantly lower than the maximum capacity. Hence, a consistent evaluation of the different access network architecture alternatives must be based on the guaranteed available capacity per simultaneous user, rather than the maximum available capacity.

Some of the most challenging issues of broadband access networks are related to management systems and deployment of new technology. These two aspects are not treated here, but addressed in more detail in [55] and [56, 57, 58] respectively.

6.1 Wireline broadband access

There are basically four types of wireline transmission media and associated systems available for broadband access networks today:

- Twisted pair cable systems;
- Coaxial cable systems;
- Fibreoptic cable systems;
- Powerline systems.

Wireline broadband access systems are treated in more detail in [49, 59, 60, 61 and 62]. In this chapter only a brief introduction will be given. Until recently copper pair has been considered to be a significant bottleneck with respect to capacity. Recent developments of complex modulation schemes have enabled the extension of the line capacity by order of magnitudes. In the short term the main advantage of copper is a variable cost option, alleviating the need for high and risky upfront investments. DSL (Digital Subscriber Line) deployment consists of fitting DSL modems at the customer premises and at the local exchange side, and utilising the installed twisted pair base. The enhanced copper or DSL technologies differ with respect to transmission capacity, transmission distance and the number of copper pairs used. In general for the DSL options, there is a trade-off between distance and capacity [48].

The DSL system technologies include IDSL (ISDN digital subscriber line), ADSL, VDSL (very high-speed digital subscriber line), HDSL (high bit-rate digital subscriber line), SDSL (symmetric digital subscriber line) and CDSL (consumer digital subscriber line, also known as G.Lite or ADSL Lite) [63, 64]. At present only ADSL and HDSL of the broadband alternatives are commercially available, and have already been installed by several operators. VDSL and SDSL are expected to become available quite soon. ADSL Lite offers lower capacity than ADSL with a potential cost reduction obtained through simpler and more robust customer premises equipment which the customer himself may install. The concept of parallel DSL systems, called inverse multiplexing, has been proposed as a further development of DSL technology, enabling an aggregate capacity of up to 155 Mbit/s or even 622 Mbit/s and can be transmitted between two network locations by combining a set of twisted copper pairs [62].

The existing coaxial cable network may be upgraded to interactive broadband capability by the use of cable modems. A cable modem is installed at the customer premises, and the coaxial network is upgraded with return amplifiers in order to provide two-way transmission. This is commonly combined with a segmentation of the coaxial cable network into smaller segments by introduction of optical fibre cables. This is called HFC technology (HFC: hybrid fibre and coaxial cable network). The coaxial cable network segment is shared among the

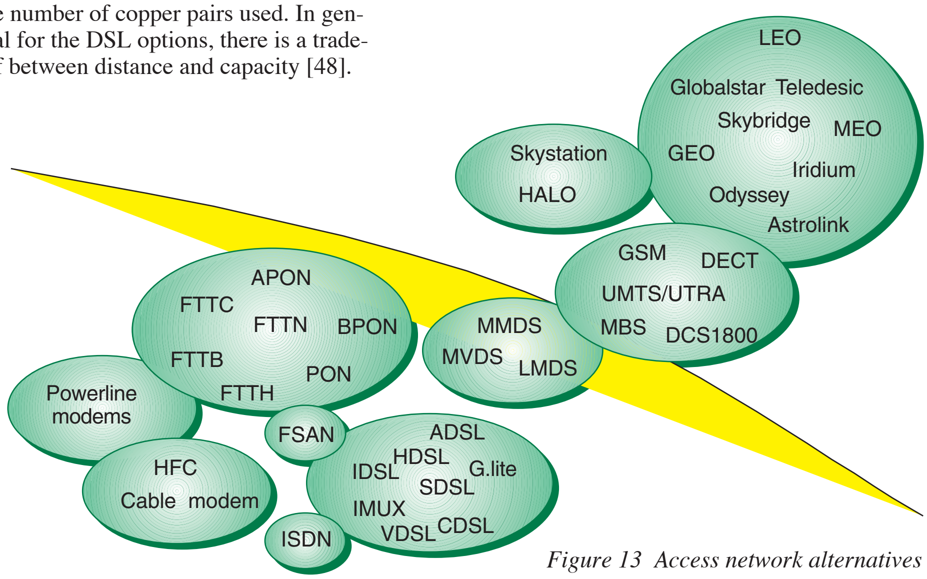


Figure 13 Access network alternatives

connected users [49]. Several hundred thousand cable modems have already been installed in North America for Internet access. AT&T's acquisition of TCI and MediaOne, and the joint venture with Time Warner may have a significant impact on the development of broadband access technology for coaxial cable networks.

Introduction of fibre in the loop (FITL) requires the deployment of fibreoptic cable. Both the associated civil works costs and equipment costs are inhibitively high at present, and only to a very limited degree have fibreoptic systems been introduced in the access network over the past years. There is a variety amongst FITL architectures regarding node configurations, ie. the location of the optical transmission terminal equipment. The most common configurations are fibre to the cabinet (FTTCab), fibre to the node (FTTN), fibre to the curb (FTTC), fibre to the building (FTTB) and fibre to the home (FTTH). Fibreoptic transmission systems are utilised in connection with ATM and SDH and may be configured as point-to-point connections, ring structures or as point-to-multipoint connections (SDH PON or BPON). The FSAN initiative, in which all the major telecommunications operators in the world are participating together with the largest equipment manufacturers, has worked out specifications for an access network based on a fibreoptic transmission in combination with DSL technology [65]. The most aggressive vendors plan to deliver FSAN compliant equipment this year.

Currently there is a significant interest in systems for transmission of data over the low voltage electricity distribution network, known as power line communications [59]. A power line modem is installed at the low voltage transformer, and an additional power line modem is installed at the customer premises. The customers connected to the same low voltage transformer share a data transmission capacity of about 1 Mbit/s. The technology may enable the power utility companies to enter the Internet access market utilising the existing low voltage electricity distribution network. Field trials have been running since 1992/93; however, power line communication will probably not be implemented on a wide scale in the short term, but may turn out to be an alternative within three to five years at access speeds of up to some few hundred metres.

6.2 Wireless broadband access

The remarkable growth of wireless communications over the past years, including terrestrial radio systems and satellite systems, has led to an increased interest in wireless technologies for broadband access [66]. The interest in wireless broadband solutions is very high at present, and a variety of concepts and system alternatives have been proposed and are currently under research and development. In the short to medium term LMDS (local multipoint distribution system) is expected to be the most relevant technology for wireless asymmetric broadband services [67]. LMDS requires line of sight. Analogue LMDS systems are available today, which utilise the 27.5 – 29.5 GHz frequency band yielding a service area radius of between 5 and 10 kilometres. Future digital LMDS systems will have higher capacity than the analogue LMDS systems. At present only pilot systems are in operation in the 42 GHz spectrum. Commercial systems are expected to be available during 1999. Currently the maturity of the broadband radio access systems lags behind their wireline counterparts, at least if significant broadband take rate capabilities are considered. Nevertheless, the broadband radio access solutions may in due time prove to be a key technology in the emerging broadband market, mainly because they enable potentially very rapid network roll-outs, low capital costs compared to wireline alternatives in sparsely developed areas, and flexibility in planning and deployment. Cell size, capacity and return channel capability are the main differentiating attributes of the wireless access solutions. However, the interactivity is one challenge of these broadcast tailored systems. The return channel may either be provided by the use of the existing twisted pair cable network, by the use of an overlaid cellular radio technology or through the use of a return channel in the high frequency band. Wireless broadband access systems are treated in more detail in [67].

6.3 Mobile broadband access

Currently the mobile access networks have very limited capability of transmitting high speed data traffic. GSM networks may transmit data rates of 9.6 kbit/s or 14.4 kbit/s. The data transmission capacity of mobile networks will be increased over the next years by the introduction of GPRS (general packet radio service), which depending on the number of time slots and the coding scheme used, may enable maximum data rates of 170 kbit/s. GPRS may be introduced without significant changes of the radio interface in the currently deployed GSM networks. The GPRS service may be further enhanced by EDGE (enhanced data rate for GSM evolution), with the potential of 384 kbit/s packet services using GSM. However, EDGE will require an upgrade of the radio interface, and may not become a reality before third generation mobile systems are introduced. At present the next generation mobile system is in the making, called UMTS (universal mobile telecommunication system). UMTS may enable several hundred kbit/s of transmission broadband capacity to outdoor mobile terminals, and up to 2 Mbit/s symmetric transmission capacity indoors. The introduction of UMTS will require the establishment of new base stations in the network, most likely with a higher density than the currently deployed GSM base stations. Mobile broadband access systems are treated in more detail in [53].

6.4 Satellite systems for broadband services

Satellite systems and concepts for interactive broadband services include geostationary satellite systems (GEO), mid earth orbit (MEO) systems and low earth orbit (LEO) systems. The satellite systems for broadband services are described in more detail in [52]. The majority of these satellite systems for wideband and broadband access are probably better suited for asymmetric, distributive and downloading services than continuous wideband or broadband services with significant requirements for upstream capacity. The lack of symmetric capability and the limited total system capacities compared to the wireline alternatives makes satellite more of a complementary system than full-scale, alternative infrastructures to the wireline systems within the next five to ten years. This is reflected in the fact that only a few of the LEO systems now under development are targeted at offering interactive broadband services in the range of Mbit/s.

The DirecPC system has been in operation from its geostationary position for some time already. Two-way Internet access is offered with a 400 kbit/s downstream capacity combined with a standard dial-up modem and ISP connection. The Motorola led international consortium Iridium put its service into operation last year. Iridium is a global LEO satellite voice and data communication system with 66 satellites. Each of the satellites is equipped with a switching system. The intention is to offer services like data, fax, paging, real-time voice, messaging and position location. The available data rate is 2.4 kbit/s. Globalstar, another LEO system, is expected to be up and running soon, with a total of 48 satellites in operation. The intention is to offer the same service portfolio as Iridium, however with a slightly higher available data rate of 9.4 kbit/s. The switching is performed at earth stations. Skybridge and Teledesic are two of the LEO satellite systems intended for broadband data services and voice. The satellite system Teledesic with 256 satellites in LEO has been designed for data rates between 16 kbit/s and 2 Mbit/s, with a design objective of 20,000 world-wide simultaneous 1.5 Mbit/s Internet links. Teledesic is planned to go into operation in 2002. The features of Skybridge are comparable to Teledesic.

6.5 Stratospheric platforms

The so-called stratospheric platforms aim at providing high capacity broadband services over a limited geographical area of approximately 3,000 km^2. The HALO (high altitude long operation) system is based on aeroplanes circulating approximately 16 kilometres above earth. SkyStation utilises high altitude balloons located around 22 kilometres above the surface of the earth. The stratospheric platforms are something in between high radio towers and satellite systems, offering potential coverage advantages compared to the former. The first SkyStation platforms are planned for operation over Rome, Lisbon and Singapore in year 2000. The aim is to provide broadband services with 2 – 10 Mbit/s access capacity. The stratospheric platform concepts for broadband services are described in more detail in [52].

7 Economics and risk

The main inhibitors for the roll-out of broadband access networks have obviously been the high capital investments required in order to upgrade the existing access infrastructure or build new access networks, and the high risks associated with placing these significant investments in a market in which future services and revenues are highly uncertain. Investment in broadband access delivery must generate positive returns, consistent with typically short term expectations of investors. The decision to invest in new technology is subject to the risks and uncertainties inherent in the competitive marketplace. Thus, identifying the key economic issues related to broadband access investment are of utmost importance. In this chapter, we will outline some of these key issues which all may have a significant impact on the overall economics, namely:

- *The investment cost level*. What kind of investment levels might be expected for various technologies deployed for broadband access in different markets and areas?
- *The service take rate*. How will the service take rate level affect investment costs?
- *Ducts and civil works costs*. What is the impact of ducting and civil work costs as a consequence of the broadband access upgrade?
- *Fibre penetration and capacity*. Given a migration towards fibre in the access network, how deep into the access network should the fibre be deployed?
- *The timing of the upgrade*. How will the required investment level change over time?
- *Revenue, payback and cashflow*. What project values in terms of cash flows and payback periods can the access network operator expect as the revenue streams from the new broadband service delivery arrive?

The costs and economic viability of broadband upgrades have been studied in several international projects. The presentation in this chapter is based on key findings from different studies carried out over the past years within the projects RACE (research and development in advanced communications technologies in Europe) 2087/TITAN (tool for introduction scenario and techno-economic evaluation of access network), ACTS 226 OPTIMUM (Optimised architectures for multimedia networks and services), EURESCOM (European institute for research and strategic studies in telecommunications) P306 (Access network evolution and preparation for implementation), P413 (Optical networking) and P614 (Implementation Strategies for Advanced Access Networks) [68, 69, 70, 71, 72, 73, 74].

The studies include extensive techno-economic evaluations of upgrade technology options, ranging from the wireline options based on DSL, ATM PONs and HFC systems to wireless alternatives like LMDS and point-to-multipoint radio access. In the studies access network upgrades are addressed both from the point of view of the incumbent public network operator (PNO), the community antenna television (CATV) operators as well as from the point of view of new entrant access network operators.

The methodology and tool developed within TITAN and OPTIMUM, and now under further development in the ACTS TERA project have been applied in the techno-economic analyses in the studies [75, 76, 77, 78]. Typically a study period of ten years is considered, including the expected price evolution of network components and development of tariff levels throughout that particular period of time. The network element costs are extracted from a database developed within the various projects. The database includes costs at a given reference year for components, installation and civil works costs. The demand forecasts for the selected bearer services for the residential and small business market as used in the described studies, are extracted from the RACE 2087/TITAN and the ACTS OPTIMUM Delphi surveys [35, 34]. The business market services and penetrations are predicted based on available statistical material. The tariffs used are European averages from the Delphi survey and other sources. The relation between penetration and tariffs – tariff elasticity – has been incorporated in the economic analysis. The effect of competition is modelled through appropriate adjustments of market shares.

7.1 The investment cost level

Initially, the range of expected investment levels for broadband access delivery should be set in absolute terms. The required investments will of course vary from technology to technology, and between markets and geographic areas. However, the studies performed all indicate a level of installed first costs (IFC) per new broadband connection which vary from just below 400 euro to between 2,000 and 3,000 euro per new connection, depending on factors like technology choice, dwelling distribution and civil work costs. In urban areas the installed first costs per new switched service connection for plain old telephone service (POTS) and narrowband integrated services digital network (N-ISDN) in the existing access network is typically in the range of 400 – 500 euro. This underlines the fact that a further upgrade of the access network probably will require huge investments for any technology selected, and that the operators will be faced with investment projects of similar or even higher financial burdens than the ones of establishing the narrowband access networks of today.

7.2 The service take rate

The total upgrade investments may be split into fixed and variable costs. The fixed costs must usually be placed initially – before the first customer subscribes, and are to a large extent service penetration independent. The variable costs are typically service specific investments such as DSL modem pairs, and depends on the take rate. The different broadband upgrade alternatives have a different cost structure with respect to required upfront investment levels and service penetration dependent or variable costs:

- ADSL upgrades in many cases only involve service penetration dependent investments, which the network operator need not take before the customer is connected. This alleviates the need for risky initial investments, although at the expense of a limited possibility for capacity offerings beyond 2 Mbit/s.
- Typically, architectures based on fibre systems such as broadband passive optical networks in combination with DSL technology incur significant upfront costs in terms of an initial deployment of fibre infrastructure, with associated risks of loss due to failing future service take up and corresponding revenues. The gain is the capability to offer capacities higher than 2 Mbit/s to the customers.
- Similarly, HFC upgrades imply upfront costs both in terms of return amplifiers and deployment of some fibre infrastructure to feed the different coaxial cable branches as the network is segmented. Also, HFC networks may in the long term provide capacities beyond 2 Mbit/s.

For both the two latter types of architectures the level of upfront costs depends on the capacity to be provided to the customers. The higher the capacity, the more fibre, and correspondingly more upfront investments are needed. The drivers for the fibre introduction are slightly different, and hence the different cost structures indicate that the effect on costs of the service take rate need to be taken into account in cost comparisons of the different technology alternatives.

Figure 14 shows the IFC per 2 Mbit/s access line for a ten year linear upgrade project, as a function of broadband penetration in 2005. Line costs are analysed for the main system alternatives for the three relevant wireline transmission media, namely fibre cable, coaxial cable and twisted pair copper cable. Results are shown for an urban, apartment block area with an average copper loop length of 400 metres between the optical node (service access point) and the buildings. The IFC for BPON, or alternatively ATM PON, in the FTTB configuration is included for two degrees of duct availability, 0 % and 100 %. The FTTB costs are plotted for each ONU serving eight (BPON-8), 32 (BPON-32), 64 (BPON-64) or 128 (BPON-128) potential customers. Please note that the potential capacity offerings to the customers are much higher for the FTTB solutions than for the ADSL and cable modem alternatives.

The alternative upgrades based on ADSL modems or cable modems both have prospects of line costs close to 500 USD for moderate take rates. The costs per line of upgrading existing twisted pair networks and coaxial cable networks with DSL and cable modem technologies respectively are comparable for take rates of up to 30 %. This illustrates the difference in the cost structure of the two alternatives. The upfront costs of the cable

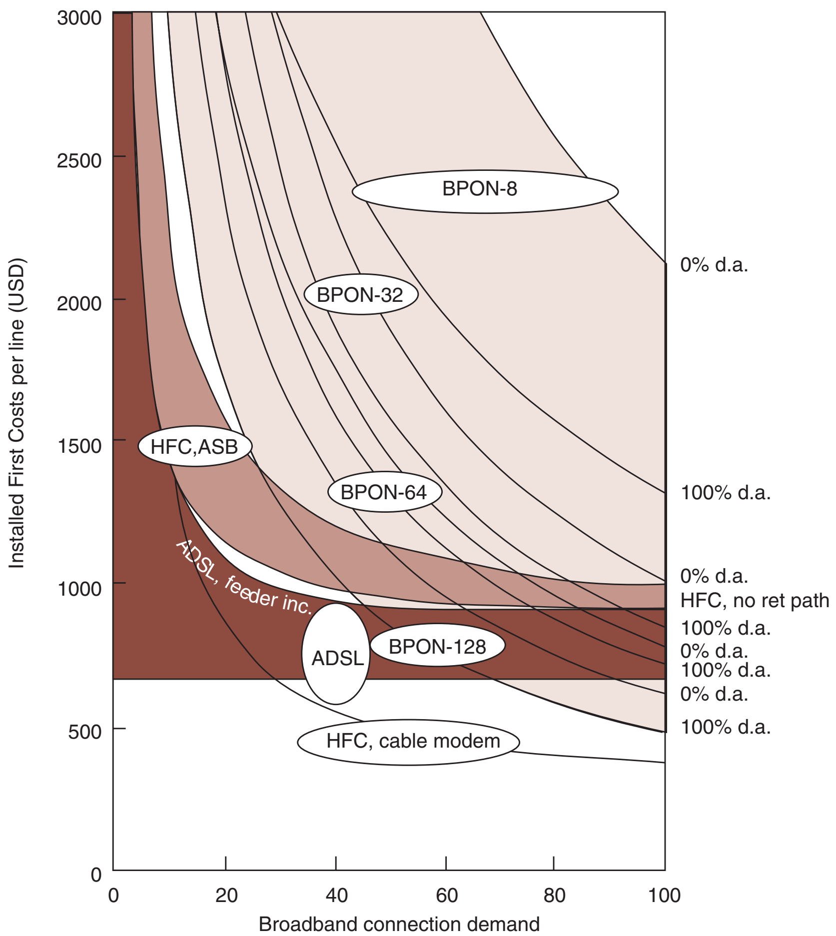


Figure 14 The cost per line in an urban area for the main wireline upgrade alternatives as a function of broadband connection demand (d.a.: duct availability)

modem upgrades are higher than the almost negligible upfront costs of ADSL, whereas the variable costs of the cable modem upgrades are lower than the variable costs of ADSL. Thus, for high service take rates, cable modem upgrades have a good potential for reduction in line cost due to sharing of infrastructure and low variable costs. Thus, for higher penetrations the cable modem technology seems to have a cost advantage, but a limitation in traffic capacity compared to the ADSL technology.

A higher degree of coaxial network segmentation or use of dedicated channel HFC upgrades, illustrated in the figure by HFC ASB (asymmetric switched broadband) or HFC symmetric switched broadband (SSB), may increase the traffic capacity in HFC networks. In the same way the twisted pair networks may be upgraded to higher capacities by the use of fibre systems in combination with VDSL, shown as BPON in the figure. However, the upfront costs increases significantly in this case, and the results indicate that the operator will have to rely on take rates of 50 % or higher in order to reach line cost levels below 1,000 USD.

7.3 Ducts and civil work costs

As mentioned in the previous section, the level of civil work costs will in many situations have a significant impact on the upgrade costs. In fact, the costs of civil works remain as one major obstacle for extensive introduction of fibre in areas with an established access network of good quality. Fibring the upper part of the access network is already likely to be cost effective in some cases, as illustrated in Figure 14 by the lower costs of the fibre alternatives with a high number of potential broadband customers per ONU. However, the lower part of the network is very sensitive to civil works costs. Fibre deployment beyond the main flexibility point in the network increases the overall costs significantly if available ducts are scarce. Some of the studies indicate that civil works costs may constitute more than 30 % of the total investment costs for high capacity broadband access network upgrades [79]. In conclusion, the costs of broadband access upgrading and correspondingly extensive fibre deployment is strongly related to civil works costs. This makes new methods for cable deployment as well as innovative concepts for utilisation of the existing cables crucial issues as the operators are preparing the business cases for broadband service introduction [80, 62].

7.4 Fibre penetration and capacity

Given the intention of a fibre-in-the-loop upgrade, the establishment of the fibre infrastructure is in itself probably a strategically more important decision than the choice of system technology, provided a system independent infrastructure is rolled out. The reason behind this is two-fold: The fact that the fibre infrastructure costs are likely to be significant and quite similar for all kinds of fibre systems, and that the difference in system costs can be rather marginal between different technological options. Secondly, the expected technical lifetime of the fibre infrastructure is long compared to equipment. Thus, rolling out fibre remains a key decision of great strategic importance in access network upgrading. But given a migration towards fibre in the access network, how deep into the access network should the fibre be deployed? This is one major question in the long term perspective for access network operators, and PNOs in particular. The recent developments in digital subscriber line (DSL) technology enable the PNOs to provide broadband capacities on the existing copper network. However, in general for the digital DSL options, there is a trade off between copper loop distance and capacity available. The cable infrastructure costs vary significantly between network areas as previously discussed, and hence quite different fibre penetration levels are likely to be seen.

This is reflected in particular in the results from a study on cable infrastructure costs, carried out in EURESCOM project P614 (Implementation strategies for advanced access networks). The analysis covers four network area types, a downtown area, an urban area, a suburban area and a rural area. The areas have been segmented and characterised according to average copper loop length in the existing access network (also reflects the density of living units in the area), availability of existing ducts and surface conditions with corresponding cable deployment type and civil works costs. Representative ranges of the characteristic parameters have been assigned to each network area segment. Figure 15 shows the asymmetric capacity provided after the upgrade as a function of cable infrastructure investment per homes passed for the four network areas. Cable infrastructure investments encompass civil work costs (digging, ducting and surface reinstatement), costs of cable installation and cable costs. The upper and lower curves in each area represent minimum and maximum levels of civil work costs.

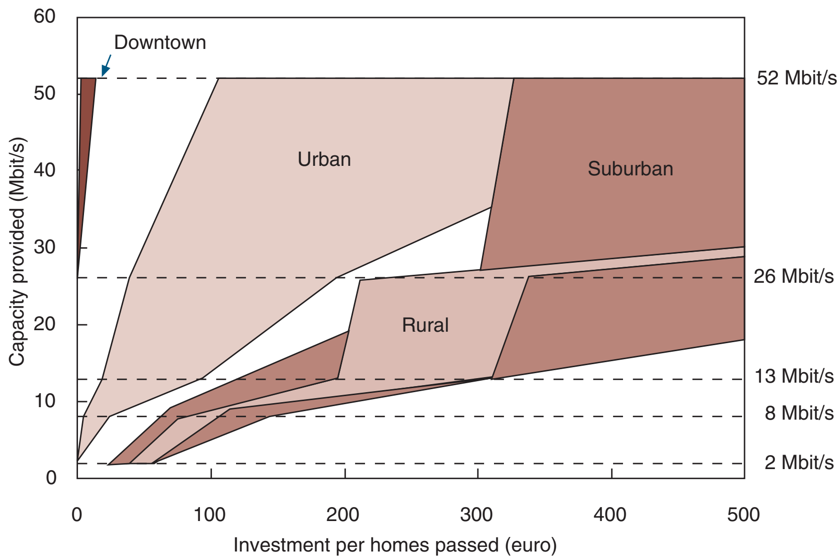


Figure 15 Asymmetric capacity provided after upgrade as a function of investment per homes passed

In general, for densely populated areas (downtown, urban and suburban areas) the investment levels required for upgrades to higher capacities have an increasingly strong dependency on the loop lengths for increasing asymmetric capacities.

The cable infrastructure cost levels presented here indicate a need for differentiating between network areas with respect to service (capacity) offerings at asymmetric capacities beyond 2 Mbit/s.

Another aspect of this is the potential capacity increase gained with additional investments on top of the initial upgrade investments, ie. a further upgrade of the network to the next higher asymmetric capacity level, indicated in the right side of the figure, eg. from 2 Mbit/s to 8 Mbit/s, or from 13 Mbit/s to 26 Mbit/s. The gain in available capacity per invested euro decreases as a function of the population density, illustrated in Figure 15 by the decreasing slope of the investment level areas as we move from densely populated areas to more scarcely populated areas. Nevertheless, for all areas the additional investments for a further upgrade of the network to the next higher asymmetric capacity level are between twice and three times the total initial investments.

7.5 The timing of the upgrade

The appropriate timing of broadband upgrading is crucial, not least in order to ensure that the operator maintains his customer relationship, but also in order to possibly reduce the investments. In some of the studies this latter aspect has been analysed in more detail. The costs of upgrade strategies involving mass deployment of residential access fibre are anticipated to become significantly lower if the system introduction is delayed enough to benefit from component cost reductions. Figure 16 shows the broadband line cost as a function of roll-out year and penetration for selected broadband PON (BPON), HFC and ADSL alternatives.

It is assumed that the indicated penetration is obtained at time of roll-out. The BPON alternatives are calculated with 50 % duct availability. The figure illustrates the assumptions with respect to cost evolution embedded in the study results. The expected decrease in cost during the next years is clearly seen.

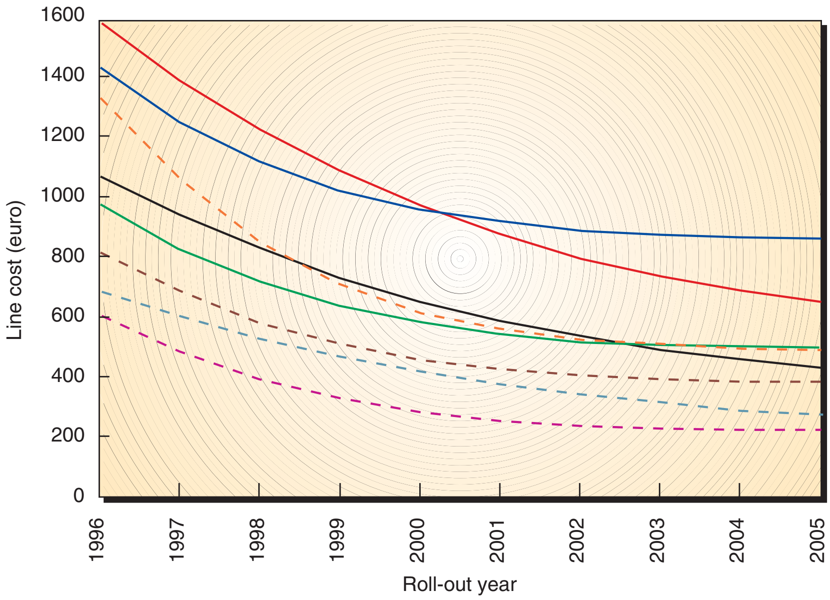


Figure 16 Line cost as a function of roll-out year and penetration

The equipment cost of the three upgrade alternatives will most likely have a quite similar cost reduction potential, as they are all emerging technologies in this market. The total ADSL line costs are expected to be reduced by two-thirds of the 1996 cost level during the ten-year period, whereas the resulting fibre and coaxial cable upgrades are expected to experience a 50 % cost reduction. The difference in cost reduction is attributed to the fact that the latter two upgrades involve civil works costs in addition to the equipment costs.

In conclusion, postponing the fibre roll-out may result in a cost advantage compared to the HFC and ADSL upgrades. In addition, prospects of future operation and maintenance savings might motivate for an extensive fibre deployment. So far however, there is no clear evidence of decreased operation and maintenance costs to offset the huge investments required.

7.6 Revenue, payback and cash flow

It is obvious that the time frame and corresponding payback periods of the upgrades to a large extent relies on the revenue levels. Figure 17 shows the payback period as a function of average annual access network related revenue per line for a ten year linear upgrade project. The payback period is defined as the period from the start of the project to the time when the cash balance (cumulative sum of the retained cash flows) turns positive. The indicated penetration is the saturation level of 2 Mbit/s asymmetric switched broadband service penetration in 2005. The BPON alternatives are calculated with 50 % duct availability. The results indicate that the cost level of broadband access upgrades is likely to be within the investment range in which payback periods in the order of five years may be expected with annual revenues per access line of 400 euro. However, it must be emphasised that these calculations are based on an early (1996) and quite extensive roll-out. A more gradual deployment which in addition is postponed in time, will require a lower turnover per access line in order to achieve acceptable payback periods. Hence, the payback periods of broadband access is likely to be in the order of five years with annual revenues per access line of 400 euro. This illustrates that access network broadband upgrades are likely to turn out to be long term projects with payback periods in the range of five to ten years.

The upgrade effects on the prospects looking beyond the upgrade period are not evident from the NPV and the payback period. The cash flows in the final year is useful as a predictor for the long term effect of expanded revenue base. With the given tariffs and penetrations all of the upgrade projects have gained strength through the broadband upgrade compared to the initial annual cash flow, ie. the final year cash flow is higher than the pre-upgrade cash flow. The results illustrate that access network broadband upgrades represent long term projects which are assumed to create future cash flows. As such, the establishment of a broadband access network platform represents a challenge comparable to the build-up of the present narrowband infrastructure: heavy investment projects with associated investment levels which in the short and medium term result in a weakened net present value. However, at the same time these investments are a requirement in order to maintain the revenue level in the long term; in other words, a necessity in order to establish an effective, broadband platform – the basis for the future "money machine".

8 Broadband access migration and strategies

The challenge for the access network operators is to derive strategies for migration towards broadband access, including evolutionary paths for either a migration of existing network infrastructures or for deployment of a completely new access network infrastructure. A discussion on the different migration paths for wireline access networks is found in [49]. The main aspects (most of which have been addressed in the previous chapters) related to devising broadband access migration strategies may be considered to be:

- The overall strategic targets and imperatives;
- The competitive situation;
- Market segments and geographic areas;
- Existing and future product portfolio;
- Development of the existing infrastructure and platforms;
- Investment profile and economic risk;
- Technology risk;
- Technology alternative performance and merits.

The definition of the broadband access network strategy depends on the *overall strategic targets and imperatives*, which for the telecommunication operators and thus broadband access operators under competition will be to optimise the net present value of the broadband access investment project(s). This very often implies minimising the risk of losses, exploiting revenue opportunities, limiting the time for return on investments, minimising life-cycle costs and minimising installed first costs. Moreover, the operator will often aim at achieving economies of scale and economies of scope [81], which are closely related to the market situation and degree of competition in the area being considered. These targets are not always easily combined in broadband access projects, and thus setting targets and accordingly strategies and decisions, are complex in the broadband access arena.

The competitive situation in the short and long term may impact *when*, *how* and for *which market segments* the access network operator rolls out his broadband access network. The impact of the competition on the operator's actual selection of technology to be used for broadband access is somewhat more unclear and may in the end turn out to be rather limited.

Market segments and geographic areas are crucial aspects to consider in working out strategies for broadband access. This is mainly due to expected capacity demand variations in the market, the local nature of the access network segment and the associated high investment levels. The capacity demands and willingness to pay of large business users are very different from the needs of residential customers and small and medium enterprises. Thus, a variation in service offer-

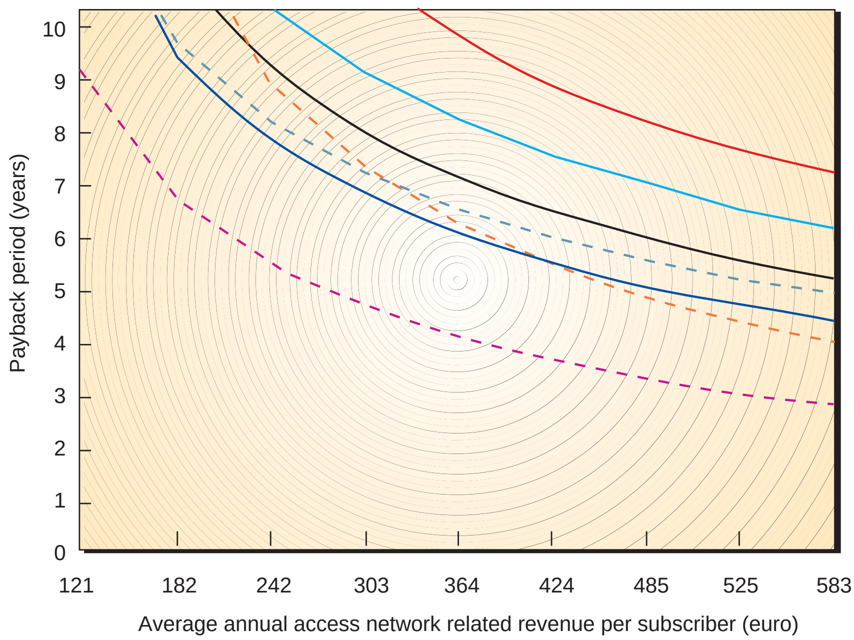


Figure 17 Payback period as a function of average annual revenue per line

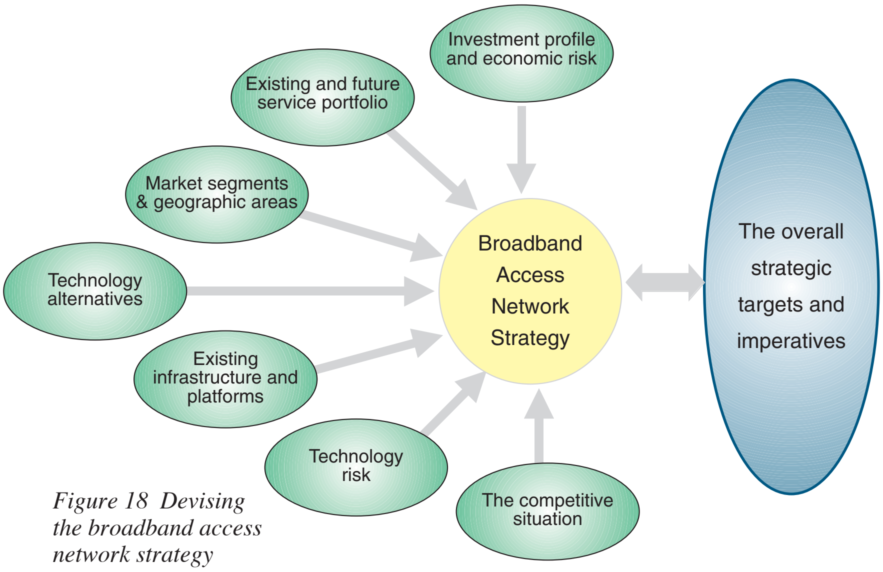


Figure 18 Devising the broadband access network strategy

ings between the market segments are needed. Furthermore, most access operators upgrading to broadband delivery will have to do a geographic segmentation of their network, mainly driven by the cost structure of the access network, with limited possibilities of cost sharing between customers and network areas. The challenge is to combine the market segmentation with the geographical segmentation.

Appropriate timing and design of the *existing and future product portfolio* is critical for broadband access network strategies, since the operator's cash flow and hence investments for the future services are so dependent on proper accommodation of the cash cow services during the migration period. On the other hand, the access network operator must avoid that competitors through their broadband access product offerings both gain customers for basic services and simultaneously win the majority shares in the new broadband access market.

Typically, the access network operator as a part of a larger telecommunications company has considerable capital invested in an existing network infrastructure, and will seek to exploit as much as possible of this infrastructure in the migration towards broadband access. Thus the *development of the existing infrastructure and platforms* is a very important criterion to take into account in broadband access strategies.

As discussed in the previous chapter the *investment profile and associated economic risk* of broadband access upgrades have so far possibly been the major inhibitor of a large-scale roll-out of such networks. In general, the operator will try to reduce the economic risk both through a gradual deployment and by increasing the share of variable costs relative to fixed installed first costs. However, the most influential economic risk will anyway be associated with the market uncertainty.

The *technology risk* is generally first and foremost associated with the maturity of the technology, and the timing of commercial available equipment in relation to planned service launches. Other general issues related to technology risks are the evolution of new coding techniques and the impact of the ongoing convergence between the broadcast, data communications and telecommunications industry. In addition there are several technology specific risks involved, such as the actual reach in operational conditions of DSL systems, the frequency licences of broadband radio access systems and the physical condition of existing plant and future increases in capacity demand connected with coaxial cable modem upgrade technologies.

And finally, the *performance and merits* of the *technology alternatives* are crucial. The evaluation of the technology alternatives must at least address the aspects of transmission capacity, quality of service, flexibility and operational stability, in addition to the economics.

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What is the willingness to pay for broadband services?

GEORG MOE AND JAN-PETTER SÆTHER

1 Introduction

The next major task for telcos is the deployment of broadband access, the magnitude of investments implies that one has to be very careful about when and where to start. For the incumbents it is a change of regime at the same time. Previously, when there was no competition, one might be tempted to argue that new technology could be deployed according to a 5 year plan without having to take care of customer needs. The old network planning offices made their forecasts based on history, in a stable market environment. Pricing was seldom based on the customers willingness to pay; rather it was based on some costing models, or set to control the demand with respect to the speed of deployment. In the present competitive environment all has become different, new operators do things differently, and pricing has become an important issue. What expectations do we have for willingness to pay for new services based on broadband access? This is the central question we are going to address here. To illustrate different aspects we will refer to a survey conducted in the Norwegian market (summer/autumn 1998).

We are not going into details regarding the results, because actual prices, elasticity values and so on are less relevant for the discussion. So we will focus on the challenges, and methodologies in our approach. But first of all, we would like to present the case; just to show why we have been doing it this way rather than another.

2 Background

The purpose of the study was to get a picture of the broadband market, before any investment in infrastructure was made. That means that the services on top of the broadband infrastructure were only described in general terms, just to give the respondent some hints of what was about to come. A major weakness of the study is the fact that the respondents hardly have any references for an evaluation of broadband services, like quality of service, distribution etc., apart from the fact that 'broadband Internet will be faster'. Price, or price level, is the only element that says something definite about the product. However, the applications described to the respondent implicitly require a given bandwidth and a level of symmetry, which gives us as researchers the possibility to evaluate the price/bandwidth ratio to some extent.

In the study we distinguish between two main 'market segments', small and medium sized enterprises (SME) with 1–100 employees and household/SOHO (Small Office, Home Office), in addition to population and business density. The main reason for this simplified segmentation is that we are looking at the roll-out of new infrastructure, we assumed that population and business density were the two most important variables for this purpose. The reason why we excluded larger companies, is that they usually have a more differentiated demand for telecomms services, in addition they are few in numbers in Norway – relatively speaking.

3 Approach

An unlimited number of factors determine the success of goods and services both in the professional market as well as in the household market, however some factors are crucial. There has to be a need for the product, and there must be a trade-off between the utility and the price and ability to pay for it. In the professional market this utility is characterised by the ability to perform necessary activities better. In the household market the utility is described by the direct welfare to the individual as final (or in connection with) consumption but also the value as signal in a social context.

Price and income are the more solid variables in terms of a quantitative approach. Even only with these two variables and a set of defined products we will see a complicated system for determining the potential demand for a new product. Substitution and complementarity, dynamic effects, time budgets and product hierarchies are in short terms examples of the complexity in this field.

Because we were investigating the roll-out of new technology in the local loop, in a new competitive environment and looking at products not very well interpreted among most of the customers we needed a methodology to analyse the market. We needed both a 'general understanding of the future' and a way to quantify this future. Needless to say, the future situation has many possible outcomes, so we had to choose a set of scenarios.

In order to get the general understanding of the future we had a look at what consultants at Ovum, Forrester, Analysys and Telenor Research & Development had written about the future in addition to other relevant literature [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24]. From that a couple of scenarios were designed.

For the quantitative part we made two sets of questionnaires, one for each main segment. For the SME market we had a traditional approach, about 1000 companies were contacted. The person responsible for IT in the company was asked. Because these people are mainly oriented towards the near term challenges we limited the future time horizon to three years. They were asked about current and future telecomms and IT preferences and spending patterns, in addition to their willingness to pay. Regarding their willingness to pay we tried to distinguish between fixed and mobile broadband access (main focus on the applications level). We analysed the responses, and made our own forecasts based on the expressed willingness to pay, and our perception of how the market would develop.

For the residential market we performed a Delphi survey, where several experts answered a questionnaire. Due to their 'expert nature', the time horizon was defined to 15 years. The SME and Delphi survey are not completely compatible, because the experts were asked to make forecasts on their own. These forecasts may be inconsistent with their perception of what people in general are willing to pay.

4 Broadband applications

It makes little sense to talk about willingness to pay unless one says something about the applications involved. The applications do in fact play a major role regarding the deployment strategy. If the applications require some sort of critical mass of subscribers, then you would expect some heavy initial investments to cover a broad area. Otherwise one would expect a more selective approach, where the expected utilisation of the network is higher.

In our study of the SME segment we made a ranking of applications, based on a short-term interest (one year from now) and a longer-term interest (three years from now). The following applications were involved:

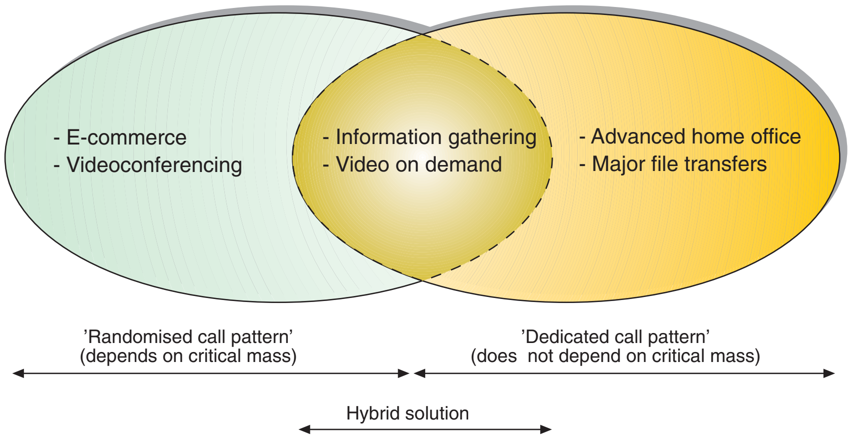

Figure 1 Categories of broadband applications

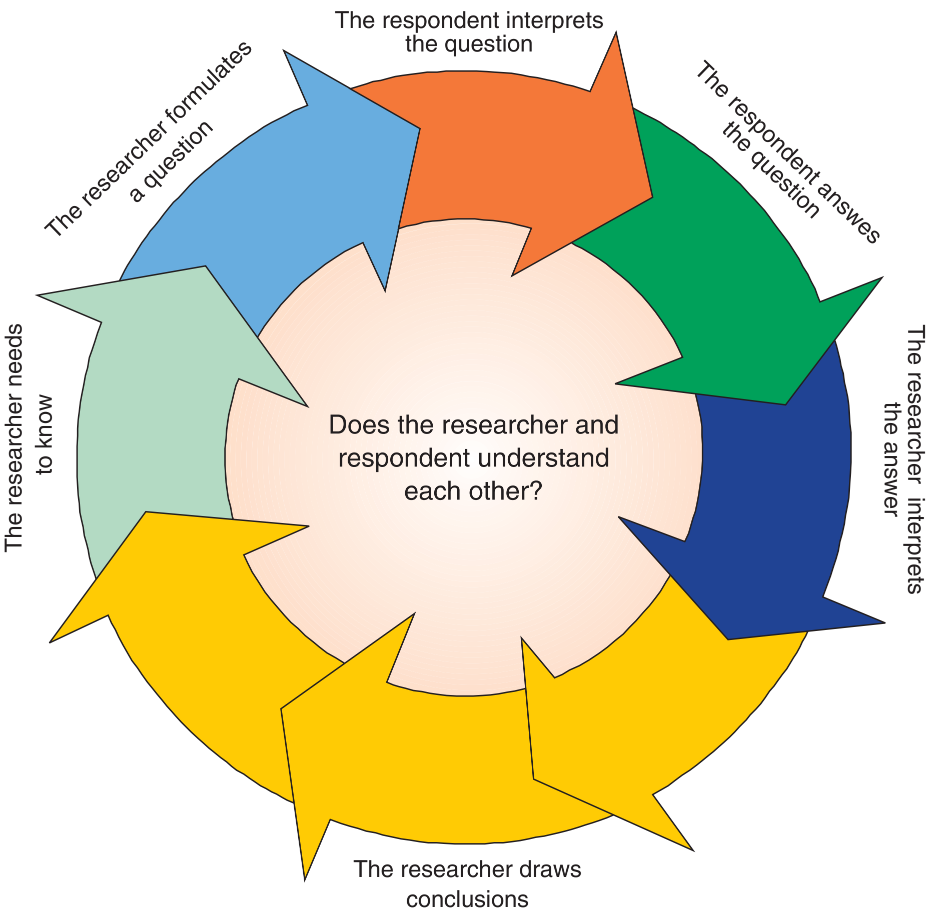

Figure 2 Communication between respondent and researcher as context-sensitive in the interpretation process

- E-commerce (providing this for customers, *and* as a tool for ordering from the suppliers);
- Video on Demand;
- Advanced home office;
- Major file transfers, related to outsourcing (symmetrical bandwidth);
- Information gathering, related to Internet and multimedia (asymmetric bandwidth);
- Video conferencing.

Within all segments the 'most wanted' applications were:

- 'Advanced home office': semi randomised demand, both in terms of bandwidth symmetry and time of day;
- 'Major file transfers': needs for symmetric transmission, mainly at given points in time (outsourcing);
- 'Information gathering': randomised demand with respect to time of day, asymmetrical bandwidth.

Interestingly enough, these applications do not require a critical mass of subscribers from a network deployment point of view. Initially this is important, because the equipment needed will be expensive. As the equipment prices fall, one has the possibility to provide the 'randomised' customer with cost effective services. Figure 1 indicates how we categorised various applications.

For the SME segment this categorisation helps us somewhat to understand the responses in our survey, at the same time it creates some sort of confusion. Let us start by looking at the confusing part.

The problem did arise during the interpretation of the results of the questionnaire. We may ask a series of questions, but it is not necessarily so that the respondent has the same understanding of the questions as we have. One might say we have a chain of misunderstanding and misinterpretation as indicated in Figure 2.

The importance here is that we were too optimistic about the willingness to pay, initially. The respondent may have interpreted our questionnaire so as to say that all the described applications of interest were available from day one, and the respondent did not make any distinctions whether the applications are suitable for randomised call patterns or not. Finally, the respondent may express a willingness to pay, based on the expectation that everybody else has access, and use applications that require broadband access. So, we ended up saying that we do not immediately believe in the respondents' willingness to pay, therefore we had to modify results that indicate willingness to pay in order to make forecasts.

Having estimated the demand curves, we made a major correction downwards in our forecasts the first couple of years, because we do not expect to be able to cover the whole market from day one anyway.

From the researchers' point of view there is another element complicating the interpretation of the expressed willingness to pay. The problem is of a fundamental nature when estimating demand functions/curves, and is related to the problems mentioned above. Depending on how one approaches the estimation of demand curves, one may find a model that describes the data well, but the resulting function does not necessarily describe the demand in the market. Suppose we have an estimated (and generalised) demand function like the one in Figure 3.

This aggregate curve is based on the answers of all the respondents. But, the respondents have given their answers based on what they perceive the supplied product/service is. Instead of being just another respondent among other respondents, they may just as well be a representative of another subset of potential customers with a completely different demand behaviour (perhaps because they perceive the supply side differently). The demand curve shown is just an average based on all respondents within a segment as defined by the researcher. The actual *set* of demand curves may as well look like shown in Figure 4 [29].

One could argue that we have not defined our segments properly before estimating the demand curve. However, the cost of the study would increase to prohibitive levels if all kinds of segments were defined and taken care of. In addition, one has the problem regarding what the respondent thinks about the supply of products and services. Failing to realise this can have serious consequences with respect to the estimated price elasticities. The estimated demand curve may indicate a price inelastic demand, whereas the actual demand curves represent a price elastic demand, all other things equal. The distinction between price elastic and inelastic demand is crucial in a competitive environment (Figure 14).

A lot of these problems have to do with the fact that few people outside the telcos and IT industry have an understanding of 'broadband services'. They do not exist today, and it is difficult to relate to something you do not know about, and probably even more difficult to express a willingness to pay.

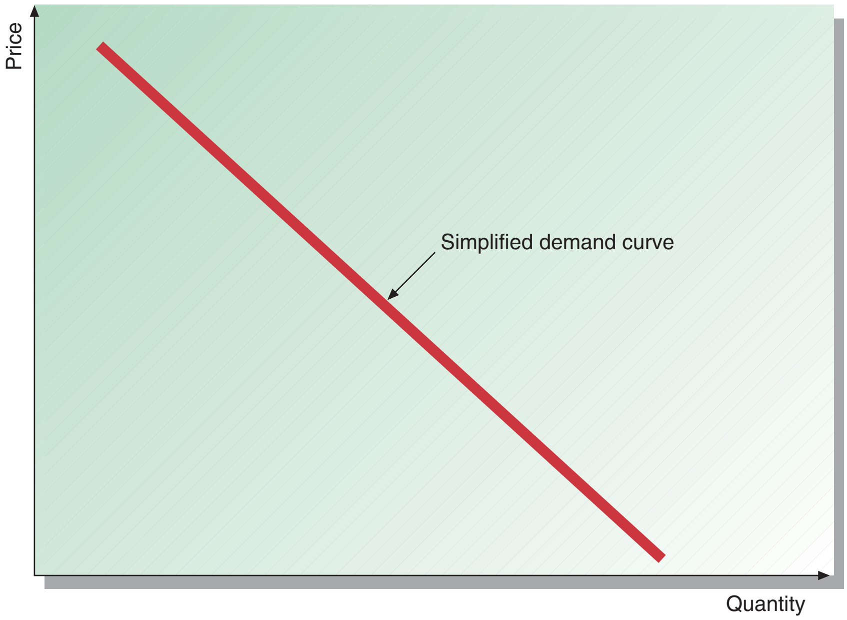

Figure 3 Simplified demand curve in the price-quantity dimension

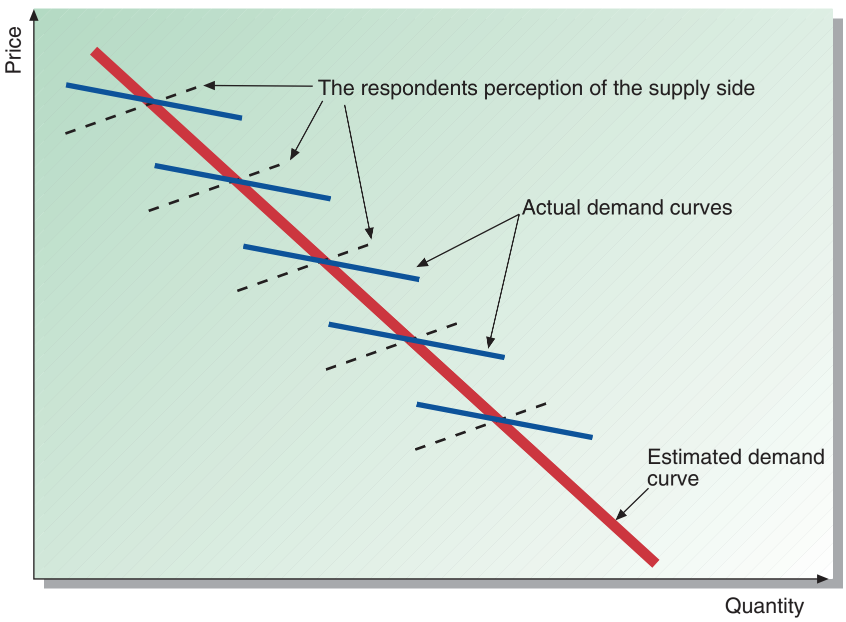

Figure 4 Possible underlying perception of supply curves, individual demand curves and a misinterpreted estimate of a demand curve

5 The complexity of demand

To indicate the complexity of demand, let us consider an individual's consumption. Using one of the simplest models possible including prices, income, a set of n commodities and a utility function with substitution gives us a set of equations with $((n(n + 1) / 2) – 1)$ degrees of freedom, which is the minimum number of elasticities that have to be estimated empirically, ie. a considerable amount. The price elasticity of for instance telephone usage is defined as the relation between the relative change in demand for an infinitesimal relative change in price $((d \log(x) / (d \log(p)))$, or as a practical approximation the change in percent of the quantity (minutes) for a one percent price change. The cross elasticities are in the same manner defined as the change in percent for a commodity when the price of another commodity increases by one percent. The income elasticities are defined as (approximately) the percentage change in demand for a commodity, as a result of an income change of one percent. All relations indicated could be estimated by varying the prices and incomes in a controlled manner, however a market economy would not allow such an experiment.

The smallest change in the model indicated above to simulate a market oriented economy should be the introduction of new products in the market and the deletion of obsolete products, ie. a more dynamic approach of the indicated framework. Here a crucial question is how new products comply with the customers' taste, their utility and their ability to afford them. How do new products interfere with the existing line of consumer products and the pricing of these products? In a short description we would suggest the following: A new product tends to be priced according to its uniqueness (however in the telecommunications world so far recovery of sunk cost is an aspect that has affected the pricing scheme). A unique product with the potential of conveying a high degree of utility to the customer is ordinarily highly priced in the introductory phase. As competitors offering the same or a very similar product approach there will be a competition in which price tends to be focused. Price and income elasticities tend to be high, which in effect boosts demand when the prices are decreasing. Total revenue for the product in question increases, and at the same time developing costs are being recovered. In turn new suppliers are entering the market and the product tend to be a so-called commodity, a standard product with many competing suppliers. The price will decrease continuously during this process, so also the value of the price and income elasticities for that particular product. For a price close to zero, the price elasticity will also be close to zero, ie. a further decrease in price will not have any remarkable effect in the demand. Typically the traffic per telephone line per day has been at a level of 25 minutes per subscriber line in USA. The level in Europe has been between a half and a third of that level, to a high extent reflecting that zero-priced local traffic (ie. flat-rated) has been more prevalent in the US than in Europe, where the main principle has been to use traffic-based tariff paying per minute or per pulse in addition to subscription tariffs. If the price is zero, the equilibrium level of minutes per telephone line per day will be finite. In practice we must accept to use rather rough estimates for elasticities.

Let us start with some general results, based on the literature studies. The results have been categorised according to the segments we use and a time scale in Figure 5. In the SME study we discovered that applications related to home offices were perceived as very interesting, which at the same time raises the question as to how to describe the 'residential' market. As long as the residential market only focuses on 'residential applications', like games, music on demand, or video on demand, then the picture is 'clear'. But, the concept of the home office is based on professional applications (and the company is paying). However, given that the broadband access is in place at home (for professional use), then there is no reason why it cannot be used for entertainment. This raises some questions regarding price, distribution and quality of service.

One of the conclusions of our study was that there is a big difference in the willingness to pay for broadband access between the SME (between the smallest SMEs) and household segment, all things equal. So, the non-price variables need a lot of attention. As mentioned earlier, the main purpose of our analysis is to focus on how we were going to deploy new infrastructure; the willingness to pay would then be average annual price levels within each of the mentioned segments.

6 Results from the SME market survey

Different models were tested with the retrieved data, indicating that a log-linear one was matchless in producing good test values. The model specification is as follows:

$x = Ap^b$ which can be derived to
$\ln x = \ln A + b \ln p$,

a format suitable for using linear regression in order to estimate parameter values. The number of accesses is represented by x, p is the price per access per year, A and b are parameters estimated in the model. b will implicitly represent the value of the price elasticity, which is ranging from –0.3 to –0.6 for the different company size segments; ie. from a certain level a ten percent price reduction would increase the demand for accesses by three to six percent. In other words broadband access is inelastic with respect to price, which seems to be in conflict with the assumption that unique new products should be very elastic with respect to price.

We have already mentioned in this article that the life-cycle of a unique product that gradually becomes a commodity as time elapses is characterised by a high absolute value of the price elasticity in the initial phase. The price elasticity will decrease as the price decreases and output increases. This is obviously in contrast to the results from the customer survey, which indicates a constant and low absolute value of the price elasticity. On the other hand we have indicated that the assumption of an aggregate demand curve that represents the whole market might be incorrect. Furthermore the answers could be tactical in the sense that customers might want to move the prices to a convenient level through their response. Last but not least, the customers might not have the realistic idea of the utility of broadband access due to the fact that computers/terminals today seem to run sufficiently well on narrowband services in combination with compression. However, increasingly powerful end-user equipment tends to fill increased capacity as it approaches. Figure 6 indicates demand curves for 2 Mbit/s access for companies of different sizes and price levels.

	Present		Near future	Future
General comments	Applications for wireless access exist. Only a price matter.		- ISDN is still increasing, but revenues per subscriber is falling. - Huge investments regarding digital entertainment and shopping. - Wireless access could be the technology of choice for new entrants. - Wireless access is also considered as complementary to fixed access, not a substitute.	ISDN has reached maturity. Internet is the primary reason why customers switch technology and operator. - VDSL in early stages.
SME		- Media, finance, travel agencies in addition to business related to consumer electronics are probably early adopters.	- Cable modems are not regarded as interesting for SMESs. - ADSL is considered as a better choice. - Wireless is not considered as a real choice.	
SOHO		It is critical for the network operator to gain access to the SOHO and residential market.	- Primary segment for ADSL. - Plug & play is essential for this segment. - Wireless only for certain applications.	
Residential	Cable modems have limitations.	It is critical for the network operator to gain access to the SOHO and residential market.	- Cable modems become mature. - ADSL only for densely populated areas. - Plug & play is essential for this segment - Wireless only for certain applications.	ADSL has a huge potential in this segment, but faces fierce competition based on other technologies.

Choice of distribution channels will be essential

Figure 5 Market segments and distribution channels at present and in the future

We have made a presupposition regarding the market adoption rate. If the results presented in the curve in Figure 6 should be converted directly into forecasts, initial demand in the year of introduction would constitute about 50 percent of the demand in the final year of the study, which surely is quite unrealistic. Market adoption rate is not very predictable. Therefore we have made a judgement of such a rate since it will take time for the companies involved to adopt broadband access. There are different reasons for this, eg. that company planning, technology platform restrictions etc. will be obstacles for the immediate demand. The adoption curve is presented in Figure 7.

In addition we have made a judgement of historical values for the prices of data communications services network components and Customer Premises Equipment (CPE), which indicates that data communications will tend to have an annual decrease of about 15 to 20 percent per year. This seems to be a realistic judgement according to historical figures. With the proposed assumptions, a delayed adoption rate and a considerable decrease in the price of broadband access, the estimate of the total market penetration is presented in Figure 8.

The results from the survey may be transformed to total market revenue for the broadband service in question. An earlier estimate of the degree of bandwidth migration was completed by the use of what we could denominate a 'calibration model' [25]. The calibration model was applied for estimating access network capacity, and it indicates a much higher absolute value of the price elasticity than what was derived from the user survey and the model applied to it. The elasticities from the 'calibration model' should, however, be interpreted as 'quasi-elasticities' which are composites of elasticities and technical trends. Both values exceed three in absolute numbers. That model was based on the simple assumption that the demand for data communications capacity in the access network depended on the price of data communication

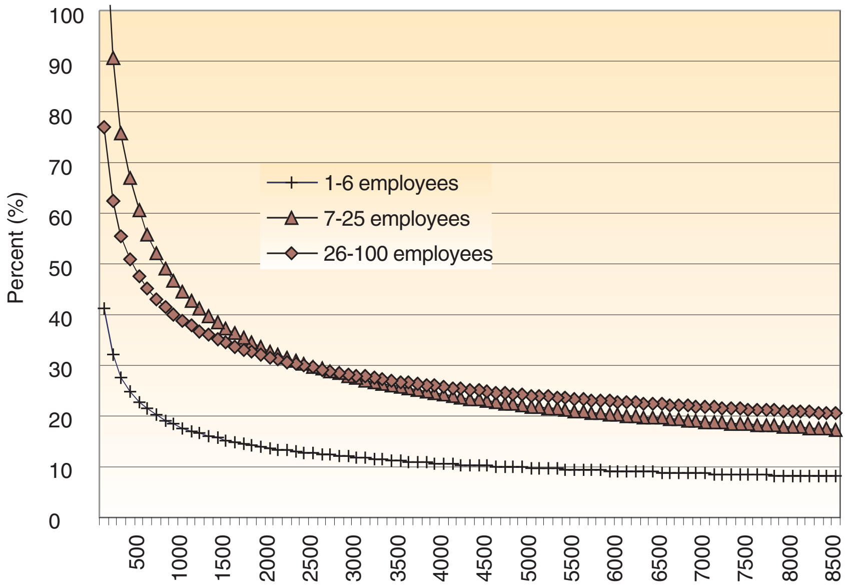

Figure 6 Percentage of companies indicating adoption of 2 Mbit/s broadband access for different price alternatives

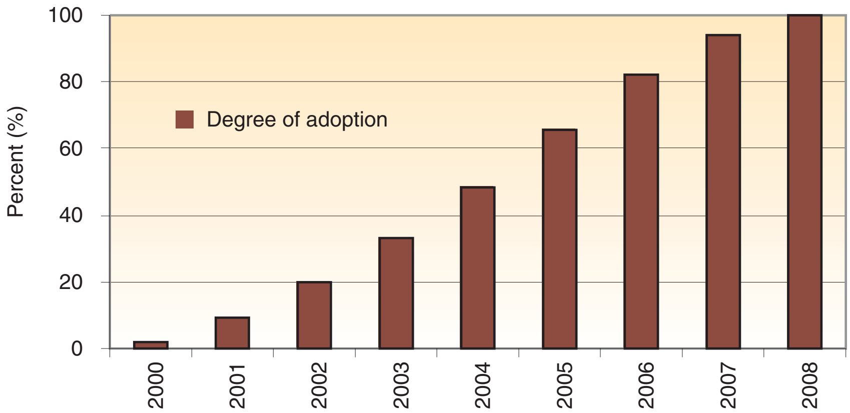

Figure 7 A tentative adoption curve as a correction for demand curves derived from user survey

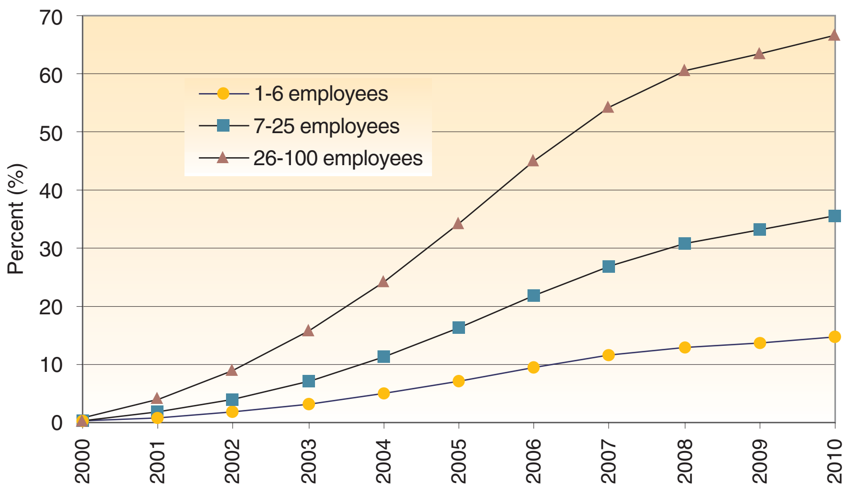

Figure 8 Penetration of broadband access (2 Mbit/s) in companies of different size (introduction in year 2000)

access (weighted index) and gross domestic product (GDP) in real terms as in the following relation:

$$dq_{t+k} = q_t \left[e\left(\frac{dp_t}{p_t}\right) + E\left(\frac{dr_t}{r_t}\right) \right],$$

in which q, p and r represent total data communications access capacity (q), price for data communications services (p) and GDP (r). e and E represent quasi-elasticities for price and income including technical change. t represents time and $t+k$ represent the time lag from a change in either price or GDP before the market responded, typically 1.5 years. Historical annual figures from 1980 to 1993 were used in the calibration process, and to a very large extent the calibration model was able to reproduce historical figures. This is no proof for the validity of the model, however there is reason to believe that price and income to a large extent explains the demand for non-voice communications capacity for the time period from 1980 to 1993. This is illustrated in Figure 9.

Revenue estimates based on 1) the survey among small and medium enterprises, and 2) the ‘calibration model’, give results as presented in Figure 10. Despite the quite different approaches chosen, we have constructed two time series of revenue figures for the Norwegian market in which the calibration model should represent the *total* non-voice communications market, while the user survey only includes the market for 2 Mbit/s access, which is part of the total non-voice communications market. The results from the two methods seem to support each other. In the final year the results from the calibration model indicate an approximately four billion NOK revenue which is one third of the total fixed telephone revenue today, not necessarily exaggerated. The results indicate that a possible value of the 2 Mbit/s market will be 700 million NOK in 2007. If we assume more than one access per company among the larger companies the 2 Mbit/s market might be considerably larger, up to 1.6 billion NOK.

The user survey included a question about the potential demand for applications that need support from 25 Mbit/s access, however the response to that question was low and did not logically make any sense. In Figure 10 an indication of higher bandwidth revenue is plotted in order to parallel the trend of the total revenue in non-voice communications. There is no reason to believe that the total market for broadband access will slow down after 2007.

7 Results from the residential market studies

In our study for the residential market we used two different approaches, one based on a Delphi survey and another based on how much a consumer spends on telecom, newspapers, entertainment and related applications. These two approaches were used in order to examine the presence and level of consistency.

A very timely question, if not always given too much attention, is how much time we will spend on different new goods and services. An increasing diversity of products is introduced in the market. Consumption takes time, therefore the use of time for every activity involving consumption of goods and services should be analysed in order to see whether there is a trade-off between the different factors. Attempts have been made at introducing a general theory of the economics of time, for instance as presented in [26]. *Time* for the consumption of goods and services is in [26] explicitly introduced in a model including prices and income as well. As we have already indicated, the simplest possible models including price, income and a utility function are rather complex. A model including time will be even more complex. As far as we have experienced, nobody has made estimates of price and time elasticities using such an approach. However the concept is theoretically very valuable in understanding that to focus on price alone is an oversimplified approach. An inquiry into this field was made by [27].

'The principle of relative constancy' tells us that the spending on media compared to the total of consumer spending is more or less constant [28]. In the USA this relationship has been more stable than in Norway. The spending on telephony has increased somewhat in Norway in the last few years, even though the prices have been reduced quite a lot. The increase can be attributed to the tremendous increase in cellular telephony and the growth of the Internet. The Internet has probably another consequence: migration from other media towards the Internet. In addition the Internet may change the valuation of time. Instead of spending a lot of time searching for something in certain shops, why not save time by accessing similar shops on the net. Some people might even accept a higher price, given that they save time. Figures 11 and 12 indicate spending patterns in Norway and USA, respectively.

The fact that the level of spending on media related applications is fairly constant is important, because it tells us that there are some important limits as to how much we are willing to spend on new services. The new applications have to be

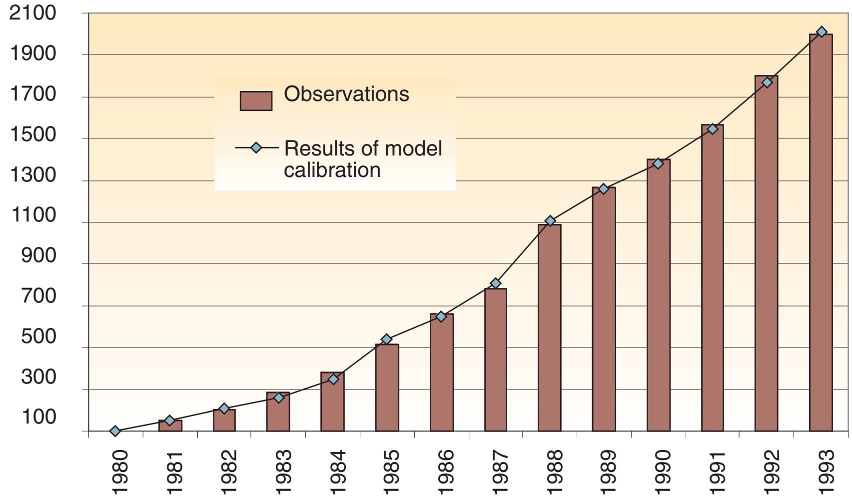

Figure 9 Demand for access capacity in packet and line switched data networks and leased lines 1980–1993. Observed values and calibrated values according to the model described above

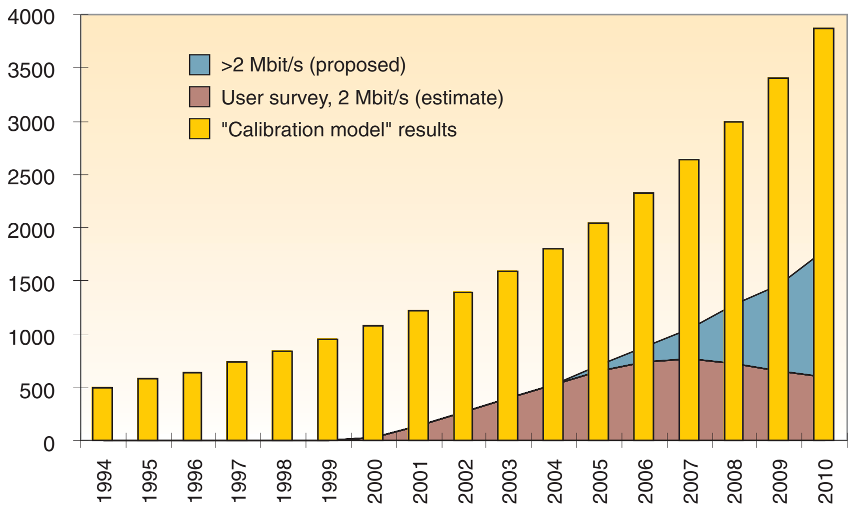

Figure 10 Total revenue from demand for access capacity 1994–2010 according to results from the 'calibration model'. Estimated revenue from demand for 2 Mbit/s access according to results from user survey. Proposed revenue from demand for bandwidths beyond 2 Mbit/s. (The input in the calibration model for annual price reductions is 15 %, similar to survey based forecast. The GDP in the calibration model is assumed to have an annual growth rate of 2 %.)

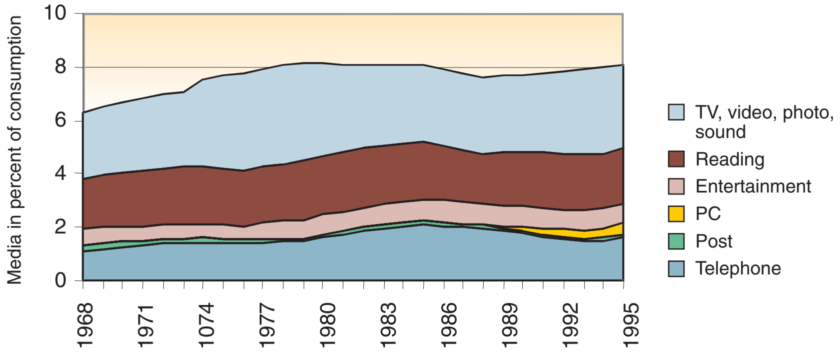

Figure 11 Media expenditures in percent of total expenditures, Norway 1968–1995. Source: Statistics Norway (SSB)

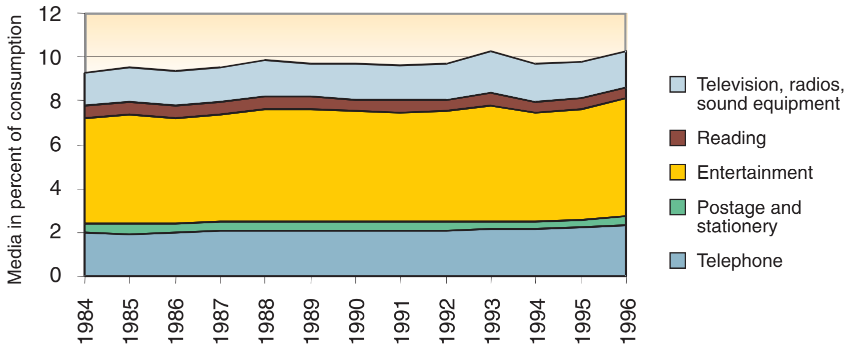

Figure 12 Media expenditures in percent of total expenditures, USA 1984–1996 Source: Bureau of Labor Statistics (BLS, USA)

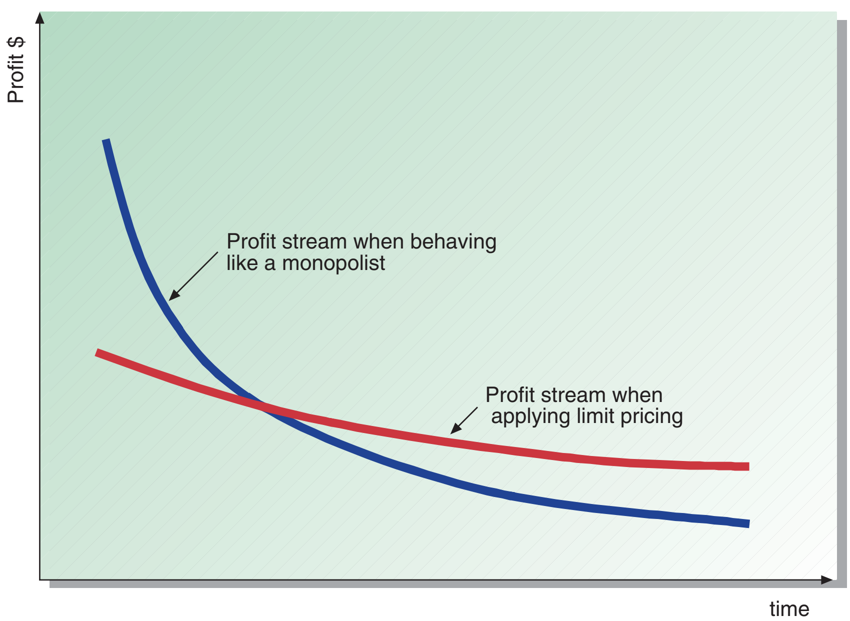

Figure 13 Pricing schemes depending on strategy and opportunity

perceived as so valuable to the customer, that the customer is willing to shift some of his/her expenditure from old and proven applications to new ones.

In the home office case this might be viewed from a perspective where the customer (company and/or employee) is willing to substitute the demand for transportation to and from the office, to telecomms related demand. This is a possible migration where 'media spending' is increased relative to other costs. The important question here is whether the employer and/or the employee will benefit from a positive payoff in terms of time and money when telecommuting substitutes physical transport.

From an isolated point of view a new product might seem very profitable or attractive because it allows high prices. But it should be viewed in the light of possible substitution effects, and how much the public is willing to spend relative to their total spending.

8 Price elasticity

The classic approach to decide upon short-run profits is to find where marginal revenue equals marginal costs, which is not quite valid in the telecomms industry. Such a solution may not necessarily maximize the long-run profits, or shareholder wealth. Assuming that the market can be described as monopolistic, one would expect prices to be relatively high (when compared to a competitive market). By keeping prices high and earning monopoly profits, the monopolist encourages competitors to enter the market.

Instead of charging prices that maximize short run profits, one may decide to engage in limit pricing; where the new price is lower than the monopolistic price. It is difficult to determine the correct price, whatever that is. Without delving into the subject, it does focus on competitive intelligence; how do you assess the threats and opportunities in the market? [29]

The following elements have to be considered when looking at limit pricing (Figure 13):

- High initial price, followed by a rapid decline (assuming initial monopolistic behaviour);
- Lower initial price, followed by a slower decline (assuming limit pricing).

In order to compare the approaches one has to calculate the net present value of the potential profit flows generated by each strategy. In turn, this implies that one has to decide upon the discount rate. Choosing a high discount rate will place higher weight on near term profits, and lower weight on profits further into the future. The discount rate should be high when the company expects a lot of risk and uncertainty in the future.

Our study of the SME segment resulted in a wide range of price levels, ranging from more than 10,000 USD per month to about 10 usd per month in the near term. We made a couple of scenarios regarding the level of expected competition for given price levels. In each scenario we made an assumption about the expected annual price reduction. Our final forecasts have been based on an annual price reduction of about 15 %. The question then remains as to which expected price level we choose when deciding how to deploy the new infrastructure. But it is quite obvious that Telenor has adopted some sort of limit pricing. After all, we will face competition from at least two other local loop operators in the most attractive areas, using cable modems and power line modems (or even wireless).

The results quite surprisingly show that price elasticity was less than |1|, which is less than favourable if one expects a very competitive environment. Revenues decrease as price falls, see Figure 14.

This fact does make it a bit difficult to determine a fair initial price level. But, the price elasticity in this case is a fairly complicated matter. There are a lot of unknowns which should be subject to further analysis. After all, what is meant by price elasticity in this context? What happens when new applications are introduced? The utility of broadband services may increase as more applications are offered and more customers start using them, and thereby generating shifts in the demand curve. In our study we have not made any distinctions between the *willingness to adopt* broadband services as a function of price level and the *willingness to use more* applications or spend more time as prices change. When isolating these effects of price levels, we can find another type of function that describes our observations. These new functions might indicate that there is an elastic demand with respect to price, or that some components are elastic, whereas others are not. As already mentioned, the study reported in [24] concludes with an elastic demand with respect to price for data related applications and access, which seems more logical. Some of that knowledge has then been incorporated in our study as a sanity check of the results from the survey among SMEs.

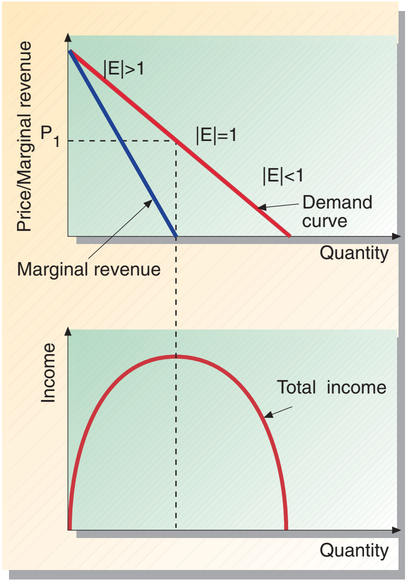

Figure 14 The relation between the price elasticity and the revenue

9 Setting the price level

Introducing broadband access services (based on ADSL technology) to the existing line of telecommunications services will raise questions such as:

- What price should we charge for that service (minutes, capacity, transferred volumes in bits)?
- How many customers?
- What traffic volumes should we expect (traffic volumes should be realistic)?
- Will revenue recover costs?

Due to the fact that network electronics could have a considerable annual price decrease, the question of optimal year of investment is also important for a relatively small operator like Telenor, which only to a very limited degree may impose producers to large-scale production with resulting low prices on components. The potential customers will be asking:

- What is in it for them?
- Is it acceptable to add another time-consuming activity to the existing, or maybe is there a potential for saving time?
- What is the price (or time saving benefit)?

Asking potential customers for their willingness to pay for a product or a ser-

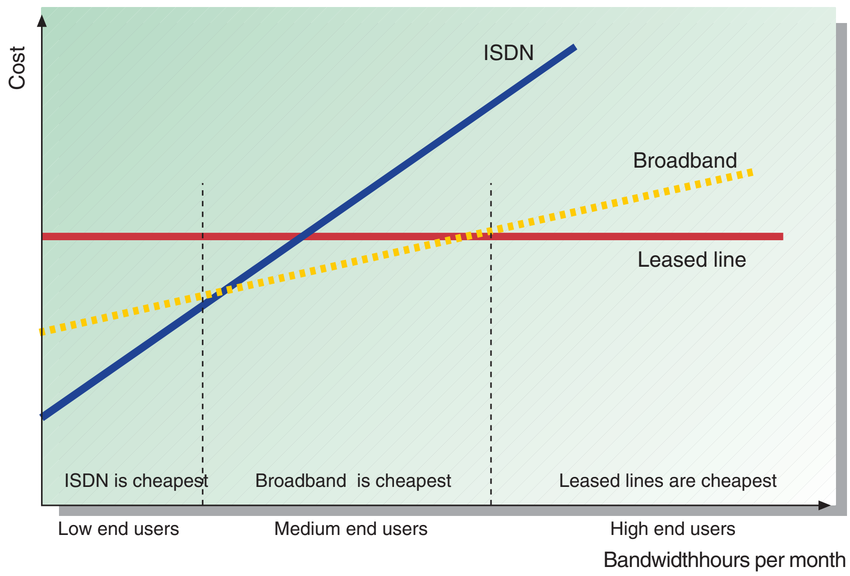

Figure 15 Cost and price structures for ISDN, broadband and leased line

vice they have no experience in using might be a hazardous basis for making a business and roll-out plan. On the other hand there are few, if any, feasible alternatives except for a general and qualified judgement. A recent service introduction in the UK might serve as an illustration: Telepoint in the UK was based on CT2 'cordless telephony' standard. In the late eighties four operators were licensed to introduce a public cordless telephony service – Telepoint or Phonepoint. The service handled outgoing, though not incoming calls from a 'telepoint' base station within a range of 100 metres. At least one of the operators made a comprehensive market survey for the service, including demonstrations of a dummy and thorough interviewing of potential customers. The demonstrations and interviewing took place in subway terminals, railway stations, etc. A pricing scheme was also developed according to what the respondents indicated about willingness to pay. The prices indicated by the respondents were fairly high. It turned out to be more base stations than customers when the expectations to the service began to erode. Thoroughly performed market surveys might very well fail. Success histories are often referred to, the unsuccessful ones are harder to trace. However, the telepoint type of services has been successful in Hong Kong and Singapore, among other things due to dense population and relatively few public phones.

One way to establish an initial price level is to perform a substitution analysis. For the SME and SOHO segments it is natural to look at the price/performance levels of ISDN and leased lines relative to usage per unit of time, or bandwidth-hours. In Figure 15 it is assumed that ISDN has a fairly simple cost structure for the customer. However, one has to take into account that the call duration per call may differ, and hence the slope of the line. Our simplification is based upon an assumption that the underlying traffic consists of large amounts of data, and therefore we have assumed a long duration per call (on average).

When looking at alternative local loop infrastructure, the customer has the following choices:

- Randomised call structure, low bandwidth: ISDN;
- Fixed call structure, high bandwidth: Leased lines;
- Semi-randomised call structure, medium/high bandwidth: xDSL.

Our basic assumption is that the price level for ADSL has to be somewhere 'between' ISDN and Leased lines, depending on usage patterns measured in hours per day or month. In addition one has to differentiate between the demand for switched and non-switched traffic. It is difficult to make such comparisons, but the points made are illustrated in a fairly simple way in Figure 15.

The low end user is assumed to spend few hours and have limited needs for speed, and therefore ISDN will suffice. Further up the road, be it either more hours or higher speed requirements, ADSL or similar technologies will satisfy the user. Larger requirements are solved by leased lines. In order to achieve this structure it seems natural to have fairly high subscription prices, and a variable price component based on time and/or data volumes.

From the customers' point of view it is more or less irrelevant whether the name of the access technology is ISDN, xDSL, cable modem or whatever. The bandwidth requirements will probably vary according to the tasks that are being performed. Let us consider the home office for a moment. Most of the tasks performed at the home office do probably not require a high bandwidth. But a few tasks do require a lot of it. The following generalisations might be useful:

- Ordinary tasks, like writing, making phone calls and sending faxes are not critical in terms of bandwidth;
- Work group document processing and video conferencing in particular do require high bandwidth;
- Information retrieval/huge file transfer may require high bandwidth;
- Work preparation and completion may require high bandwidth.

Within this context it would be reasonable to focus on bandwidth on demand rather than the use of a specific access technology. The access technology does only provide the user with the possibility to have a better peak performance, most of the time a lower bandwidth will suffice. At the same time this will probably reduce the network load and thereby reducing network costs. However, the local loop will be more expensive. Instead of having a relatively high price level for new broadband services, and a relatively slow penetration speed in the market, bandwidth on demand may give the opportunity to add a price premium if it is charged according to usage, and still be attractive to more customers. Stretching it a bit further, it makes sense to say that you are paying a price premium for the bandwidth flexibility and still have a cheap connection for everyday purposes. Figure 16 illustrates the bandwidth requirements for the typical home office user described above.

Most of the day 1–2 ISDN B-channels will do the job, whereas higher requirements are limited to a short time of day. In Figure 16 we have assumed a two-price structure. However, it is probably natural to introduce more flexible prices, ie. both bandwidth and time-of-day based prices.

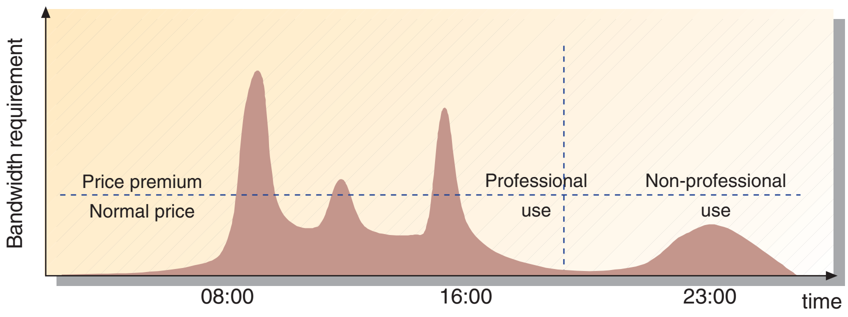

Figure 16 Bandwidth requirement during the day with a dual-price structure

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Long term forecasts for broadband demand

KJELL STORDAHL AND LARS RAND

1 Introduction

What are the market drivers for future broadband demand? This paper shows that the long term demand for broadband services depends on a set of different market drivers. Some of the market drivers like application evolution, development of new technology and network architectures, terminal equipment technology, mass production of network components and tariff evolution are presented.

The long term demand for broadband services is estimated based on an international Delphi survey. The experts participating in the Delphi survey used information about market drivers as a basis for their evaluation of the evolution of a future broadband market. A comparison is done between the expectations the experts had about the market developments in 1994 and 1997. The results from the Delphi survey are used to model analytical forecasting functions for broadband demand. The aggregated forecasts for specific broadband capacities are split into asymmetric and symmetric broadband forecasts.

1.1 Technology development and new network architectures

In the transport network deployment strategies for substitution of PDH transmission equipment with SDH transmission equipment are now being carried out. In parallel the fibre capacity is expanded by the introduction of wavelength division multiplexing (WDM). Over the last years the development of new technology has dramatically reduced costs by significant expansion of the system capacity. During a 20 year period the transmission cost per capacity unit has been reduced from 10,000 to 1. However, the technical problem of high capacity switching is not yet solved. One possibility is to use ATM, another possibility is to use IP, and a third one is to implement ATM over the IP platform.

In the access network a wide range of fibre architectures are relevant, of which deployment depends on factors such as the subscriber area:

- Hybrid fibre coax (HFC);
- Fibre to the cabinet (FTTCab);
- Fibre to the node (FTTN);
- Fibre to the curb (FTTC);
- Fibre to the building (FTTB);
- Fibre to the home (FTTH).

In addition new multiplexing techniques, access protocols for point-to-multipoint configurations and modulation techniques are developed. Also the digital subscriber line (DSL) technologies, like ADSL (asymmetric digital subscriber line), HDSL (high bit rate subscriber line), VDSL (very high speed digital subscriber line) and SDSL (symmetric digital subscriber line) are of great importance for utilising twisted pairs [1, 2]. The technologies may substitute each other or may be deployed as supplements in different parts of the network.

Introduction of passive optical network components as TPON and ATM PON and the use of ATM- and SDH technology will increase the transmission capacity and reduce the costs. Wireless broadband access is a technology currently under development. The access radio technology is expected to evolve from carrying narrowband services to transport of services up to 2 Mbit/s capacity through local multipoint distribution service (LMDS) and multipoint multichannel distribution (MMDS) [3–5]. Another relevant architecture in the future is the universal mobile telephone system, UMTS.

Other alternatives are satellite communication combined with a wireline return channel. The cable operators will upgrade their networks with return channels offering both POTS/ISDN, Internet and broadband services together with CATV. The most relevant architecture is a combination of passive optical network and a coax droop called hybrid fibre coax system, HFC. The access technologies mentioned may substitute each other or may be deployed as supplements in different parts of the network.

1.2 Terminal equipment technology

The terminal equipment is evolving rapidly into several future options including specific electronic interfaces/terminals which may be used together with a TV, like a network computer. Another possibility is the use of a PC. There are several drivers connected to the terminals. During the last 20 years, from the 8080 to the Pentium processor, the number of transistors per chip has doubled every 18 months (Moore's law), while the speed in million instructions per second (MIPS) has increased proportionally [6]. In 1983 the cost per Mbyte was USD 300, while in 1995 the cost was reduced to 15 cents. Future exponential development of the storage capacity will enable software decompression of MPEG-2 video streams and direct computer storage.

1.3 Market drivers

The new technologies, the mass production of network components and low transmission costs are continuously creating new applications. At the same time an extraordinary expansion of the Internet has occurred. It seems that it is not a killer application for the broadband market, but that Internet is a 'killer network'. From 1998 wideband services were offered on the Internet, and broadband services are also expected to emerge soon. At the same time some CATV companies are installing cable modems and are offering broadband services on their networks. Some of the main drivers for the development of the broadband market are: new technology, new applications, increased computing power and storage, mass production, price reductions, the Internet revolution and the competition [7].

2 Prediction of network component cost trends

Within the European programs RACE and ACTS the projects RACE 2087/TITAN, AC 226/OPTIMUM and AC 364/TERA have developed a methodology and tool for calculation of the overall financial budget of any access architecture. The tool handles the discount cost system, operations, maintenance, life cycle costs and the cash balance. This enables a comparison of various optical or hybrid architectures through a global system assessment. The tool has the ability to combine low level, detailed network parameters of significant strategic relevance with high level, overall strategic parameters for performing evaluation of various network architectures [1, 8–11].

The TITAN project developed a methodology based on an expansion of the Wright and Crawford's learning curve models to predict future cost of the network components [12–14]. In the OPTIMUM project, Wright and Crawford's learning curve models for cost predictions were examined. The models for cost predictions were extended not only to estimate the costs as a function of number of produced units, but also as a function of time. The cost prediction of each network component is described by expansion of the learning curve given as a function of the parameters:

- $f(0)$ the predicted costs at time 0;
- $n(0)$ the relative proportion of produced components at time 0;
- Δt the time interval between 10 % and 90 % penetration;
- K the learning curve coefficient (relative decrease in the cost by the double production).

The extended learning curve function is:

$$f(t) = f(f(0), n(0), \Delta t, K, t) = f(0)[n(0)^{-1} (1 + \exp[\ln(1/n(0) - 1) - 2t \ln 9/\Delta t])^{-1}]^{\log_2 K}$$

The parameters in the learning curve: $f(0)$, $n(0)$, Δt and K are given in the OPTIMUM cost database, which contains more than 200 different network components. The components are grouped in volume classes. The values used for the various volume classes are shown in Table 1. In the same way the K parameter is estimated based on type of component. The K value indicates how much the component price is reduced by a doubling of the production.

In the cost database all components are listed with a given $n(0)$, Δt and K value in addition to the estimated cost $f(0)$ at time 0. Then the extended learning curve is uniquely defined and the prediction of the costs is determined.

Table 2 shows that new components based on electronics or advanced optics experience a significant price reduction. When the production is doubled, the price is reduced by 20 % and 30 % respectively. An additional doubling of the production will reduce the cost by 36 % and 51 % respectively.

3 The Delphi survey

A Delphi survey is a method by which the opinions of experts are canvassed, in order to achieve consensus on a particular issue. The methodology involves asking a set of questions, analysing the results and resubmitting the questions to the experts, together with a summary of the first round results. The experts then resubmit their opinions, which may have changed following a consideration of results from the previous round. The procedure can be repeated a number of times and usually leads to a reduction in the variance of the answers received. Medians are used as a measure in the Delphi survey because they are more robust estimators than the mean value and standard deviations, and also less affected by extreme answers.

In 1994 the TITAN project carried out an international postal Delphi survey on broadband service demands among experts in ten European countries [14–15]. An additional comprehensive two-round, on-site Delphi survey was carried out during the OPTIMUM workshop "Techno-economics of Multimedia Networks" in Aveiro, Portugal in October 1997. The following countries were represented in the survey: Belgium, The Czech Republic, Denmark, Finland, France, Switzerland, Germany, Greece, Holland, Hungary, Ireland, Italy, Norway, Portugal, Spain and Sweden. The number of participants were 36 in the first round and 32 in the second round.

3.1 Broadband applications

The Internet development and the new technology continuously create new applications. To be able to evaluate the different broadband applications, they are divided into groups. The questions in the survey do not address single applications, but the main group of applications. The main groups of applications in the study are:

1 Tele-entertainment (Symmetric and asymmetric)

- Multimedia telegame
- Virtual reality
- Video on demand
- Audio/music on demand;

2 Information services (Asymmetric)

- Information retrieval
- Electronic magazines
- Information retrieval by intelligent agents
- Electronic newspaper;

3 Teleshopping (Asymmetric)

- Teleshopping
- Advertising;

4 Private communications services (Symmetric)

- Videophone
- Teleconferencing

5 Teleworking (Symmetric and asymmetric)

- Videophone
- Joint editing/publishing
- Teleconferencing
- Teleparticipation
- Information retrieval
- Multimedia applications;

6 Telelearning (Symmetric and asymmetric)

- Video on demand
- Videophone
- Virtual reality;

Table 1 Variation in n(0) and t for each volume class

Volume class	$n(0)$	Δt
1	0.5	5
2	0.1	5
3	0.01	5
4	0.5	10
5	0.1	10
6	0.01	10
7	0.001	50

Table 2 The K values for component groups

Component group	K value
Civil work	1
Copper	1
Installation	1
Sites and enterprises	0.95
Fibre	0.9
Electronics	0.8
Advanced optical components	0.7

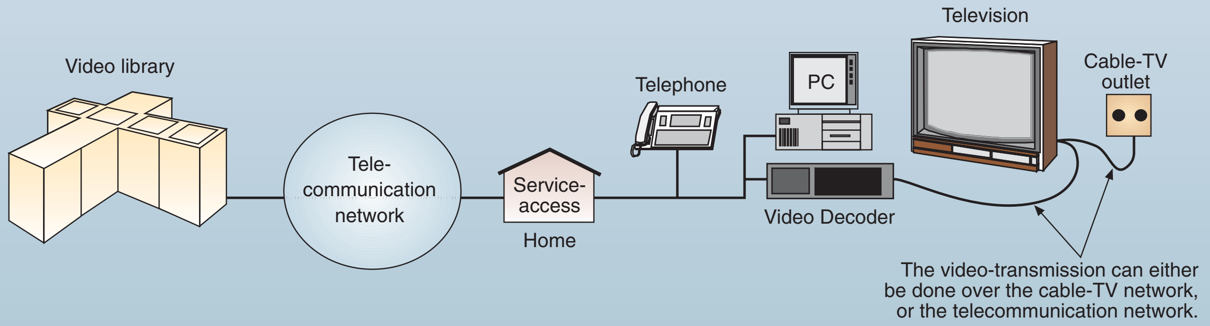
Example of application: Video on demand and Audio/Music on demand

General description:

This is an application where a video library is accessed, and programs may be ordered and transmitted to the home. This application could substitute some part of the time spent on ordinary TV and part of the money spent on hiring videos in video shops.

Technical assumptions:

The user may use either an advanced telephone or a PC to communicate with the video library. The transmission of the video may be done either via a Cable-TV network or a telecommunication network. The access capacity will be in the range of 2– 4 Mbit/s.



Given the following alternative prices per hour (1997 ECU), what do you believe will be the expected use of this group of applications (Tele-entertainment)?

Note: We assume that the tele-entertainment applications are supplementary to the traditional TV channels, but there may be some substitution effects.

Round 1					
Prices per hour:	0.5 ECU	2 ECU	5 ECU	10 ECU	20 ECU
Minutes per day:	70	40	12	5	1

Having seen the above results, what would your answers be to the corresponding question today?

Round 2					
Prices per hour:	0.5 ECU	2 ECU	5 ECU	10 ECU	20 ECU
Minutes per day:					

4 *Comments (if any):*

Figure 1 An example from the Delphi survey questionnaire

7 Telecommunity (Symmetric and asymmetric)

- Telesurveillance
- Videophone
- Telediagnostics.

3.2 Access capacity

The technology and network components are rather expensive today, but mass production may exponentially reduce production costs and consequently the prices. The following access capacities were examined in the Delphi survey:

- *2 – 4 Mbit/s asymmetric access including a 384 kbit/s symmetric upstream capacity;*
- *25 Mbit/s asymmetric access including a 384 kbit/s symmetric upstream capacity;*

- *25 Mbit/s asymmetric access including a 6 Mbit/s symmetric upstream capacity.*

Several factors contribute to an application's requirements in terms of bandwidth over the network. In most cases, high capacity is needed for large volumes of information.

First of all, the type of medium (speech, text, graphics, video, or several media simultaneously – multimedia), may indicate the possibility for large volumes of information. The types of applications demanding high bandwidth transmission are fast transfer of video, high quality images/graphics, large data files, or a simultaneous combination of these in multimedia applications.

High quality videophone, telecommunity and telemedicine are applications benefiting from a high symmetric upstream capacity. For example, interactive video applications transferring moving pictures like videotelephony or videoconferences, require a minimum image frequency depending on the speed of change in the pictures transferred. This increases the bit rate requirement, and so does the image resolution and colour richness.

3.3 The Delphi questionnaire

The questionnaire starts with a short description of the application, followed by some questions relating to it. The main questions in the survey are:

- Usage as a function of charge;
- Penetration as a function of charge;
- Penetration as a function of time (forecast);
- Demand as a function of disposable household income.

An illustration of the design of the questions in the questionnaire which includes a description and an illustrative figure is given in Figure 1.

As shown in Figure 1, in the second round of the survey the participants were presented the medians from the same questions in the first round of the survey. The participants took this into consideration when answering the second round questions.

In order to use the presented applications, an access in the range of 128 kbit/s – 25 Mbit/s is needed. The users will have to pay more for enhanced performance and quality generated by higher bandwidth. All the equipment and network components will gradually become less expensive, depending on factors like new technology, sales volume, competition, etc. Broadband communications costs can be divided into four elements:

- Costs for necessary terminal equipment;
- Subscription charges;
- Traffic charges;
- Charges for delivered information (eg. charge for hiring/ordering a video).

In the Delphi survey we were interested in how much the customers are willing to pay for the traffic and the subscription (connection) charges. It was assumed that the customers already possess the necessary terminal equipment like TV, PC, etc. Supplementary expenditure for specific adapters and 'interface' hardware for the applications which have to be installed, was assumed to be covered by a subscription (connection) charge. The costs of the delivered information were not taken into account.

Some information may be financed by advertisements. The teleshopping application may be financed by the sellers and not by the customers. The costs of other information like electronic newspapers may be substituted by a reduction of costs for buying hard copies (traditional

Table 3 Leading Group of Applications, percentage score

Choices 1994 survey *)	Answers 1994 *)	Choices 1997 survey	Answers 1997
Video on demand	28 %	Teleworking	28 %
Home office	27 %	Information services	25 %
Videotelephony	18 %	Tele-entertainment	24 %
Remote education	8 %	Teleshopping	7 %
Multimedia telegames	7 %	Private communications services	6 %
Home ordering system	4 %	Telecommunity	4 %
Interactive TV/specialized channels	4 %	Telelearning	3 %
Electronic newspapers	3 %	Others (Telebanking)	1 %
Advertising and marketing	1 %		
Telecommunity	0 %		

**) Source [15]*

newspapers). Nevertheless, it is reasonable to believe that the customers have to pay for some type of information.

4.1 Household budget and usage

A household has an annual disposable income, which is the income after tax or the part of the income which is available for purchasing goods and services, for savings etc. Part of the service budget is related to

- budget for entertainment;
- budget for telecommunications;
- budget for newspapers, magazines, dictionaries, specific books and videos, etc.

The household has both a time budget and a financial budget, dependent on the number of persons in the household. The budgets limit the use of applications. It is reasonable to expect some substitution effects between the household's use of time today and possible use of broadband accesses. In the questionnaire we have asked how much additional time a household would spend on the new broadband applications as a function of additional payment.

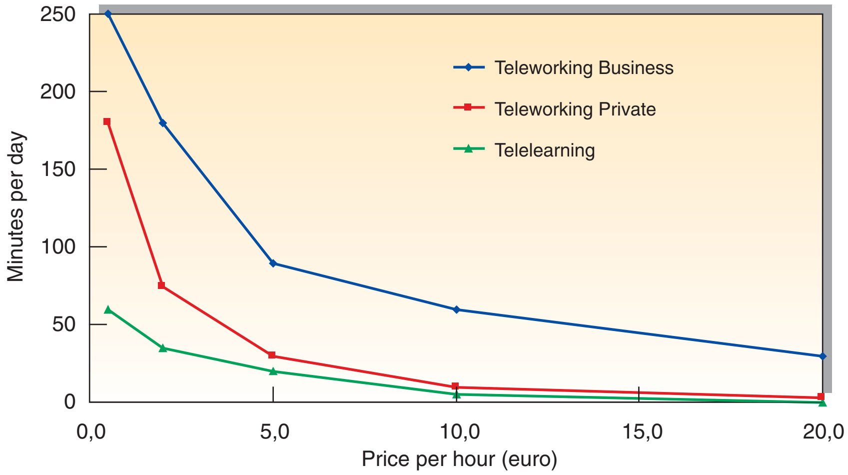


Figure 2 Demand curves for broadband access for teleworking and telelearning

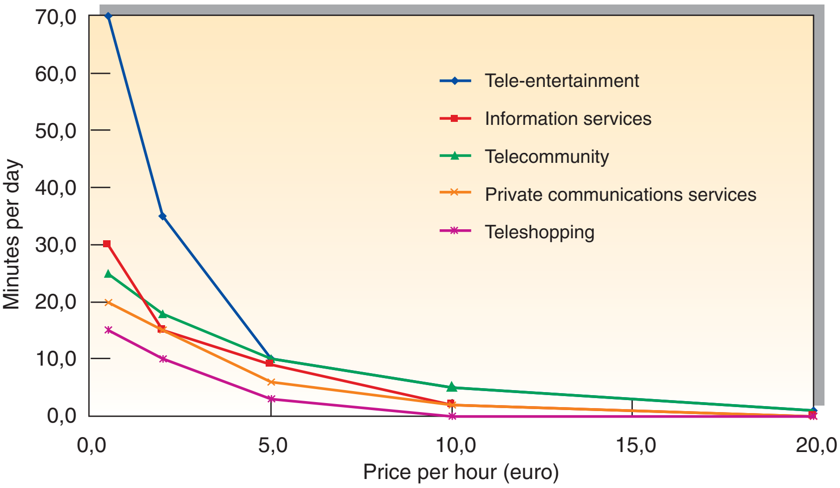


Figure 3 Demand curves for other private broadband applications groups

4.2 Ranking groups of applications

The respondents were asked to point out the three most important services for the future. This makes up 33 % the highest possible score for an application group. Table 3 shows the ranking of the group of applications in 1994 and in 1997. Teleworking, information services and tele-entertainment stand out as the anticipated most popular services for broadband. A comparison with a similar Delphi survey in 1994 [15] shows that the three most promising broadband applications were video on demand, home office and videophony. It looks like information services have become more popular from the 1994 survey to the 1997 survey. In addition, from the first to the second survey other application groups have become more interesting than private communications services (videophony).

A telecommunication access line may support the use of many of these groups of applications, so for each group of applications questions were asked on the demand at different prices in order to quantify the demand.

4.3 Potential usage of applications

For every service the respondents were asked to indicate the demand in minutes per day for a given set of prices per hour. Hence a demand curve can be constructed for each application group based on medians from the survey. In Figure 2 a distinction is made between company paid teleworking and teleworking paid by the households themselves, since companies are expected to have a higher willingness to pay than private households.

The demand for telelearning is trickier because it concerns a small share of the households and for a limited time of the year. The household usage will be high some days and zero at other times depending on the type of courses and education frequency. Demand curves for other private broadband application groups are shown in Figure 3. The results show that tele-entertainment follows the same demand curve as telecommuting from a price of five euro per hour, but has a higher saturation level – so the expected demand is much higher at a low price. Tele-entertainment services, which are defined as video on demand, audio/music on demand, multimedia telegame and virtual reality, are very attractive services, but are quite price elastic.

Figure 4 shows medians for round 1 and round 2 and identifies the range from the 25 quartile to the 75 quartile of the answers on demand for broadband connections for different hourly prices. The figure indicates significant reductions in the variance of the answers received in the first round compared to the second round.

Teleworking, information services and tele-entertainment stand out as the most promising broadband applications in the future. The interest for information services can be explained by the rapid development of the Internet and the related narrowband applications. The interest for tele-entertainment is caused by a high degree of usage of existing applications. Teleworking is of special interest and may be one important driver for the broadband market. Teleworking is used by self employed persons with their office at home (SOHO), by one person in the family financed by the company, or by some in the family, but financed internally. Today there is a positive trend towards supporting teleworking at home. For employees with qualified and independent work there are reasons to predict that society and the companies are willing to support and finance extensive use of teleworking with a broadband connection. In that way the employees can work more effectively and in a more flexible way. Society also supports teleworking because of reduced pollution and reduced traffic at rush hour times, etc. Some large companies now offer a home office solution combined with a company paid narrowband access (N-ISDN) for some of their employees.

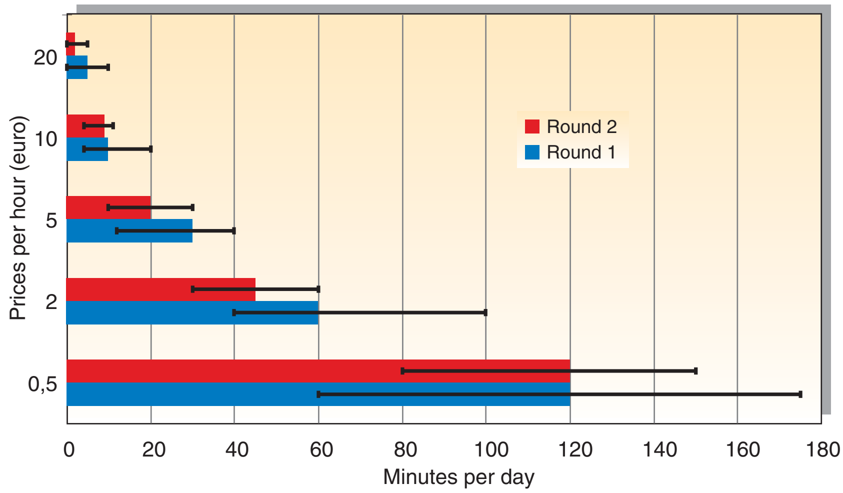


Figure 4 Demand curves for broadband access – all applications

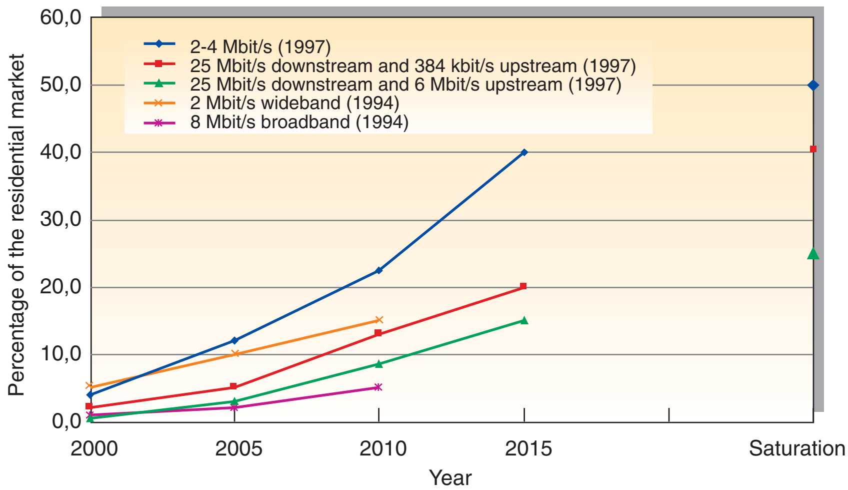


Figure 5 Forecast for broadband access in the residential market

4.4 Demand forecasts

The respondents were asked to indicate the expected penetration in the residential market for broadband access for the years 2000, 2005, 2010, 2015 in addition to the saturation level. Figure 5 indicates quite a high demand for broadband connections in the residential market. The penetration forecasts for 2 Mbit/s have not changed much from the 1994 Delphi survey. In 1994 the experts predicted, for 2 Mbit access, a penetration rate of 5 %, 10 % and 15 % respectively for the years 2000, 2005 and 2010. In the 1997 survey the forecasts are 4 %, 12 % and 23 % respectively for the years 2000, 2005 and 2010. The difference in the predictions is somewhat larger for faster connections, but the results show the same pattern. While the experts in 1994 expected a

Table 4 Revised broadband forecasts as percentage of the residential market

Access capacity	2000	2005	2010	2015	Saturation
2 Mbit/s	2	12	23	40	50
8 Mbit/s	0.5	5.5	14	22	40
26 Mbit/s	0.1	3	9	15	25
Sum	2.6	20	45	75	*)

**) The saturation for the various accesses will occur at different points in time*

Table 5 Parameter estimates and multiple correlation coefficient for broadband penetration forecast functions

Parameter estimates	*a*	*b*	*g*	*M*	R^2
2 Mbit/s	- 0.07496	- 0.19266	5	50	98.56
8 Mbit/s	- 4.79468	-0.13249	500	40	99.38
26 Mbit/s	- 4.57674	- 0.15775	500	25	99.37

penetration rate for 8 Mbit/s of 1 %, 2 % and 5 %, the respective penetration forecasts for 25 Mbit/s in the 1997 survey are 2 %, 5% and 13 %.

4.5 Analytical forecasting functions

The development of analytical forecast models for broadband access was a part of the OPTIMUM project. The results from the Delphi survey contain only 2 Mbit/s and 25 Mbit/s accesses. There are reasons to believe that also 8 Mbit/s will be a conventional offered access. Evaluation of the results shows that the sum of the two 25 Mbit/s gives about the same demand as the 2 Mbit/s. During the first ten years the demand for 2 Mbit/s will probably be significantly higher than 25 Mbit/s. Since the total demand for 25 Mbit/s seems optimistic, it has been suggested to transfer 25 Mbit/s with 384 kbit/s return demand to a 8 Mbit/s demand. In addition it has been suggested to split the given demand in a symmetric demand and an asymmetric demand. Since 8 Mbit/s is a lower capacity than 25 Mbit/s it has been suggested to increase demand by 10 %. In addition we will use 26 Mbit/s, which is closer to the new standard than 25 Mbit/s. The forecasts for 8 Mbit/s and 26 Mbit/s for the year 2000 is also reduced to 0.5 % and 0.1 % respectively. The revised forecasts are found in Table 4.

The demand forecasts in the table include both symmetric and asymmetric accesses. The fraction between asymmetric and symmetric will change over time, but during the first years, there will mainly be asymmetric accesses. The models developed in the OPTIMUM project are based on the results from the 1997 Delphi survey. Different analytical forecasting models for fitting the Delphi data are tested. The extended Logistic model with three parameters give a rather good fitting. The model is defined by the following expression:

$$Y_t = M / (1 + \exp(\alpha + \beta t))^{\gamma}$$

where the variables are defined as follows:

Y_t	Demand forecast at time t
M	Saturation level
t	Time
α, β, γ	Parameters.

The parameters α, β, γ cannot be estimated simultaneously by ordinary least squares regression since the model is non-linear in the parameters. The main objective in the fitting is not to get the best overall fit, but a reasonably good fit for the first years. Therefore, the parameters in the model are estimated by ordinary least squares regression (OLS) for different values of γ. The OLS estimation is based on the following transformation:

$$\ln((M/Y_t)^{1/\gamma} - 1) = \alpha + \beta t$$

The saturation level M and the parameter γ are fixed values in the estimation process. M is found from the Delphi data, while γ is estimated by systematic calculations of RMSE (root mean square error) for a set of different values. The multiple correlation coefficient, R^2, for the models is rather high. The estimated values are given in Table 5.

The broadband penetration forecasts are shown in Figure 6.

4.6 Symmetric and asymmetric demand modelling

The forecasts have to be divided into asymmetric and symmetric demand. Introduction of analytical functions are convenient for describing the share of asymmetric and symmetric accesses. The question is how the symmetric demand will develop compared to the asymmetric demand. The symmetric demand will probably be low for the first years compared to the asymmetric demand. After

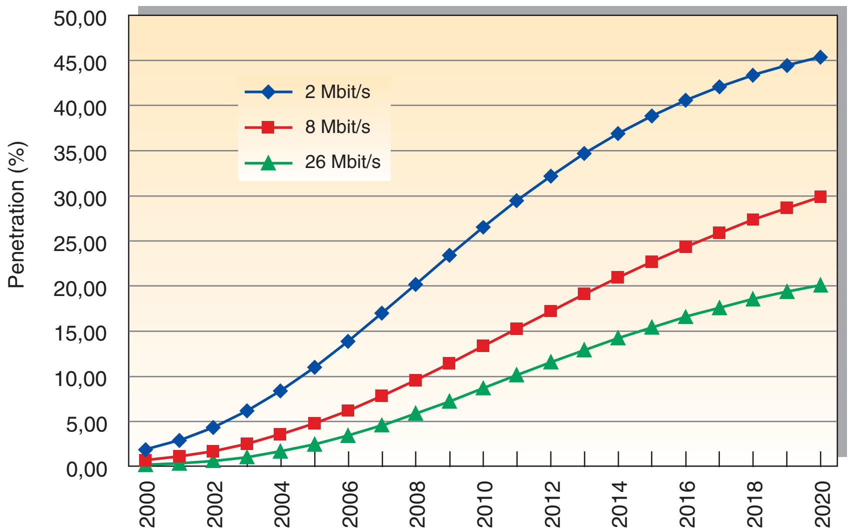


Figure 6 2 Mbit/s, 8 Mbit/s and 26 Mbit/s broadband forecasts some years the symmetric demand will probably have a relatively higher increase. In the end we assume that the proportion of symmetric subscriptions will converge to a given level. One important element is how the PCs are used as broadband terminals, either for communication with specific information sources, or for communication between users. The behaviour may be modelled by constructing analytical functions defining market shares as a function of time between the asymmetric demand and the symmetric demand. The analytical functions should be simple.

It is suggested to use the Logistic model to describe the evolution of the distribution of asymmetric and symmetric demand. The following parameters are defined:

- S Saturation level
- S_t Share of symmetric demand
- t Time
- T Time to 50 % saturation
- a Growth per year
- α, β Parameters in the Logistic model (Model 2).

The model is given by:

$$S_t = S / (1 + \exp(\alpha + \beta t))$$

The Logistic model is symmetric on both sides of $S/2$. The model is uniquely defined if S, α and β are defined. Instead of defining the parameters, we have decided to determine the function by the following assumptions:

1) Define the saturation level S;
2) Define the time (number of years) T, until half saturation is reached;
3) Define the market share S_0 at time 0, which is the year of introduction.

The parameters in the model are found by:

$$\alpha = -\beta * T$$

$$\beta = (1/T) * \ln(S/S_0 - 1)$$

The degree of symmetric demand depends on the offered broadband capacity. The analytical specification differs, depending on connection capacity. The saturation for 2 Mbit/s symmetric demand is suggested to be 40 % in the long run, while the 8 Mbit/s and 26 Mbit/s symmetric demand is suggested to be 30 % and 25 % respectively. The time to reach half saturation for 2 Mbit/s, 8 Mbit/s and 26 Mbit/s is estimated to be eight years, and the starting proportion of symmetric broadband communication demand is estimated to be 2 %. The distributions are shown in Figure 7.

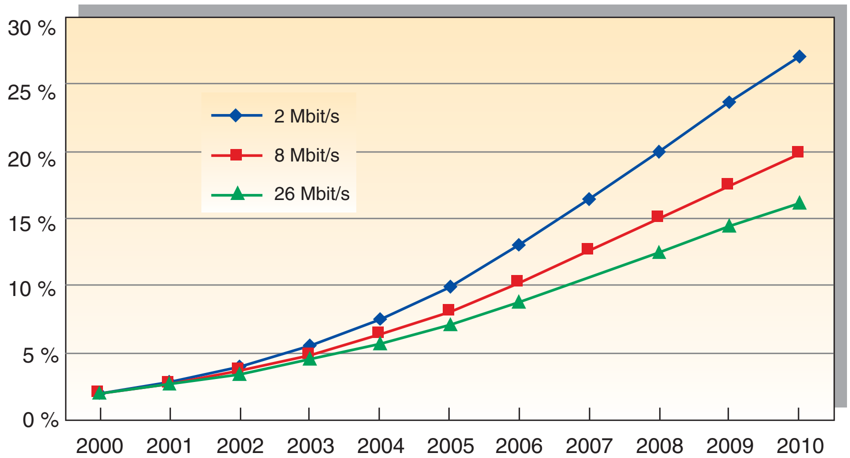


Figure 7 Proportion of the symmetric communication penetration of the total broadband penetration demand. The given assumptions lead to forecasts for asymmetric and symmetric demand as shown in Figure 8

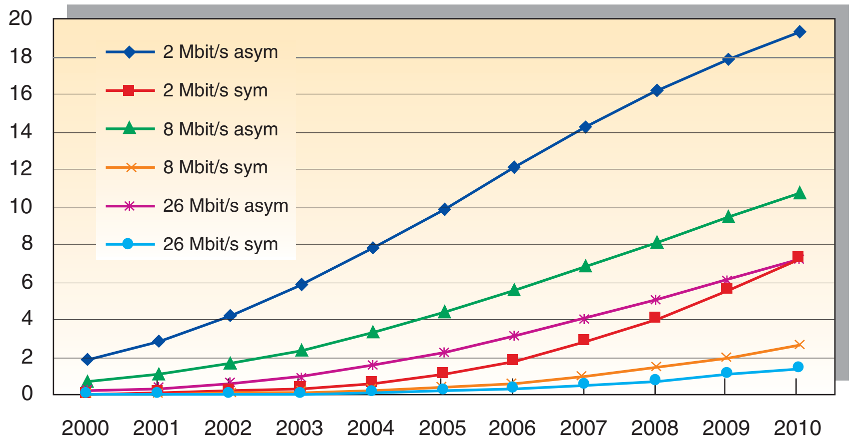


Figure 8 Forecasts for asymmetric and symmetric connections (%)

4.7 Demand for access capacities

The access lines with different capacities may support the use of many of the earlier mentioned applications. Thus, questions were asked on the demand for broadband access for three different access types as a function of annual costs. Figure 9 shows the estimated demand curves for 2 Mbit/s, 8 Mbit/s and 26 Mbit/s broadband connections. The difference between the demand curves is very small and indicates that residential users are not willing to pay much more for a high capacity connection despite the better quality.

4.8 Analytical demand models

As a part of the OPTIMUM project analytical demand models dependent on price were developed. Based on the same arguments as for analytical forecasting functions, 2 – 4 Mbit/s, 25 Mbit/s with a narrowband return channel and a broad-

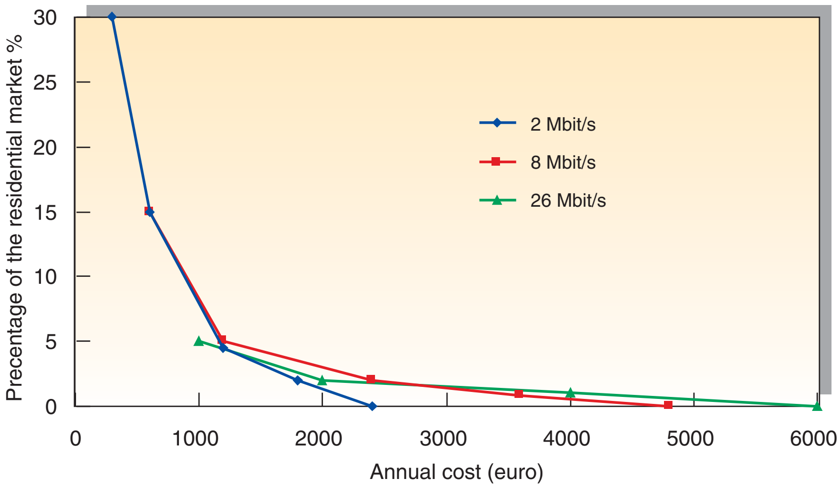


Figure 9 Demand curves for broadband access as a function of annual cost

band return channel are transferred to 2 Mbit/s, 8 Mbit/s and 26 Mbit/s. The suggested demand model based on three parameters is:

$$y = e^{(\alpha+\beta p)^{\gamma}}$$

y Demand;

p Price;

α, β, γ Parameters in the model.

The parameter estimates are found by OLS regression for a given set of γ values. A variant of this model is based on the assumption that the demand is 100 % when the price is 0. Evaluation of the results show that the fitting is not satisfactory. To improve the fit, the parameters α and β are determined such that the demand curve passes through the two initial points, while the γ parameters are determined by minimising the squared distance between the demand curve and the results from the Delphi survey.

Now, let the initial values be:

$$(y_I, p_I) \text{ and } (y_L, p_L)$$

Hence:

$$\beta = -[(\ln y_L)^{1/\gamma} - (\ln y_I)^{1/\gamma}] / (p_I - p_L)$$

$$\alpha = (\ln y_I)^{1/\gamma} - \beta p_I$$

The parameter γ is found by minimising the following expression:

$$Q(\gamma) = \sum\left(y_i - e^{[\alpha(\gamma)+\beta(\gamma)p_i]^{\gamma}}\right)^2$$

In the non-linear estimation procedure, not only the last equation is minimised but also the first years achieve a reasonably good fit. For all models γ equal to around 10 gives a rather good fit. The framework for the demand curves is described hereafter. It is important to underline that the tariff in this context consists of both a one year subscription tariff and also a usage tariff based on the expected traffic during one year. The methodology described in the previous sections is used to predict the tariff evolution for broadband connections. The predictions are calculated in the following steps:

The tariff p is found by transforming the demand model to the formula:

$$p_t = [(\ln y_t)^{1/\gamma} - \alpha]/\beta$$

The parameters α, β and γ are found by the above equations. Then the tariff predictions for the years 2000, 2001, ..., 2010 are determined by inserting the demand forecasts $\{y_t\}$ in the same years. The tariffs are found in Table 6. The tariff evolution for broadband services in the mass market is shown in Figure 10.

4.9 Willingness to pay for access capacity

Willingness to pay as a function of disposable household income is estimated for broadband access based on answers from the respondents. Disposable income is the household income after tax, ie. the part of the income that is available for saving and purchasing goods and services. Figure 11 shows that households with an annual disposable income in the 10,000 to 15,000 euro range cannot afford to pay more for a high capacity connection. Incremental willingness to pay for broadband access is very small, even for wealthy households.

Table 6 Assumption tariff evolution for broadband services (mass market)

Parameters	2 Mbit/s asym	2 Mbit/s sym	8 Mbit/s asym	8 Mbit/s sym	26 Mbit/s asym	26 Mbit/s sym
Demand, year 2000	1.900 %	0.037 %	0.637 %	0.013 %	0.150 %	0.003 %
Demand, long run	40 %	40 %	30 %	30 %	25 %	20 %
Tariff, year 2000	1800 euro	2700 euro	3240 euro	4860 euro	5192 euro	7788 euro
Tariff, long run	500 euro	750 euro	900 euro	1350 euro	1442 euro	2163 euro

For households with an annual disposable income of between 25,000 and 60,000 euro the willingness to pay for subscription and traffic charges for the highest capacity access is only 2 % of the household's disposable income.

4.10 Price and capacity

The previous sections have shown a low willingness to pay for higher capacity and better quality. The questionnaire also included direct questions on the household's willingness to pay for increased capacity relative to a 128 kbit/s access, ie. an ISDN basic access. Figure 12 confirms a low willingness to pay for incremental increased connection capacity. The difference between the 75 % quartile (25 % answered higher) and the 25 % quartile (25 % answered lower) are shown in the figure as a measure of the variation in the answers. The uncertainty increases with increased capacity.

5 Conclusions

The results from the 1997 Delphi survey show that there will be a substantial demand for broadband services in the residential and SOHO markets during the next ten years. However, the households are not willing to pay too much more for additional broadband applications and additional capacity. Households with low disposable income will not afford to have a subscription, while households with a reasonable disposable income are willing to pay up to 2 % of their disposable income. The possibilities for substitution effects between new and old media (newspapers, magazines, video rental, video games, etc.) are taken into account.

The Delphi survey indicates that customers will be unwilling to pay much more for increased capacity. It is interesting to see that the demand curves for 2 Mbit/s, 8 Mbit/s and 26 Mbit/s are quite similar. The results are supported by the price/quality question where the experts indicate that the households are willing to pay twice as much for a 50 Mbit/s access compared to how much they are willing to pay for an ISDN BA access, and only 2.2 times as much for a 500 Mbit/s access. This is a quite important finding, because a 50 Mbit/s access is possible using VDSL modem for customers with short subscriber lines, while 500 Mbit/s is impossible because of the physical limitation on the twisted pair. To offer 500 Mbit/s access an FTTH solution will

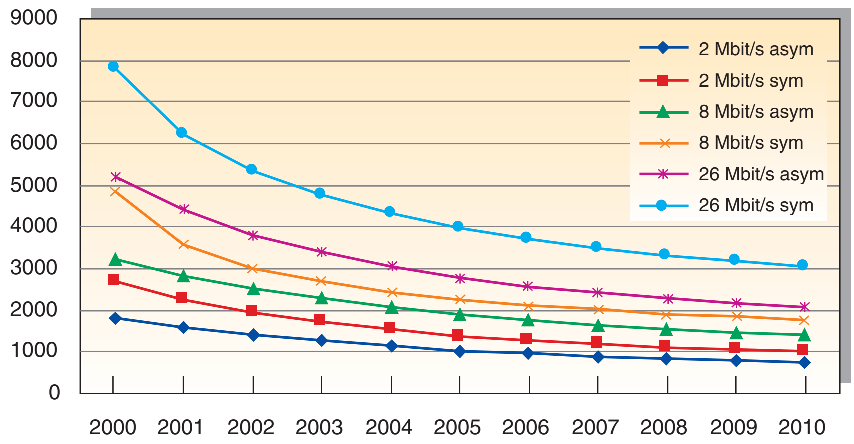


Figure 10 Tariff evolution for broadband services (mass market) euro

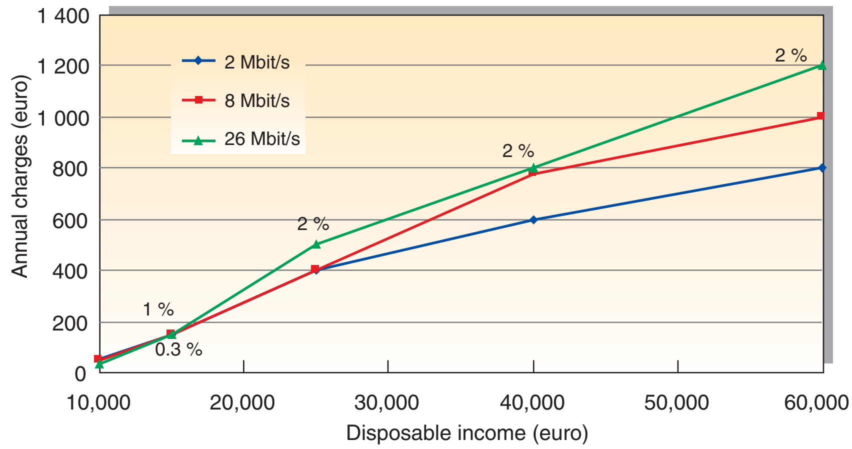


Figure 11 Income spent on broadband accesses as a function of disposable income

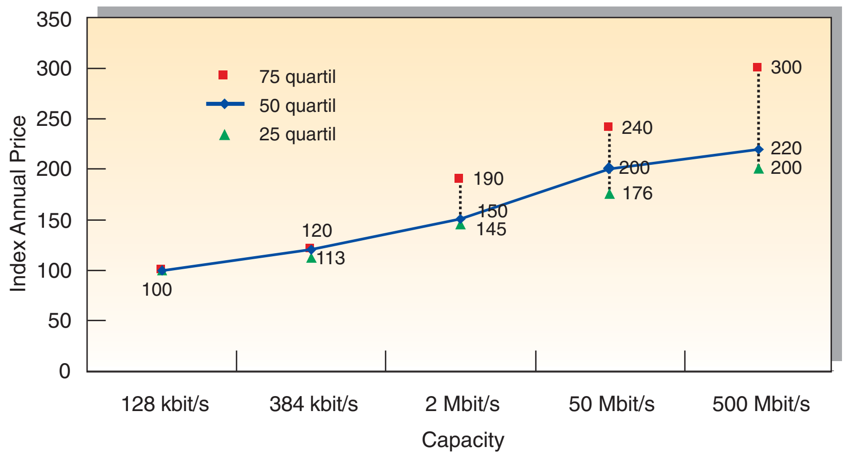


Figure 12 Willingness to pay for increased capacity relative to 128 kbit/s

probably be needed, but the customers are not willing to pay more than 2.2 times the price of an ordinary ISDN access!

Comparison of the results from the 1997 Delphi survey and the one carried out in 1994 shows that the results are rather similar. It is interesting to note that the penetration forecasts for a 2 Mbit/s access for the years 2000, 2005 and 2010 are quite close, with the 1997 forecasts being a little bit higher. For higher access capacities we see the same pattern. Usually, the experience when comparing old forecasts of new telecommunication services to new forecasts is that the old forecasts have been too optimistic. The forecasts of the Internet evolution is of course an exception.

Like in the 1994 Delphi survey, the variation in the answers among the experts in the 1997 Delphi survey was significantly reduced from round 1 to round 2. The variation was measured by 25 % and 75 % quartiles. The results indicated that it was unnecessary to carry out an additional round.

To realise the potential broadband demand, a key option is the development of the broadband drivers mentioned in the introduction. Models to predict cost trends for network components show that increased production gives significant reduced cost.

In addition analytical broadband forecasting functions and demand functions are developed together with forecasts for asymmetric and symmetric demand. The analytical forecasting functions and demand functions are modelled based on the results from the Delphi survey.

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Broadband demand survey in the residential and SOHO market in Norway

SYNNØVE ISTAD AND KJELL STORDAHL

1 Introduction

A Delphi survey has been carried out to make demand forecasts of broadband services in the Norwegian residential and SOHO (Small Office Home Office) market for the next five to ten years. A *Delphi survey* is a method where the opinions of experts are canvassed, in order to achieve consensus on a particular issue. The methodology involves asking a set of questions, analysing the results and resubmitting the questions to the experts, together with a summary of the first round results. The experts then resubmit their opinions, which may have changed following consideration of results from the previous round. The procedure can be repeated a number of times, and usually it leads to a reduction in the variance of the answers received. The Delphi methodology involving experts was used instead of performing a market survey including family members. The reason is that we expected it would be difficult for residentials to give accurate answers to rather complicated questions about future broadband demand.

2 The Delphi survey

The Delphi survey was carried out in September/October 1998. Questionnaires for the first round were sent by post to experts, intending to participate at a conference on "Broadband communication and multimedia" organised by the Norwegian Research Board (NFR). The participants were experts from the sectors of telecommunications, research and universities. Approximately 90 people participated at the conference. In the first round of the survey 28 answers were received. During the conference the experts were asked to fill in the Delphi questionnaire for the second round. Only 17 questionnaires were received. Because of the high non-response and also the limited number of returned questionnaires, there are significant uncertainties related to the results. The questionnaire consisted of 17 questions, very similar to the questions included in the Delphi survey carried out in the OPTIMUM workshop on techno-economics at the University of Aveiro in October 1997 [1]. The list of relevant application groups is identical in the two surveys. In that way, it is possible to compare the results from the surveys.

3 Technical prerequisites and facts

The *applications* in the questions concern the use of different media such as voice, data/text, graphics, live images, or a combination of these, so-called multimedia. To be able to offer transmission of all of these media on the same subscriber line we need a rather high capacity. The capacity on the copper subscriber line can be upgraded by introduction of ADSL modem and VDSL modems. The capacity can be expanded to 2 – 50 Mbit/s depending on the length of the subscriber line. The introductory information given on the different technologies was similar to the one used in the 1997 Delphi survey [1].

The access technology opens for high capacity. In the questionnaire the following access capacities are introduced:

- 2 Mbit/s asymmetric access including a 384 kbit/s symmetric upstream capacity;
- 8 Mbit/s asymmetric access including a 384 kbit/s symmetric upstream capacity;
- 25 Mbit/s asymmetric access including a 384 kbit/s symmetric upstream capacity.

In addition to the technical access solutions different mechanisms influence the demand for broadband communication in the residential and SOHO market. Establishment of broadband connections for teleworking will mainly be paid by companies. In Norway a lot of companies are now offering a PC to their employees. The PC can be used as a broadband terminal in the future. Telelearning is an application which could be partly financed by public means. Traffic costs for teleshopping are supposed to be included in the product costs and not as communication costs. The traffic cost can be paid by the companies through an 800 number.

A household's willingness to pay is related to communication costs, ie. subscription costs and traffic costs. Costs related to the terminal equipment or the information content are not included in the questionnaire.

4 Broadband applications

The different broadband applications under consideration are in the questionnaire divided into groups. The questions in the survey do not address single applications, but the main groups of applications. The main groups of applications in the study are listed in the following (the same list as used in [1]):

1 *Tele-entertainment (Symmetric and asymmetric)*
- Multimedia telegame
- Virtual reality
- Video-on-demand
- Audio/music on demand

2 *Information services (Asymmetric)*
- Information retrieval
- Electronic magazines
- Information retrieval by intelligent agents
- Electronic newspaper

3 *Teleshopping (Asymmetric)*
- Teleshopping
- Advertising

4 *Private communications services (Symmetric)*
- Videophone
- Teleconferencing

5 *Teleworking (Symmetric and asymmetric)*
- Videophone
- Joint editing/publishing
- Teleconferencing
- Teleparticipation
- Information retrieval
- Multimedia applications

6 *Telelearning (Symmetric and asymmetric)*
- Video-on-demand
- Videophone
- Virtual reality

7 *Telecommunity (Symmetric and asymmetric)*
- Telesurveillance
- Videophone
- Telediagnostics.

Table 1 Leading groups of applications

	Sum	Score
Tele-entertainment	15	29 %
Information services	13	25 %
Teleworking	9	18 %
Telelearning	6	12 %
Teleshopping	5	10 %
Private communication services	2	4 %
Others	1	2 %

5 Demand driving applications

The experts were asked to point out the three leading groups of broadband applications in the year 2010. Table 1 shows that tele-entertainment, information services and teleworking got the highest scores and are supposed to be the highest broadband demand driving application group.

In the European survey [1] the same three demand driving groups of applications were indicated.

6 Expected use of broadband applications

All households have a time budget and an economic budget which are dependent on the number of persons in the household and the household's disposable income. Today, when the broadband applications are not available, the time budget and also the economic budget are spent on other services. When the broadband applications are introduced, substitution effects between the traditional services and the new broadband services are expected. In the near future the traditional services are expected to dominate. The objective with the Delphi questionnaire is to estimate to what extent a household will use the new broadband applications as a function of additional payment, taking into account the potential substitution effects.

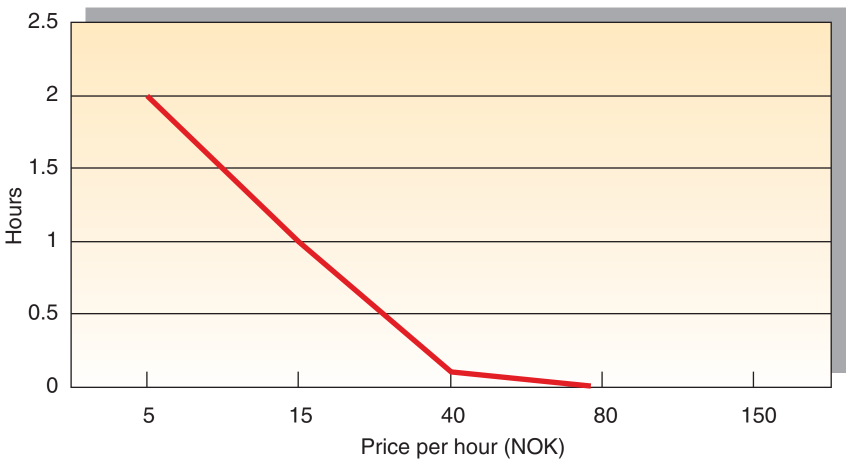

Figure 1 Expected broadband communication per day

The survey results on expected broadband communication per day for a household are shown in Figure 1. The broadband connection has a downstream capacity of 2 Mbit/s and an upstream capacity of 364 kbit/s. Necessary terminal equipment for multimedia applications is supposed to be available.

The figure illustrates how the usage per day is expected to be two hours if the price per hour is five NOK and one hour if the price is 15 NOK. The usage time is reduced significantly, to 0.1 hour, if the price per hour is 40 NOK. We can see an equal trend from the results achieved in the 1997 Delphi survey. Assuming that the number of active usage days per year is 300, we get usage costs or traffic costs per year for the two surveys as shown in Table 2.

We can see from the table that expected traffic costs for an average Norwegian household will not exceed 4,500 NOK. This means that a household is not willing to take on higher annual costs for broadband services than they pay today for narrowband services. Based on the European survey we can estimate annual traffic costs for a household up to 4,000 NOK. The subscription costs are not included in the above estimates.

7 The broadband forecasts

For each of the broadband connections 2 Mbit/s, 8 Mbit/s and 25 Mbit/s the experts were asked to estimate the broadband demand forecasts for the years 2000, 2005, 2010, as well as the saturation level. The results from the survey show that the experts are much more optimistic than the experts in the 1997 Delphi survey [1]. There may be different causes for the deviations. One reason may be high non-response and few received questionnaires; another reason may be a too homogeneous group of experts in the Norwegian survey, mainly consisting of people related to research on multimedia and broadband evolution. On the other hand, it seems reasonable that the results from the Norwegian survey should give more optimistic results compared to the results on a general European level, since Norway has a rather advanced infrastructure and high demand for new services like ISDN and GSM.

8 Demand curves for access capacity

Different access capacities may be used for offering the described applications. For a set of given annual costs for 2 Mbit/s, 8 Mbit/s and 25 Mbit/s services the experts were asked to estimate the fraction of the residential market expected to ask for the service. The question of willingness to pay was related to the year 2010. The results indicate that within a period of ten to 15 years it is expected that a substantial part of the subscribers will have a broadband connection which in turn means that the subscribers have many alternatives for communication. This is called a high externality effect.

The figure shows that the expected demand is quite similar for the three access capacities. The experts believe that the households are not willing to pay much more for higher capacity and better quality. These results support the opinion of the experts in the international Delphi survey. An interpretation of the results is that the households *de facto* are unwilling to pay more for a higher capacity. Another interpretation is that the experts today have difficulties understanding what an increased bandwidth really means for broadband communications. Today, a 2 Mbit/s connection is a rather high capacity. The demand curve for access capacity in the European survey is parallel with the expected Norwegian demand curve, but at a lower level. At an annual cost of 4,000 NOK the Norwegian experts expect a demand of 25 %, while the European experts estimate 15 %. With annual costs of 8,000 NOK the numbers are 10 % and 5 %.

9 Disposable income and willingness to pay

Figure 3 shows the expected willingness to pay for broadband connections as a function of a household's disposable income. The results indicate that the household only to a limited degree is willing to pay more for higher capacity. In the disposable household income bracket between 200,000 NOK and 600,000 NOK the households are willing to use about 1 % of annual expenses on broadband communication. With disposable income above 600,000 NOK the willingness to pay as percentage of disposable income decreases slightly. In the

Table 2 Estimated traffic costs per year in the Norwegian Delphi survey compared to the European survey

Price/hour ECU	Price/hour (NOK)	Hours	Active user days	Traffic costs per year (NOK)
	5	2	300	3000
	15	1	300	4500
	40	0.1	300	1200
0.5	4	2	300	2400
2	16	0.75	300	3600
5	40	0.33	300	4000

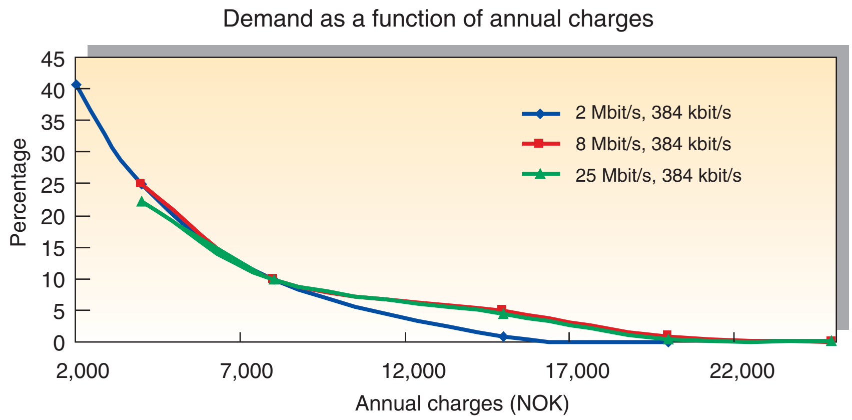

Figure 2 The broadband demand in percentage of the residential market as a function of annual charges

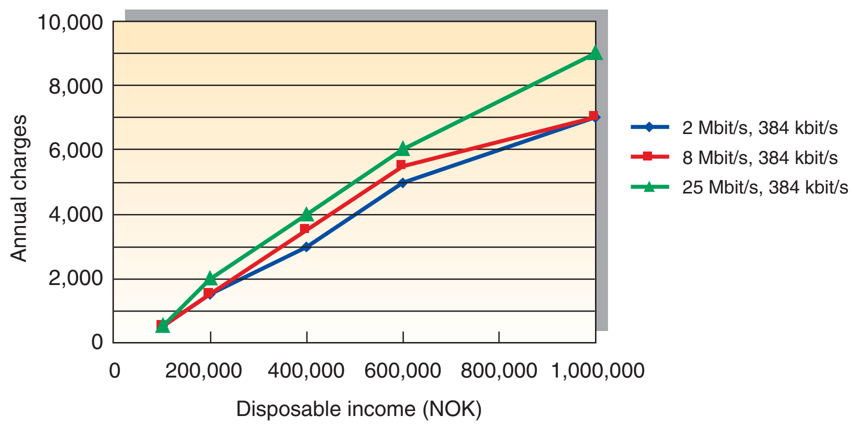

Figure 3 Willingness to pay for broadband communication as a function of disposable household income

Table 3 Willingness to pay in percentage related to ISDN costs as a function of increased bandwidth

Capacity	128 kbit/s	2 Mbit/s	8 Mbit/s	25 Mbit/s	50 Mbit/s	500 Mbit/s
Index annual charges	100	135	150	160	167	175

European Delphi survey the experts estimated that the households were willing to pay between 1 % and 2 % of their yearly disposable income.

10 Price versus broadband capacity

The experts were asked to estimate a price for different access capacities relatively to ISDN as a reference access. The yearly costs for the reference access were set to 100. The experts should add an additional percentage in price for increased capacity.

The table confirms that the households are unwilling to pay much more for very high access capacities. Today an average household in Norway has about 5,000 NOK in annual telephone expenditure. The table indicates that the households are unwilling to pay more than 9,000 NOK for an extremely high bandwidth (ie. 500 Mbit/s). These results are quite comparable to the results achieved in the European survey [1].

11 Symmetric broadband access

In the coming years the broadband communication is assumed to be highly influenced by the Internet. The communication generated is rather asymmetric since the customers mainly communicate with some Internet data sources. When the subscribers get terminals which are able to download and store large volumes of data like videos, a new demand for exchange of large volumes of data is likely to be created. The evolution of broadband terminals ie. PCs will support this development.

Figure 4 shows the expected growth of symmetric 2 Mbit/s accesses and 8 Mbit/s accesses, according to the survey results. In 2005 the share of the symmetric access capacity is estimated to be 5 % for 2 Mbit/s and 2 % for 8 Mbit/s. In the long run it is assumed that the saturation level of symmetric broadband access will be 30 % for 2 Mbit/s and slightly lower for 8 Mbit/s. The uncertainty in the answers increases significantly with the prediction time. The difference between the 25 % quartile and the 75 % quartile increases from 3 % in 2005 to 26 % in 2015. The experts assume that from 2005 to 2015 between 25 % and 35 % of those who demand 2 Mbit/s access will demand symmetric capacity.

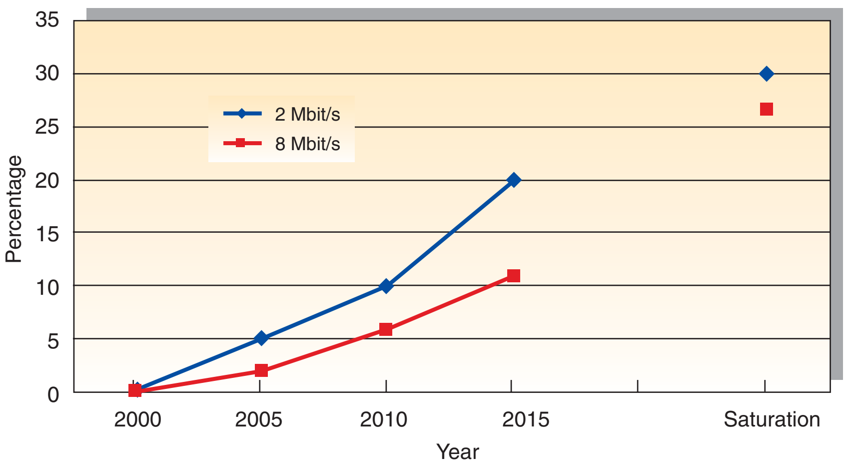

Figure 4 Expected demand of 2 Mbit/s symmetric access and 8 Mbit/s symmetric access

Table 4 Increased willingness to pay for mobile broadband access relative to fixed broadband access (in percentage)

Year	2000	2005	2010	2015	Saturation
Percentage	30	30	30	20	30

12 Mobile broadband access

The respondents were asked to estimate in percentage how much more the subscribers are willing to pay for a mobile broadband access rather than a fixed connection. The question was repeated for the years 2000, 2005, 2010, 2015, and for the saturation year. Table 4 shows that the subscribers are not willing to pay more than 30 % in addition to the fixed broadband access price to get a mobile broadband access.

According to the survey results the expected demand for a 2 Mbit/s mobile broadband access increases from 8 % of the households in 2005 to 20 % in 2010. At the saturation point it is expected that 30 % of the residents will demand a mobile access.

13 Access technology

The experts were asked to give a percentage distribution of the different access technologies envisaged to be the most relevant ones in the future. The relevant access technologies listed in the questionnaire were:

- Coaxial cable modems;
- Copper line modems (digital subscriber line, DSL);
- Fibre (fibre-to-the-home, FTTH);

- Broadband radio access systems;
- Satellite systems;
- Power line modem.

The results are presented in Table 5. The experts expect that the two dominating technologies will be coaxial cable modems and copper line modems (DSL), assuming that each technology will cover 35 % of the households by the year 2010. The respondents also estimate that the power line modem technology will cover about 10 % of the broadband subscribers.

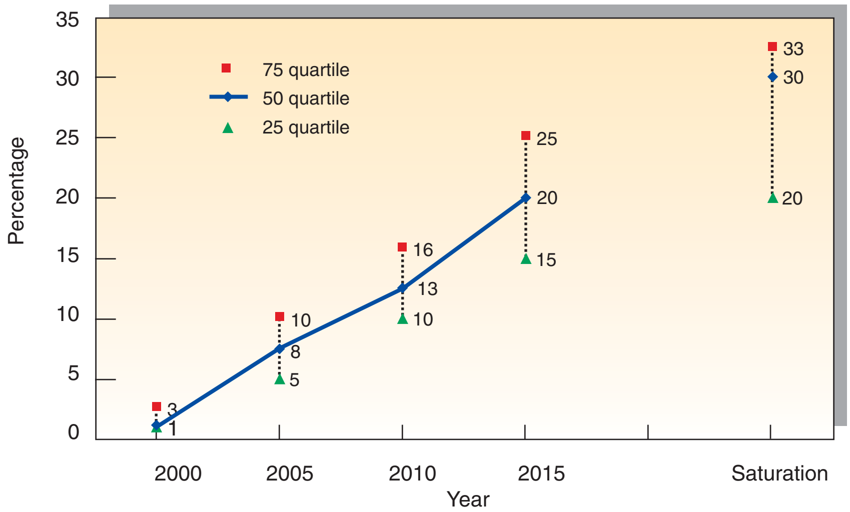

Figure 5 Expected demand for a 2 Mbit/s mobile access

14 Conclusions

The Norwegian Delphi survey on broadband demand shows that there will be a significant demand for broadband services in the residential market during the next ten years. Tele-entertainment, information services and teleworking are the applications expected to be driving the demand.

The households are unwilling to pay much more for higher connection capacity. They expect the technical evolution to reduce prices significantly and enable the operators to offer better quality and higher capacity at reasonable prices. Furthermore, the households are only willing to pay marginally more for a mobile broadband access connection than for a fixed broadband access connection with similar capacity.

It is expected that copper line modems (DSL) and, more surprisingly, coaxial cable modems will be the preferred access technologies.

In comparing the results from the Norwegian Delphi survey with the results from the European survey [1], we find very similar results, except for the estimated broadband forecasts, in which the Norwegian experts expect a much higher demand than the European respondents.

Table 5 Expected coverage (in percentage) of access technology to Norwegian households in year 2010

Technology	Percentage
Coaxial cable modems	35 %
Copper line modems (digital subscriber line, DSL)	35 %
Fibre (fibre to the home, FTTH)	5 %
Broadband radio access systems	5 %
Satellite systems	10 %
Power line modem	10 %

Reference

1 Stordahl, K, Rand, L. Long term forecast for broadband demand. *Telektronikk*, 95 (2/3), 34–44, 1999. (This issue.)

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Regulation of broadband access networks

PER MOGNES AND TERJE NORD

Introduction

This article deals with future regulation of broadband access networks in general. Even though this is an issue of immense importance to the strategic planning of new and old industry players, it is safe to say that it is not an issue in the present regulatory framework applying to the telecommunications sector. Bluntly stated, the only regulatory discourse regarding broadband access networks has been within the context of whether mandatory access to the dominant players' copper lines is within the scope of the present interconnection regime. A natural point of reference for an article such as this one is thus the present status of policies regarding interconnection and access and the most likely developments in that regime. We will, however, also discuss other regulatory developments relevant for possible future regulation of broadband access networks.

It is not possible to accurately predict the outcome of the regulatory process in the years to come neither by extrapolation of the existing regulatory regime by some form of scenario building, nor by analysis of the balance of power between different institutions and ideologies. Furthermore, it is not possible to isolate a regulatory discussion to the issue of broadband access networks alone. We thus readily accept that a description of a future regulatory regime that may seem plausible at present may be next to worthless tomorrow as market and technology may fundamentally alter the underlying assumptions. We have therefore chosen to take a broad approach to the matter, and will discuss it within the context of dimensions we believe are the fundamental ones. For instance, will public policy decisions regarding (the weight given to) the generic issues described in points 1–3 in the panel below be influential to the further direction of the regulatory regime, and also have impact on the actual market development?

Before getting into the specifics we should make it clear that we have delimited the subject of regulation of broadband access networks to imply regulation of public networks and public services only.[1] Furthermore, we keep possible political decisions and public subsidisation of broadband access network investments outside the scope of the article. We have kept the focus to the European setting, and thus given the regulatory processes within the European Union much weight. In this setting a more precise definition of broadband access networks is not necessary (eg. transmission rates) since the EU legislation does not define broadband networks.

We devote considerable effort to the understanding of the balance between sector specific regulation and general competition policy (point 1), because it will denote the regulatory toolbox available to regulators as broadband access networks become a reality. We also believe that finding optimal access rules (who should be given access at what price) that combine the objectives of fostering competition and compatibility in a complex network industry like telecommunications is of paramount importance in future regulation, and we also devote some space to this issue (point 2). The last dimension mentioned (point 3) is not directly discussed in the article, but is inherent in present regulation of the industry, and the outcome regarding points 1 and 2 will decide the focus of this issue.

The article is organised in four sections. First we give the historical background for regulating the telecommunications industry and a short description of the regulatory development towards its present state. In section two we give an overview of anticipated regulatory processes relevant to the formation of a future regulatory regime applying to broadband access networks. The last two sections represent the discussion part of the article. Section three deals with the issue of securing access to bottleneck network facilities, the question of when and why something becomes or ceases to be a bottleneck facility, and discusses the most likely regulatory solutions regarding broadband access networks as we see it. In the final section, we take a closer look at a few other critical issues regarding future regulation of broadband access networks.

Regulation of telecommunications in a retrospective glance

For decades telecommunications (networks and services) have been provided by a secure monopolist. Until the late 1980s public enterprises holding a legal monopoly was the common rule in most countries around the world.[2] The absence of competition was motivated by the existence of large fixed costs in several parts of the network, whose duplication was neither privately profitable nor socially desirable. The telecommunications industry was deemed to be a natural monopoly and the services public utilities – a period often referred to as "the good old days" by incumbent telecommunication operators around the world.

1. The scope and extent of sector specific regulation

Market ⟷ **Regulation**

Competition policy — Sector specific regulation

2. Fostering competition or compatibility

Competition ⟷ **Compatibility**

Access to bottleneck facilities — Standardisation, services regulation, seamless networks

3. Technology dependent or technology neutral regulation

Vertical focus ⟷ **Horizontal focus**

Traditional approach — Convergence approach

[1] *We also refer to broadband access networks possible of transferring two-way simultaneous services only.*

[2] *In the USA AT&T was a private, regulated corporation.*

Over the ten year period 1988–97, the European Community enacted an extensive package of telecommunications legislation designed to enable Europe to respond to the challenges of rapidly evolving and converging technologies and the globalisation of the information economy. A few factors contributed to the reform movement.[3)] The growing awareness of the inefficiencies of the incumbent monopolists (poor incentives to reduce costs and a severely distorted price levels and structures), and the technological change made it evident that some segments could be served equally well, and sometimes better by new players than by the incumbent telephone operator. Furthermore, the impact of the developments in the United States, in particular the AT&T divestiture consent decree and the resulting transformation of the US market began to be felt in Europe. At the same time the progressive deregulation of the telecommunications sector and the privatisation of British Telecom in the UK since 1982 made Europe more receptive to the concept of market deregulation.[4)] In addition, the European Court of Justice confirmed in the *British Telecommunications case* that EU competition rules applied to the telecommunications sector [3].

Table 1 gives an overview of the main developments in EC Telecoms policy and its provisions.

Table 1 Overview of key developments in EC Telecoms Policy

Period	Key measures	Relevant milestones
First phase: (– 1987) First Community measures	Standardisation Public procurement Competition rules do apply	• BT case
Second phase: (1987 – 1992) Initial market opening	Liberalisation of value added services and terminals markets	• Green Paper on telecommunications
	Creation of an Open Network Provision framework	• Terminals directive / Services directive
		• ONP Framework / Leased lines directive
Third phase: (1992 – 1998) Full liberalisation	Co-ordinated liberalisation	• Review (1992/93) / Infrastructure Green Paper (1994/1995)
	Interconnection regime	• Extension of the Services directive (satellite, cable, mobile, full comp.)
	Competition rules	• Reform of ONP (interconnection, licensing, USO)
Fourth phase: (1998 –) Beyond full liberalisation	Process of defining new regulatory principles and options	• 1999-Review
	Convergence	• Green Paper on convergence
	European Case-law	

As the informed reader will know the telecommunications industry is still a heavily regulated industry. The focus of regulatory attention has however changed over the period. While in the first phase (–1987) one focused on issues like standardisation activities, public procurement procedures and the implications of above referred to decision in the BT case (often called the legal cornerstone of the EU telecommunications framework), the second phase (1987 – 1992) was about progressive market opening and issues like

- Full liberalisation of markets for value added services in order to introduce competition [4];
- The separation of regulation and operations, a pre-requisite for the development of an open market, and open, transparent and non-discriminatory regulatory decision making;
- The definition of a harmonised set of access conditions, best known as Open Network Provision (ONP) [5].

Phase 3 (1992 – 98) – full liberalisation – was initiated by the EU Telecom Review from (92/93) where member states agreed upon the decision to liberalise the market by 1 January 1998 (including the remaining public voice telephony and telecommunications network infrastructure monopolies). This time lag was meant to give the incumbent companies time to prepare for the forthcoming competition. Furthermore, there was agreement to adjust the ONP framework to fully liberalised market conditions and to establish a regulatory framework for interconnection and access to services and networks. This implied an asymmetric regulatory regime, where former monopolists are subject to more stringent regulatory requirements (mandatory provisions, non-discrimination, cost orienta-

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3) *The so-called reform movement has implemented at least two separate processes all around the world. First, incumbent operators are being privatised and are provided with better incentives to minimise cost, as well as more flexibility to rebalance rates in conformance with business and economic principles. Second, markets have been deregulated or at least legally liberalised.*

4) *For good surveys of the UK reforms, see reference [1] and [2].*

tion, price regulations, etc.) than do other operators. The scope and extent of the requirements do however differ substantially across nations.

With full liberalisation, and the emerging sector specific EU framework, the definition of access and interconnection within the ONP framework acquired more and more importance. This was refined particularly with the adoption of the ONP Interconnection directive in 1997 [6]. At the same time, recent developments in EU Competition Law made it easy to relate access to bottleneck facilities in telecommunications more explicitly to the *essential facilities concept* [7].

The European Union's experience of regulation for securing access to so-called network bottleneck facilities in the telecommunications sector is however still in its early stage. It is at the moment shaped by a three pillar approach, based on the interplay of 'hands-on' sector specific *ex ante* regulation of access, an *ex post* use of the competition rules, and, to some extent, the search for structural solutions aimed at the development of competitive access markets, ie. cable-TV network investments in merger notification processes.

In a stable environment (as the traditional telephone market is often assumed to be) the cost associated with direct regulatory intervention may be minor compared to the benefits of assuring efficient and open access and interconnection to the incumbent bottleneck provider. However, the more the situation is one of rapidly changing markets, the limitations and costs of sector specific approach becomes more apparent.[5)] As markets are converging, and the more rapidly innovation proceeds and new investments by the bottleneck holders are needed, the stronger the argument for an approach based on general competition law principles will be. From this line of argument, the development path should in the long run be towards a competitive regime, which is based on competitive access markets, and the application of general competition rules.

In the meantime striking the right balance between sector specific regulation, competition rules and structural solutions will be the regulatory challenge. Industry, on the other hand may find this regulatory framework too complex and uncertain.

Regulation in the making

The former and the present regulatory framework in telecommunications still very much have the properties of monopoly regulation as introducing competition has been and still is the regulators' major objective. That is, primary focus on regulation of the bottleneck facilities of the dominant operator and the securing of one-way access of input for entrants. Furthermore, incentive regulation of the incumbents is sustained. By incentive regulation we understand the regulatory schemes offered to the incumbent operators securing performance-based returns and more freedom to set rates in accordance with standard business practices. The economic discussion is then how incentive regulation must trade off cost efficiency and the limitation of operator's rents, and how service pricing should be structured in order to attain economic efficiency, etc. The advent of competition should reduce the attention paid to the incentives and raises a set of new issues, such as efficient competitors, the co-ordination of investments in facilities and new technology between operators, the duplication of networks, and so on.

From an economic point of view some important general features of the telecommunications industry must be taken into account:

- Networks are multiplied and are also multipurpose information infrastructures, and due to network externalities[6)], must be interconnected. Generally speaking, firms with large existing networks tend to be against compatibility, even when welfare increases with compatibility. Securing of interconnection then becomes both a technological compatibility and a regulatory harmonisation issue.
- Large fixed cost is an inherent characteristic of the industry, and some segments may even be natural monopolies. These segments become bottlenecks to which other operators must have access in order to compete. Interconnection policies must be designed so as to allow efficient entrants to come in and keep out inefficient ones. The price signals must be the right ones ('make or buy decision to the entrants') and give the bottleneck owner a reasonable compensation so that they have incentives to build and maintain the bottleneck and not to exclude their rivals from access to the bottleneck. Lastly, interconnection prices must induce an efficient use of the network.
- The location of the bottlenecks changes with the evolution of technology, and furthermore (as competition in the sector increases and substitute facilities evolve) bottlenecks are rarely pure bottlenecks, but most often 'incomplete bottlenecks'.

We will return to these features in the discussion part of the paper. The rest of this section is devoted to giving a brief overview of the regulatory processes anticipated by the EU Commission that may have relevance for the future regulation of broadband access networks. The following tables give a summary description of the key provisions in the EU 1999 Regulatory Review, the EU regulatory approach to convergence, electronic commerce and next generation mobile systems (UMTS).

[5)] *Sector specific regulation, particularly with regard to price regulation, is a deep intervention in market mechanisms, with a high risk and responsibility for the regulator. It becomes highly dependent on definitions, which implies a high degree of technicality, and therefore has a great potential for legal conflict. And it inevitably leads to substantial intervention in the day-to-day business practices and strategies of the bottleneck holder, with the danger of heavy handed regulatory approach.*

[6)] *Externalities imply that one firm or customer affects others without compensation being paid. Other things being equal it is better for customers to be connected to a large network than a smaller one.*

[7)] *Separating the concepts of unbundling and interconnection is important for designing regulation, because, for the purpose of fostering an efficient competitive environment, the process of setting guidelines for unbundling and interconnection is driven by different economic considerations.*

Table 2 EU 1999 Review – issues and schedule

Focus and time schedule	Issues relevant for broadband access regulation
1999–2000: Analysis, investigation, consultation and policy formation	Generic issues: • Sector specific regulation vs. competition rules • Market convergence – horizontal, technology neutral regulation of access • European harmonisation vs. national subsidiarity Specific issues • FMC • End-user access (unbundling requirements) • Facilities vs. services competition • Regulation of scarce resources (frequencies, numbers, domain names) • USO • Licensing • Internet (telephony, Internet access conditions)
2000–2001: Formation of a revised EU legislation	EU Commission proposals for new legislation submitted to the European Parliament and the Council. • Consolidation and simplification of EC rules • Extension of infrastructure regulation • Introduction of 'Sunset Provisions' (efficient competition test – for removal of some provisions of sector specific regulation) • Institutional set-up at EU level, relationship between different regulatory levels
2001–2006: Adoption of new legislation by EP and Council, and implementation into Member States national laws	A political process that may be very time consuming, but much effort will be put into the harmonisation of European regulation, and the idea of 'one-stop shopping'

Access to bottleneck facilities

As mentioned in the introduction a thorough analysis of the scope and extent of the present interconnection regime and its likely development is probably the best way to say something meaningful about regulation of broadband access networks. Regulators can greatly affect the nature and development of competition through their choices of scope and extent of the *ex ante* requirements of interconnection and unbundling in the sector specific regulation.[7)]

We define interconnection as an agreement that gives access to competing operators' customer base and vice versa. Interconnection is an important issue both in the context of network externalities (compatibility) and the development of competition. The present interconnection services are related to the public switched telephony service (call origination, call termination and transit as specified services). From an economic point of view the physical access to the customer is always a source of market power (mobile operators for instance control the only access to their mobile customers). Call termination is thus an input that could effectively be used for restriction of competition in the retail market. Additionally, the operator has incentives for price discrimination between on-net and off-net calls. If one operator dominates the market entirely by its size (market share), refusal to supply the input or unreasonable pricing of it combined with price discrimination in the downstream telephony market, may effectively squeeze an operator with a small market share. Thus, interconnection services are mandatory to provide at a reasonable price and quality (soon including carrier pre-selection and number portability), in order to avoid practices of foreclosure.

Regulatory requirements regarding interconnection services other than those enabling a seamless service in a competitive telephony market (fixed and mobile), will depend upon market development. For instance, what kind of services the incumbent operator offers his own customers and what services competitors would like to realise for their customer base at that point in time. In a competitive market termination of circuit switched broadband services in each other's networks could become manda-

Table 3 Convergence, electronic commerce and UMTS

Regulatory process	Issues relevant for regulation of broadband access networks
Convergence Policy formation regarding a regulatory framework for convergence	• Regulation of access to networks and digital gateways • Technology neutral regulation (horizontal approach) • Adaption of the existing framework
Electronic commerce Setting the principles and removal of regulatory uncertainty	• Internet access conditions • Removal of regulatory risk may help boost supply of services requiring broadband capabilities
UMTS Standardisation activities, securing sufficient allocation of frequencies, co-ordinated introduction, criteria/principles for regulation [8]	• Part of a global standard capable of providing broadband services over a wireless platform • Licensing and regulatory framework in place ahead of market. May set a standard for regulation of broadband access networks

tory if commercial negotiations fail and such failure would seriously impede the value of the service to end-users. If the market situation on the other hand still is one of total dominance for the incumbent operator, regulatory requirements regarding the whole range of interconnection services, and restrictions regarding the pricing of such services, could probably be a plausible requirement. We do not however find this a very likely scenario.

The issue of bringing the logic behind regulation of interconnection into the Internet domain is still premature. Only market development and the future industry structure can give any answers regarding the need for such public intervention. However, the links between different Internet Service Providers' networks (ISPs) bring about concerns similar to the ones in traditional telecommunication. In a new and dynamic market general competition rules would normally be regarded a better tool than direct regulation.

Resale of an incumbent's service is a means for new entrants to enter a market, build a customer base, and compete with the incumbent at the retail level. It provides entrants with the quickest form of entry, since it requires no up-front capital investment. An obligation to provide such access to all services the incumbent itself provides at retail level is not likely, unless infrastructure competition is totally absent. Setting the right price for such wholesale services is a complex issue.

The option of using the ONP framework to secure broadband service offerings has been discussed by the EU Commission in the past [9]. Recent revisions for adaptation of the directives to a competitive environment [10] however show that regulatory obligations will be restricted to the provisioning of additional types of leased lines, taking market demand and progress with standardisation into account. A thorough assessment of the need for continuation of the directives or the need for further measures will be done within the 1999 Review process.

Requiring the unbundling of network elements so that the competitor can purchase piece parts as needed to supplement or replace its own network, would in addition allow for competitors to lease access lines, thus avoiding costly duplication of facilities in that network segment. In this way, competitors can build their own networks much more quickly than they could by providing their own loops. The regulatory risk is as Pablo Spiller [11] puts it, "that regulators underestimate the costs associated with extensive unbundling. Indeed, extensive unbundling and the resale requirement may provide a disincentive for entrants to build competing facilities, thereby impeding the facilities based competition regulators hoped to achieve in the long run. Finally, coercing the incumbent to share its technological innovations can destroy or unfairly award to competitors the returns from research and development through competitors' use of the incumbent's network."

The appropriate level of unbundling is a function of the network segments degree of being an essential facility. Unbundling of essential facilities is a means to prevent an incumbent from foreclosing efficient entry. Forced unbundling of non-essential facilities, however, overrides the role of competition in allocating network investments and can needlessly stifle innovation. What essential facilities are, though, depend on the characteristics of the network, the availability of competitive services and what is perceived as the evolution of technology. Indeed what today are believed quite generally to be essential network facilities may not be regarded essential once other network facilities represent viable alternatives.

Access to the local loop

The case of local loop unbundling (LLUB) is thus based on the benefit of stimulating local competition (in the telephony service and in high speed data access),[8] making the assumption that the local loop is at the moment an essential facility. In a newly released study, Ovum, defines LLUB as an "... interconnect service provided at a point between

[8] *Other less robust arguments that are used in favour of LLUB is 1) avoiding access network duplication, 2) full competition rather than oligopoly, 3) strengthening of existing competitors to the incumbent.*

the customer premises and the line-side of the access network operator's local switch. LLUB thus gives an entrant dedicated access to the customer via the local loop." [12].

Two variations of LLUB are being discussed:

1 Direct access to the transmission medium in the local loop. This would imply copper loop[9)] rental with the point of interconnect being at the distribution frame which marks the end of the copper loop, either at the local switch or in a remote concentrator unit. This allows the entrant to operate its own transmission system to provide the customer access service.

2 Bitstream access, which compromises both the transmission medium and the transmission system. When requiring bitstream access, regulators will need to determine the particular interconnect service that should be provided.

Ovum recommends the regulators to require some form of local loop unbundling to be offered by the incumbent operators.[10)] The EU Commission has made it clear that LLUB falls outside the requirements of the interconnection directive in its present form, but leaves it open to national authorities to incorporate such requirements in their national legislation. The issue of access to the access network (in effect LLUB as a useful tool to jump-start competition) will also probably be further discussed in the 1999 Review process (see table above). The Norwegian regulatory authority has, for example, reached the decision [13] that now is not the right time for such an obligation.[11)] Telenor, on the other hand, has during the process decided to develop direct access products with certain usage restrictions.[12)] If a regulator is requiring bitstream access, the regulator will need to determine the particular services which should be provided. Agreeing upon the set of designated bitstream services and the conditions attached (the issues of (i) who may require access, and (ii) at what price), is not trivial. The Norwegian regulatory authority says it will continuously evaluate the level of competition in the Norwegian market, and the regulatory and market experiences with LLUB from other countries. Regulatory intervention in the access network is therefore not excluded as an alternative neither in the European framework nor in the Norwegian regulatory regime.

We do however assume that the probability of such an *ex ante* regulation of the bottleneck holder decreases over time. Regulators may find that regulation and the efficiency of access is the right approach in a stable environment (as when the voice telephony market is the focus). However, the more convergence of markets becomes the dominant feature, and the more rapidly innovation proceeds and innovative investments by the bottleneck holders are needed, the more an approach based on general competition law principles should become preferred.

Ownership of cable-TV networks

As mentioned earlier the development of viable competitors in the access market building their own access networks either based on fixed line technology or alternative access technologies (substitutes), may fundamentally alter the essentiality of the incumbent's copper lines. Such developments must carefully be taken into consideration when making the regulatory decision concerning the need for public intervention. On the other hand, the regulatory framework may also greatly influence the development of new markets (for instance the incumbent's incentives to develop new ways of access or the incumbent's and the cable-TV operator's incentives to make the necessary infrastructure investments). At present there are two mass distribution systems available in the local loop, which have the capabilities to develop multi-functional broadband access. The public telephone networks of the incumbents, and the many cable-TV networks (with a total penetration of 30 % in the European Union).

Cross-ownership of the cable-TV networks by the incumbent telephone operator may constitute a barrier to the investment incentives to upgrade these networks with full multi-functional access capabilities. In the Cable-TV Review [14], the EU Commission discuss the investment incentives given to the local bottleneck provider under different regulatory conditions like: 1) extension of the ONP regime to cover cable-TV networks, 2) legal separation, to establish a minimum separate development base for both networks, and 3) full scale divestiture of the cable network by the incumbent telephone operator, to establish a business case for both networks to develop full future capabilities. In fact, the EU Commission chose option 2 as a minimal solution for the European Union as a whole. They went on to state that "in certain circumstances it might be that the only means which would allow the creation of a competitive environment consists in the divestment of the cable television network ...". How far a divestiture of bottleneck facilities could be enforced under EU competition rules will be an issue for future case law. However, the EU Commission has made it crystal clear that: 1) sector specific regulation is not the right means to create competitive access markets, 2) companies that enjoy a dominant position in two markets must take particular care not to allow their conduct to impair genuine undistorted competition (Art 86), and 3) an extension of an operator dominant in both telecommunications and cable-TV networks into related fields could raise serious competitive concerns (merger-regulation).

Regulating mobile communication services

In the mobile communications field, next generation technology does also promise next to broadband capabilities. Such broadband capabilities mixed with mobility could over time make the mobile operators a serious competitor to the existing potential broadband access networks. In the EU Council's common position paper [8], UMTS is described to be a system for mobile multimedia: "A third generation of mobile communications system capable of providing, in par-

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9) *It is not at the moment considered technically feasible to offer direct access to the transmission medium in the case of fibre loops, as capacity is then shared between many customers which makes separating a physical path for unbundling impossible.*

10) *Ovum's stand in this matter is actually considerably revised from earlier reports. Confront Ovum's report for the Norwegian regulatory authority (Pt) from 1997 where they unambiguously recommend copper rental.*

11) *This conclusion is confirmed by a Parliamentary decision in spring 1999.*

12) *Usage restrictions on the transmission medium, that is restrictions on the rental of dedicated subscriber lines related to standard termination of either PSTN, ISDN or ADSL.*

ticular, innovative wireless multimedia services, beyond the capability of current second generation systems such as GSM, and capable of combining the use of terrestrial and satellite components." If the UMTS vision is to come through, the regulatory framework must secure the availability of frequency spectrum, a scarce resource, as well as providing for an enabling regulatory environment. It seems to us that much of the same regulatory logic as the one described above for fostering investments from cable-TV operators will be used in this context. Thus, general competition law should be used as the regulatory framework for UMTS. Mobile communications has, however, some characteristics that will complicate part of the picture. We will return to the specifics of mobile regulation, but first also mention the importance of the standardisation process, which will remain a key factor in providing quality services at an affordable cost and enable roaming and interworking between systems. The flexibility of interfaces and the capacity to evolve in parallel with technology is as crucial for UMTS as it has been for GSM. However, such standardisation has an inherent tendency to become industrial policy, and what we have observed is a tug of war between different geographical regions.

Policy is an integrated part of regulation, and especially the relationship between frequency administration, the choice of licensing techniques and the attached licensing conditions may be problematic as different public policy aspects have conflicting interests in due matter. Harmonisation is not compatible with competition and the European solution traditionally differs somewhat from the American. Especially the issue of technology competition is problematic as Europe in order to promote pan-European markets and services is supporting one standard, and spectrum resources are being dedicated to that particular standard. The outcome of the different initiatives in ETSI, 3GPP, ITU and work within autonomous industrial co-operatives will be decisive for strengthening the further development of the mobile multimedia market.

The following regulatory aspects for licensing UMTS[13] are important:

- The process of selecting eligible candidates must be open and non-discriminatory. The mechanism for picking winners (auction, 'beauty contest' or other procedures) and the likely criteria and conditions attached to a licence must be decided and communicated to stakeholders prior to the licensing process.
- Efficient utilisation of spectrum resources implies finding the right balance between giving each operator enough spectrum to enable sufficient service capabilities and the need to have enough operators within the available spectrum to maintain and promote a fully competitive market. According to the Licensing directive, any limitation to the number of operators should only be made on the basis of the scarcity of the spectrum. A harmonised European approach regarding finding available frequencies is already proposed.
- The requirements in the license or other regulation concerning 1) network quality and service capabilities, 2) roll-out and coverage, and 3) provisioning of roaming, facility sharing, etc.
- Private networks and other use of uncoordinated spectrum.

Alternative broadband access networks

In addition to the traditional access network systems (copper-, coax-, radio-based systems), adoption of novel access technologies like broadband radio (for instance broadband DECT and LMDS) or powerline modems running on the electric transmission grid may turn local infrastructure into a truly competitive segment. When such solutions represent viable alternatives (if technology and demand develop), the local infrastructure segment will become less of a bottleneck segment. Thus, the rationale for asymmetric regulation of the incumbent provider of copper line access in order to jump start competition, will vanish. Further development of infrastructure regulation will be a less relevant issue. On the other hand, it could make regulation of services even more relevant. In order to secure for instance the provisioning of a quality broadband service to the end-users, transmission and quality standards might be necessary. Future regulation should therefore imply more emphasis on technology neutrality to avoid giving biased investment incentives to the industry players.

Other critical issues

Negotiation versus direct regulation of access agreements

Negotiating interconnection is a complex undertaking, and as such it is extremely difficult to attempt to set all economic and technical conditions via direct regulation. On the other hand, commercial negotiations have shown to produce substantial delays, particularly when there is no clear framework for resolving disputes. Most countries have therefore chosen to let charges be a result of commercial negotiations between the parties, with the regulator looking over their shoulder accepting the terms in the agreement. A key ingredient of a clear framework for resolving interconnection disputes is thus a cost methodology to apply should negotiations fail. So far, most countries have chosen to apply a cost based methodology. The rationale for such an approach is straightforward: cost oriented rates attempt to replicate competitive conditions, and as such provide the right signals to entrants and incumbents in terms of investment and network expansion. There is less agreement, though, on how to measure costs and which cost should be measured.

With true competition market forces will drive prices to their efficient levels. Thus, in the case of true competition the regulator should allow the parties to negotiate prices freely. In the transition process toward this competitive market regulators want to prevent anti-competitive behaviour of the incumbent (price well above cost to discourage competition or collect the majority of rents) by establishing a framework for pricing. The process of agreeing upon the right principles regarding charging methodology is at the moment a hot issue in the regulatory discourse (sector specific regulation). Although fully allocated historical cost has been mostly used, consensus is being built concerning the advantages of using a forward-looking incremental cost. Thus, a form of Long Run Incremental Cost (LRIC) methodology, already implemented in some countries and strongly advocated by the EU Commission, will probably be the chosen cost standard in most countries regarding input facilities pricing.

The extent to which we must expect sector specific regulation to require this kind of charging policies to apply also in the case of broadband access networks,

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[13] *See for instance [15].*

depends on the actual state of the market at that time. That is, how competitive the market is, and how far one has come in the direction of applying general competition rules to the sector. It will also be influenced by the actual experiences of different cost based pricing schemes. The cost of regulatory oversight will increase as the market develops. We would expect that the more blurred the relationship becomes between services and the underlying delivery system the stronger the regulatory cost becomes associated with requiring the necessary oversight. Additionally, the flaws of asymmetric regulation[14], that is regulation that either exclusively or differentially applies to one or a group of providers, will be more apparent once multimedia markets develop. Regulation designed in a world with a one-to-one correspondence between delivery system and service will no longer be appropriate as the number of services offered over different delivery systems is expanding rapidly. The need to focus more on dynamic efficiency (that is giving the low cost producers the right entry or investment incentives for innovation with a focus on long term efficiency) will be given more weight in the future regulatory discourse. We support the hypothesis proposing that the greater the differences between the sunk cost of the potential competitors, the weaker the argument for asymmetric regulation [16]. If our expectations regarding technology- and market development are correct, regulation of access to broadband network facilities will be an issue for the competition rules only. We will then have commercial negotiations and price setting. Prices for such facilities must however still be reasonable, and the only practically available benchmark will probably become other operators' charges for the same input product or any relevant retail tariffs.

[14] *Two general forms of asymmetric regulation exist. Line of business restrictions prevent a delivery system from providing a particular service (eg. fixed network operators to enter the cellular market). A second, more indirect form of asymmetric rules are those that impose on one group of providers (deemed dominant) the requirements to post tariffs, to provide evidence for cost orientation, to supply certain services, etc.*

The need for structural separation of certain network segments that occasionally is brought into the regulatory debate, like splitting the incumbent's infrastructure activities (the bottleneck segments) from (potentially) competitive segments like service provisioning activities, should, following the same line of logic, be an even less relevant regulatory instrument. We will, however, remind the reader that this is a popular approach in other network industries like electricity and railways. Thus, one cannot totally ignore the possibility of regulatory decisions like (although very unlikely) the Internet backbone network becoming vertically disintegrated regulated utilities, or regulators trying to encourage the development of an ADSL local loop that would be providing services to all operators on complementary segments. Under structural separation, the utility in general sells wholesale services to other firms who then market final services to the consumers. Price regulations would still be necessary.

Radio spectrum allocation

A vast array of radio communications techniques and services has become vital to the industrialised world's economy and safety of people. Given the increasing dependence of society on the provision of information and communication by wireless means (in satellite-, broadcasting-, mobile- and other terrestrial based radio communications systems), spectrum matters are becoming critical from an economic, political, consumer, and public welfare point of view.

The planning of the usage of radio spectrum by services at a national, regional and global level depends on the decisions taken at World Radio-communications Conferences (WRCs). At WRCs the 186 member countries of the International Telecommunication Union (ITU), decide whether, how and under what conditions frequency requirements for existing and planned radio communications systems can be accommodated. WRCs therefore result in legally binding international commitments. The development and negotiation of European positions for WRCs and the voluntary adoption of harmonised measures, are done by the European countries in the framework of CEPT (European Conference of Postal and Telecommunications administrations). Considering that the demand for radio spectrum is increasing steadily due to technological, market and regulatory developments, and that this is not counter-balanced by additional radio spectrum becoming available through the introduction of new and more efficient technologies, the consequence is that the scarcity of radio spectrum is increasing. When in addition to that, the existing mechanisms may be insufficient to phase out or relocate existing systems to other parts of the radio spectrum in time (as in the case of developing countries), the conflicting interests become apparent at WRCs in terms of differing frequency requirements.

The spectrum administration, consisting of the process for assignment of radio spectrum to individual users and the licensing of radio communications operators, is done at the national level, subject to certain conditions agreed in the World Trade Organisation (WTO) and for the European Economic Area, the EU Competition Law. The aim is to establish a regulatory level playing field within the WTO member countries for all users of radio spectrum which is based on open, objective, non-discriminatory and transparent ground and which supports technological innovation and competition[15].

With regard to internal market considerations in the EU, radio spectrum availability affects the scope for the pan-European provision and free movement of services and equipment. The harmonisation of the use of radio spectrum is therefore considered particularly important in this context to facilitate the introduction of pan-European and global systems and to realise the economies of scale necessary to make European industry competitive in world markets. With regard to this, standardisation and type approval policies are central means in the overall EU policies.

The issue that dominated the negotiations at the WRCs in 1995 and 1997 concerned frequency availability for the provision

[15] *This includes ensuring that choices with regard to the attribution of radio spectrum do not privilege technical solutions at the expense of competing technologies, and that no blocking or unreasonable limitation of market access for operators from other WTO member countries are taking place (ref. UMTS licensing controversy between US and EU).*

of satellite-based broadband services which will allow for high-speed Internet access and video conferencing to take place anywhere in the world. At the WRC in 1997 spectrum was opened up for the provision of such services. The forthcoming WRC in 1999 will take further decisions on spectrum requirements for the mass market broadband communications systems, eg. satellite broadband systems (as proposed by for example Teledesic and SkyBridge) and terrestrial mobile broadband systems (eg. UMTS). The limited amount of frequencies available for the provision of satellite broadband services and the huge capital investments required to develop such wireless Internet infrastructures will have consequences for the level of global competition in this important area of the emerging information society.

User access through private networks

The EU regulation framework provides conditions for non-restrictions in the use of or access to public telecommunications networks. It may include harmonised conditions like technical interfaces, usage conditions, tariff principles and access to numbers. The actual possible network segments between the public networks termination points and the user terminal systems, which we may call private networks, are however not included. These network segments are historically provided and owned by most incumbent public operators. According to the ONP principles, the location of network termination points shall, however, be defined by the national regulatory authority and should represent a boundary, for regulatory purposes, of the public telecommunications network. This boundary is in many cases drawn at the foundation wall or in connection with other private property boundary lines. Thus to ensure user terminal access to public broadband networks, it may be necessary to put regulatory requirements on private networks.

Concluding remarks

Current regulation does not, as described in this article, address broadband access networks. Apart from discussing broader access to local loop elements of the incumbent operator, the issue has not been discussed in any detail at all. Furthermore, it is not possible to isolate the future regulatory development to broadband access networks alone. Predicting the overall future regulation, we would say that:

- For the foreseeable future, sector specific rules will be required in addition to normal competition law to ensure universal service, interconnection and consumer protection. Concerning universal service the question needs to be asked whether the existing universal service model fits the goal of delivering the benefits of the information society to all.
- In the medium term, sector specific regulation will be needed in the telecommunications sector to promote competition in the following circumstances:
  - a) when dominant operators have an interest in refusing interconnection/ access;
  - b) when there are network externalities;
  - c) when a supplier controls a bottleneck.

The following set of general principles will hopefully underpin the formation of any future regulatory framework applying to broadband access networks.

1. Regulation shall only cover areas that cannot be left to competition (the principle of lightness). Obeying the basic economic principle that the existence of large fixed costs and large returns to scale contradicts marginal cost pricing regulation will be kept in mind. This recognising the fact that broadband access networks will never be built if their owners are allowed to charge only marginal costs (LRIC). The computation of marginal cost also leaves the regulators in charge of setting prices and is discretionary. It will lead to heavy-handed regulation.
2. Policy objectives must be clearly identified, by which regulation must be related. The objective of creating a 'level playing field' is thus only an intermediate objective. New objectives for instance related to the building of a very costly 'information superhighway' should require totally different regulatory means, if any.
3. Regulation must be technologically neutral. The current differences between the regimes for fixed and mobile should be abandoned.

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IP or ATM in the access network?

FRODE B. NILSEN

This paper discusses the applicability of IP and ATM in the future broadband access network. These are the two possible statistical multiplexing technologies that can be used to accomplish service integration. The development of a service integrated network is required in order to provide efficient and cost-effective broadband access. The main conclusion of the paper is that ATM has beneficial properties in the access domain and it involves less risk when it comes to deployment. However, it is likely that the access network will operate in an IP oriented context. Then the combination of IP and ATM becomes an important issue. This combination creates new opportunities that affect the role of the access network. The paper asks if the traditional provision oriented role carried forward by ITU is obsolete.

1 Introduction

The future broadband access network will be different from the existing narrowband copper based network in three respects:

- Technological variety;
- Open provisioning;
- Service integration.

Hence, we are facing paradigm shifts along three dimensions that change the architectural requirements of the access network. Technological variety means that both fibre solutions, satellite systems, cable-TV networks, radio systems and xDSL solutions over the existing copper network can be part of a unified architecture. An open architecture is required for operating in a competitive environment with different core network operators. Service integration refers to an access network in which all kinds of traffic are mixed by means of statistical multiplexing[1]. This is in contrast to static multiplexing and dedicated connections which are currently being used. The objective is to provide a common access solution replacing the set of specific solutions being used today for platforms like ISDN, FR, IP and ATM. The rationale for service integration is efficient and cost-effective provisioning of broadband access. The challenge is to maintain QoS in the mixed traffic stream.

This paper focuses on service integration and the crucial point is how to perform statistical multiplexing with QoS guarantees. The key question is whether IP or ATM should be used. We argue that ATM is the most appropriate multiplexing technique for the access network. This is based on an assumption that guaranteed QoS is indeed a critical factor and that ATM currently is a more mature technology in this respect.

Otherwise our view rests on a general argument that deploying an ATM based access network involves less risk than using IP. The point is that an ATM assumption is compatible with both views traditionally carried forward by the telco and datacom industries, respectively. The telco view considers ATM as the universal protocol supporting end-to-end user communication. In the datacom view the role of ATM is reduced to a transmission technology with local significance. An overlaid IP layer is considered to be the proper level for universal end-to-end user communication. Note, however, that the application of ATM is still beneficial since the QoS capabilities can be exploited by the IP level.

We argue that the datacom view is most likely to prevail in the future and discuss how an ATM based access network fits into an IP oriented context. This is in particular related to the interface between the access network and core network operators. Since both IP and ATM are equipped with rich functionality concerning control and switching new opportunities arise. Hence, we ask if the provision oriented role of the access network as traditionally carried forward by ITU is obsolete. Different industrial groups like ATM Forum and ADSL Forum propose novel solutions implying a new understanding of the access network. The first evolutionary step is session oriented free selection of core network provider. In the most radical case the access network can be equipped with switching capabilities, thus working closely together with the core network. In an IP oriented context the ATM based access network will comprise an underlying subnet in a larger IP network. Then an assessment of techniques like CLIP, NHRP, MPOA and MLPS for providing IP over ATM is required.

1.1 Organization of the paper

The rest of the paper is organized as follows. Section 2 presents a generic architectural model of the future broadband access network. It includes a discussion of fundamental issues concerning housing facilities, hierarchical network levels and basic transmission technology. The model is in turn used as a reference for the discussion of IP and ATM in the access network. However, the need for service integration is first discussed in general terms in section 3. The focus is the rationale for service integration and how this is related to both the core network and access network domains. Then in section 4 the general battle between IP and ATM as possible technologies to realize service integration is discussed. The two different views being representative for the telco industry and the datacom industry, respectively, are central to the discussion. Equipped with the general knowledge from section 3 and section 4 we are ready to discuss specifically how IP and ATM can be applied in the access network. This is the subject of section 5 which provides an answer to the question posed in the title of the paper. The same applies for section 6 discussing the role of access network. The key issue is if the role should be redefined as a result of the new opportunities that arise when IP and ATM are introduced. The paper is concluded in section 7.

1.2 Acronyms

A number of acronyms are used throughout the paper. They are summarized in the following table for the convenience of the reader.

ADSL	Asynchronous DSL
AR	Access Router
AS	Access Switch
ATM	Asynchronous Transfer Mode
BAP	Broadband Access Point
CATV	Community Antenna TV
CLIP	Classical IP over ATM
CoS	Class of Service
CR	Core Router
CS	Core Switch
DSLAM	Digital Subscriber Line Multiplexer
ENET	Ethernet
FR	Frame Relay

[1] *Also called dynamic multiplexing.*

HDSL	High Speed DSL
IDSL	ISDN DSL
IETF	Internet Engineering Task Force
IP	Internet Protocol
ISDN	Integrated Services Digital Network
ISP	Internet Service Provider
ITU	International Telecommunication Union
L2TP	Level 2 Tunneling Protocol
LAN	Local Area Network
LANE	Local Area Network Emulation
LAP	Local Access Point
LIS	Logical IP subnet
LMDS	Local Multipoint Distribution Service
MPLS	Multi-Protocol Label Switching
MPOA	Multi-Protocol over ATM
NHRP	Next Hop Resolution Protocol
NT	Network Termination
OLT	Optical Line Termination
ONU	Optical Network Unit
OSPF	Open-Shortest Path First
PDH	Plesiosynchronous Digital Hierarchy
PMD	Physical Medium Dependant
PON	Passive Optical Network
POP	Point Of Presence
PPP	Point to Point Protocol
PPTP	Point to Point Tunneling Protocol
PSTN	Public Switched Telephone Network
QoS	Quality of Service
RSU	Remote Subscriber Unit
RSVP	Resource Reservation Protocol
RTP	Real-time Transport Protocol
SDH	Synchronous Digital Hierarchy
SN	Service Node
SNI	Service Node Interface
TC	Transmission Convergence
TE	Terminal Equipment
VDSL	Very High Speed DSL
XDSL	(Any) Digital Subscriber Line

2 Broadband access requires a new architecture

Figure 1 is a generic illustration of how the future broadband access network architecture is likely to be. The specific model and terminology used here is a result of a study performed by Telenor [1]. However, the model is perfectly in line with similar work carried out by other operators and equipment vendors [2–8].

The trend towards open provisioning means that different administrative domains will be involved as marked with vertical dashed lines. In addition to the access operator marked with a yellow color, it is natural to distinguish between transport providers and service providers. In the case of a switched network service we use the term platform operator instead. As suggested by the figure cross-domain management is an important issue for the future broadband access network. Management is beyond the scope of this paper, though.

The trend towards technological variety is illustrated by three different cases to the right in the figure. The topmost case corresponds to the existing narrowband solution with copper lines terminating in an RSU. The vertical lines branching off at this point indicate how access to various platforms is currently realized. The existing solution is characterized by having dedicated connections and no concentration of traffic in the access network. In the future broadband architecture access will take place in terms of service nodes (SN) as shown to the left in the figure. The significant difference from the existing solution is that the depth of the access network increases. Further, traffic will be concentrated in several steps between the end user and the service node.

The term local access point (LAP) is used for the natural aggregation point covering the customers within a geographical area of moderate size. Compared to the existing access network a LAP may correspond to a point where an RSU is located. Assuming that deployment of ADSL [9] is the initial step towards broadband access, a DSLAM will be located at the same point. The next step is to concentrate traffic even before the LAP. This is illustrated by the triangles in the figure. The bottommost case is representative for a CATV solution [10]. The local feeding point for the cable network will then constitute a LAP. An alternative interpretation of the same case is a radio solution where the base station constitutes a LAP. In any case access takes place over a shared medium so that traffic is aggregated all the way to the customer premises. The case in the middle is representative for a hybrid solution with a tree-structured PON in combination with VDSL over the last drop [11]. If the fibre network covers a moderate number of customers it is natural to let the root of the tree, denoted an OLT, define a LAP. If the fibre network has extended coverage it might be more appropriate to let the optical termination point in each leaf, denoted ONUs, constitute LAPs.

The point denoted broadband access point (BAP) is central in the architectural model. A BAP links a number of local areas on one side to one or more service nodes on the other side. A LAP is linked to only one BAP whereas an SN can be connected to several BAPs. Hence, a BAP defines the termination of a local access network with the corresponding interface to the service nodes denoted SNI. The model facilitates use of intermediate transport providers at both sides of the BAP. This may happen either in terms of leased lines or over switched networks. In the latter case it is assumed that permanent virtual connections are used as indicated by the dashed lines. The point is that arbitrary switching is not allowed, thus prohibiting direct connection between two LAPs (or BAPs).

The physical location of a BAP depends on the customer base in the connected LAP areas, and also the location of the SNs. One extreme case is to co-locate the BAP with one of the connected LAPs. The other extreme is to co-locate a BAP with an SN. In practice, the optimal location will be determined by a trade-off of the transport costs carried by the access operator and the service providers, respectively. The same trade-off will also determine the number of LAPs and BAPs in a nation wide access network.

3 The Internet drives service integration

The vision of a world-wide service integrated network was originally associated with the work on B-ISDN and ATM as the enabling technology [10]. However,

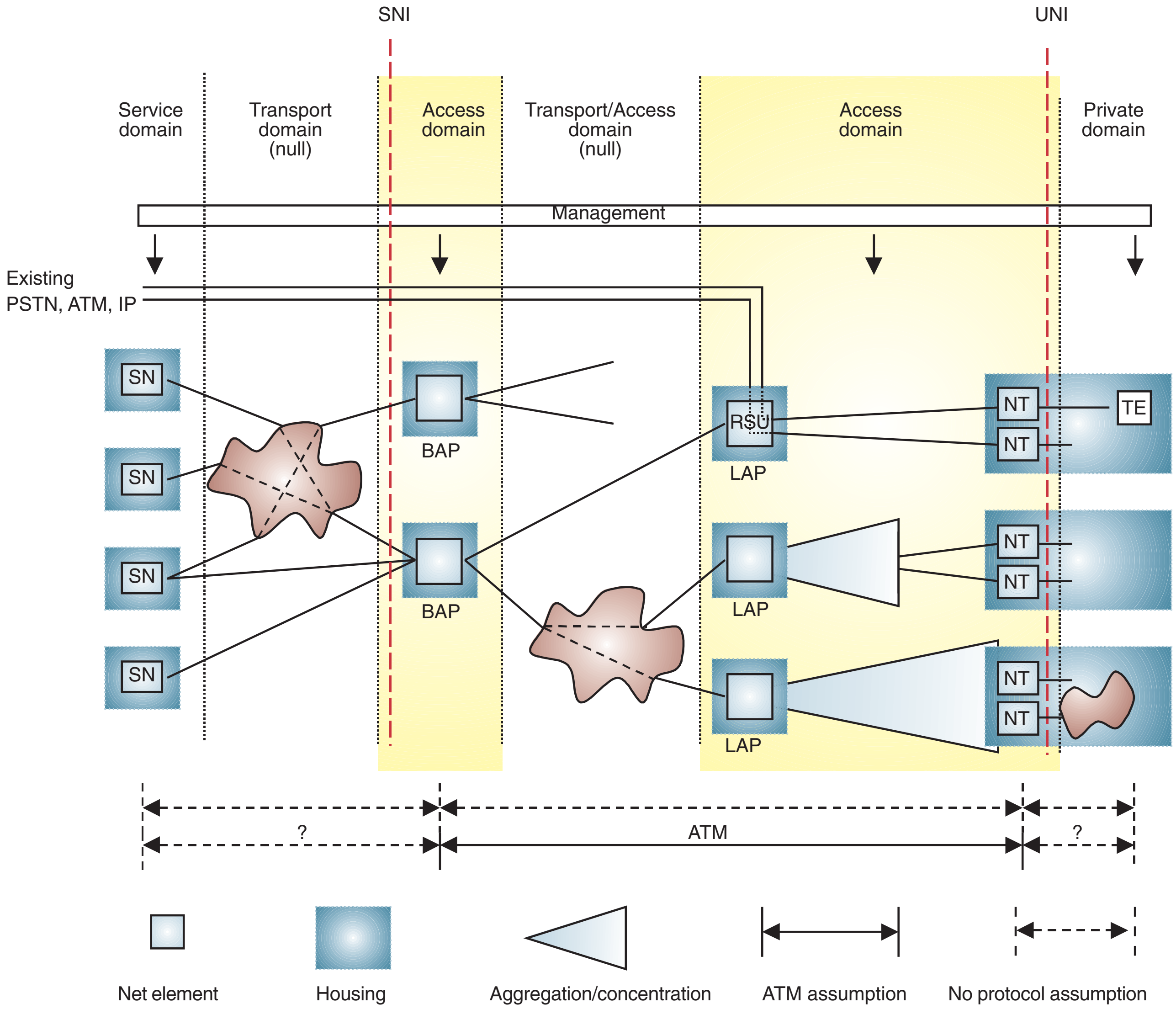

Figure 1 An architectural model of the future broadband access network

the mass market has failed to request any large-scale service except ordinary telephony up till now. For this reason there has been no driving force towards service integration. The recent growth of the Internet as the killer application in addition to telephony has led to a new situation. The challenge today is to develop an overall network architecture which can efficiently provide both a real-time service (telephony) and a best-effort data service (Internet) all the way to the customer premises.

It is natural to consider the development towards service integration in two phases. In the short term the objective is to provide an efficient solution for Internet access that exploits the existing line switched architecture. This does not imply true service integration since the existing telephony service is operating in parallel. In the long run the objective is to provide the telephony service over a new integrated platform which can also be used for any other service, including Internet access. Such a platform is presumably based on either IP or ATM.

3.1 The short-term solution does not affect the access network

Using the existing line switched architecture, in terms of dial-up connections or leased lines, is the normal way to connect to the Internet today. In either case the resulting point-to-point link runs IP between the customer premises and an access router as illustrated in Figure 2. These routers are located at selected places in the core network and administrated by various ISPs. It is customary to denote such a connection point a POP. The session protocol normally being used between the customer and the POP is PPP [11]. This protocol has mechanisms for accounting, authentification and authorization.

The problem with the solution outlined in Figure 2 is that the bursty nature of IP traffic gives a low utilization of the dedicated link between the customer and the POP. For dial-up connections the holding time is also much longer than is the case for an ordinary telephony session. The effect is that the existing access and transport networks, which to some extent are tailored to telephony, are increasingly being used to carry IP traffic with widely different characteristics.

The problem can be solved as illustrated in Figure 3 by moving the access routers closer to the customers. Concentration of IP traffic close to the customers results in a multiplexing gain and gives improved overall link utilization. As the customer base grows the number of access routers will increase and the routers being moved closer to the customers.

An alternative to the IP solution is to use ATM or any other packet switched platform like FR or X.25 to achieve concentration of traffic before the POP. This is illustrated in figure 4 for the case of ATM. As suggested it requires that access switches are located close to the customers. Compared to the IP solution multiplexing takes place at a lower level but the gain in terms of improved link utilization is otherwise the same. The disadvantage of using ATM for transport of IP is increased overhead and packet loss. This results in a throughput reduction of about 10 % compared to the pure IP solution. One advantage of the ATM solution is that it is possible to change the ISP connection in a flexible way. Another point is that ATM can be used to carry other data services than IP. One important example is transport of Ethernet frames between remotely connected LANs. Note however, that it is possible to implement dynamic ISP selection and generic data transport also on an IP platform. The protocol suite PPP, PPTP [12] and L2TP [13] can be used to establish transparent tunnels in an arbitrary IP network.

In general, the IP solution is preferable when the ISP itself is taking responsibility for connecting the customers to the POP. The ATM solution is a more natural choice when the ISP buys a generic access service from a secondary pro-

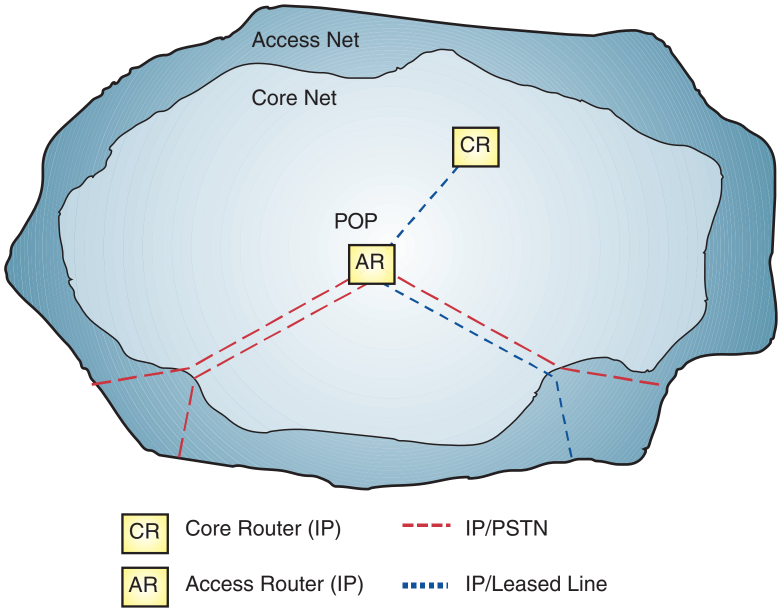

Figure 2 The prevailing solution for Internet access today

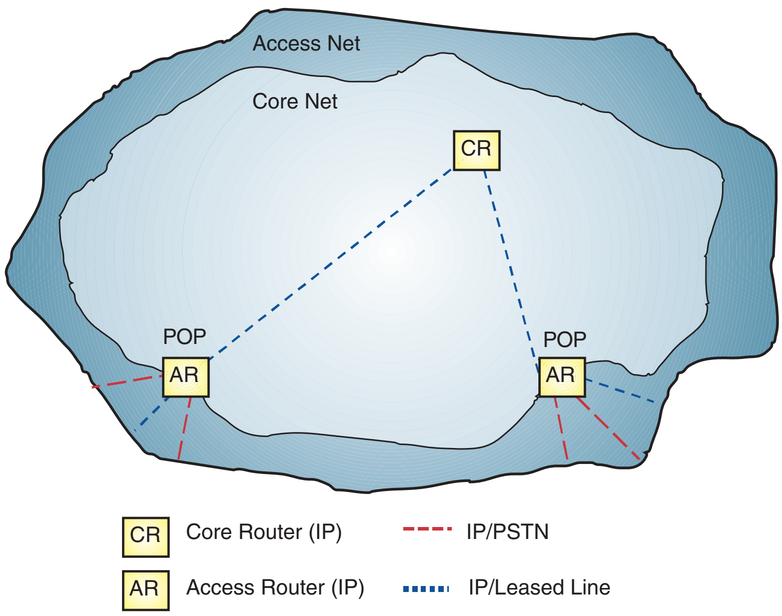

Figure 3 Pure IP solution for concentration of Internet traffic

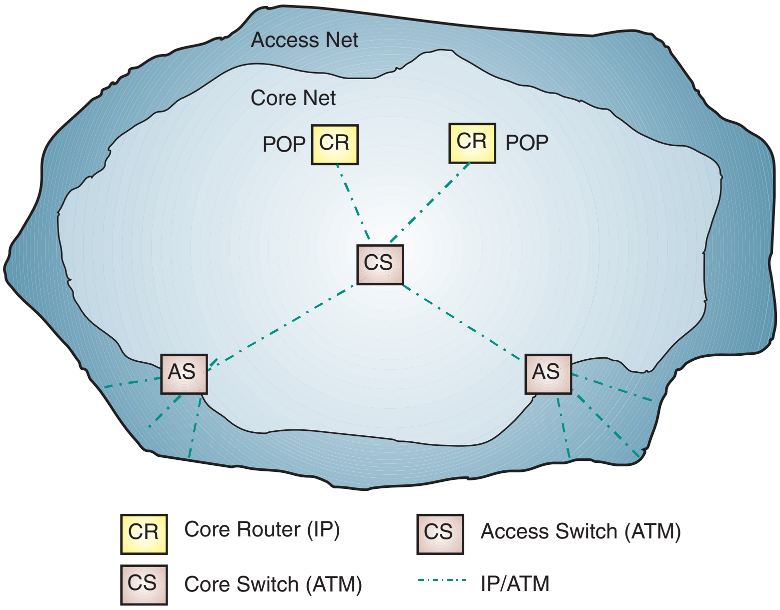

Figure 4 ATM solution for concentration of Internet traffic

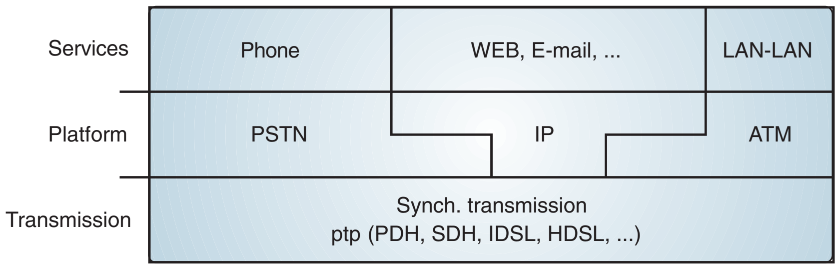

Figure 5 The existing situation with IP and ATM operating as parallel platforms along with PSTN

vider. In any case it is important to note that the access network itself is not affected. The connection to the closest switch or router is dedicated for each customer and operates in parallel with the telephony service. There is no concentration of IP or ATM in the access network domain.

3.2 The long-term solution implies a service integrated access network

The transport infrastructure in terms of dark fibre and PDH/SDH links is increasingly being used to build switched platforms like ATM or IP in addition to telephony. Figure 5 is a pictorial representation of the situation today in terms of a three-layered model. The figure suggests that the PSTN platform is dominating, with IP and ATM as parallel networks. The platforms are realized on top of a synchronous transmission infrastructure. Figure 6 is a net projection of this representation showing a stylistic view of how the transport network is being used for different purposes. The dashed lines indicate that access to the various platforms happens in terms of dedicated links as discussed in section 3.1.

An expected evolution is that either IP or ATM will gain popularity and eventually constitute a unified platform for all service production. This will initially happen in the transport network domain as illustrated in Figure 7. Eventually the same evolution will take place in the access domain so that concentration of traffic can take place even closer to the customers. The last step is indicated by the arrows in the figure.

It is important to note that the development of a universal service integrated platform represents a paradigm shift that affects the current understanding of the terms access network and transport network. When IP or ATM constitutes a layer on top of the existing infrastructure, a new type of transport and access network is formed. A side effect is that the existing clear distinction between the two domains gets blurred. We return to this issue in section 6. Note also that the development of an integrated platform moves the focus from network aspects to service aspects. It should be added, however, that a fully paradigm shift is probably 10 years into the future.

4 There is a general battle between IP and ATM

In order to discuss the role of IP and ATM in the future broadband access network we need to have a general opinion on whether IP or ATM will be the preferred choice to accomplish end-to-end service integration. This is *the* most controversial issue in the combined telco and datacom industry today. It is important to keep in mind though, that the two industries approach this issue in different ways. Historically, the datacom industry has been data oriented without any regard to real-time requirement. It is only recently that this industry has gained interest in supporting real-time applications. The telco industry has traditionally been oriented towards telephony and real-time applications. Even if they have also developed efficient solutions for data communications it is only recently that this has become equally important in terms of traffic volume and revenue basis. The growth of the Internet is a main contribution in this respect.

The next two sections describe the views on IP and ATM that these two industries represent. The telco industry is in general ATM oriented, whereas the datacom industry is IP oriented. In section 4.3 we argue that the IP oriented datacom view is most likely to win the ongoing battle.

4.1 The telco view is ATM oriented

The key issue regarding the question about IP or ATM is how the Internet and the associated IP protocol is considered. The traditional view of the telco industry is shown in Figure 8 and considers Internet as an important service, but still as a service along with telephony, VoD, etc. The Internet is regarded as the killer application that has been missing in order to stimulate the development of a service integrated platform based on ATM. Note also that ATM defines basic transmission as indicated by the lower level in the figure. A number of standards exist that define cell transmission for point-to-point and broadcast media.

The main point of the telco view is that ATM is designed for QoS, thus enabling service integration. In contrast, the existing IP technology does not have any support for real-time traffic. Nevertheless, it is still possible to handle real-time requirements at a higher level by end-to-end control [14]. Some examples of this approach are the RTP protocol and also the H.323 protocol family used for IP telephony. The overall idea is to monitor the end-to-end quality and exploit the available resources in the best possible way without actually giving any guarantees about the service quality. Experience has shown that this works satisfactorily as long as the network is not heavily loaded.

4.2 The datacom view is IP oriented

The prevailing view of the datacom industry is that the IP technology will be further developed to support QoS. This means that resources can be pre-allocated in the network rather than relying on the end-systems to utilize the available

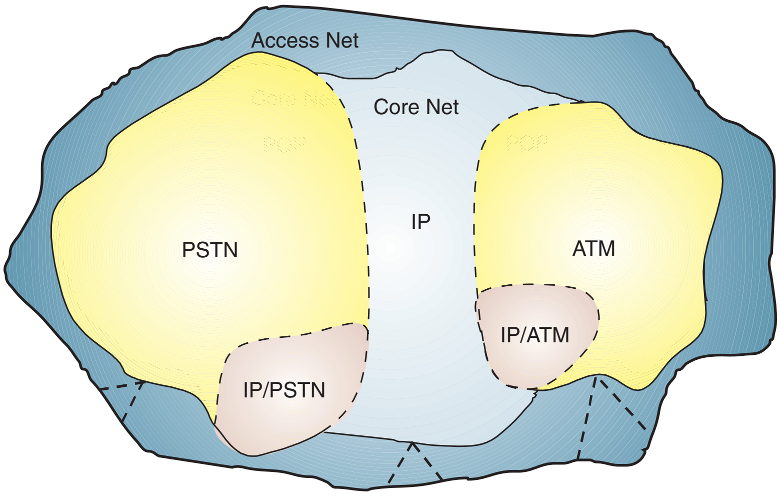

Figure 6 A network projection of the platform level in Figure 5

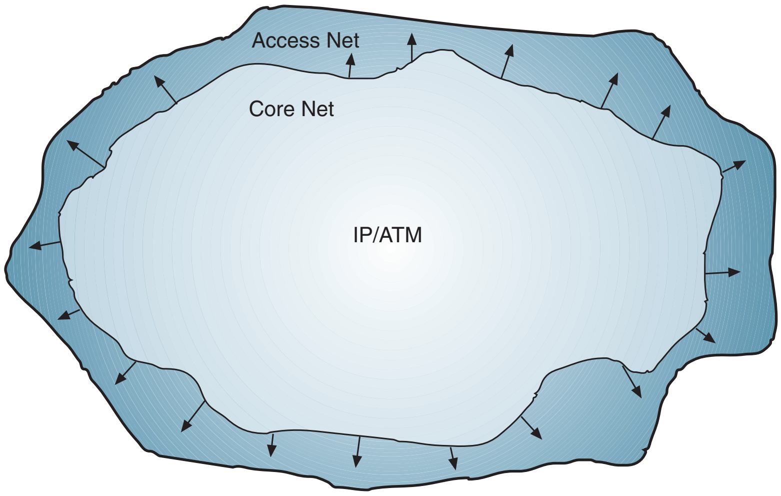

Figure 7 The long term development towards a service integrate platform based on IP or ATM

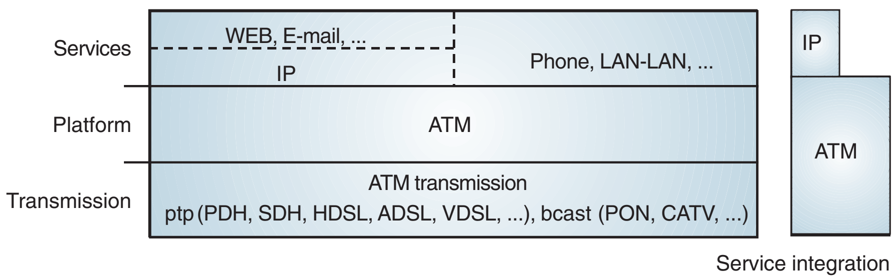

Figure 8 The ATM oriented telco view on service integration

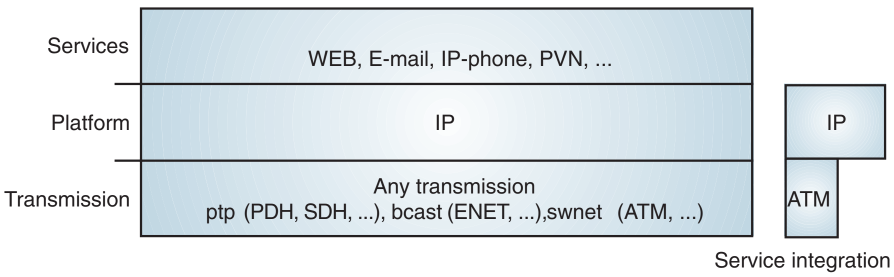

Figure 9 The IP oriented datacom view on service integration

resources in the best possible way. The situation with a service integrated IP platform is shown in Figure 9. As opposed to ATM it is important to note that IP is not a transmission technology. It is rather assumed that IP packets can be encapsulated by a transmission unit offered by an underlying subnetwork. Hence, IP can coexist with other network layer protocols. There is a number of standards for encapsulation of IP packets including both point-to-point links, broadcast networks and also switched networks. ATM is an example of the latter case and is increasingly being used for transport of IP traffic.

4.2.1 IP QoS is a controversial issue

The evolution towards IP QoS is a hot topic including at least three components:

- QoS routing;
- Traffic prioritization;
- Resource reservation.

The first item implies that new routing protocols supporting QoS metrics must be developed. One example of such an effort is the extension of the OSPF protocol [15]. The standard IP routing protocols being used today are rudimentary as they base their optimal route calculation only on minimizing the number of hops. The second item means that packets are scheduled in the routers according to some priority scheme different from first-come-first-served. Tagging of packets is either based on statically assigned traffic classes or dynamic assignments set up by the users. The former is generally denoted CoS, whereas the latter facilitates true QoS. The two ongoing initiatives corresponding to these cases are called DiffServ and IntServ, respectively [16]. The third item is needed when true QoS is to be supported. User-driven resource reservation requires that some sort of signaling mechanism is introduced. One ongoing effort in this area is the RSVP protocol [17, 18].

Implementing QoS and resource reservation is in general a complex issue for IP networks since there is no notion of a connection. The challenge is to take the connectionless nature into account so that any reserved resources are moved according to the dynamics of the routing protocols. Two key concepts in this respect are soft-state and transient flow detection. The technical challenge is to combine the connectionless nature with resource reservation. The aim of RSVP is to handle the trade-off between these conflicting goals. The basic idea is to associate resource reservation with transient traffic flows. In order to co-ordinate this with the dynamic behavior of the routing protocols the reservations are volatile (soft-state). The difference compared to making reservations along established connections in an ATM network (hard-state) is that the reservation requests must be repeated regularly in order to be maintained. A reservation is being maintained or moved depending on what is the current optimal route.

An alternative approach is to handle QoS at a level subordinate to the IP level. The requirement is that the underlying subnet technology is equipped with QoS features. Further, there must be a tight interaction between the two levels. The initiative called MPLS is a standardization effort in this direction [19–22]. It relies on tagging traffic flows at the IP level and then make an assignment to a switched connection at the lower level. This creates a short-cut bypassing any intermediate routers. Any QoS requirements can in turn be associated with the switched short-cut rather than being handled at the IP level. The most prominent example of an MPLS implementation is IP over ATM as discussed in section 4.4.2. The disadvantage of the MPLS approach compared to implementing QoS at the IP level is that all involved subnetworks must be QoS enabled. This is not the case for the large installed based of legacy systems like Ethernet.

It should be noted that quality can be provided in a best-effort IP network by always providing sufficient resources. This approach is generally called capacity over-provisioning. It works within a single administrative domain where all the resources are controlled by a single operator taking responsibility for infrastructure investments. The problem arises at the border to neighboring domains which are outside the control of the actual operator.

To summarize, there is today a heated debate on what is the proper way to provide IP QoS. Different solutions are being implemented by operators but lack of consensus and standardization complicate interoperability across administrative domains.

4.3 The datacom view is likely to win the game

As illustrated to the right in Figures 8 and 9 "IP over ATM" is a key element regardless of the view taken. The difference is that the telco industry traditionally has considered ATM as the level of service integration. In contrast, the datacom industry claims that this should take place at the IP level. We argue that the most likely outcome in the long term is that IP will be used for building a world-wide service integrated platform with end-to-end guarantees. The are four arguments in favor of this view [15]:

- It is easier to build a world-wide platform based on IP since a large set of underlying transmission technologies can be used. An obvious disadvantage of the telco view is that a homogenous infrastructure based on ATM is required.
- There are implementations of IP for all kinds of end-systems and operating systems, and this SW is normally free.

Further, TCP/IP is the dominant application development environment.

- IP is designed for distributed routing protocols so that every packet is forwarded on an individual basis. This gives fault-tolerance and simplified administration. In particular, it is easy to build networks crossing administrative domains.
- IP is a simple protocol assuming a minimum of functionality from the network elements. The main responsibility for implementing reliable communication is left to the end-systems.

In sum these features make IP a flexible networking technology that scales well. A key property compared to ATM is the connectionless nature. Since every packet is forwarded on an individual basis there is no state information associated with the network elements; ie. the network does not have any notion of which pair of stations are communicating at any specific time. The stateless property ensures scalability, flexibility and fault-tolerance. At the same time it represents a challenge with respect to QoS. The most important argument in favor of ATM is that resource reservation is simplified when it can be associated with established connections between the communicating parties.

4.4 IP over ATM is an interesting case

The argument that IP in the long-run will be best suited to build a world-wide service integrated network rests on the scalability feature in addition to the ability to work over heterogenous underlying networks. However, it is reasonable to anticipate that ATM will play an important role as a carrier of IP traffic within restricted areas and administrative domains. The access network can be considered as an example of this as we will discuss in section 6. Hence, the interaction between IP and ATM becomes an important issue. We distinguish between a layered view and an integrated view as discussed in the next two subsections. It should be emphasized, however, that the interaction of IP and ATM is an issue only when the IP level sees the underlying ATM infrastructure as a true network. Transporting IP over an established ATM connection between two end-points is straightforward.

4.4.1 The classical view is layered

The classical view is to consider an underlying ATM network as an opaque cloud offering interconnection between arbitrary end-points. The functionality at the ATM level is otherwise isolated from the functionality at the IP level. Consequently, there are duplicated functions at the two levels, the primary example being the relationship between ATM signaling and IP routing. The standardized solution which are classified as layered are as follows [23]:

- LANE [24]
- CLIP [25]
- NHRP [26].

The first two are simple technologies with bad scaling properties. This is due to centralized servers being responsible for address resolution. The result is that a large ATM network need to be partitioned into a number of smaller logical subnets so that the communication at the ATM level does not cross the logical subnet boundaries. To pass subnet boundaries intermediate IP routers are introduced and the communication is lifted up to the IP level. Figure 10 is an illustration of the situation where the logical subnets are termed LIS. The third solution is based on a distributed protocol called NHRP. It performs address resolution beyond subnet boundaries. The rationale is that intermediate routers can be bypassed by providing a direct ATM connection. This gives improved performance. The initiative called MPOA [27] is an embracing standard including all the three listed solutions as special cases. A common feature of the classical layered solutions is that IP is transported over ordinary ATM connections between end systems as illustrated in Figure 10. The figure indicates how NHRP supports connections crossing subnet boundaries.

4.4.2 An integrated view improves efficiency

As already mentioned the disadvantage of a layered view is duplicated functionality. In particular, IP routing and ATM signaling cover the same basic requirement. An interesting development trend today is integration of IP and ATM in terms of systems that use IP routing on top of a raw ATM switching fabric

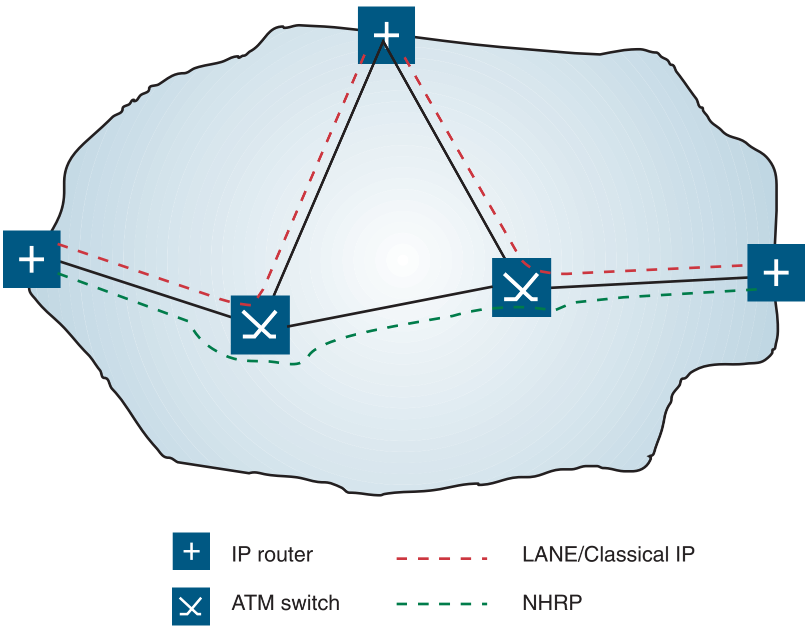

Figure 10 Classical transport of IP traffic over established ATM connections

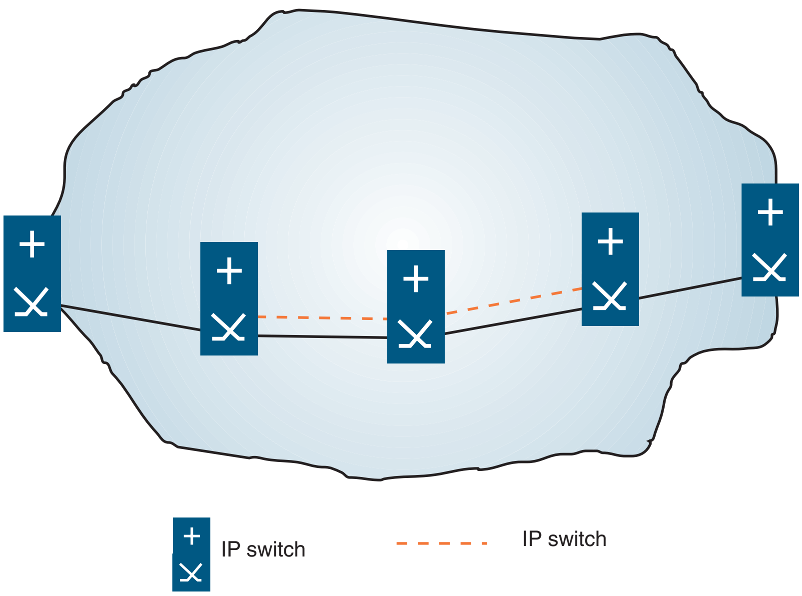

Figure 11 Piecewise short-cuts along a route in an IP switched network

[28–31, 23]. In contrast to the classical view this can be called ATM under IP. The basic idea is to combine the scalability features of IP with the high switching performance offered by ATM. It is interesting to note that ATM switches are more cost effective that IP routers measured in terms of dollar per bytes per second [28, 32].

Today a number of specific technical solutions all based on the same integration idea are being studied. An effort to co-ordinate the various initiatives is called MPLS [19–22]. It is also customary to use the terms IP-switching or tag switching as generic designations for the same idea. The essential difference from the classical layered view is that the standard signaling protocols in ATM are not used to set up end-to-end connections. Instead specialized light-weight signaling protocols are developed that facilitate establishment of short-cut connections. These protocols are tailored to be used together with IP.

It is important to emphasize that the rationale for creating a short-cut is to gain performance by avoiding processing at the IP layer. However, the operation of the network is not critically dependent on short-cuts. If it is not desirable or possible to establish a short-cut, traffic is routed at the IP level in the ordinary way. Another point is that a short-cut can be restricted to cover only a portion of the route between two nodes. This is illustrated in Figure 11. Likewise, there can be several piecewise short-cut portions along the route. Note also how this figure is different from Figure 10 that applies to the classical case.

5 An ATM based access network is recommended

Section 2 outlined the structure of the future broadband access network but did not discuss how the anticipated service integration being discussed in section 3 can be realized. Equipped with the general discussion from section 4 we are ready to discuss how IP and ATM could be applied in the access network to accomplish this task.

Vendors of broadband access network equipment normally have two types of systems in their product portfolio today. Letting *X* denote an arbitrary technology like PON, xDSL or LMDS, we distinguish between systems using either ATM or IP as the protocol layer above basic transmission:

- ATM/*X*;
- IP/frame/*X*.

In the first case ATM cell transmission is defined for the actual medium by a TC layer above the PMD layer. For IP based systems a variable length frame format needs to be defined first. The frames are in turn used to carry encapsulated IP packets.

The two parallel development tracks reflect the general battle between IP and ATM that is characteristic for the combined telco and datacom industry. The interest in IP based systems is mainly driven be the need for broadband access to the existing best-effort Internet. The advantages of ATM based systems are QoS support and increased flexibility. The latter refers to the fact that it is straightforward to use ATM for access to overlaid platforms other than IP.

Despite our general argument in favor of IP from section 4.3 we recommend that ATM should be used for statistical multiplexing and service integration in the access network. There are two reasons for this.

- ATM has better multiplexing properties, in terms of resolution and real-time behavior, over low-speed links. This is due to the short fixed-length cells used by ATM. The generally longer and variable-length packets used by IP contribute to both latency and jitter resulting in reduced real-time behavior. This is in particular true for low-speed links as is the case in the access network.
- It is still uncertain whether the IP oriented datacom view will eventually prevail. A service integrated access network should also be able to support other platforms than IP in the short-term and mid-term migration period. Hence, we argue that it is a significant risk to base the access network deployment too strongly on the assumption that a universal end-to-end IP platform will be developed and standardized.

Note that the significance of the first argument is weakened as the line speed increases. Hence, in high-speed backbone networks it is likely that IP will be an appropriate statistical multiplexing

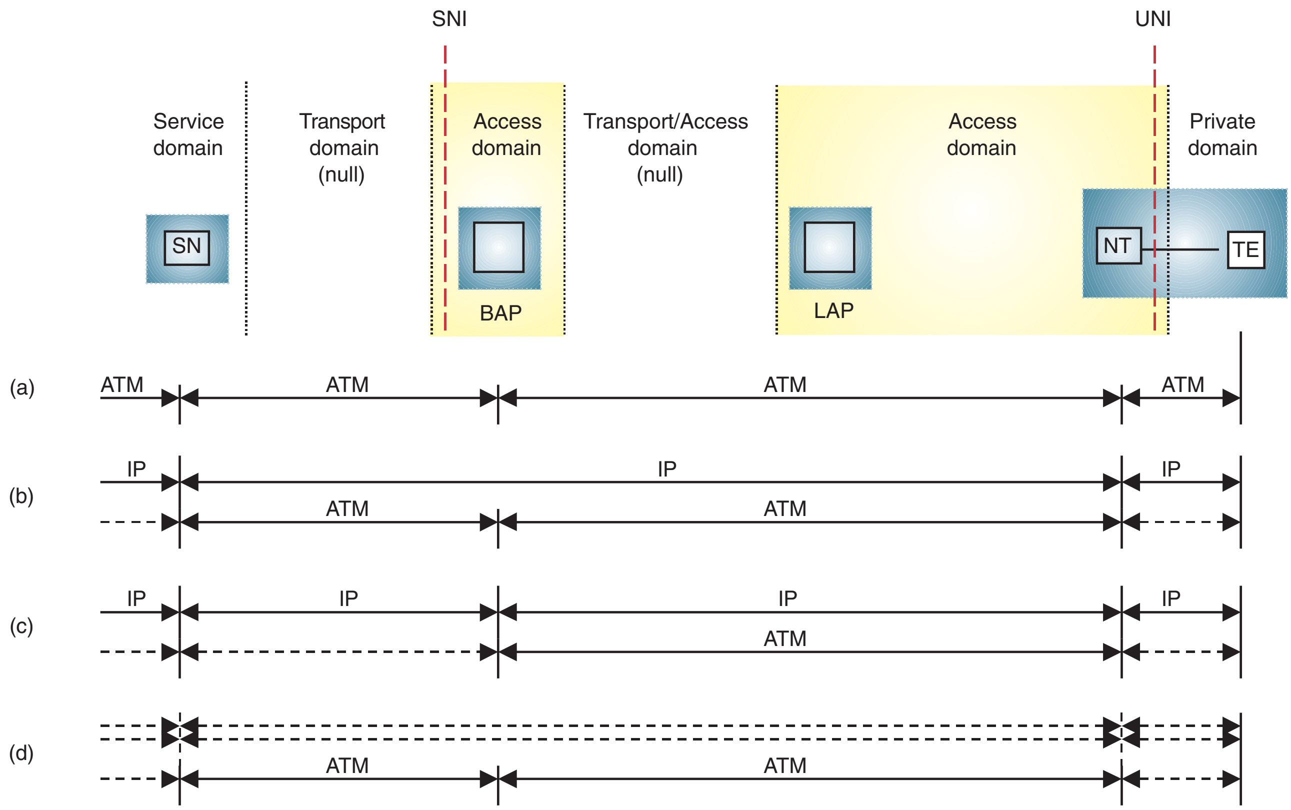

Figure 12 Elaborated view on how an ATM based access network may fit into a wider context

technology which can also support traffic with real-time requirements. The key point about the second argument is that the ATM oriented telco view is not excluded. At the same time the protocol assumption is compatible with the IP oriented datacom view.

The view that ATM is the preferred protocol for statistical multiplexing in the access network is illustrated by the bottommost double arrow in Figure 1. The small vertical crosslines signify points at which ATM cells are being processed; ie. the figure tells that both BAP and NT will participate in interpretation of the ATM cell stream. Depending on the actual transmission technology it might be additional equipment between these points that also processes ATM cells. The typical example is equipment located in a LAP. To simplify the figure any such intermediate points are suppressed. The dashed horizontal arrows and cross lines at the bottom of Figure 1 indicate open protocol issues. In accordance with the layered view from Figure 9 we distinguish between a basic transmission level and an overlaid platform level.

Figure 12 gives an elaborated view on how an ATM based access network can fit into a wider context. We distinguish between four cases denoted (a)–(d), each being characterized by the operating environment at the SNI and UNI interfaces.

Case (a) corresponds to the pure ATM oriented telco view with cell transmission at every stage. No platform level is indicated since ATM is also a networking technology supporting end-to-end user communication. The cases denoted (b) and (c) correspond to the datacom view in which IP is used at every stage to accomplish internetworking across underlying transmission technologies. Hence, IP provides an overlaid platform supporting end-to-end user communication. The difference between (b) and (c) is that the BAP is transparent for IP in the former case. Consequently, ATM transmission must be used also between the BAP and the SN. Letting the BAP interpret IP as in the latter case gives improved flexibility with regard to the transmission technology being used between the BAP and the SN. It is also possible to let the BAP be equipped with a richer set of functionalities as discussed in the next section. Case (d) corresponds to a situation in which no specific protocol view prevails. Rather arbitrary parallel platforms are being developed as illustrated by the pair of dashed lines. It is reasonable to anticipate that ATM is being used between the BAP and the SN in this case so that the BAP becomes platform independent. An obvious disadvantage of coexisting platforms is that it is necessary to support a larger set of protocols at the UNI and SNI interfaces.

In accordance with the discussion in section 4.3 we anticipate that the operating environment will be dominated by IP in the long run. This applies to both the service domain and the private customer domain. Hence, case (c) is considered to be the most likely outcome. The ATM based access network will then act as a carrier of IP traffic. This can be accomplished in a number of ways depending on what is considered to be the role of the access network as discussed next.

6 The role of the access network is affected

The traditional role of the access network has been to connect end customers to service providers on a semi-permanent basis. We call this provision oriented in the sense that the customer relationship is associated with a subscription that lasts for a period of time. Physically the access is realized either in terms of a leased line or a dial-up connection to the closest switching point for the actual platform. Changing the customer relationship normally involves manual intervention like updating registry systems, physical reconnection or installation of new transmission equipment.

An access network based on ATM is more flexible and facilitates automized management and control, thus reducing the need for manual intervention. Provided there exists a universal overlaid platform it is also possible to let the access network interact closely with connected core networks. As already stated we expect the latter to be based on IP. Together these two features open for a different understanding of the role of the access network. By putting extended functionality like routing in the network and enable user controlled management it is natural to consider more complex scenarios than provisioning which is dominating today.

Figure 13 shows three interpretations of the role of the future access network. In accordance with alternative (c) in Figure 12 we assume that IP will constitute an overlaid layer and that ATM is used for underlying transmission in the access domain. The cases denoted (A)–(C) in Figure 13 are distinct in the way customers are associated with SNs. A solid line style is used to indicate fixed associations whereas a dashed line style is used to signify an association that is established on-demand. Case (A) corresponds to the traditional provision oriented view with a fixed association. Case (B) represents a session oriented view with a dynamic selection of service provider. Case (C) is the most radical and dynamic scenario. By letting the access network be equipped with routing capabilities it can interact closely with core networks.

A common feature of all cases in Figure 13 is the existence of an association between the customer and the BAP. It is realized in terms of an ATM connection which is semi-permanent in the first two cases and switched in the latter case. Any QoS guarantees are linked to the underlying ATM connection. Otherwise there is a significant difference between cases (A) and (B) on one side and case (C) on the other side. In the latter case there is no association between the BAP and the SN. The key issue is what kind of functionality the BAP is equipped with at the IP level.

In case (A) end customers are associated with service providers on a semi-permanent basis. This is the conservative interpretation carried forward by ITU and is called provision oriented. It implies that the access operator configures the network elements so that all traffic from a given customer follows a specified path all the way to the service node; ie. any ATM cross-connect equipment between the customer and the BAP and also the IP forwarding table in the BAP are statically

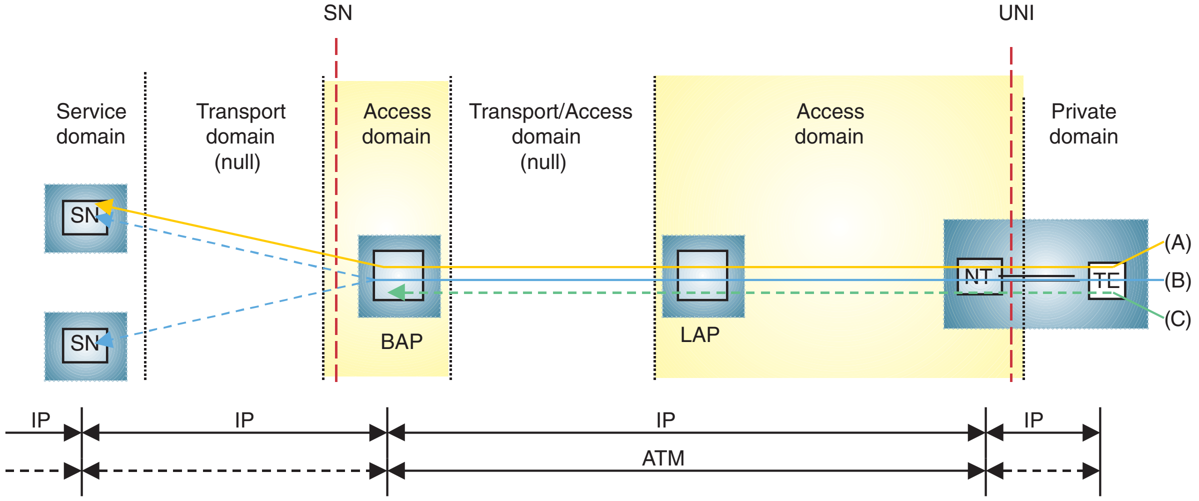

Figure 13 Different interpretations of the role of the access network

configured by management. There is no dynamics in terms of user control or routing. A customer can have provisioned connections to several SNs at the same time, of course, and he is free to pick which one to use at any time. Even if case (A) is called provision oriented it is important to note that each customer does not have a dedicated channel. Traffic from different customers is statistically multiplexed on the way towards the SN. This happens at the ATM level within the access network and at the IP level in the BAP.

Case (C) illustrates the most radical interpretation of the role of the access network and assumes that a full fledged router is located in the BAP. This gives full dynamics in the sense that IP packets are routed individually without any association to an SN. Neither are there any pre-established connections at the customer side. Rather, connections are established as needed depending on the forwarding decision at the IP level. Among the different solutions for running IP over ATM, both CLIP and LANE can be used. Hence, the access network can be considered as an IP subnet using ATM as underlying transport. Note that if ATM is used also between the BAP and the SN, or at the customer side, it is possible to use either NHRP, MPOA or MPLS. The gain is that the routers at the two ends of the access network can be bypassed in terms of a shortcut at the ATM level.

An important point about case (C) is that the access network operator takes responsibility for administrating a router in the BAP which provides an interconnection point for other network operators. One immediate consequence is that traffic can be routed also within the access network domain. This breaks fundamentally with the classical understanding of the access network. Nevertheless, such solutions are being studied by industrial groups like ATM Forum [5] and ADSL Forum [3]. The obvious advantage is increased flexibility. The challenge is handling of security, accounting and charging.

Case (B) is an intermediate solution facilitating free selection of service provider. This happens per session and the customer must go through a procedure every time to handle authorization, authentification and configuration. Compared to case (C) this solution gives reduced dynamics. In some sense case (B) is comparable to a dial-up connection. The difference is that the BAP takes the role of a generic access server and that appropriate signaling mechanisms are being developed. The PPP protocol is central in this respect.

To summarize, the introduction of IP and ATM in the future broadband access network opens for increased complexity and added functionality which affect the role of the access network. A likely evolution scenario is to start from the provision oriented case (A), then turn to case (B) and free selection of service provider. The ultimate step is (C) which considers the access network as a sub network in a larger IP network. Note that the traditionally distinct border between core and access gets blurred in cases (B) and (C). The point is that the access operator takes common responsibility of tasks which are otherwise left to the various core network providers. Hence, the access network will expand towards the service providers rather than the other way round, which is the case today.

7 Conclusion

The main conclusion of the paper is that ATM is considered the best technology to obtain statistical multiplexing and service integration in the access network. This is partly due to an argument that ATM gives better QoS performance over low-speed links. But it is also due to the fact that an ATM based access network is applicable regardless of whether IP or ATM will constitute the universal platform for end-to-end user communication. It involves less risk to start deploying an ATM based access network since it can also be used in an IP oriented context.

Despite the uncertainty about what will be the preferred platform for end-to-end user communication, we argue that the IP oriented view carried forward by the datacom industry is the most likely outcome. The connectionless nature of IP makes it a scalable, flexible and fault-tolerant networking technology. A pertinent question is how an ATM based access network can fit in a wider IP oriented context. The point is that the combination of IP and ATM opens for new opportunities affecting the role of the access network. We do not make any conclusions at this point. A likely evolution is that the broadband access network will initially be provision oriented in the same way as the existing narrowband network. The next step will be to implement free selection of service provider per session. The ultimate step is to let the access network become a true IP subnet interworking closely with arbitrary subnets in the core domain.

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Wireline broadband access networks

LEIF AARTHUN IMS

1 Introduction

The future broadband access network architecture needs to be flexible enough to efficiently support the provision of a full set of broadband and narrowband services with a wide range of capacity demands in a highly diverse demographic environment.

The selection of transmission medium or sets of transmission media and corresponding network topologies, node configurations and system technologies is among the key strategic issues in the development of the access network. Capacity demand, service types, flexibility and costs are the main differentiators in the evaluation of the various access network architectures. In the following the term architecture denotes (a) specific combination(s) of transmission medium, network topology, node configuration and system technology.

A variety of broadband access technologies are available. The five main wireline upgrade alternatives are shown in Figure 1, namely digital subscriber line (DSL) modems, coaxial cable modems, fibre systems, power line modems and the hybrid fibre-copper systems. The latter comprise all the architectures based on a combination of fibreoptic transmission in the upper part of the access network and different copper drop technologies in the lower parts of the network. These hybrid combinations are probably the most interesting ones, in particular in the long term. This paper describes the main technologies and architectures commercially available today, some of the emerging technologies and some alternatives which are expected to reach the market within the next years. The paper discusses the key parameters that differentiate the various access network solutions and some of the key issues faced by the access network infrastructure providers in the migration of the present network to broadband. The likely migration paths from the existing wireline access networks towards broadband are outlined. The intention is neither to provide a complete overview of access network technologies and architectures, nor to give a thorough description of the respective technology and architecture options. The main objective is to provide a brief introduction to this aspect only. Several of the technologies are treated in more detail in the following contributions in this issue of *Telektronikk* [1, 2, 3, 4, 5, 6, 7].

2 Service characteristics and network architectures

The selection of the network architecture is strongly related to the services and applications to be provided over the network [8, 9, 10]. Hence, the service and application attributes are of great importance in the selection of architectures. The relationship between the applications and the proposed bearer services is addressed in more detail in [11]. The terms 'application' and 'service' are not unambiguously defined in the telecommunication environment. In the context of this paper the application refers to the use of the telecommunication service made by the customer and the fact that the service is the product sold to the customer by the service provider. Additionally, the telecommunications services can be divided into information services and communications services. Information services permit the access to a service centre for access to data bases, movies on demand, etc. Communication services allow the interconnection of remote users and the dialogue between them for videotelephony, file transfer, etc. The impact of the service selection on the choice of the access network architecture may be based on the values of the following attributes:

- Modulation technique;
- Bit rate for digital services;
- Bandwidth required;
- Symmetry;
- Communication configuration;
- Communication establishment;
- Mobility.

The *bandwidth* and bit rate required to support the service are a fundamental attribute of services with respect to the selection of the architecture, since some types of physical media and transport systems may not provide the required capacity. The bandwidth required is not an independent parameter as it is determined by the type of modulation and coding adopted for the information transfer.

The *symmetry* of the service differentiates between architectures which have been conceived for asymmetric services, like asymmetric digital subscriber line (ADSL), traditional coaxial cable systems, some radio systems, and symmetric architectures like high speed digital subscriber line (HDSL) and optical fibre point-to-point systems.

The point-to-multipoint, or multicast and broadcast *communication configuration* are most readily implemented in shared medium architectures as passive optical networks (PONs), tree-and-branch coaxial cables and point-to-multipoint radio systems. In other types of architectures, including synchronous digital hierarchy (SDH) rings, the point-to-multipoint configurations require some additional functionality in the active equipment. However, point-to-point, or narrowcast configurations require additional capabilities like filtering, blocking, and encryption in shared medium architectures.

The *communication establishment* impacts the mix of capacity permanently allocated in the access network and capacity allocated on demand. Video distribution services such as television broadcasting, pay per channel (PPC), pay per view (PPV) and near video on demand (NVOD) require a fixed amount of bandwidth per customer. Additionally, the establishment of connections on demand and the control of information flow and format require the presence of a signalling channel up to the nearest network element capable of realising such functions.

Mobility implies that some category of services can be implemented either on a fixed architecture or on a wireless architecture only, at least in the distribution part. Services which allow mobility are necessarily implemented on wireless architectures, but other features for control of the position of the subscribers and call handling are required.

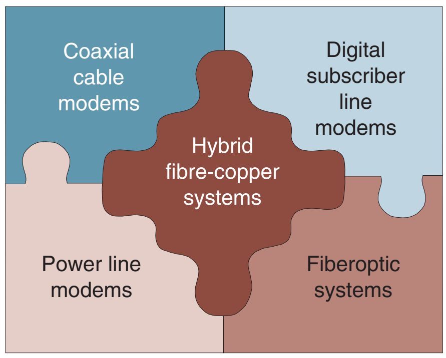

Figure 1 The main groups of broadband wireline access network alternatives

3 Topology, node configuration and system technology

Today there is a wide range of alternatives for upgrading the physical layer of the access network to broadband [12, 13]. The different available wireline transmission media are twisted pair copper cable, coaxial cable and fibre cable. For each of the media there are several different options with respect to network topology, node configuration and system technology.

The physical network topology refers to the physical network links. The network topology can be rather complex, depending on the number of levels of the network itself. However, the main topology options are point-to-point networks and point- or multipoint-to-multipoint networks. In the former each physical link is dedicated to connect two (active star, double active star) network terminations. The latter connects several network terminations (single/double passive star, bus, tree).

The node configuration refers to the configuration of the network terminations of one particular transmission medium, ie. the network nodes at which the terminal equipment is located. For fibre architectures, several node configurations have been proposed: fibre to the cabinet (FTTCab), fibre to the node (FTTN), fibre to the curb (FTTC), fibre to the building (FTTB) and fibre to the home (FTTH) are commonly used, depending on the local network area conditions.

The system technology attributes are the multiplexing technique, the access protocol for point-to-multipoint configurations and the modulation techniques (basically classified in analogue and digital techniques). Typical multiplexing techniques are frequency division multiplexing (FDM), time division multiplexing (TDM), subcarrier multiplexing (SCM) wavelength division multiplexing (WDM), high density wavelength division multiplexing (HDWDM) and optical frequency division multiplexing (OFDM). Commonly used access protocols are frequency division multiple access (FDMA) time division multiple access (TDMA), code division multiple access (CDMA), subcarrier division multiple access (SCMA) and wavelength division multiple access (WDMA).

4 Digital subscriber line architectures

Until recently twisted pair has been considered to be a significant bottleneck with respect to capacity. Recent developments of complex modulation schemes have enabled the extension of the line capacity by order of magnitudes. In the short term the main advantage of copper is a variable cost option, alleviating the need for high and risky up-front investments. In addition the installed base of 600 million lines world-wide constitutes an immediate advantage. The enhanced copper or digital subscriber line (DSL) technologies differ with respect to transmission capacity, transmission distance and the number of twisted pairs used [14]. The DSL system technologies include: IDSL (ISDN digital subscriber line), ADSL, VDSL (very high-speed digital subscriber line), HDSL (high bitrate digital subscriber line) and SDSL (symmetric digital subscriber line) [15, 16]. At present only ADSL and HDSL are commercially available, VDSL and SDSL are expected to become available quite soon.

- IDSL (ISDN digital subscriber line) is the transmission system used for ISDN Basic Access.
- ADSL uses one twisted copper pair for transmission of between 2 Mbit/s (4 km) and 8 Mbit/s (2 km) downstream and up to 640 kbit/s upstream. The transmission distance varies from 2 km to 4 km, depending on the selected transmission capacity. POTS or ISDN is transmitted on the same twisted pair.
- HDSL usually requires two pairs for symmetric 2 Mbit/s transmission, but systems for one or three pair transmission are available. The typical transmission distance for HDSL is in the range of 3 km. Analogue telephony may not be transmitted simultaneously on the same twisted pair.
- SDSL (symmetric digital subscriber line) is a broader class of systems, which still are symmetric, but not necessarily transmit 2048 kbit/s capacity. SDSL typically uses one twisted pair, and may include the option of transmission of analogue telephony on the same twisted pair.
- VDSL provides both asymmetric and symmetric transmission, with asymmetric capacities as high as 26 Mbit/s (1 km). The 13 Mbit/s capacity VDSL standard modem has a 1.5 km transmission distance [17]. For both downstream capacity options the upstream capacity is at least 2 Mbit/s. The symmetric VDSL versions will have 26 Mbit/s (0.3 km) and 13 Mbit/s (1 km) transmission capacities. Analogue telephony is to be transmitted on the same twisted pair. However, there is an uncertainty with respect to the coexistence of symmetric and asymmetric VDSL systems in the same cable sheath.

In general for the digital subscriber line (DSL) options, there is a trade off between distance and capacity available. Table 1 shows the transmission distance for the various symmetric or asymmetric capacities obtainable with the transmission equipment available today. Transmission distances are shown for 0.4 mm twisted pair cable and for asymmetric switched broadband (ASB) and symmetric switched broadband (SSB) service transmission.

Figure 2 depicts the variations in transmission reach of the different DSL systems with reference to a commonly found access network, including the local exchange, distribution cabinets, telephone cables and local distribution cables.

Figure 3 shows an ADSL architecture with a multiplexer located in the local exchange. In Figure 3, at a later stage in the network evolution, the access multiplexer is co-located with the remote subscriber unit (RSU) in the service access point (SAP). An SDH ring between the local exchange (LEX) and the SAP is depicted. The infrastructures for plain old telephone system (POTS) and N-ISDN are included for clarity.

Fibreoptic transmission systems are commonly considered to be the only wireline alternative for providing capacities higher than the ones offered on individual DSL systems on the existing twisted pair network, such as 155 Mbit/s. However, by combining a set of twisted copper pairs, each with DSL systems installed (ADSL or VDSL), an aggregate capacity of say 155 Mbit/s or even 622 Mbit/s can be transmitted between two network locations on the existing twisted copper pair network. Thus, the possibly prohibitive high civil works costs associated with installation of fibreoptic cable may be avoided. This concept of parallel DSL systems is called inverse multiplex-

Table 1 Transmission distance (in km) for the various symmetric or asymmetric capacities on 0.4 mm cable

Bitrate	2 Mb	4 Mb	8 Mb	10 Mb	13 Mb	26 Mb	52 Mb
ASB	3.5	3.3	2.5	2	1.5	1.0	0.6
SSB	2.5	1.6	1.1	0.8	0.6	0.3	0.2

ing, and is described in more detail in [3]. The main motivation behind inverse multiplexing lies in the fact that it may be a rather inexpensive way to avoid the high civil works costs of fibreoptic cable installation in the primary access network in particular.

In *the lower part* of the high capacity domain we find the transmission solutions IDSL, HDSL and SDSL. IDSL and HDSL are being widely deployed today, and SDSL is also technically mature and manufactured by several suppliers. However, products for the *upper part* of the high capacity domain, typically based on VDSL technology, still have not reached the market at a significant scale. Today, it is products within the *middle part* of the high capacity domain which has the highest momentum within the industry with an increasing number of vendors of ADSL technology. The products are now further developed towards higher capacity limits, flexible configuration of transmission parameters, efficient management of different user groups and Internet service providers and improved operator interfaces. Currently, the concept of inverse multiplexing is being developed towards prototyping.

Recently significant attention has been devoted to the concept of ADSL Lite, which is also known as UADSL (universal asymmetric digital subscriber line), CDSL (consumer digital subscriber line) or G.Lite. The ADSL Lite is very similar to ADSL from a technological point of view. The primary motivation behind ADSL Lite is the potential cost reduction obtained through simpler and more robust customer premises equipment which the customer himself may install. However, this potential cost advantage over ADSL is achieved at the expense of relaxed transmission capacity. Initially the ADSL standards were established in ANSI and are now further developed to ITU recommendations, possibly with additional recommendations for ADSL Lite. Additionally, the ADSL-forum and the Universal ADSL Working Group (UAWG) are influential promoters of ADSL technology and ADSL Lite, respectively.

5 Coaxial cable modem architectures

The coaxial cable networks, or Community Antenna Television (CATV) networks, were originally designed to distribute analogue television signals. The coaxial cable network consists of cascaded unidirectional coaxial amplifiers, usually offering an overall bandwidth of 300 MHz or 450 MHz. These conventional CATV networks now constitute an increasingly valuable asset for the cable operators as the momentum of the convergence of services and technology in the broadcasting, data communications and telecommunications sectors in-

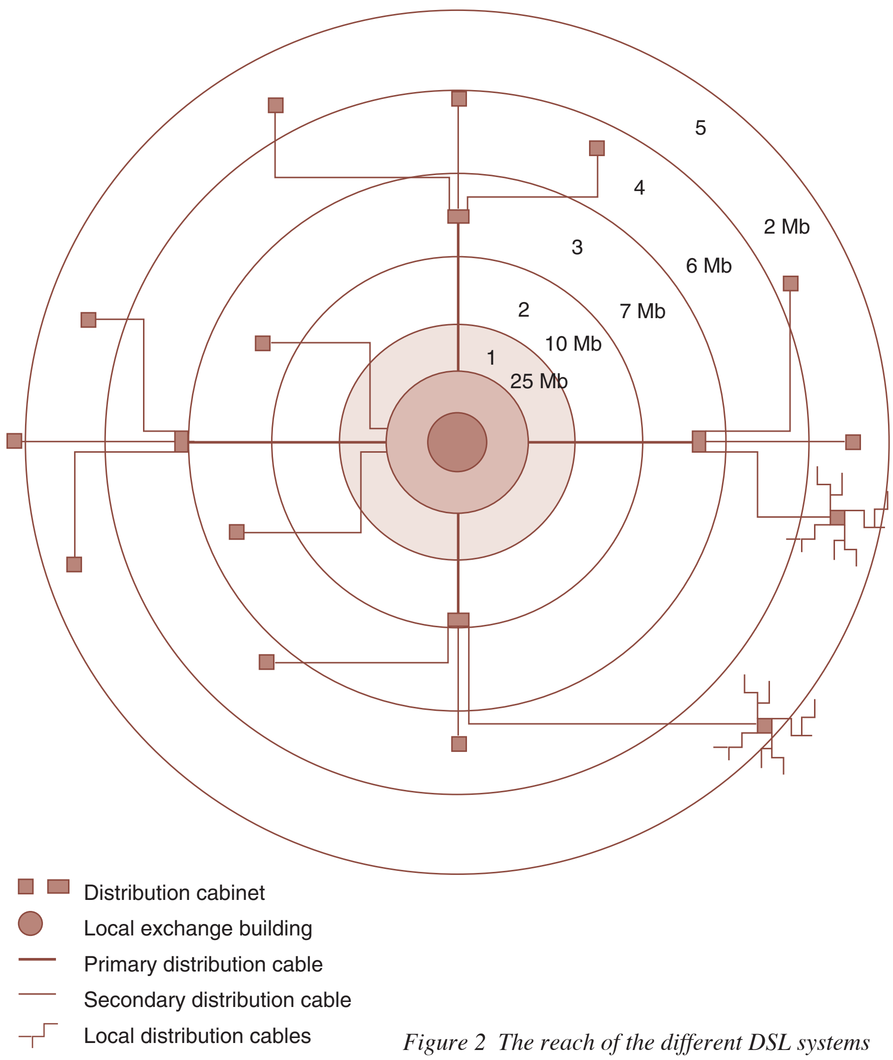

Figure 2 The reach of the different DSL systems

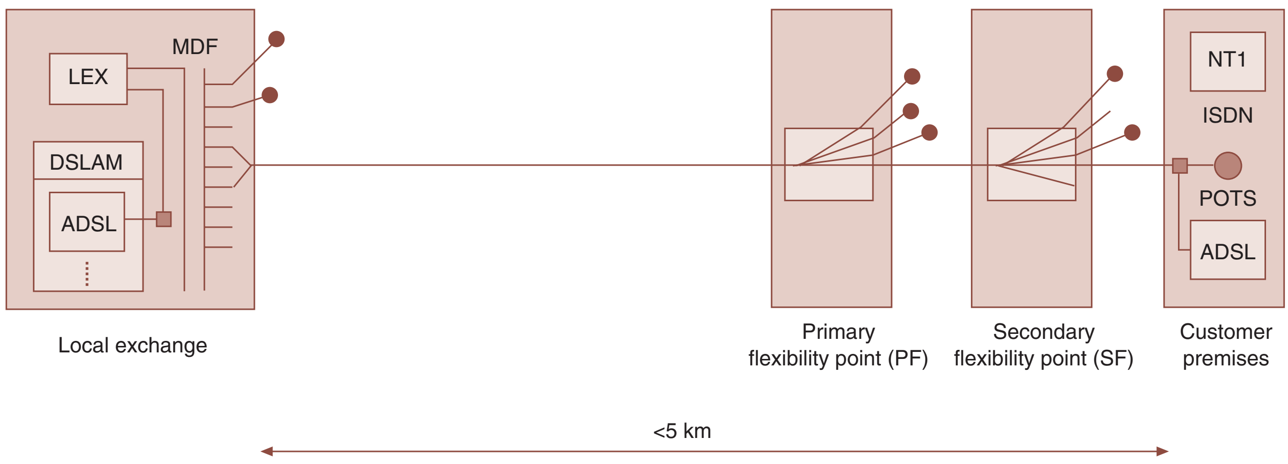

Figure 3 ADSL architecture with the access multiplexer located in the local exchange

creases. However, a conventional, coaxial cable based access network has no return capability, hence the introduction of interactive services in coaxial cable networks requires implementation of return channels. Upgrading the coaxial cable network to interactive broadband usually implies the installation of asymmetric or symmetric broadband cable modems at the customer premises. Coaxial cable modems have already been sold in numbers of several hundred thousands in the US. The three different types of cable modems are [18]:

- Asymmetric cable modems, which use separate channels for upstream and downstream transmission. These modems are the ones most commonly used for asymmetric services, such as fast Internet access.
- Symmetric cable modems, which use a shared upstream and downstream channel. These modems are normally used for interconnecting local area networks (LAN).
- Cable modems with telephone-return, in which only the downstream channel is implemented in the coaxial network. The twisted pair network and conventional modems are used for the upstream, or return channel transmission.

However, there is currently no evident cable modem standard, with the result that the implemented cable modem systems are proprietary. Several associations are working on different cable modem standards, such as IEEE, DAVIC, ATM Forum and the Broadband Link Team, in addition to several US cable operators. The IEEE 802.14 standard is the standard

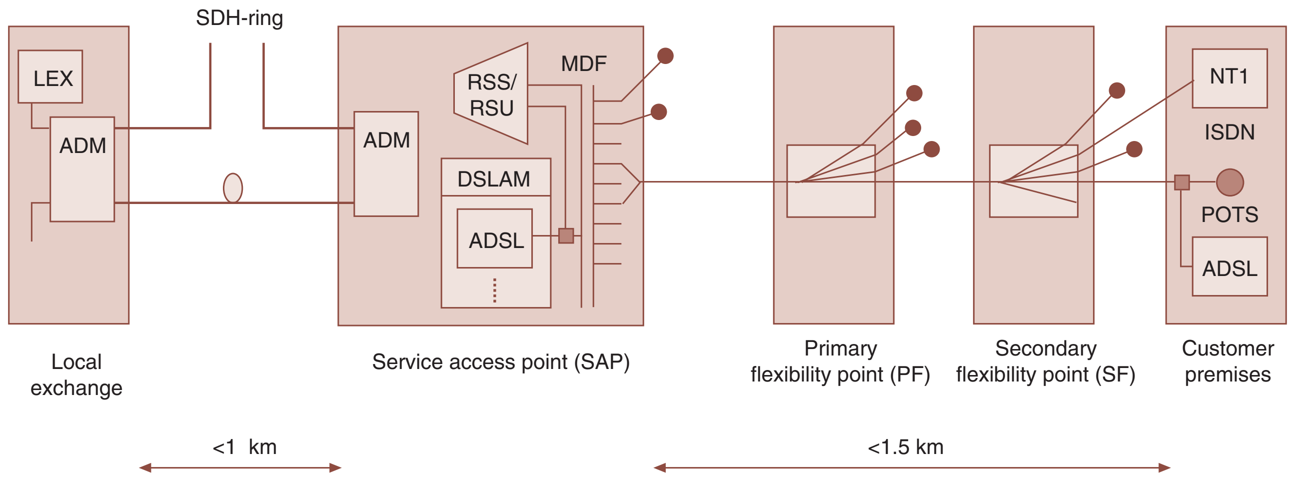

Figure 4 ADSL architecture with the access multiplexer located in the service access point

most likely to be used in the future. In the remainder of this section, the description of the coaxial cable modem architecture is based on systems similar to the IEEE 802.14 standard systems [19]. Typically in such networks the frequency spectrum from 5 to 45 MHz is dedicated to upstream digital transmission. This 40 MHz band is sectioned into multiple 1 MHz – 6 MHz wide radio frequency (RF) channels, each with a capacity between 1.6 Mbit/s and 10 Mbit/s. The frequency spectrum between 50 and 450 MHz is used for downstream analogue broadcast transmission, and the 450 MHz to 750 MHz frequency spectrum for downstream digital transmission. Figure 5 illustrates an architecture designed for coaxial cable modems. The figure shows that coaxial cable return amplifiers are installed in addition to cable modems and a cable router terminates the coaxial cable network segment at the hub side. In the case of each subscriber being fitted with a 10 Mbit/s cable modem typically 500 – 600 subscribers share 50 – 60 Mbit/s upstream capacity on one coaxial network segment, with 10 Base-T Ethernet interfaces at the customer and hub side. ATM-25 interfaces are expected to be available quite soon from several vendors, and there is work going on within IETF on the issues related to IP transport in such networks [20].

In coaxial cable modem networks the simultaneous users on one coaxial network segment share 50 – 60 Mbit/s transmission capacity. Today, implementing cable modem technology in existing coaxial cable networks with several thousands of customers connected per coaxial cable segment is first and foremost to be considered as an alternative to narrowband ISDN, if a cost-effective network dimensioning is to be used. Providing higher capacities, comparable to the capacities enabled by ADSL technology, will in most cases require a splitting of the coaxial network into smaller coaxial segments in order to achieve the required return path capacity. Typically, the network is split into smaller segments by the use of fibreoptic feeder cables and (hybrid fibre coaxial) HFC technology. HFC is treated in a separate section of this paper. In this section the focus is on the coaxial cable modem architecture.

6 Optical fibre system architectures

Optical fibre is the transmission medium which offers the highest bandwidth, with transmission capacities potentially as high as Tbit/s [21]. The concept of introducing fibre-optic cable and transmission systems in the access network dates back to the early eighties, and several field trials have been carried out. However, introduction of fibre in the loop (FITL) requires the deployment of fibre cable, which is usually associated with high civil works costs. In addition, the present fibre optics terminal equipment is rather costly, due to low production volumes. FITL upgrades have only to a very limited extent been implemented over the past years, and it is expected that it will still be years before the fibre deployment in the access network for residential broadband services reaches economically justifiable levels in non-greenfield areas.

Depending on the local network area conditions, there is a variety amongst FITL architectures regarding node configurations, ie. the location of the optical transmission terminal equipment. The most common configurations are:

- Fibre to the cabinet (FTTCab);
- Fibre to the node (FTTN);
- Fibre to the curb (FTTC);
- Fibre to the building (FTTB);
- Fibre to the home (FTTH).

The architectures based on FTTCab, FTTN, FTTC and very often architectures based on FTTB are hybrid solutions, ie. such networks are implemented by the use of fibre systems in combination with twisted pair, coaxial cable or wireless drop technologies. These hybrid architectures are described in more detail later in the next section of this paper. This section is devoted to the pure broadband fibreoptic access network architectures.

The majority of the fibre based broadband access systems installed today are either rolled-out in an FTTB or an FTTH

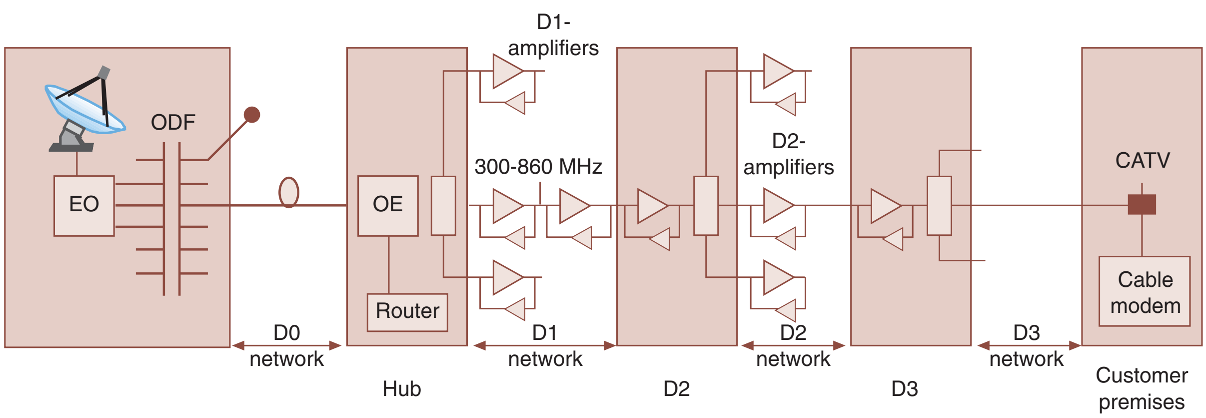

Figure 5 Architecture designed for coaxial cable modems

configuration. Fibre-optic transmission systems for capacities from 34 368 kbit/s and higher are currently being installed to customers with the highest capacity demand, ie. exclusively business customers. Also available today are fibre-optic transmission systems with four channels of 2 048 kbit/s capacity each. Usually point-to-point connections are used, alternatively ring topologies. The systems with at least 155 520 kbit/s capacity are normally SDH systems, which can easily be adopted to carry ATM traffic. Alternatively, the fibre-optic transmission systems can be based directly on ATM transport.

More advanced optical technologies like wavelength division multiplexing (WDM) may enable future access networks with significantly increased flexibility and capacity, as presented in more detail in [2]. However, the near-term and medium term challenges in the access network will most likely be solved by further utilisation of the above mentioned set of technologies. In the long term, the deployment of WDM may become a cost effective solution also in the access network for very high capacity demands.

7 Hybrid fibre and twisted pair copper architectures

The potentially very high capacity offered by optical fibre transmission systems combined with the simultaneous and prohibitive high costs of civil works for deploying new fibre cable has spurred a significant interest in particular in residential architectures based on fibre systems in combination with less costly drop technologies.

Telecommunication over a passive optical network (TPON) was the first generation fibre in the loop (FITL) systems in terms of a hybrid fibre and twisted pair copper architecture. These systems utilise a shared fibre infrastructure to deliver a range of services to a set of customers. TPON is used to support telephony, ISDN basic access (BA) and ISDN primary rate access (PRA) and leased lines, either in FTTCab, FTTN, FTTC, FTTB or FTTH configurations. But the concept of TPON was conceived prior to DSL technology becoming widely available, and as such the TPON is mainly considered to be tailored for existing services. Usually the TPON is deployed in development and growth areas, areas where the existing twisted pair network is replaced, or in greenfield areas.

The second generation FITL systems will provide broadband capacity, for instance with a twisted pair digital subscriber line (DSL) modem pair between the optical node and the customer premises. The recent developments in DSL technology enables the PNOs to provide broadband capacities on the existing copper network at a reasonable cost. However, in general for the DSL options, there is a trade off between copper loop distance and capacity available as described earlier in this paper. For instance, the transmission distance on 0.4 mm twisted pair cable for 2 Mbit/s asymmetric capacity is 3.5 km, whereas 25 Mbit/s asymmetric capacity has a distance limitation of 1.0 km on this cable. Thus, in order to offer higher capacities the copper loop length of the existing infrastructure must be shortened, typically by replacing parts of the current twisted pair cable between the local exchange and the customer with fibre optic cable. Hence, hybrid fibre and twisted pair copper architectures utilising DSL systems are likely to constitute the future broadband access network for operators with an existing twisted pair network. One major question in the long term perspective for access network operators, and PNOs in particular, then becomes: How deep should the fibre be deployed? The cable infrastructure costs vary significantly between network areas, and hence quite different fibre penetration levels are likely to be seen. FTTCab, FTTN, FTTC and FTTB are probably the most relevant node configurations for these hybrid solutions, and they reflect different degrees of fibre penetration in the access network.

In addition to the maximum transmission distances of the DSL systems, the actual distribution of copper loop lengths within the exchange area is of importance and may influence the upgrade strategy. At a strategic level, the average copper loop length within exchange areas is likely to be a crucial parameter. One key question is: What average copper loop lengths within exchange areas in European countries will be required in order to offer certain capacities? For typical statistical copper loop length distributions within exchange areas in some European countries, the cumulative distribution typically fits a linear function up to the 90 percentile, with the average as 50 percentile. This is shown in Figure 6. Typically 90 % of the copper loop lengths are shorter than approximately twice the average copper loop length for the whole exchange area. Thus, a 90 % coverage with 8 Mbit/s DSL requires average copper loop lengths of 1,300 metres.

Figure 6 summarises the theoretical cumulative copper loop length distributions for areas with different average loop lengths. The coverage of customers in the area (in per cent) is shown as a function of loop length. The bitrates on the horizontal loop length axis corresponds to the asymmetric capacities that may be provided on 0.4 mm twisted pair copper cables (Table 1). As can be seen from the figure, for an exchange area with a 800 m average loop length, 13 Mbit/s asymmetric capacity may be offered to 90 % of the customers, since 90 % of the copper lines in the area are below 1500 m. However, in an area with 2000 m average loop length, 13 Mbit/s may be provided to only 40 % of the customers.

Several architectures for a combined transmission twisted pair cable and fibre-optic cable are relevant, with SDH based and ATM based solutions as the most interesting ones. In the longer term a cost effective and flexible roll-out of a fibre based access network will require traffic concentration deeper into the network than today’s local exchange locations, ie. at the position of the fibre node. Concentration capability is a very important distinction criterion between the different fibre access architectures. In addition, the solutions may vary with respect to fibre topology. Topologies like ring, point-to-point and passive optical networks (PONs) are all relevant, as illustrated in the figures.

Today SDH systems are installed in large numbers in the transport network, often implemented in ring structures. SDH is probably the technology with the highest maturity and availability also when it comes to fibreoptic systems for the access network. An SDH architecture for the access network may be based on a ring topology and add and drop multiplexers (ADMs) located in the optical node. Alternatively, introduction of SDH technology in the access network may be based on point-to-point transmission and line terminals located in the optical node. However, in these network architectures the traffic is not concentrated in the optical node. This is one of the major reasons why conventional SDH technology is not considered as an obvious access network alternative in the medium to long term.

Several concepts for traffic concentration in the optical node are relevant. An ATM concentrator may be installed in the node, including SDH line terminals for point-to-point transmission between the node and the exchange. In a typical SDH PON architecture the optical network unit (ONU) contains an ATM concentrator, whilst a passive optical network is used for the fibre optic transmission. SDH PON may be regarded as a further development of current local loop or access multiplexers, for instance in order to extend the capacity in SDH based DLC (digital loop carrier) systems to include DSL modems. Figure 7 illustrates an SDH PON architecture for broadband services and narrowband services, with a 155 Mbit/s transmission capacity between optical line multiplexer (OLM) and ONU.

A third alternative is to establish a ring structure with concentration capabilities in the optical node, ie. the ONU. Figure 8 shows an ATM architecture for the access network based on a ring topology, with some optional interfaces indicated. Today such systems are often equipped with cards supporting interfaces such as synchronous 2 Mbit/s PDH, *n* * 64 kbit/s and ATM, from 2 Mbit/s and up to 155 Mbit/s.

Broadband transport of ATM on a passive optical network (BPON) is currently the architecture being standardised [22], mainly based on the work carried out by the FSAN initiative [23, 24]. The concept of BPON (ATM based broadband passive optical network) is already well-known as systems that typically offer 622 Mbit/s or 155 Mbit/s downstream capacity and 155 Mbit/s upstream capacity [23]. The access is shared between 16 or 32 optical network units (ONUs) with an inherent statistical multiplexing capability. The optical line terminal (OLT) terminates the network at the exchange side. A typical BPON architecture is shown in Figure 9. BPON is combined with for instance VDSL modem for the transmission of higher capacities on the existing twisted pair the last few metres towards the customer. Figures 9 – 11 show typical architectures considered possible in the long term. Figure 9 illustrates a BPON architecture for broadband services in parallel with a twisted pair network for narrowband services between the local exchange and the customer.

One key question related to the introduction of hybrid fibre and twisted pair copper architectures is the degree of network integration in the primary network. In Figure 9 there is no network integration in the primary access network, with narrowband services and broadband services being transmitted in parallel on twisted pair cables and fibre optic cables respectively. Figure 10 shows a BPON architecture in which the twisted pair cables in the primary access network are replaced by fibreoptic cables, and the narrowband services and broadband services are transmitted on separate fibre optical cables in the same primary network ducts.

Figure 11 depicts a fully integrated BPON architecture for broadband services and narrowband services, in which the twisted pair cables in the primary access network are replaced by fibreoptic cables, and all services are integrated on the same fibre cable system in the primary network.

Architectures with a combination of optical fibre and twisted pair cables are based on technology which currently is relatively mature, as for instance SDH. Ring topology and point-to-point SDH systems are already well-proven technologies and have been available for several years. The BPON technology combined with VDSL modems is less mature, but the FSAN initiative is a driver for the standardisation of this alternative in the ITU [22]. Several field trials have been carried out, some systems are already operational in Japan, and several vendors plan to have FSAN and ITU compliant systems commercially available in 1999.

8 Hybrid fibre and coaxial cable modem architectures

Similar to upgrading the twisted pair network with DSL modems, upgrading the coaxial cable network with cable modems for high capacity demands, will require the access network architectures to be based on fibre systems in the upper part of the network in combination with coaxial cable modems in the distribution part of the network. As penetration of broadband services increases and the capacity demand increases, the shared resources of the coaxial cable network segment must be shared by fewer customers if a comparable level of service shall be retained. This implies a segmentation of the coaxial cable network into smaller segments (eg. with 500 homes passed per segment), and most often a simultaneous upgrade of the D1 network with optical fibre cables. This is called HFC technology (HFC: hybrid fibre and coaxial cable network) [25, 26]. The size of the coaxial cable segments in terms of homes passed, and accordingly the fibre penetration is a crucial question related to HFC upgrades.

The cable television industry has been deploying HFC technology for a decade now, mainly to support the broadcast video business. HFC networks support a mix of analogue and digital channels by the use of frequency division multiplexing (FDM) techniques. The HFC networks currently being installed often has active components with an available bandwidth of 750 MHz. For non-active components the available bandwidth is in the range of 1 GHz [25].

Figure 12 shows an HFC architecture designed for the combined use of coaxial cable modems and fibreoptic transmission systems. The fibre nodes are connected to the CATV head-end via fibre trunks equipped with linear lasers. Often the head-ends are interconnected by the use of SDH or ATM based core networks. HFC solutions are currently being installed in significant numbers, and the technology is thus considered to be relatively mature. In HFC systems the D2- and D3 network technology is the same as the one described in the chapter on coaxial cable modems.

9 Transmission on power line cables

Power line communications refers to the transmission of data over the low voltage electricity distribution network. The installed electricity distribution network constitutes a significant asset with its near-ubiquitous customer coverage, and offering telecommunications services over this network may make the very strong access network competitors to the incumbent operators. Power line communications are described in more detail in [4].

There are in principle two main classes of systems for transmission on power line cables: power line telecommunications (PLT) and power line communications (PLC). The former includes the most recently developed systems. Two-

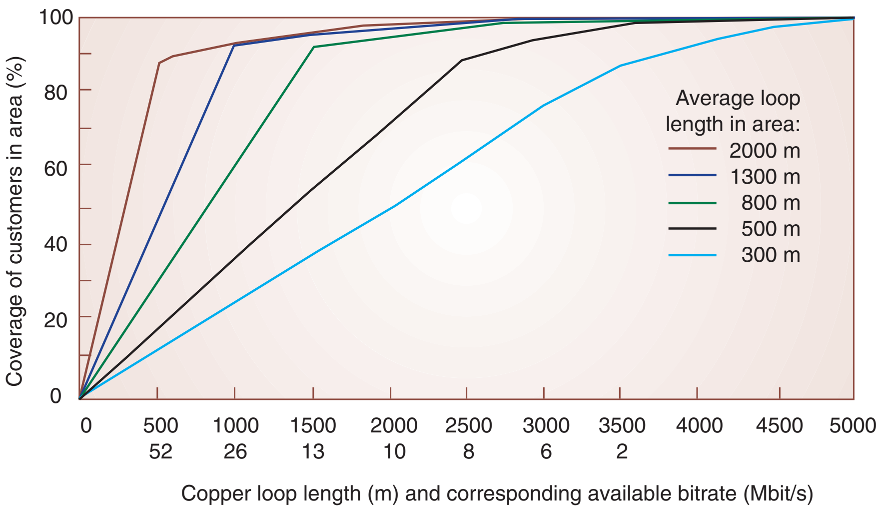

Figure 6 Cumulative copper loop length distribution

way PLC systems were developed in the late eighties with transmission capacities in the range of kbit/s, and has since then been applied for purposes such as remote power meter reading and network load management [27]. Currently there is a significant interest in the PLT systems in particular, since these may be the means by which the power utility companies may enter the Internet Access market.

In a power line telecommunications system a power line modem is installed at the low voltage transformer, which can serve from some few homes in rural areas to some hundred homes in urban areas. A data transmission capacity of about 1 Mbit/s is shared between the customers connected to the low voltage transformer. An additional modem is installed at the customer premises. Power line telecommunication technologies use frequencies in the range from 1 MHz to 30 MHz, which is a challenge in terms of electromagnetic compatibility [4].

Field trials have been running since 1992/93, when Norweb connected 25 households to their first trial network [27]. However, the technology is still rather immature and there are no published standards for PLT. Only a limited set of vendors now have commercial systems available, or are targeting a release of commercial systems by 1999, including Ascom AG, West End and Norweb Communications. Power line modems as an access network solution will probably not be implemented on a large scale in the short term, but within a period of between three and five years the technology is likely to become an interesting alternative for customers requesting capacities up to say 300 kbit/s [28].

10 Migration and evolutionary paths

Given the previously described large number of available access network architecture alternatives, the challenge for the operator is two-fold: the target architecture for future broadband access delivery must be determined, and – equally important – the migration or evolutionary path(s) toward this target architecture must be selected. Thus, access network migration towards broadband

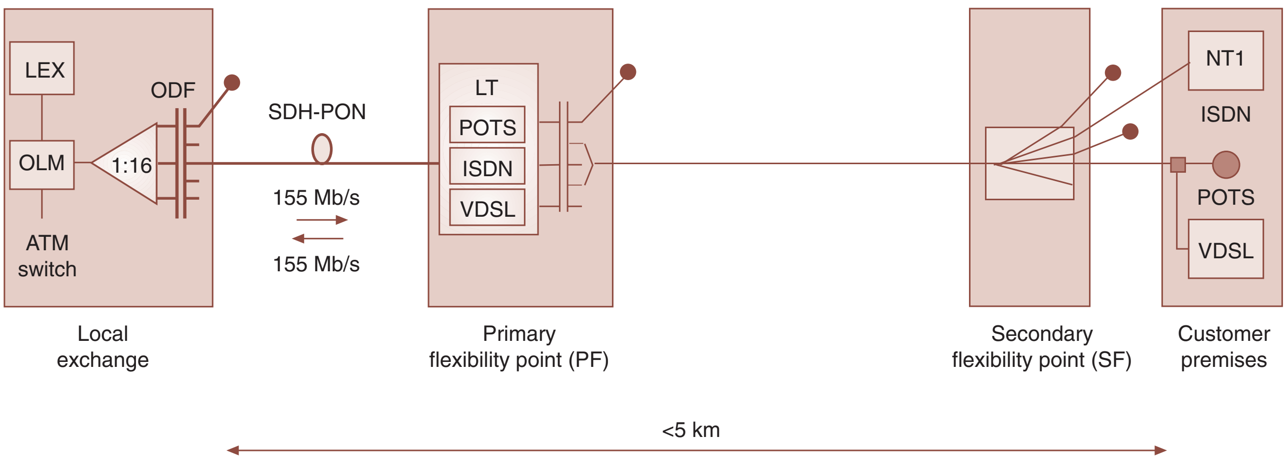

Figure 7 SDH PON architecture for narrowband and broadband services

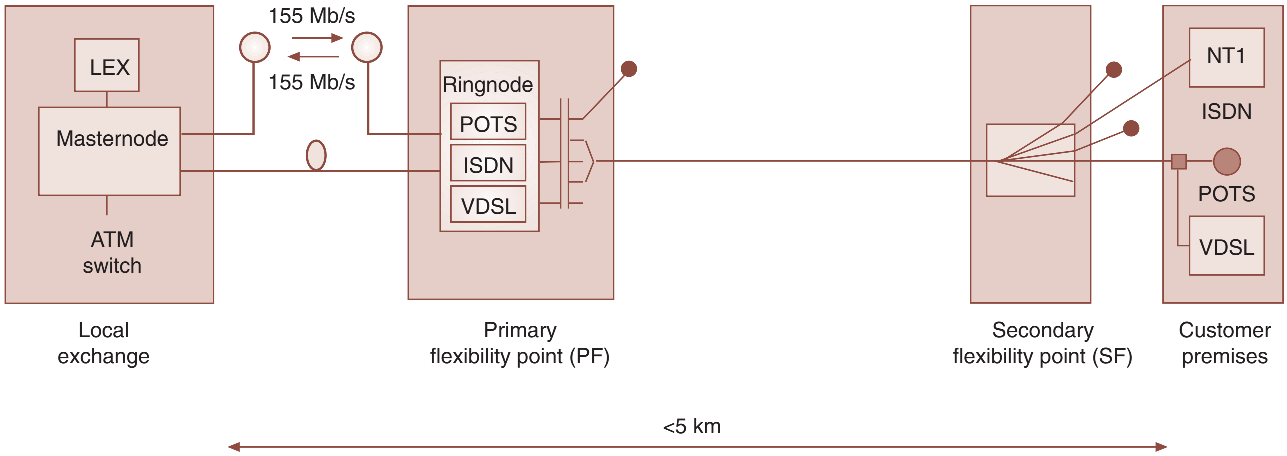

Figure 8 Access network ATM architecture based on ring topology and ONUs located in the optical node

is to a large extent related to the existing network, the target architecture, and the corresponding intermediate infrastructure changes required in order to upgrade the network to the target architecture.

In this chapter wireline access network migration will be discussed, mainly in view of some of the most interesting migration paths for the twisted pair and coaxial cable networks [29]. Neither access network protocol and interface migration issues nor access network management system migration aspects are included in the following. The access network deployment timeline and migration options – both in the short, medium and long term – are illustrated in several figures in this chapter. The operators are faced with three main broadband upgrade options for existing wireline access networks:

- Twisted pair network upgrade;
- Coaxial cable network upgrade;
- Wireless broadband build.

The wireless broadband migration alternatives are in this paper discussed as a migration path from the existing twisted pair network, even if it is an alternative upgrade for the coaxial cable network.

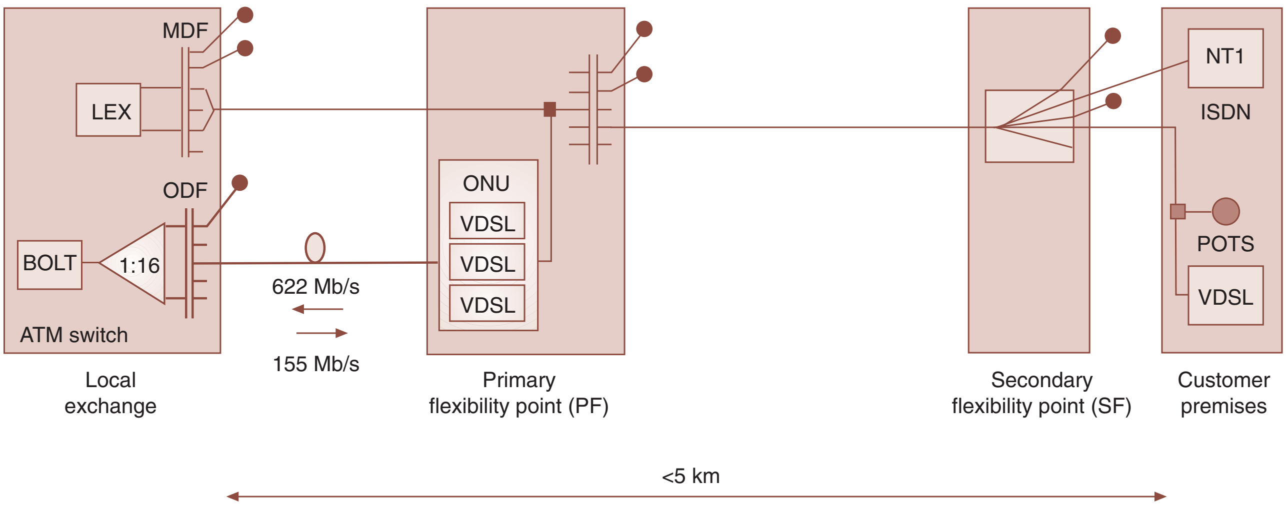

Figure 9 BPON architecture for broadband services in parallel with twisted pair network for narrowband services between the local exchange and the customer

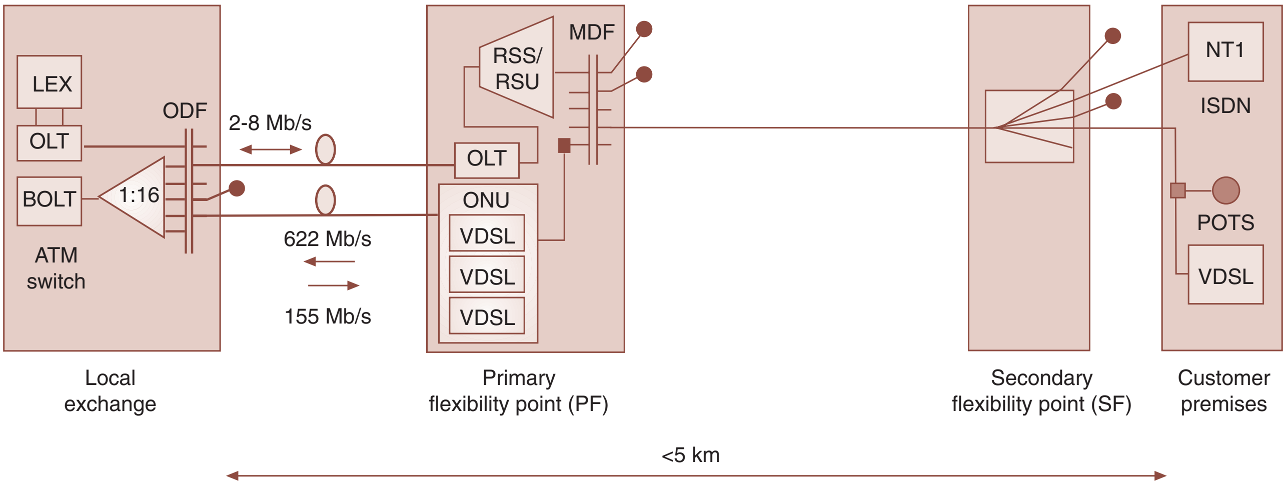

Figure 10 BPON architecture for broadband services in parallel with twisted pair network for narrowband services between the main flexibility point and the customer

The figures depict from left to right the evolution of existing copper pair and coaxial cable networks within the next ten year time frame. The circles indicate the network architecture established at that particular point in time and during the preceding upgrade period. Solid lines between the circles represent network upgrades, whereas dotted lines indicate no infrastructure changes during that particular period. The different alternative migration paths are found among the set of alternative routes from the existing network to the final networks. Figure 14 shows the migration paths for the twisted pair network. Several alternative solutions are illustrated for the end of the considered period:

- ADSL;
- Inverse multiplexing in combination with VDSL drop (IMUX-node + VDSL);
- Fibreoptic systems in combination with LMDS drop and twisted pair return (Fibre node + LMDS with twisted pair return);
- Fibreoptic systems in combination with LMDS drop (Fibre node + LMDS);
- Access network multiplexer for ADSL and remote subscriber system or remote subscriber unit co-located in

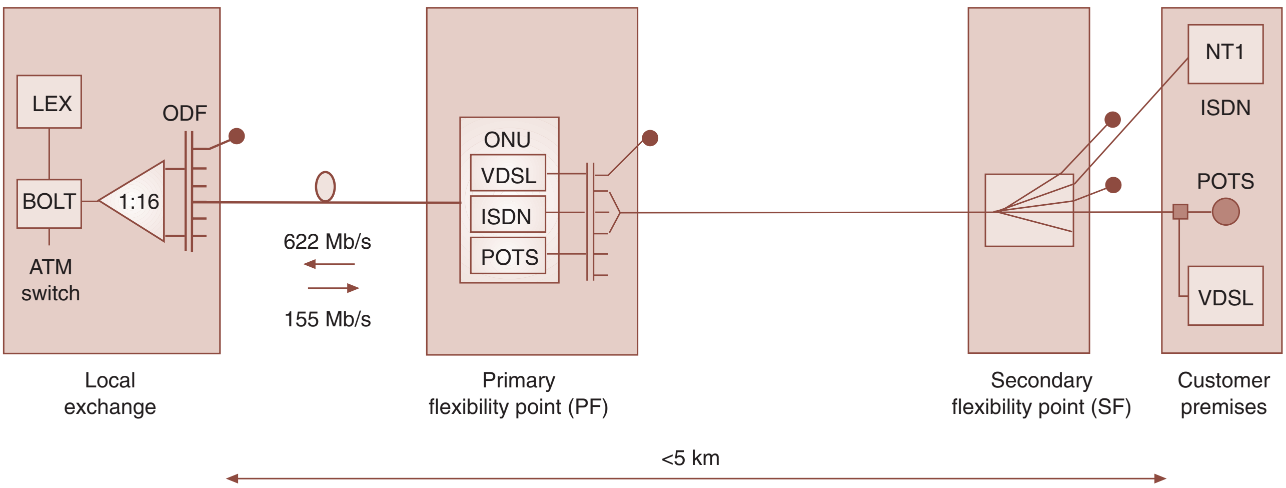

Figure 11 Fully integrated BPON architecture for broadband services and narrowband services

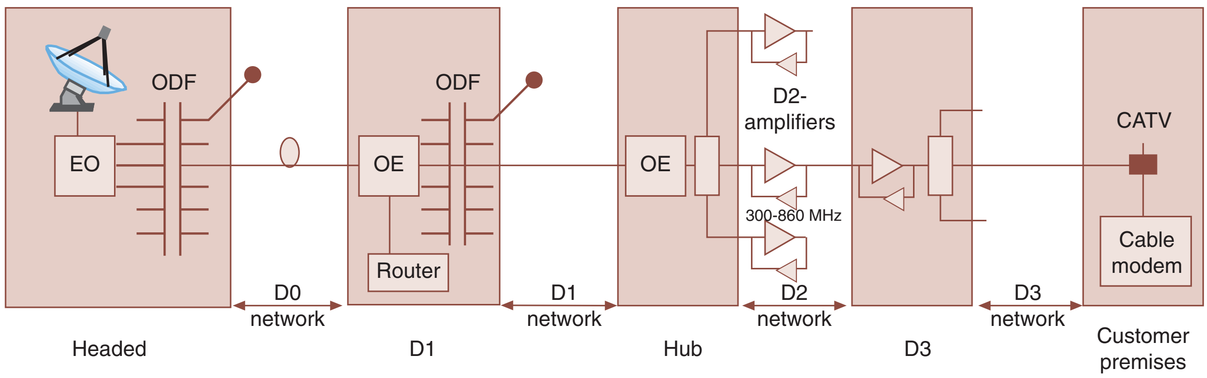

Figure 12 HFC architecture designed for the combined use of coaxial cable modems and fibreoptic transmission systems

the fibre node (ADSL + fibre node RSX);

- Two parallel fibreoptic transmission systems in the primary access network, one for feeding an RSX and one for the broadband services with VDSL drop (Fibre node RSX + VDSL);
- Fibreoptic systems in combination with VDSL drop (Fibre node + VDSL).

ADSL: In the network architecture *ADSL* the broadband customers are served with ADSL modems, and POTS and ISDN are provided on the existing twisted pair infrastructure. An ADSL connection is assumed to be able to transmit capacities in the 2 Mbit/s to 8 Mbit/s range downstream, and up to 640 kbit/s upstream, with a capacity dependent reach of between 2 km and 4 km.

IMUX-node + VDSL: *IMUX-node + VDSL* implies establishment of transmission nodes for transmission of aggregate capacity between these local access nodes and the local exchange. Inverse multiplexing (IMUX) is used to establish the high capacity connection on the existing twisted pair infrastructure between the local access node and the local exchange. By using VDSL modems between the node and the customer premises capacities in the range of 26 Mbit/s to 52 Mbit/s may be provided. The architecture is primarily an alternative to architectures with fibreoptic transmission in the primary access network.

Fibre node + LMDS with twisted pair return: The network architecture *Fibre node + LMDS with twisted pair return* is a first generation broadband wireless upgrade based on fibreoptic nodes and LMDS base stations. The traffic from the fibre node to the customer premises is transmitted via radio, whereas the twisted pair network is used for the return path.

Fibre node + LMDS: In the network architecture *Fibre node + LMDS* fibreoptic nodes and LMDS base stations are established. Both the downstream and the upstream traffic from the fibre node to the customer premises is transmitted via radio.

ADSL + fibre node RSX: This network architecture is based on the establishment of a fibre node infrastructure, in which an access network multiplexer and ADSL modems are installed in the fibre node in addition to an RSX (remote subscriber system or remote subscriber unit). ADSL modems are installed at the customer premises and POTS and ISDN are provided on the existing twisted pair infrastructure between the customer premises and the RSX in the fibre node.

Fibre node RSX + VDSL: In the network architecture *Fibre node RSX + VDSL* a fibre node infrastructure is established. Two parallel fibreoptic transmission systems are used in the primary access network, one for feeding the RSX and one for the broadband services. The latter may for instance be a broadband passive optical network system. The RSX is installed in the fibre node for POTS and ISDN in parallel with optical network units for transmission of broadband services with VDSL between the node and the customer premises.

Fibre node VDSL: The network architecture *Fibre node VDSL* consists of a similar establishment of a fibre node infrastructure, but with a fully integrated fibre optic transmission system in the primary access network for POTS, ISDN and broadband services. In the secondary network VDSL modems, POTS modems and ISDN modems are used in addition to combined modems for narrowband and broadband services.

In addition to the decision on the target network itself, the operator must decide when and how the architecture is to be deployed. Time combinations of the mentioned architectures are likely to be used. This is illustrated in Figure 13, where the initial introduction of the *IMUX node + VDSL* architecture alleviates the need for an immediate introduction of fibreoptic transmission systems in the primary access network. Some years later fibreoptic cables are deployed to the node where the inverse multiplexer is located, and the twisted pair cables in the primary access network may be disconnected. In the secondary network the same set of VDSL modems may be used throughout the period under consideration.

Starting from the large variety of migration paths in Figure 13, we have selected

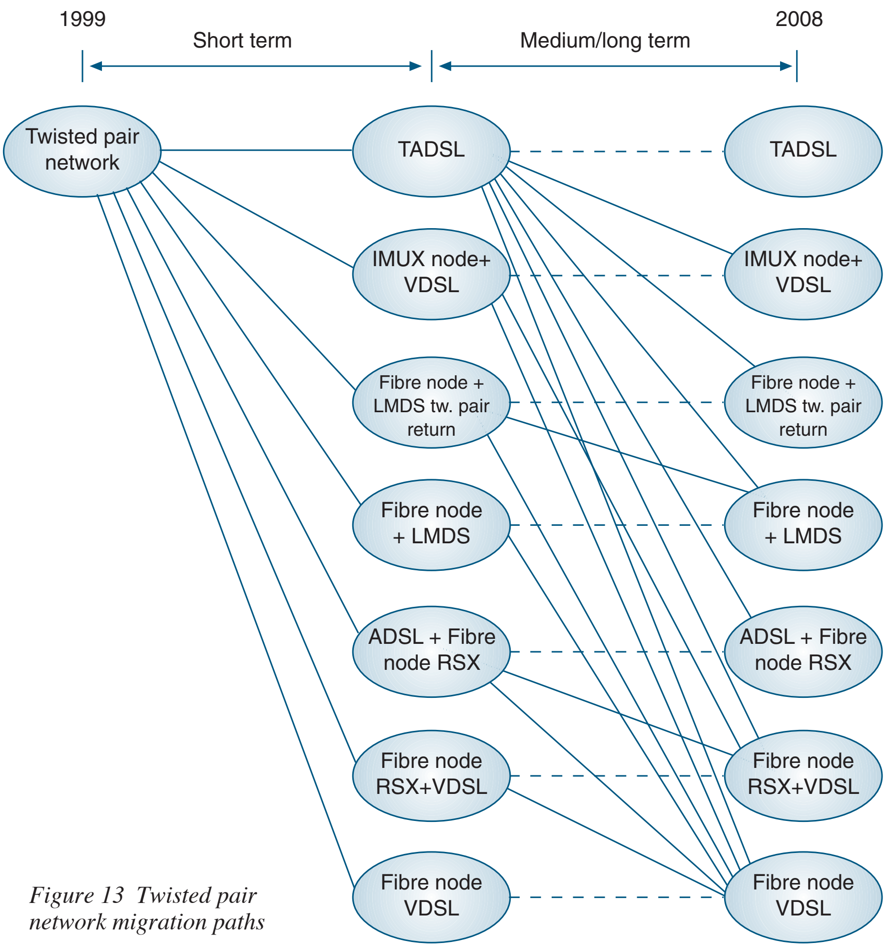

Figure 13 Twisted pair network migration paths

some of the ones considered to be most relevant, and numbered them, as shown in Figure 14.

Migration path 1, *Twisted pair ISDN → ADSL → Fibre node RSX + VDSL*. In the short and medium term the broadband customers are served by ADSL modems, and POTS and ISDN are provided on the existing twisted pair infrastructure between the local exchange and the customer. An access multiplexer and ADSL modems are installed in the local exchange. In the long term the ADSL equipment is gradually removed from the network, and a fibre node infrastructure is established. However, narrowband and broadband services are not fully integrated. In the primary access network two parallel fibreoptic transmission systems are used, one for feeding the RSX and one for the broadband services. The latter may for instance be a broadband passive optical network system. In the fibre node an RSX is installed for POTS and ISDN together with optical network units for transmission of broadband services with VDSL between the node and the customer premises.

Migration path 2, *Twisted pair ISDN → ADSL → Fibre node VDSL*. This alternative has the similar evolution as Migration path 1 initially. However, in the long term the narrowband and broadband services are fully integrated on the same primary access network transmission system.

Migration path 3, *Twisted pair ISDN → ADSL + Fibre node RSX → Fibre node RSX + VDSL*. In the short and medium term a fibre node infrastructure is established, with an access multiplexer and ADSL modems installed in the local exchange in addition to an RSX. In the long term the ADSL equipment is gradually removed and replaced by VDSL modems. During the period there is no integration in the primary access network of narrowband and broadband services on one fibreoptic transmission system.

Migration path 4, *Twisted pair ISDN → Fibre node RSX + VDSL*. This migration path results in the same target network as *Migration path 3*, but does not – in opposition to *Migration path 3* – have *ADSL + Fibre node RSX* as an interim solution.

Migration path 5, *Twisted pair ISDN → ADSL + Fibre node RSX → Fibre node VDSL*. In the short and medium term the same migration path as outlined in *Migration path 3* is followed. However, in the long term a fully integrated network for narrowband and broadband services is implemented.

Migration path 6, *Twisted pair ISDN → Fibre node RSX + VDSL → Fibre node VDSL*. In the short and medium term the same migration path as outlined in *Migration path 4* is followed. In the long term though, a fully integrated network for narrowband and broadband services is implemented.

Migration path 7, *Twisted pair ISDN → Fibre node VDSL*. This migration path in the long term results in a target architecture as *Migration path 5* and *Migration path 6*, without the intermediate architecture solution. A fully integrated network for narrowband and broadband services is implemented initially.

Migration path 8, *Twisted pair ISDN → IMUX-node + VDSL → Fibre node VDSL*. In the short and medium term the network architecture *IMUX-node + VDSL* is implemented, omitting installation of fibreoptic cable in primary network in the initial phase. In the next phase the twisted pair cables in the primary access network are disconnected, and fibreoptic cables are deployed to the location of the inverse multiplexer. The same set of VDSL modems may be used in the secondary network throughout the period.

Migration path 9, *Twisted pair ISDN → Fibre node + LMDS with twisted pair return → Fibre node + LMDS*. In the short and medium term LMDS base stations are established, fed with fibreoptic cables. The traffic from the fibre node to the customer premises is transmitted via radio, whereas the twisted pair network initially is used for the return path. In the long term all traffic is integrated in the LMDS network.

Migration path 10, *Twisted pair ISDN → Fibre node + LMDS*. This migration path in the long term results in a target architecture as *Migration path 9* without the intermediate solution *Fibre node + LMDS* with twisted pair return. Initially all traffic is integrated in the LMDS network.

Figure 15 illustrates some migration paths for the coaxial cable network. Three different solutions are indicated for the end of the period under study:

- Cable modem, twisted pair return;
- Cable modem, return amplifiers;
- Fibre node cable modem (HFC).

Cable modem, twisted pair return: In the network architecture *Cable modem, twisted pair return* coaxial cable modems are installed at the customer premises. The existing twisted pair network is used for the return channel. A transmission capacity of between 10 – 30 Mbit/s is shared among some thousand cable subscribers. There is no need for installation of return amplifiers in the coaxial cable network. At the hub the return channel is terminated in a router port for further transport of the broadband services.

Cable modem, return amplifiers: The network architecture *Cable modem, return amplifiers* is similarly based on installation of cable modems at the customer premises. In addition return amplifiers are installed in the coaxial cable distribution network.

Fibre node cable modem (HFC): The network architecture *Fibre node cable modem (HFC)* is similar to the *Cable modem, return amplifiers* architecture except that the existing coaxial cable network is segmented into smaller coaxial cable branches. Parts of the D1-network and eventually the D2-network is upgraded with fibreoptic cable and transmission systems. This is known as HFC technology (HFC: hybrid fibre and coaxial cable network). In such a network a transmission capacity of between 10 – 30 Mbit/s is typically shared among 500 cable subscribers, as opposed to the two

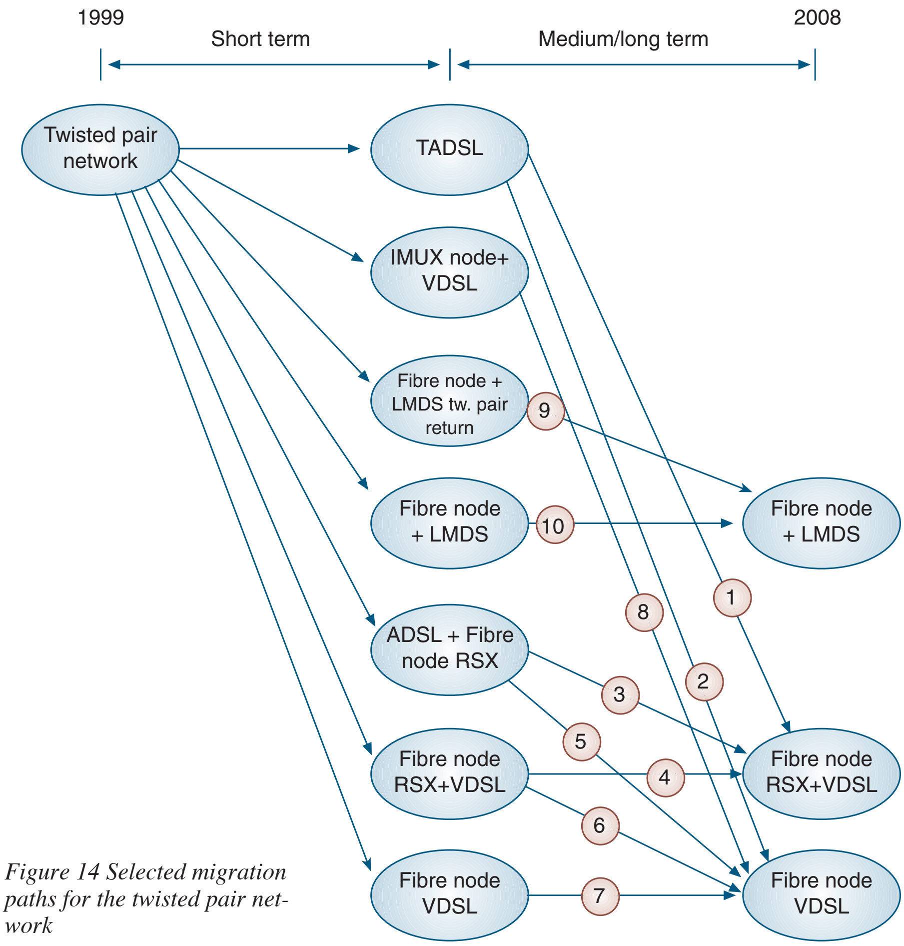

Figure 14 Selected migration paths for the twisted pair network

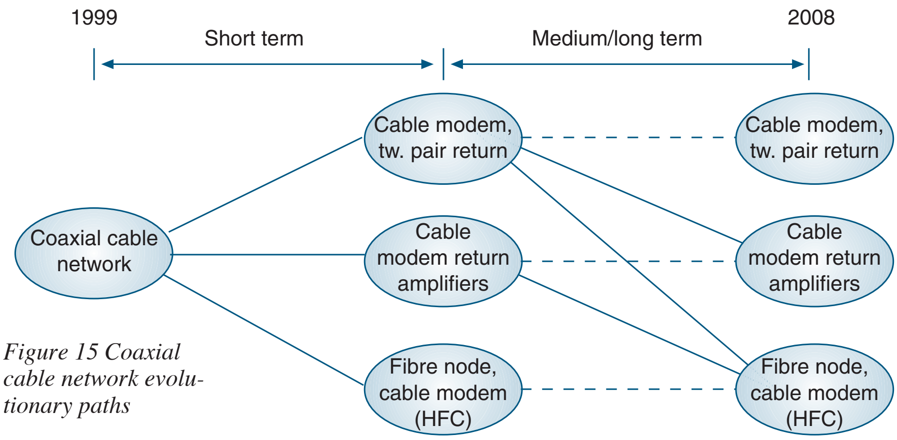

Figure 15 Coaxial cable network evolutionary paths

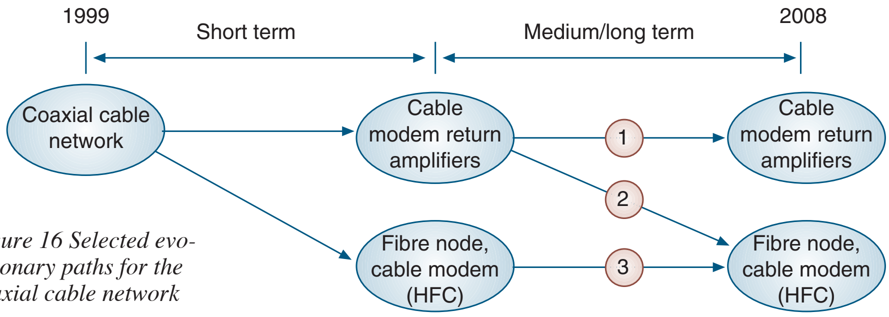

Figure 16 Selected evolutionary paths for the coaxial cable network

former solutions, in which some thousand cable subscribers shared this capacity.

Starting from the large variety of migration paths in Figure 15 once again we have selected some of the ones considered to be most relevant, and numbered them, as depicted in Figure 16. Note that the architecture *Cable modem, twisted pair return* neither is considered as a viable long term solution nor as an intermediate alternative.

Migration path 1, *Coaxial cable network → Cable modem, return amplifiers*. In the short and medium term coaxial cable modems are installed at the customer premises, and return amplifiers are introduced in the coaxial cable network.

Migration path 2, *Coaxial cable network → Cable modem, return amplifiers → Fibre node cable modem (HFC)*. In the short and medium term the same migration path as outlined in *Migration path 1* is followed. However, in the long term the existing coaxial cable network is segmented into smaller coaxial cable branches and parts of the D1-network (and eventually the D2-network) is upgraded with fibreoptic cable and transmission systems. In the long term coaxial cable segments with 500 cable subscribers are targeted.

Migration path 3, *Coaxial cable network → Fibre node cable modem (HFC)*. This migration path in the long term results in a target architecture as *Migration path 2* without the intermediate solution *Cable modem, return amplifiers*. Instead, already in the short term the existing coaxial cable network is segmented into smaller coaxial cable branches and an HFC network is established.

The above presented migration paths are considered to be among the most interesting ones for the evolution of the twisted pair networks and coaxial cable networks, and they illustrate that in the evaluation of access network migration towards broadband both the existing network, the target architecture, and the corresponding intermediate infrastructure changes have to be carefully examined.

11 Summary

This paper has briefly described the main broadband access network architectures currently being considered. The key parameters that differentiate the various access network solutions have been discussed, as well as some of the key issues faced by the access network infrastructure providers in the migration of the present network to broadband. Finally, some of the likely migration paths from the existing wireline access networks towards broadband have been outlined.

In conclusion, no single network architecture seems to be the obvious choice at present. Instead, boundary conditions given by the existing infrastructure and customer segment characteristics may possibly require simultaneous roll-out of several technology alternatives. However, the operator in terms of his knowledge of existing network, his network area characteristics, his customer base and business target, has a good starting point for limiting the choices and selecting the appropriate architecture for entering the broadband service delivery market.

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Fixed broadband wireless access

HARALD LOKTU AND ERWAN BIGAN

1 Introduction

Wireless local loop (WLL) emerged some years ago as an attractive alternative to copper for POTS services. The related advantages were fast deployment, because civil work is minimised and progressive investments, as radio equipment is only installed for those prospects which actually do subscribe to the service. Narrowband WLL is now a mature technology with several million POTS connections world-wide. Different frequency bands are used in different countries, ranging from VHF/UHF up to 3.5 GHz. WLL has mainly been used in developing countries and eastern Europe to improve teledensity. It has also been used by a few operators in the UK, Atlantic being one of them.

Broadband wireless local loop offers the same advantages, but still lacks the maturity of its narrowband counterpart. Most broadband wireless local loop systems deployed to date are one-way. They are Multiservice Multichannel Distribution Systems (MMDS), which offer a wireless means to carry CATV services. MMDS systems are available off-the-shelf, and several million homes are connected through MMDS world-wide. Most of these systems operate in the 2.5 GHz frequency band. New systems operating in higher frequency bands (28 GHz in the USA, 40 GHz in Europe) have been introduced to increase the number of TV channels. The acronym MVDS (Multichannel Video Distribution System) is used to designate TV distribution in the 40 GHz band.

The use of higher frequency bands also permits the introduction of a radio return channel. The typical range is reduced from a few tens of kilometres for MMDS at 2.5 GHz, down to a few kilometres for LMDS (Local Multipoint Distribution System) at 28 GHz. LMDS systems were first designed to offer packet-switched multimedia services to residential customers (fast Internet access). However, they have the potential for becoming truly multiservice (POTS, ISDN, leased lines, TV, fast Internet access, ATM) because bandwidths in excess of 1 GHz are available in the 28 or 40 GHz band. In particular, the support of leased lines has become a priority in order to satisfy the needs of alternative operators in developed countries.

Broadband wireless local loop is also becoming a reality through another approach. Broadband symmetrical point-to-multipoint (PMP) systems are optimised for *n* * 64 kbit/s services (circuit-switched POTS and ISDN, fractional E1 leased lines) to small- and medium-size businesses (SME). A number of frequency bands may be used for broadband symmetrical PMP depending on national regulations and industrial development being 3.5 GHz, 10.5 GHz, 26 GHz, or 28 GHz. The distinction between LMDS and broadband PMP is not always clear-cut.

Bi-directional LMDS or broadband PMP systems are being deployed by several vendors for the purpose of conducting field trials. The number of connected customers world-wide probably lies in the range of hundreds. According to the consulting firm Ovum, the broadband wireless market is expected to reach today's narrowband wireless market size of a few millions by 2002.

2 State-of-the-art of fixed broadband wireless access

2.1 Overview of broadband wireless access technologies

2.1.1 Point-to-point

Point-to-point radio relay systems have been readily available off-the-shelf for a number of years from a large number of vendors. Initially deployed in core networks (medium to high capacity), they are now mainly used in access networks (small capacity, ie. *n* * 2 Mbit/s), either to connect business customers or for mobile base station backhaul. These compact systems operate in the fixed service frequency bands between 7 and 38 GHz. Their range typically lies between 2 and 20 km depending on the frequency band, the required availability, and the rain zone. There is no doubt that point-to-point radio relay is the most mature broadband wireless access technology.

2.1.2 Point-to-multipoint

Symmetrical broadband point-to-multipoint (PMP) systems have been designed to connect either small- and medium-size business customers or mobile base stations, at E1 rates or *N* * 64 kbit/s services (POTS, ISDN, fractional E1 leased lines) which can be delivered through multiplexers. When connecting businesses or mobile base stations, only a fraction of the E1 capacity may be required. Due to limited availability of spectrum, these radio systems should eventually offer bandwidth-on-demand, although some initial versions only support fixed bandwidth allocation. These systems are typically available in the frequency bands 3.5 GHz, 10.5 GHz, 26 GHz, or 28 GHz. The lowest frequency bands yield the longest range (eg. 10–20 km at 3.5 GHz) at the expense of limited capacity (total aggregated capacity in the order of 100 Mbit/s). On the other hand, the highest frequency bands offer the highest capacity (total aggregated capacity in the order of 1 Gbit/s), at the expense of reduced range (eg. a few km at 26 or 28 GHz).

2.1.3 Local Multipoint Distribution System

The acronym LMDS (Local Multipoint Distribution System) designates bi-directional asymmetrical point-to-multipoint systems able to deliver multi-services to either residential (TV, Internet access, POTS) or business customers (leased lines, ISDN, Internet access etc.). The digital telephony, data and video signals are initiated at central offices, head-ends or satellites. The signals are combined and transmitted, using optical fibre or microwave links, to multiple LMDS nodes placed on towers or on top of high buildings. The radio signals are distributed to households and businesses where they are received using a rooftop antenna. An up/down-converter is mounted close to the antenna. A set-top box or multiplexer is installed indoors to connect the various customer terminal equipment. A coaxial cable connects the outdoor and indoor units. The downstream bit rate capability is up to 25 – 50 Mbit/s per customer and the upstream bit rate is up to several Mbit/s per customer. Operation at high frequency bands (eg. 28 GHz) is necessary to handle such large bit rates. The typical range is a few kilometres.

The traffic asymmetry depends on the service mix to be delivered This is the reason why LMDS systems have been designed to operate in frequency bands where great flexibility is left to the operator regarding which spectrum capacity should be allocated to the down- and uplink. This is the case of the 28 GHz frequency band, which was auctioned by the FCC in the USA early 1998. In Europe, LMDS systems may be deployed in the 26, 28 or 40 GHz band. The 26 GHz frequency band is well suited for symmetrical applications, whereas the 40 GHz band is dedicated to broadcast applications.[1)] The European status of the 28 GHz band is still unclear because the old CEPT frequency band plan for symmetrical applications will need to be reworked to take into account sharing of the band with satellite systems.

2.1.4 Broadband satellite systems

Geo-stationary Earth Orbit (GEO) satellite systems are widely used for broadcast as well as transmission applications. They can also be used to offer fast Internet access, using POTS return channel. However, they have only found limited use in access networks. Low Earth Orbit (LEO) satellite systems have been proposed in order to reduce the large propagation path loss and delay. These proposals (Teledesic, Skybridge) target asymmetrical broadband wireless access at bit rates up to several Mbit/s per customer.

Compared to broadband terrestrial systems (broadband PMP, LMDS), satellite systems are best suited to handle very low customer densities because of the much larger spot size. These systems could thus be used to offer broadband access to the upper tier customer category as for instance international business travellers, international news correspondents or to selected business customers. These systems are still at the design stage, with service opening being planned in a few years.

2.1.5 Universal Mobile Telephone System (UMTS)

Third generation mobile systems (UMTS) will handle voice as well as data traffic. Micro-cells will provide bit rates up to 2 Mbit/s in hot spots. Up to a few hundred bit/s will be offered in most areas. Because of the limited available bandwidth, UMTS is not expected to handle large numbers of broadband customers. On the other hand, broadband PMP or LMDS systems will be increasingly used in conjunction with point-to-point radio relay systems to connect mobile base stations (second generation mobile systems, UMTS) to core networks.

2.1.6 Terrestrial broadcasting

Terrestrial broadcasting being MMDS, digital terrestrial TV in the VHF/UHF band may also play a role in broadband access networks. Some MMDS networks are already used to offer fast Internet access using POTS return channel. Future digital terrestrial TV networks will offer the same possibility, but to a smaller fraction of customers because of the larger cell size. There is on-going research towards low bit-rate radio return channels for these systems, which could alleviate the need for POTS' return in case such systems are used to offer fast Internet access to residential customers in the future.

2.1.7 Radio Local Area Networks (RLANs)

RLANs are used to avoid cabling problems and/or to provide limited mobility. Off-the-shelf equipment allows bit rates up to 1 – 2 Mbit/s and future generations target 10 – 20 Mbit/s. Although RLANs are used mainly indoors within business premises, they can also be used marginally in access networks. A few vendors propose license-free point-to-point radio relay equipment based on RLAN technology and they also envisage point-to-multipoint systems packaged for outdoor use. The bit rate capability is still limited to 1 – 2 Mbit/s gross bit rate to be shared. Furthermore, these systems operate in unlicensed frequency bands (eg. 2.4 GHz band) for which no quality of service (QoS) can be guaranteed because the overall bit rate or transmission delay is affected by interference.

2.2 Radio specific issues affecting the choice of technology

2.2.1 Propagation

Most broadband wireless access systems operate at frequencies above 10 GHz for which clear line-of-sight (LOS) is required between the transmitter and the receiver. This reduces the coverage provided by broadband systems for terrestrial wireless access. The actual coverage depends on the base station antenna height, the cell size, and the environment. As a crude indication, the typical coverage LOS probability is between 30 and 70 %. Accurate planning tools are needed to identify those prospective customers that can be connected through radio. If 100 % coverage is required, alternative access techniques must be used in conjunction with radio.

The second propagation issue is rain attenuation, which becomes significant above 10 GHz and reduces the range. The range then depends on the required availability and the climatic zone. Range reduction usually increases deployment costs, except when base stations are utilised at full capacity.

2.2.2 Spectrum availability

Spectrum is a prerequisite for successful operation of any radio based telecommunication service. The large bandwidths

Table 1 Spectrum in Europe

Frequency band	Total available bandwidth
3.40 – 3.60 GHz	2 * 90 MHz
10.15 – 10.65 GHz	2 * 150 MHz
24.50 – 26.50 GHz	2 * 1 GHz
27.50 – 29.50 GHz	2 * 1 GHz
40.5 – 42.5 GHz (+42.5 – 43.5)	2 – 3 GHz

[1)] *The UK has proposed a frequency band plan permitting highly asymmetrical applications in the 40.5 – 42.5 GHz, and CEPT is currently working towards extending this band up to 43.5 GHz which would give this band a truly multiservice capability.*

Table 2 Wireless deployment scenarios

	Residential	SME (<2 Mbit/s)	Large business (>2 Mbit/s)
Alternative wired techniques	A/VDSL, HFC, FTTC/H	HDSL, FTTB	FTTB
Urban/suburban	LMDS	PMP, LMDS	PP
Rural	MMDS, DVB-T	PP, PMP	PP

required for broadband applications can only be found at high frequencies, most often above 20 GHz.

There is a number of candidate frequency bands for broadband radio access. Table 1 lists those frequency bands that are most likely to be used for this application in Europe, along with the total available bandwidth.

Not all these frequency bands are available for broadband access in every country. However, summing up the total available bandwidth in any country usually yields several gigahertz of spectrum. Therefore, lack of spectrum for broadband radio access applications is not a key issue. The most serious issue is the lack of harmonisation: although most of these bands have been harmonised by CEPT, different bands are available in different countries. This may to some extent inhibit cost reduction through volume production.

2.2.3 Deployment scenarios

The following analysis is purely qualitative. A quantitative analysis should rely upon techno-economic evaluation. Such techno-economic analysis can be found in a different article of this journal issue. Table 2 outlines possible deployment scenarios for point-to-point (PP) radio relay, broadband symmetrical point-to-multipoint (PMP), and LMDS.

LMDS is the only radio technology that can handle both business and residential customers in principle. However, answering the needs of alternative operators in developing countries, the current generation of LMDS systems primarily targets business customers. Besides, the short range favours LMDS for dense urban or suburban areas. PMP may be used to connect business customers in relatively low density areas, but deployment in lower frequency bands should be preferred in that case (eg. 3.5 GHz). Isolated customers may be best connected using PP systems. MMDS or DVB-T may be used to offer fast Internet access to residential customers, with POTS return channel. The longer range of MMDS or DVB-T compared to LMDS makes them most favourable for rural areas.

3 Evolution of fixed broadband wireless access

3.1 Evolution of broadband service requirements

The future evolution of broadband access networks is characterised by a broad range of very dynamic and rather complex scenarios. Within the long term virtually all electronically based information requested by people and computers in at least developed countries, is predicted to be both accessed and processed in a digital format. Together with the low cost related to the storage and processing of digitally based information, this trend provides the necessary framework for cost-effective development of an increasingly large variety of new services and service combinations. Consequently, the traditional categorisation of services into telecom, datacom and broadcast is no longer appropriate and is gradually being converged into a combined service scenario often referred to as multi-media services.

An immediate consequence of this development is that broadband access networks have to be able to support a large variety of service configurations. Hence, the different broadband access technologies must to a large extent be capable of offering the same services generating a highly competitive environment from a technological point of view. Furthermore, with such inherent service flexibility, both the residential and business customers may be served with the same access technology platform. This development is for the moment also strongly encouraged by the ongoing deregulation of the previous monopolist markets for services.

The highly dynamic and competitive future market for delivery of such services will require short time to market and ability to reconfigure the access network according to the service configuration requested by the customers. Within this context, broadband wireless access (BWA) systems will be one of the most interesting candidates for delivery of true multi-media services combining fixed and broadcast services in a cost-efficient way.

3.2 Wireless access networks

3.2.1 Access network architectures

Wireless access networks for fixed broadband services are currently evolving along three major routes towards the future network. The far most developed one so far seems to be the broadcasting oriented approach, which in a European perspective is dominated by the DVB group within EBU. Originally intended to provide specifications for digital video broadcasting, it has expanded the scope of its work to include bi-directional asymmetric access as well. Furthermore, there is also a telecom-oriented route towards the future based on bi-directional symmetric access. P-P and P-MP systems are at the moment the most evident examples of this trend. In Europe the progress along this path is led by the Broadband Radio Access Network (BRAN) project within ETSI. Finally, a datacom oriented route is also present of which Wireless LAN (WLAN) systems based on IP presently is the most successful example.

The reference model for interactive services adopted by DVB is shown in Figure 1. It proposes a broadband broadcasting medium in the direction towards the user and in addition a bi-directional symmetric medium for the interactive part with considerable lower capacity. The reference model itself includes in principle both wireless and wireline technologies but clearly assumes that the access mode is asymmetric. An impor-

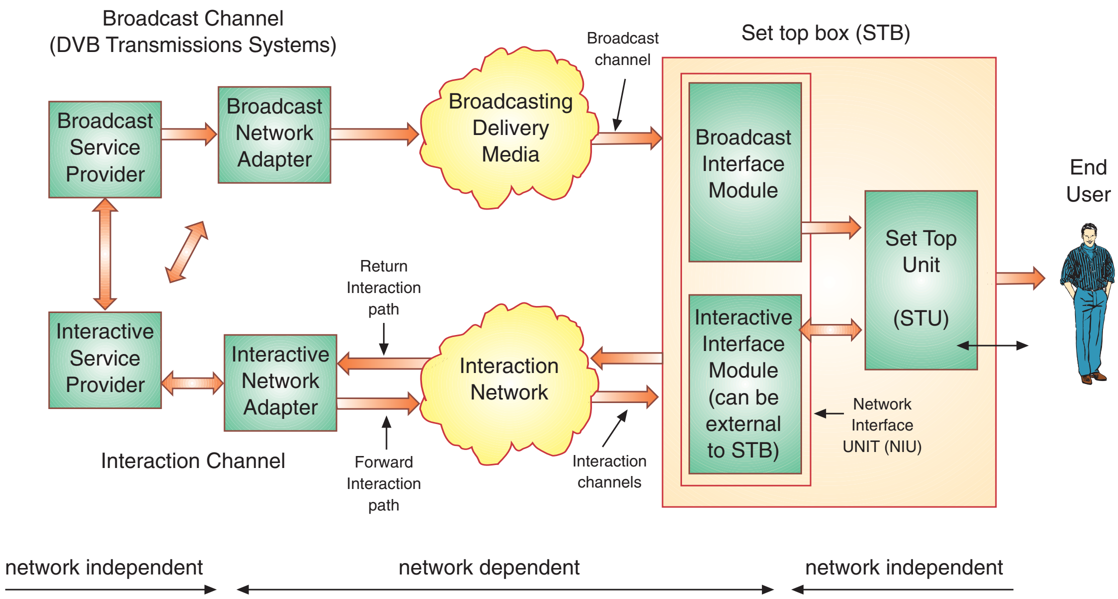

Figure 1 DVB interactive reference model

tant inherent feature of the reference model is that it promotes implementation of hybrid access networks using a combination of different media for service delivery. Both wireless-wireless and wireless-wireline configurations are envisaged and the hybridisation could be both between the forward and return media as well within each of the directions themselves.

Due to the focus on broadcast services, the typical access architecture is a point-to-multipoint (p-mp) or star configuration. The DVB standard prescribes a multiplexing scheme in the forward direction based on 188 byte time slots or cells being referred to as an MPEG-2 transport stream (TS). However, no addressing or routing/switching scheme is devised and hence, such functionality is often implemented in a centralised manner. The major networking operation is performed by the MPEG-2 TS multiplexer and demultiplexer mainly adding and dropping time slots from the transport stream in a static way. There is no multiplexing hierarchy defined for the MPEG-2 TS which prevents a seamless interconnection with standard core networks.

The interactive network is according to the DVB reference model provided as an overlaid network. This is appropriate if a reduced service access network is assumed with for instance PSTN or ISDN as interaction networks. However, to be able to establish a full service access network in an efficient way, the forward broadcast and interaction network should in the future be merged into a single forward network. Furthermore, dynamic switching or routing functionality must be provided. At present this is being done by encapsulating IP or ATM traffic into the MPEG-2 transport stream in the forward direction while pure IP or ATM is employed in return direction.

A general reference model adopted by the ETSI BRAN project is shown in Figure 2. Besides defining a set of interfaces, it describes a general access network consisting of access points (AP) and access terminations (AT). The ATs are connected directly to one or more access point transceivers (APT) or via one or more radio relays (RR), which together with the access point controller (APC) constitutes an AP. Optionally, terminal equipment (TE) may communicate directly via radio relays without passing through an external switch. The access network is interfaced to the TEs and the local networks through adequate interworking functions (IWF).

Unlike the DVB reference model, the described reference model defines a flexible multipoint-to-multipoint (MP-MP) or mesh architecture combining point-to-point and point-to-multipoint connections. This allows for dynamic routing functionality being implemented both at the RRs and APC as well as at the radio terminations (RT) providing support for both distributed and centralised routing of traffic. As such it defines an architectural framework for implementation of a re-configurable service delivery mechanism. This framework is also believed to provide the necessary support for implementation of close to 100 % wireless coverage of the customer locations in a given area.

The BRAN model is basically established to specify delivery of telecom and datacom type services within the scope of a switched full service access network for broadband services. As such it will support switching and multiplexing based on asynchronous (ATM) and most likely a pure IP based scheme as well. For the time being the working assump-

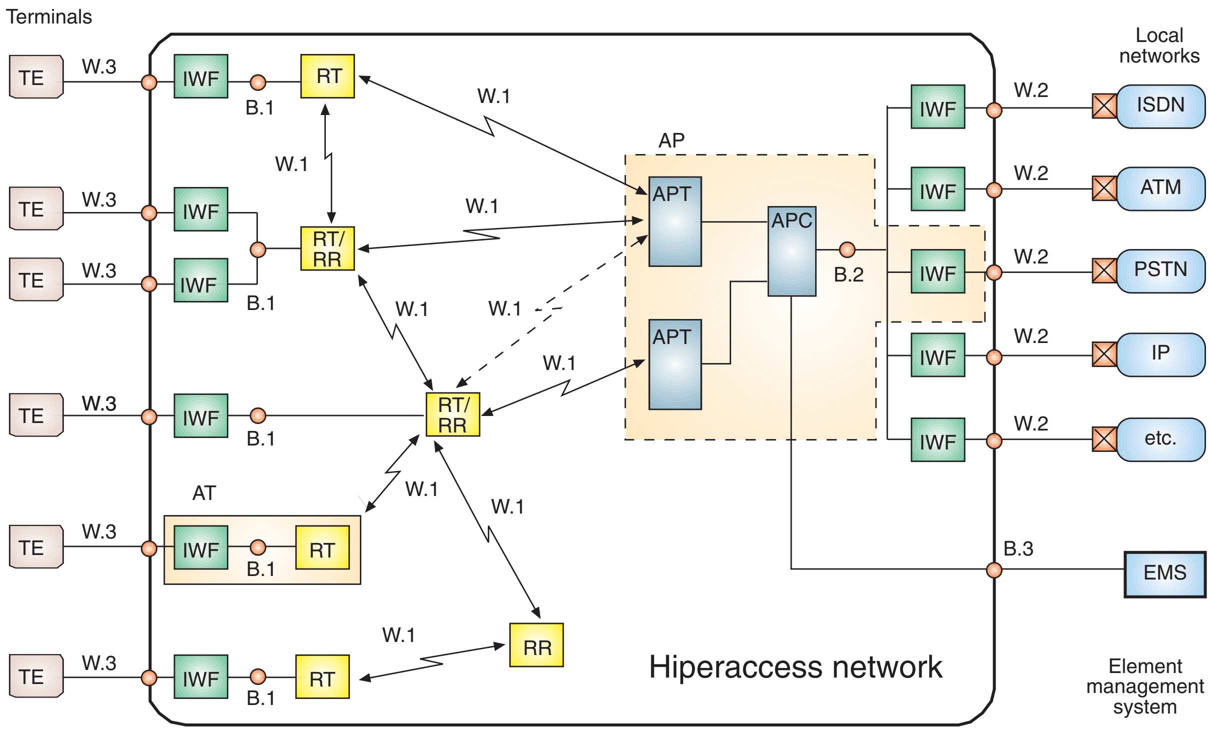

Figure 2 ETSI BRAN general reference model for fixed service broadband access networks

tion in the specification work is ATM which employs a 53 byte cell structure. The access mode is symmetric but does not preclude delivery of asymmetric services. It provides a switching hierarchy allowing an efficient interconnection between the core and access network. As opposed to the DVB approach it offers inherent dynamic routing functionality. The BRAN model only considers wireless access and does not allow a hybrid implementation of the forward and return direction to the user

3.2.2 Broadband technologies for terrestrial wireless access

To address the evolution of wireless technologies for broadband access to fixed services, a review of ongoing research projects in the EU funded ACTS program was carried out within the EURESCOM project P614 [3]. The major results are summarised in Table 3.

Table 3 ACTS projects with broadband access trials or demonstrators

PROJECT	Max Channel Bit Rate [Mbit/s]		Frequency Band [GHz]		ACCESS	Range [km]		ENVIRONM.
	Up	*Down*	*Up*	*Down*		*Up*	*Down*	
FRANS-2	40	622	29		Fixed	–	0.5	Outdoor
ATMmobil	155		38		Fixed	0.3		Outdoor
FRANS-1	N * 2	155	2.2	42	Fixed	< 2	0.5	Outdoor
CRABS	8	34	40		Fixed	2-5		Outdoor
CABSINET	–	35-40	40		Fixed	5		Outdoor
MEDIAN	155		60		Portable	< 0.01		Inoffice
AWACS	34		19		Portable	0.05 – 0.1		Indoor
WAND	20		5		Portable	0.05		Indoor
ATMmobil	20		5		Portable	0.05		Indoor
SAMBA	34		39	42	Mobile	–		Outdoor

The study revealed a trend towards higher capacity and higher frequency bands. Channel or information bit rates in the range 2 to 622 Mbit/s were targeted and spectrum in the range 2.5 to 60 GHz were considered. Two major categories were found: portable or nomadic access for indoor environments and fixed outdoor access. The vast majority of projects had chosen ATM as preferred multiplexing scheme and both solutions based on asymmetric and symmetric access are proposed.

There is a close relationship between different features given in Table 3. Maximum range of radio path length is traded against range as well as increasing radio frequency both for indoor and outdoor environments. Hence, if the combination of large capacity and range is envisaged, asymmetric network access must be expected if cost-effective solutions shall be provided. Consequently, to separate the forward and return connection a frequency division duplex (FDD) will be used to provide long-range outdoor access, either in the same frequency band or alternatively in a lower part of the spectrum. Conversely, time division duplex (TDD) will be employed for short-range indoor access.

These emerging technologies may be mapped onto both the BRAN and DVB reference model. The evolution towards a full service network most likely implies an ATM multiplexing scheme. To provide close interconnection to the ATM core networks, the access maximum bit rates should comply with standard rates of 25.6, 51.8 or 155.5 Mbit/s. Due to the expected merger of telecom and broad-

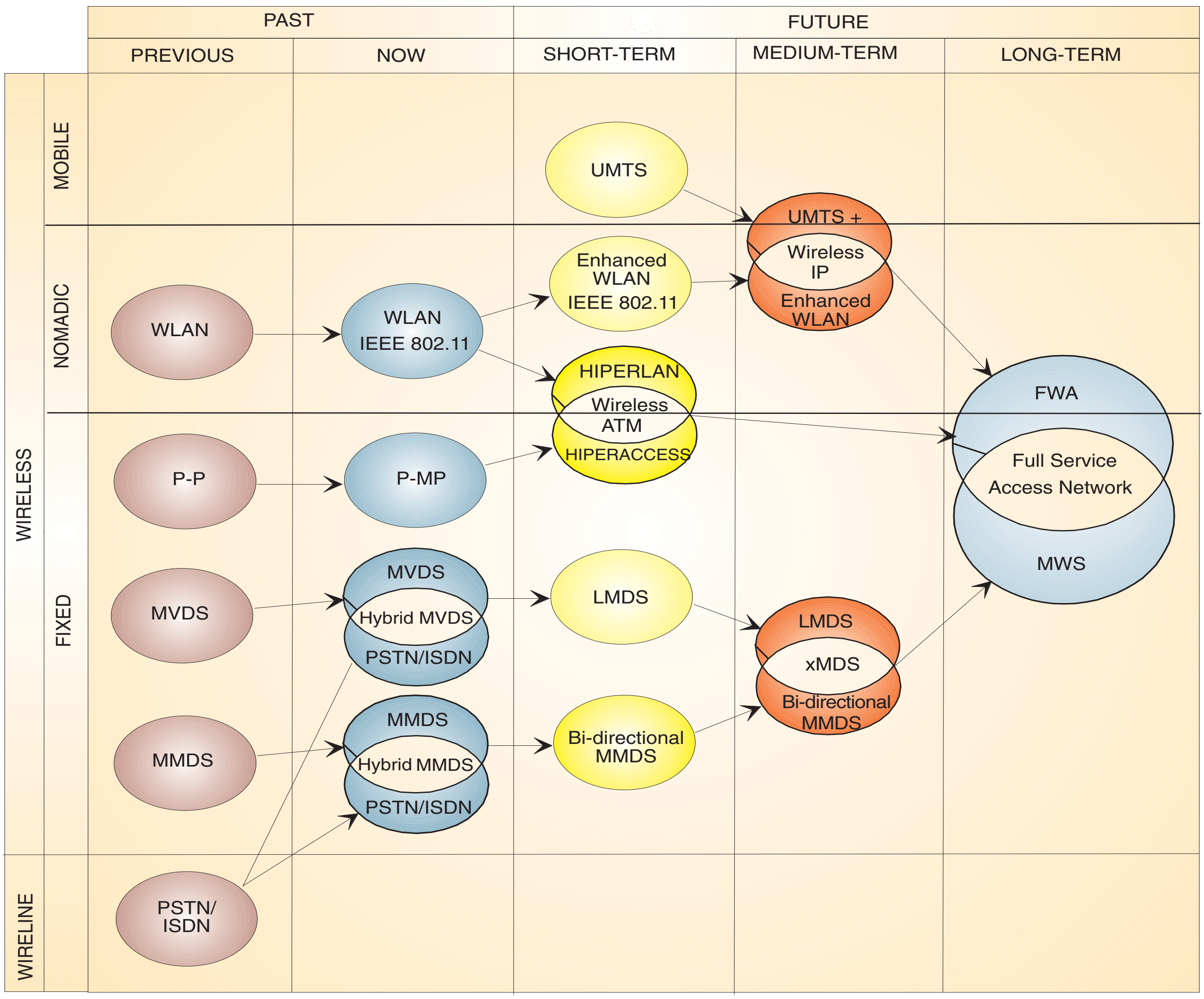

Figure 3 Migration paths towards a wireless FSAN

cast services, asymmetric access may be the preferred solution in the short term. In the long term symmetric access will be preferred due to the larger inherent service flexibility.

3.3 Migration towards future systems

A possible migration towards future systems for fixed wireless access is shown in Figure 3. At the moment, no true bi-directional broadband system for wireless access has reached a large scale deployment in the market. There is a number of technologies available in the market however, mostly offering near-broadband capability in terms of available information bit rate. Hybrid MVDS and MMDS systems offer broadband capacity in the forward direction but have so far only offered narrowband wireline capacity in the return path. P-MP and WLAN systems offer symmetric capacity above 2 Mbit/s capacity but are still not widely deployed.

Within the short term perspective of 2–3 years true asymmetric broadband access systems will be launched in the market of which MMDS or LMDS like systems seem to have the highest potential for large scale deployment. Within the medium term of up to five years, these broadcast oriented systems will probably merge into a more generic system denoted xMDS where the major difference would be the radio aspects.

The P-MP technologies will mostly evolve into ATM based solutions in the short to medium term. From a European perspective this is promoted by the ETSI BRAN project in close collaboration with the ATM Forum. Their fixed service P-MP like solution will offer at least 25.6 Mbit/s capacity and is denoted HIPERACCESS (HIgh PErformance Radio ACCESS system). In parallel, the BRAN project is establishing a standard for nomadic access name HIPERLAN (HIgh PERformance LAN) based on ATM. The two BRAN systems will have a common core partly defining a generic wireless ATM system.

In the short term a new generation of WLAN technology enhanced to at least 10 Mbit/s capability will emerge. Also UMTS will be launched mostly offering in-door broadband access limited to fixed or nomadic services. There is strong effort being conducted to standardise IP on the UMTS platform and in the medium term there will most likely be a family of wireless IP systems for combined nomadic and fixed access available.

Moving towards a future full service access network (FSAN) a the convergence of cell (ATM) and packet (IP) oriented access into a generic delivery mechanism for fixed wireless access (FWA) is bound to happen in the end. The broadcast oriented route towards a generic approach is in the European perspective being established in CEPT under the heading of multimedia wireless systems (MWS). It is unlikely however that these two routes will arrive at single system definitions in a long-term perspective of ten years. An achievable objective could be to establish a generic framework for standardisation of broadband wireless access allowing for a range of different system implementations adapted to the particular service configurations required.

4 Conclusion

In this paper we have addressed wireless access to broadband services. An overview covering the present state-of-the-art of wireless systems for fixed access is presented, and the evolution towards a future system has been discussed. At the turn of the millennium, broadband wireless systems show indications of reaching the maturity necessary for volume production and large-scale deployment. A part or full merger of different technologies will happen on the way towards a competitive future imposes increasingly more complex requirements on system design and engineering.

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Abbreviations

ACTS	Advanced Communications, Technologies and Services
AP	Access Point
APC	Access Point Controller
APT	Access Point Transceiver
AT	Access Termination
ATM	Asynchronous Transport Multiplex
BRAN	Broadband Radio Access Network
BWA	Broadband Wireless Access
CATV	CAble TeleVision
CEPT	European Post and Telecommunications Consultative Committee
DVB	Digital Video Broadcast
ETSI	European Telecommunication Standards Institute
FCC	Federal Communication Commission
FDD	Frequency Division Duplex
FTTB	Fibre To The Building
FTTC	Fibre To The Curb
FWA	Fixed Wireless Access
FSAN	Full Service Access Network
GEO	Geostationary Earth Orbit
HDSL	High speed Digital Subscriber Line
HFC	Hybrid Fibre Coax
HIPERACCESS	HIgh PErformance Radio ACCESS network
HIPERLAN	HIgh PErformance Radio Local Area Network
ISDN	Integrated Services Digital Network

IP	Internet Protocol
IWF	InterWorking Function
LEO	Low Earth Orbit
LOS	Line-Of-Sight
MMDS	Multi-channel Multi-point Distribution System
MVDS	Multi-channel Video Distribution System
MPEG	Motion Pictures Expert Group
LMDS	Local Multi-point Distribution System
MWS	Multi-media Wireless System
POTS	Plain Old Telephone Service
PSTN	Public Switched Telephone Network
SME	Small and Medium Enterprise
RLAN	Radio Local Area Network (see WLAN)
RR	Radio Repeater
RT	Radio Termination
TE	Terminal Equipment
TDD	Time Division Duplex
TV	TeleVison
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunication System
VHF	Very High Frequency
WLAN	Wireless Local Area Network
WLL	Wireless Local Loop

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Mobile broadband access

RUNE HARALD RÆKKEN AND STEIN WEGARD SVAET

This article focuses on mobile broadband access networks. Our viewpoint is to look at systems emerging from the mobile communications society, where the vision of wireless communications as the customer's first choice is highly alive. We foresee the transition to personal communications based on tailoring of services, service mobility, user mobility and terminal mobility. The work on third generation mobile communications systems is now in an intense stage, aiming at finalising the first sets of specifications by the end of the century. Our intention is to look beyond the first phase of third generation mobile communications systems, making visible the concept of mobility into multimedia networks.

1 Introduction

1.1 From Morse telegraphy to cellular services

Morse telegraphy between land and ship relying on short wave radio was probably the first useful application of communication to mobile users. Land mobile applications have been present since the 1930s, in the form of closed user groups connected to a base station. Police forces were among the pilot users of such services. Later on, several similar services were launched to the public, like the Norwegian service named OLT (offentlig landmobil tjeneste = public land mobile service) which was made available in the late 1960s and was up and running until the beginning of the 1990s.

During the operation of OLT it soon became evident that this was not well suited for offering mobile communications to the mass market. Capacity problems were envisaged due to limited available radio spectrum. Hence it was regarded advantageous to use a cellular layout of the base stations to allow reuse of the radio frequency spectrum to raise the total system capacity. In the same period, during the 1970s, switchboard operators were removed and calls in the wireline networks were set up automatically. Hence the idea of forming an automatic international mobile network took place in the Nordic Telecommunications Administrations. The basic idea was to make as many as possible of the teleservices offered via the wireline network available to mobile users, and the mobile system should be capable of automatically tracking the users and forwarding calls to them regardless of position within the operation area. This is known as roaming in the mobile society's language. The system should also be able to automatically switch the user's access point from one base station to another during a conversation. This is denoted a handover. Such characteristics of a mobile communications system seem inevitable today, but especially the two last paragraphs were quite revolutionary at the end of the seventies [2].

1.2 First generation cellular

In 1981 the world's first automatic cellular international mobile telephone system was commercially put into operation in Norway, Sweden, Denmark and Finland. The system was named NMT – Nordic Mobile Telephone. The system was analogue and was mainly designed for speech communications. The launch of the NMT system was a great enhancement in making public telephony available outside the wireline network.

The first versions of NMT terminals weighed more than 10 kilos and were mainly manufactured for installation in cars. At the end of the eighties hand portable mobile phones started appearing. Miniaturisation has continued and today true pocket phones are available for the analogue mobile systems.

Characteristics of first generation cellular systems are: analogue transmission, basic speech service, data capabilities not built into systems, limited roaming capabilities.

In addition to NMT there are several other systems belonging to the so-called first generation cellular mobile phones, like the AMPS (Advanced Mobile Phone Services), TACS (Total Access Communication Systems), NETZ-C, MATS-E and others, totally holding some 93 million subscribers world-wide [3].

1.3 Next step – digital cellular

During the 1980s standardisation work was going on to design a harmonised mobile communications system for use throughout Western Europe. Reservation of a common frequency band throughout Western Europe, together with the European Post and Telecommunications Union (CEPT) as a co-ordinator of this work made it possible to set time pressure and national industry policies aside and agree upon a unified standard for mobile communications for use throughout Western Europe. The standardisation work was later on taken over by ETSI, and the resulting system was the well-known GSM.

As for the first generation cellular systems, it was demanded that the system should route calls automatically to a mobile in any position inside the coverage area. The idea this time was that services should be based on services for the digital integrated services network ISDN and allow for encryption of user data over the air interface.

It was also demanded that it should be possible to have several GSM systems in one country, making mobile communications the first area of telecommunications exposed to full competition.

Characteristics of second generation systems are digital transmission, basic speech service, supplementary services, limited data capabilities and continental roaming. GSM has later on spread to different parts of the world, hence living up to its name Global System for Mobile Communications. There are by February 1999 some 140 mill. GSM users worldwide. GSM and its sister systems D-AMPS in USA and PDC (Personal Digital Cellular) in Japan are digital by nature and hence more suited for data communications than the first generation cellular systems. However, for the digital cellular systems operating today the vast majority of the connections made is for speech telephony. Maybe not a big surprise, as only very low data rates are available, eg. 9.6 kbit/s as the highest available data rate for GSM. Besides, the available terminals are not well suited to data communications, and the users are not yet quite familiar with messaging services.

1.4 Improvements of second generation systems

9.6 kbit/s cannot be considered as wideband wireless access. Hence, within the standardisation bodies work is going on to improve the data capabilities within the second generation systems. Figure 1 shows GSM terminals optimised for speech and data services. The first step is the possible introduction of high speed circuit switched data (HSCSD) into GSM. Using four time slots per user and with the new rate of 14.4 kbit/s per timeslot, this may give a user rate of 57.6 kbit/s. Technologically the service is expected to be available in 1999. If and

Figure 1 GSM terminals optimised for both speech and data services

when the operators will introduce HSCSD for GSM is of course dependent on how they consider the market for such a service.

The next step in tailoring GSM to data communications is to introduce packet data services into GSM. The standard called General Packet Radio Service (GPRS) is being specified at the moment. Depending on the number of time slots and the coding scheme used the maximum data rate will be approximately 170 kbit/s, but it is believed that the rate of 115 kbit/s will be more widespread. The introduction of packet data services in GSM will make it necessary to introduce new network nodes into the GSM network. The technology for GPRS is expected to be commercially available in the year 2000. Whether the different operators will choose to introduce GPRS is then dependent on how they consider the market for a cellular packet switched service. It is even possible to enhance the GPRS service. A service named Enhanced Data Rate for GSM Evolution (EDGE) is also being considered for enhancing the data rates for GSM services. The operation of 384 kbit/s packet services using GSM is being considered within the standardisation bodies.

Since none of those services are implemented yet, it is difficult to forecast what the market for GSM-based data services will be. What we know is that there is an emerging market for wireless access to broadband services. Improving terminals and man-machine interfaces will probably be the most important factor to make mobile data take off. We do however see that the terminal manufacturers are quite innovative at the moment, giving a certain pressure on the data capabilities of the mobile networks.

1.5 Trends

Several trends are appearing, which in a serious manner will affect the development of wireless broadband access over the next decades. We will pay attention to some of those trends.

1.5.1 Increased mobility

One trend that has been around since mobile telephony was introduced is heading for increased mobility and ubiquitous access to the wanted services. With the introduction of the S-PCN (Satellite Personal Communications Networks) based on Low Earth Orbit satellites the coverage will be ubiquitous. It is however expected that in the future there will be different coverage areas for the different services, due to the fact that increased data rates give decreased coverage area due to radio propagation mechanisms.

Four types of mobility are being referred to:

- *User mobility:* One access number is connected to a user, regardless of terminal and access network used. One sort of user mobility is SIM card roaming (‘plastic roaming’) within GSM, which can also be used to extend GSM coverage by use of LEO satellite systems;
- *Service mobility:* Uniform access to the same set of services across terminal and access network used;
- *Terminal mobility:* Continuous mobility across locations, relying on radio based mobile terminals that also give the possibility of changing access point during conversation;
- *Session mobility:* During a communication session the user can move between terminals and access networks. One example is a person being alerted on his radio pager that someone wants a video conference with her. Then the user has the possibility of transferring the session to a terminal and access network offering the requested services.

1.5.2 Demand for higher bandwidth

Telecommunications is no longer restricted to person to person voice calls. Users also require access to information services, messaging, teleconferencing, collaborative working, databases, Intranet access, WWW, etc. This has led to an ever-increasing demand for bandwidth, and the trend will continue. Data applications tend to become more and more bandwidth consuming, and multimedia information and communications technologies will be more and more integrated into business processes rather than just used as a support tool.

Traditionally, the available bandwidths have been higher in the fixed networks than in the mobile ones, due to the fact that radio spectrum is a very limited resource. However, when people get used to access services from the fixed network they also want access to the same set of services using mobile terminals. This leads to the demand for higher bandwidths also within mobile communications.

1.5.3 Fixed and Mobile Convergence

Fixed and Mobile Convergence (FMC) has been a buzzword for some time. FMC can be the bundling of mobile and fixed services done by the service provider, or even in the simplest case issuing one bill for mobile and fixed subscriptions. For the user, this will lead to obvious benefits such as single point of contact and access to the wanted set of services independent of terminal and access network, offering communications based on personal addressing. The service provider's possibilities of bundling services is, however, dependent on the regulatory situation.

FMC at a service level, as described above, can be implemented in several ways, ranging from use of interworking functions within the network to full integration based on one common service platform, transport network and switching/routing platform. FMC at the infrastructure level implies the latter option, ie. integration of platforms and networks. Obviously, the integration will ease the provision of FMC services. However, the optimum degree of integration must always be subject to attention based on benefit for the customer and cost and revenue for the network operators. Also Mobile IPv6 provides for enhanced mobility suitable for mobility handling within or across access networks. Internet technology is a very promising candidate for core and access network technology in future mobility systems, possibly paving the way for true implementation of Fixed and Mobile Convergence.

1.5.4 Multimedia access

Users are more commonly requesting a variety of services requesting different service qualities. Examples of such services are:

- 7 kHz audio (AM quality);
- 20 kHz audio (CD quality);
- video telephony;
- video conferencing (128 – 768 kbit/s);
- messaging services;
- telefax group 4;
- data base access;
- broadcasting services.

These services become available to mobile users, either by designing systems for higher bit rates or by accommodating for protocols to tailor the services to the bit rates being offered by the different radio systems. One consequence of multimedia services is also that the demanded bandwidth might be different in the different directions, giving asymmetric links. This is typically the case when there is a need for a wideband information transfer channel in one direction and a narrow channel for control information in the opposite direction.

1.5.5 Internet based services to thin clients

The design of advanced data applications based on Internet Web technology in mobile environments has recently started. Traditionally, Internet technology has been designed for powerful PCs. To fulfil the demand for mobility without limiting the communication capabilities, future application platforms must handle communication platforms with lower transmission capabilities, using less powerful terminals like smartphones, microbrowsers, PDAs (Personal Digital Assistants), palm top computers, etc. Within year 2000 the prognosis is 22 million users world-wide using other types of terminals than PCs to access the Web [4]. WAP Forum's aim is to standardise a protocol for wireless Web access. WAP Forum has through the published Wireless Application Protocol (WAP) specification identified a set of protocols and programming languages which will allow further development of mobile phones into microbrowsers. Figure 2 shows a WAP terminal. The idea is to offer wireless applications using Web browsers utilising protocols filtering and adapting the information from the Web server to a format suited for the thin client (mobile terminal).

Figure 2 WAP terminal

The introduction of the WAP is based on the assumption that there is a demand for Internet access from portable terminals and has paved the way for making a variety of terminals, including the mass-market handsets then becoming true information appliances.

1.5.6 The telecommunication terminal as a module in a multifunctional device

Bringing the cellular phone and the electronic personal organiser more or less wherever one goes is quite usual among people today. Products containing both an organiser and a mobile phone in one package are already on the market. As electronic commerce is becoming more and more widespread the next step of integration could be that also the wallet turns electronic and becomes a part of a communicating enhanced PDA. Keys and physical access control could also be made electronic and integrated in a multifunctional device. Figure 3 shows two-slot terminals which give space for both the SIM card and a credit card. These are already on the market. There is a trend for telecommunication companies entering banking and banks entering telecommunications, hence diminishing the borders between the different players.

A development in the direction of integrating what people usually carry in their pockets into one electronic device will

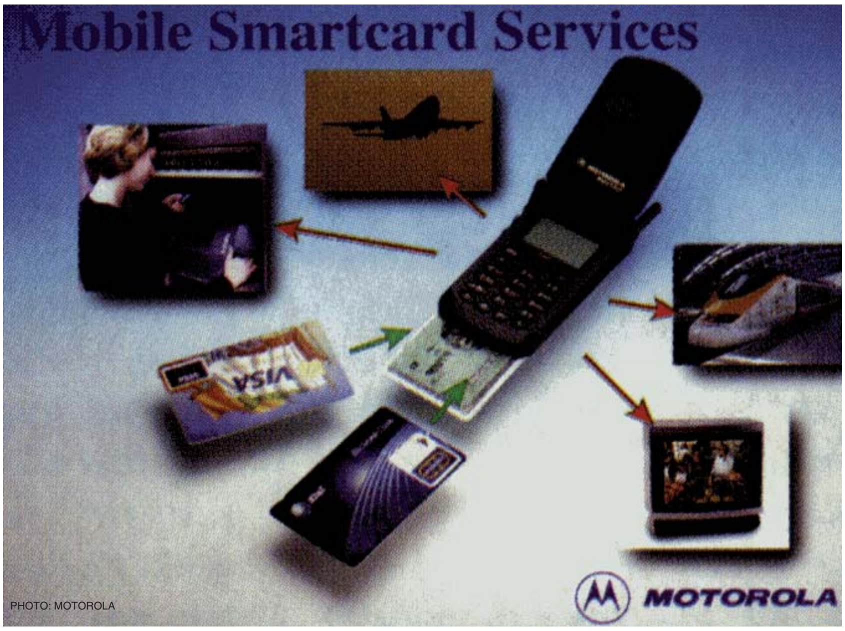


Figure 3 Two-slot terminals giving space for both the SIM card and a credit card

depend on the level of security that can be obtained. Satisfactory security solutions to prevent fraud, eavesdropping or unauthorised use are essential. Also, acceptable ways of handling lost or stolen devices have to be found.

1.5.7 Smart antennas

Personal and mobile communications systems have experienced an overwhelming increase in the number of users in recent years. With an increasing number of users and also additional services like enhanced data services being introduced there is a growing need for capacity. Increased spectrum efficiency is one way of meeting the growing need for capacity in cellular systems. Traditional base station antennas are omnidirectional or sectored, resulting in a 'waste' of power because most of it will be transmitted in other directions than towards the desired user. In addition, the power radiated in other directions will be experienced as interference by the rest of the users. One very promising technique for increasing spectrum efficiency is the use of the *smart* or *adaptive antennas* [5]. This technique adds a new way of separating users on one base station, namely by space, introducing the concept of SDMA – Space Division Multiple Access. By directing the antenna beam towards the communication partner only, more users can be assigned to the same base station. An additional capacity gain is achieved by reduced interference levels, making smaller frequency reuse distances possible. Hence, smart antennas can increase both capacity and QoS in wireless broadband access networks.

1.5.8 Things that think and link

There is a tendency to include 'intelligence' in all kinds of electric and electronic devices. For instance there could be a communication device in the coffee machine, so that it could be remotely controlled via the Internet. Other applications are toys that have communication capabilities enabling them to 'educate' each other, like the Furby dolls that can be trained as well as share their 'knowledge' with other Furbys [6]. Hence, there will be communications needs not only connection people, but increasingly there will also be communications needs between electronic equipment, maybe not even including the user in the communications. There are several candidates for such kinds of communications. Two of the best known are the initiatives BlueTooth [7] and HomeRF.

2 Overview over system concepts for wireless broadband access

2.1 Emerging concepts

2.1.1 UMTS and IMT-2000

As early as 1985, the CCIR Interim Working Party 8/13 (IWP 8/13) was established to study a third generation system concept known as FPLMTS (Future Public Land Mobile Telecommunications System). This working group is now known as ITU-R task Group 8/1, and the system concept has changed its name to IMT-2000. The concept is the near term realisation of the ITU vision of global wireless access in the 21st century, including mobile and fixed access.

At the end of the 1980s the European Commission boosted the research activities in the area of mobile broadband systems through the RACE programme (Research into Advanced Communications for Europe). The term UMTS was in fact introduced by the RACE Mobile project [1]. Later on, these research activities have been continued within the ACTS programme (Advanced Communications Technologies and Services).

ETSI followed the ITU in 1991 with the formation of a Sub Technical Committee called Special Mobile Group 5 (SMG 5) responsible for the standardisation of a third generation mobile system called Universal Mobile Telecommunications System (UMTS). Although being developed by ETSI up to now, the UMTS development has enjoyed the support not only from Europe. The development of UMTS has therefore now become more global, under the responsibility of 3 GPP (Third Generation Partnership Project), which is a global organisation.

A general feature that is common for IMT-2000 and UMTS is modularity, in the sense that access networks are clearly separated from core networks at specified interfaces. The standards will open for a many-to-many relation between access and core networks. This concept is motivated by the need for different access networks in different environments (eg. satellite, wide-area cellular, cordless or fixed) and different core networks. The concept also invites to competition between different standards and implementations. Within ITU, this concept is referred to as the IMT-2000 Family of

Systems. The current understanding is that network segments of UMTS (eg. access networks) may become members of the IMT-2000 family. The modularity principle is illustrated in Figure 4.

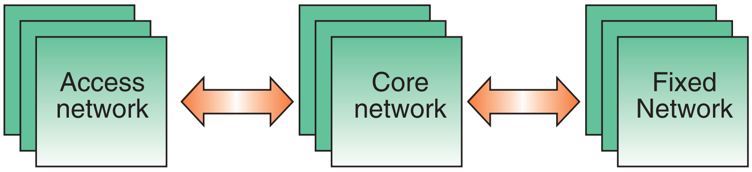


Figure 4 Modularity principle of third generation mobile communications systems

The access network functionality is mainly concerned with radio transmission and radio resource management including functions for local mobility. The core network functionality is concerned with the functions for control of the calls or transactions, the subscriber data, global mobility and provision of mobile specific services. The fixed network may be of any relevant type, eg. (B)ISDN or a Public Data Network as for instance Internet. It should be noted that the separation of the mobile communications system into an access network and a core network may lead to terminology confusion, since in a general context the sum of the two may be referred to as an access component to the fixed network.

The first implementations of third generation systems concentrate first of all on the cellular application, where a cellular access network component in the 2 GHz band is developed. The allocation of 230 GHz in the 2 GHz band was endorsed by WARC 92, and is one of the important early results of third generation standardisation. There is, however, a notable difference in emphasis on the applications for IMT-2000 and UMTS. Whereas UMTS in the first phase focuses solely on the cellular application, possibly enhanced with indoor or campus applications, the IMT-2000 also includes wireless local loop application and the satellite access component. This is probably due to the stronger influence within the ITU from countries with less developed telecommunications infrastructure. The wireless local loop application is a viable solution for rapid deployment of fixed telecommunications, particularly applicable in developing countries, where the market is believed to be at least as large as the market for mobile communications.

There is also a difference between UMTS and IMT-2000 with regard to the relation to GSM. UMTS is tightly linked to GSM. The first phase of standards will be based on the same type of fixed infrastructure, so UMTS may be seen as an evolution of GSM. This tight linkage is of course due to the fact that UMTS has come about from a European initiative supported by GSM operators and manufacturers. For IMT-2000, a tight link to one second generation standard is neither technically nor politically feasible since there are several competing second generation standards world-wide.

2.1.2 Broadband Radio Access Networks

Broadband systems for local radio based access may be classified into two categories, namely

- Systems providing LAN functionality;
- Systems providing fixed radio connections to customer premises.

In the R-LAN category, the main functionality is to provide communication between portable computing devices and broadband core networks, giving telecommunications access and being capable of supporting multimedia applications in the future. Local user mobility within the service area is supported. The RLL category focuses on replacing the wireline to the customer premises, and has its strengths compared to the wired access in that it allows rapid and flexible deployment. The systems are intended to be able to compete with and complement other broadband wired access systems including xDSL and cable modems.

ETSI BRAN (Broadband Radio Access Network) is developing specifications for a family of broadband wireless access systems that support various applications. The BRAN Family members are:

- HIPERLAN/2 (HIgh PErformance Radio Local Access Network), which provides local access with controlled QoS to broadband applications and services as well as to telecommunications services, eg. Internet and video conferencing. The services are accessed through wireless terminals, including portable computers, using unlicensed radio spectrum in the 5 GHz band.
- HIPERACCESS (HIgh PErformance Radio ACCESS network), which provides remote radio access to broadband applications, supporting a range of data communications services. The radio spectrum for this application comes from almost anywhere in the 2 GHz to 60 GHz region.
- HIPERLINK (HIgh PErformance Radio network LINK), which is a network-to-network radio interconnect which will support ATM and possibly other protocols.

Each of the above BRAN Family members will support ATM transport and signalling protocols. Support for other protocols, eg. Internet Protocol, is not precluded.

2.2 Characteristics of emerging concepts

2.2.1 UMTS

Easy to use and customisable services together with prices competitive with fixed access are the key success factors to UMTS. Similarly, there will be a need for a wide range of terminals which are affordable to the mass market and which still support the advanced capabilities of UMTS. Figure 5 depicts a possible UMTS terminal. The majority of the surface of the terminal is allocated to the display rather than the keyboard. This reveals the emerging idea that in the future data services will be of increased importance to the user.

Market studies show that speech will remain the dominant service up to year 2005 for existing fixed and mobile telephone networks, including GSM [8]. Hence, the main motivation for users to move from second generation cellular to UMTS will at the first stage be demanding advanced data and information services. Long term forecasts for UMTS shows a strongly growing multimedia subscriber base. The potential to support 2 Mbit/s data sets UMTS clearly above second generation mobile systems. In addition, the inherent Internet Protocol (IP) support of UMTS is a powerful combination to deliver interactive multimedia services as well as other new wideband applications such as video telephony and video conferencing. It is also considered if UMTS should be improved by allowing BRAN type of access networks to increase the available data rates in certain environments. UMTS is also being designed to provide both connection-less and connection-oriented data services with data rate on demand, depending on the user's needs and the current status of the network. Hence it is possible to put up a table on what the introduction of UMTS means to the user (Table 1).

UMTS offers the user a consistent set of services even when she roams from her home network to other UMTS operators – a Virtual Home Environment (VHE). VHE will ensure the delivery of the same service profile independent of the user's location or mode of access (satellite or terrestrial). The ultimate goal is full mobility into multimedia networks, and that the different underlying technologies should be invisible to the user. In the future there will be a mixture of access networks giving the user access to her information. Some of the access networks will give access to services via a public network operator; other networks will be made available eg. within campus areas. Figure 6 shows a reference configuration for UMTS phases 1 and 2. In later stages of UMTS there will be a possibility of accessing the UMTS services via a multitude of access networks.

2.3 General architecture and functionality

2.3.1 Architectures

2.3.1.1 UMTS architecture

As previously stated, the UMTS architecture is in line with the modular concept, where access networks and the core network are clearly separated and may evolve rather independently. For the first phase of UMTS, the development of a new access network called UTRAN (UMTS terrestrial radio access network) is the main focus. UTRAN will be connected to a core network of the GSM type, and will probably also be comparable with the American IS-46 core network standard. At the time of implementation, the GSM type core network will consist of a connection-oriented part as known today and a connectionless GPRS part under development. Figure 7 depicts a UMTS architecture. It has also been discussed to include other new access networks in phase 1, and it is likely that access networks of the BRAN type may be added. These access networks are intended for high speed Radio LAN or RLL applications, and are discussed separately. Also shown in Figure 7 is the USRAN (UMTS satellite radio access network). After phase 1 there may be developments of the core networks that are alternatives to the GSM/GPRS infrastructure. This is illustrated in Figure 7.

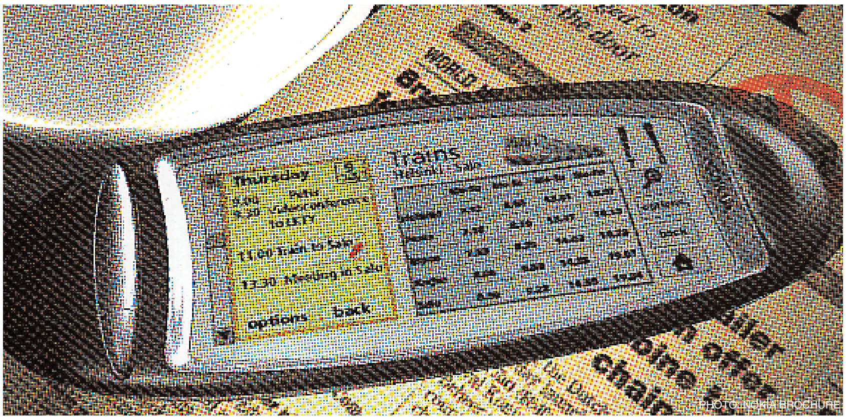


Figure 5 Possible UMTS terminal

Table 1 What UMTS means to the user [8]

Far more than second generation	• basic and advanced services • ever-increasing range of services built around virtual home environments • attractive multi-mode terminals for access to second generation services • future proof for the 21st century
UMTS	• a full third generation global mobile and wireless system • 2 Mbit/s capability in diverse radio environments • highly personalised mass market • new and innovative interactive and multimedia services
UMTS access via ...	• a full member of the IMT2000 family • ITU identified spectrum for both terrestrial and satellite radio • UTRA, a revolutionary air interface optimised for both FDD and TDD spectrum
UMTS networks and services	• build on the footprint of the evolving GSM core network • are compatible with Internet Protocols • support convergence of fixed and mobile services • access via mobile or fixed, public or private networks

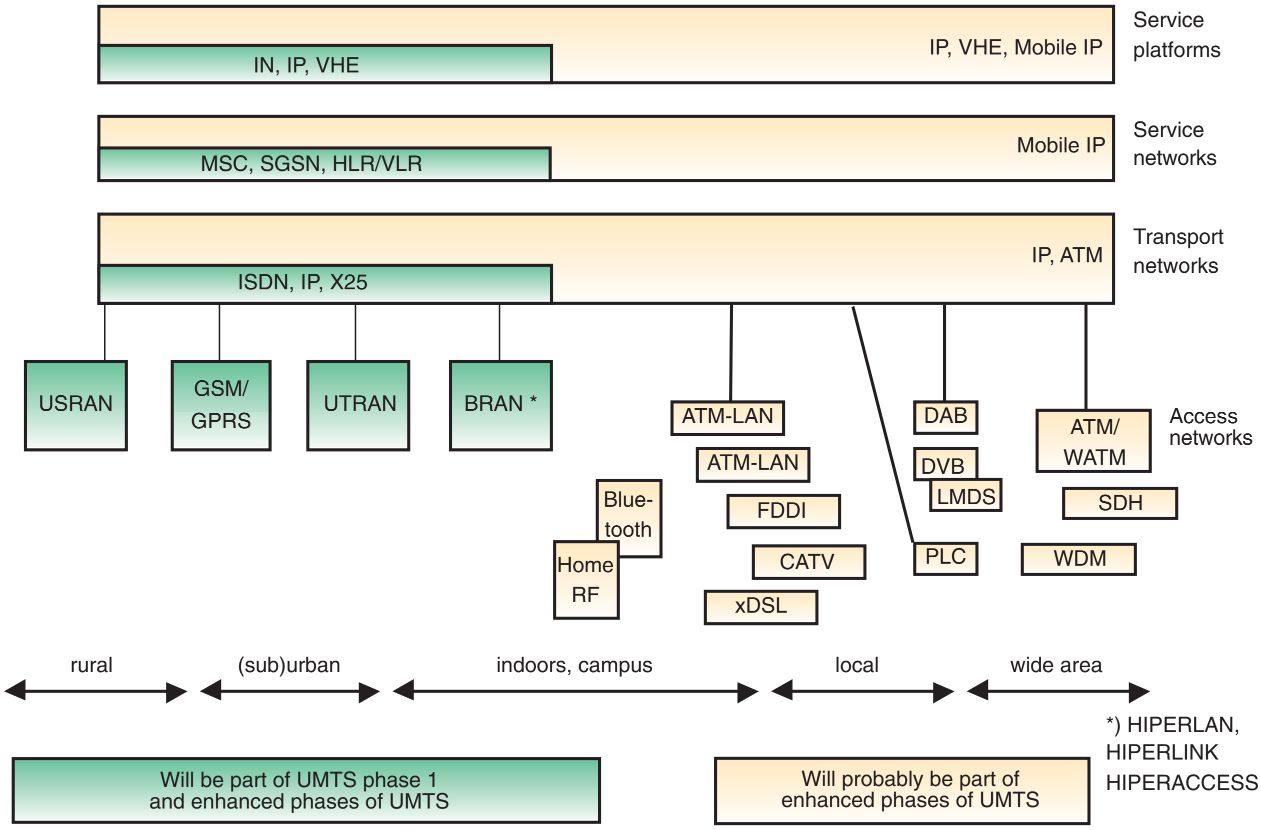


Figure 6 Reference configuration for UMTS phases 1 and 2

Future core network technologies are currently under debate in standardisation, and several options exist. These are based on two main technologies, namely IP technology and ATM technology.

2.3.1.2 Broadband Radio Access Networks

ETSI and ATM Forum are working on a Common Reference Model for broadband radio access networks supporting ATM [9]. Its purpose is to obtain a common understanding of reference models, services, features and interface specifications. The current common reference model is illustrated in Figure 8.

As seen, the WACS (Wireless ATM Access Systems) Node consists of the WACS Terminal and the WACS Terminal Adapter. The WACS Access Point is decomposed into the WACS Access Point Transceiver and Controller. The WACS Access Point is connected to an End-user Mobility Supporting ATM switch, which is the gateway to the external network. The reference point W.1 is the radio interface and contains the functions for transparent ATM transport, support of mobility and security functions. It also contains the UNI protocol with mobility enhancements. The reference point W.2 between the WACS Access Points specifies the signalling related to establishment and release of connections and handover between WACS Access Points. R.1 is a standard interface for connection to external net-

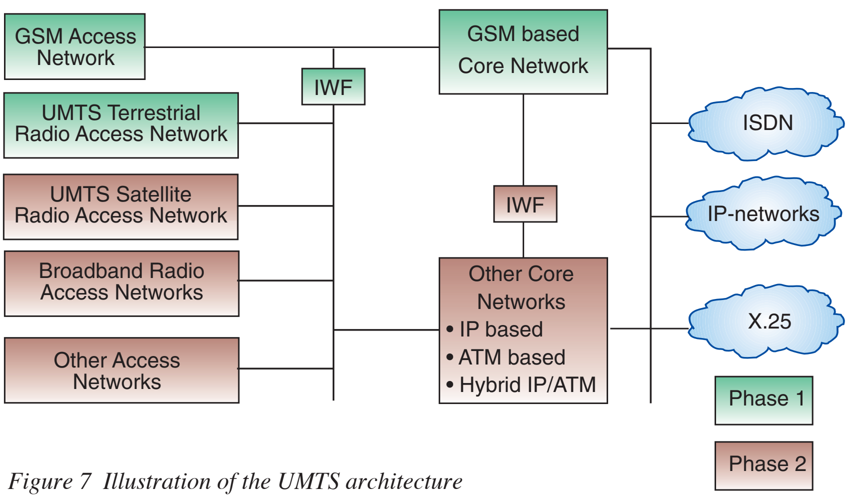


Figure 7 Illustration of the UMTS architecture

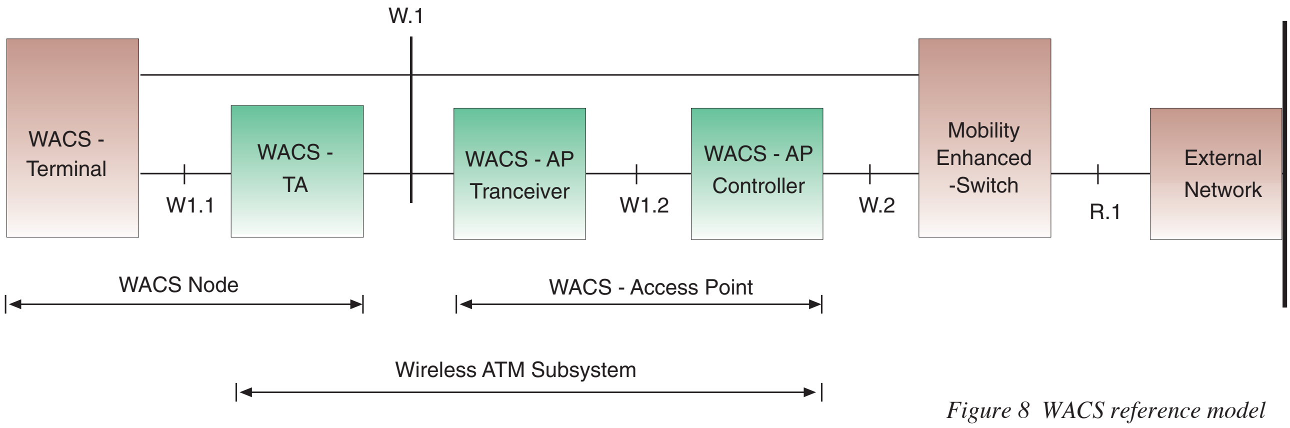


Figure 8 WACS reference model

works, and enhancements to support terminal mobility may be included. Examples of interfaces are (M-)UNI or (M-)NNI. The above reference model is general for all BRAN networks. In case of HIPERACCESS, the interface between the WACS Terminal and the WACS Terminal Adapter may be specified, since it is unlikely that these are integrated in the same equipment. The interface is assumed to be a standard UNI.

2.3.2 Functionality

2.3.2.1 UMTS

The required network functionality for UMTS is under continuous development. The functionality falls into the following categories:

- Radio resource management, necessary for allocation and control of radio communication resources;
- Mobility management, including functions for location registration, paging, functions for supplying routing information, and functions for handover;
- Call-, connection- and bearer control, required to perform the set-up and release of calls. For connection oriented services, the functionality is well developed and described. For connectionless services, necessary functionality for end-to-end control must be specified;
- Interworking with other networks. Interworking with ISDN, B-ISDN, X.25 PDN and IP data traffic will be specified;
- Access, service and security control regulating the access to services and networks;
- Network management, necessary to ease and support tasks such as planning, installation, provisioning, operation, maintenance, administration and customer service.

2.3.2.2 BRAN

The broadband radio access networks provide the following functionality:

- *Call-, connection- and bearer control:* Connection set-up and release in accordance with ATM signalling specifications. Traffic management is performed to control QoS. Device addressing shall be consistent with world-wide roaming.
- *Radio resource management:* Monitoring of the radio conditions, and dynamic allocation of radio link capacity to fulfil the traffic contract.
- *Mobility management:* Local mobility management functionality in case of HIPERLAN. The mobility function of handover is also supported by HIPERACCESS, but is more intended for the purpose of providing better quality of the radio link than providing mobility for the users.

2.4 Frequency spectrum allocated to UMTS

The frequency allocation for UMTS was given by WARC 92, resulting in a 220 MHz allocation in the 2 GHz frequency band. The frequency allocation for UMTS is shown in Figure 9.

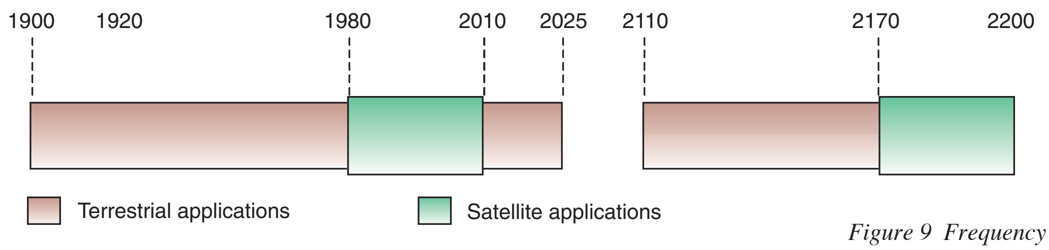


Figure 9 Frequency allocation for UMTS

2.5 Radio interfaces for UMTS

2.5.1 UTRAN

The UMTS radio access system UTRAN (UMTS Terrestrial Radio Access Network) is aimed at supporting operation with high spectral efficiency and service quality in the different environments in which wireless and mobile communications take place. UTRAN will offer both connection oriented and connectionless services to the user. The maximum bit rate offered via UTRAN is 2 Mbit/s, the available bit rate at a given location is however dependent on a number of factors, like,

- The mode of operation, as the core network rate for circuit switched services will be limited to 64 kbit/s, whereas 2 Mbit/s will be available in packet mode;
- The distance between the base station and the user. The cell size will decrease as the data rate increases. This implies that the maximum bit rate of 2 Mbit/s in packet mode will be available only in certain environments.

In practical implementations of UMTS some users may be unable to access the highest data rates at all locations. For example, the physical constraints of radio propagation and the economics of operating a network will mean that the system services might only support lower data rates in remote or heavily congested areas. In the early stages of UMTS deployment, UMTS services will probably predominantly be offered in high traffic locations. To allow users to gain access to their services ‘everywhere’ operators may wish to arrange roaming agreement with second generation operators (for example GSM operators) or UMTS satellite operators to increase the coverage area. Seamless operation and roaming between private and public UMTS networks as well as access to services via fixed and mobile will be possible to support these users. The access scheme chosen for UTRAN is W-CDMA (Wideband Code Division Multiple Access). Hence, the operation of UTRAN will be a bit different from GSM, for example. Characteristic for CDMA systems are that all other users appear as ‘noise’ to the desired user. This means for instance that the coverage area from a base station will decrease as the number of active users within the cell increases.

2.5.2 USRAN

Satellite technology can relatively easily provide global coverage and service. Hence it is expected to play an important role in the extension of UMTS coverage. UMTS is being standardized to ensure that satellite and terrestrial systems are harmonised, ensuring that roaming and handover between satellite and terrestrial networks will be possible. No unique USRAN (UMTS Satellite Radio Access Network) specification exists, and it probably never will. Instead it is reasonable to believe that systems like Iridium, Globalstar and ICO which are already satellite components to GSM through interworking and roaming agreements, also might become satellite components of UMTS. In addition, there are other system concepts that might fit into the UMTS/USRAN concept, like the Inmarsat Horizons concept. Those systems will probably provide speech services and 144 kbit/s to laptop PC type terminals.

2.5.3 BRAN

It is assumed that HIPERACCESS systems are primarily deployed in a ‘licensed’ spectrum. However, this does not specifically preclude their use in a ‘licence-exempt’ spectrum where there may be little or no co-ordination of frequency use.

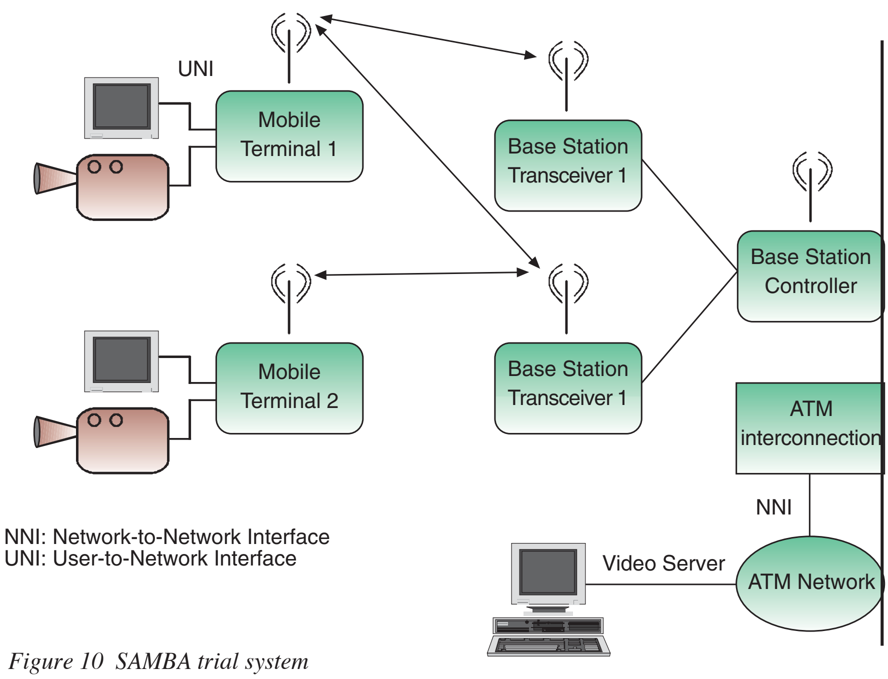


Figure 10 SAMBA trial system

3 Mobile broadband system (MBS)

The MBS (mobile broadband system) concept may be viewed as a cellular system providing very high user bit rates, typically tens of Mbit/s. The fact that the system is cellular is an important distinction from the ETSI BRAN concept, and implies that the radio link and the mobility management functions are designed for high speed terminal mobility. The MBS concept has been studied within research for several years, and pilot systems have been implemented to demonstrate the concept. Due to the high bitrate, the envisaged applications of MBS are many, including for instance video telephony, teleworking, city guidance and TV broadcasts. Of course, more conventional applications as found in R-LAN and cellular systems with lower bit rate are also possible for MBS. The biggest challenge for MBS is to provide the high bit rate radio link with sufficient quality. The system operates at microwave frequencies, where there are available frequency bands around 40 and 60 GHz. In many environments there are unavoidable distortion effects of multipath propagation, due to delay spread on the required broadband signals, and strong Doppler effects and path losses.

As mentioned earlier, the MBS concept has been studied within research bodies. Within the EU research programme RACE, the project R2067 MBS studied the concept and realised a demonstrator at 60 GHz to verify reliable transmission including handover. In the EU research programme ACTS, a follow on project called AC204 SAMBA (System for Advanced Mobile Broadband Applications) has developed the concept further and implemented a trial system operating at 40 GHz. Both the MBS and SAMBA projects have based the system concept on ATM, with a target user bit rate of 155 Mbit/s. For the implemented demonstrators, the user bit rate has been limited to around 30 Mbit/s, however, still high enough to demonstrate HDTV on a cellular system. The trial system implemented in the SAMBA project is shown in Figure 10.

Both the MBS and SAMBA projects have made significant contributions to key issues such as radio link characterisation, antenna design, mobility management functions and development of specialised hardware.

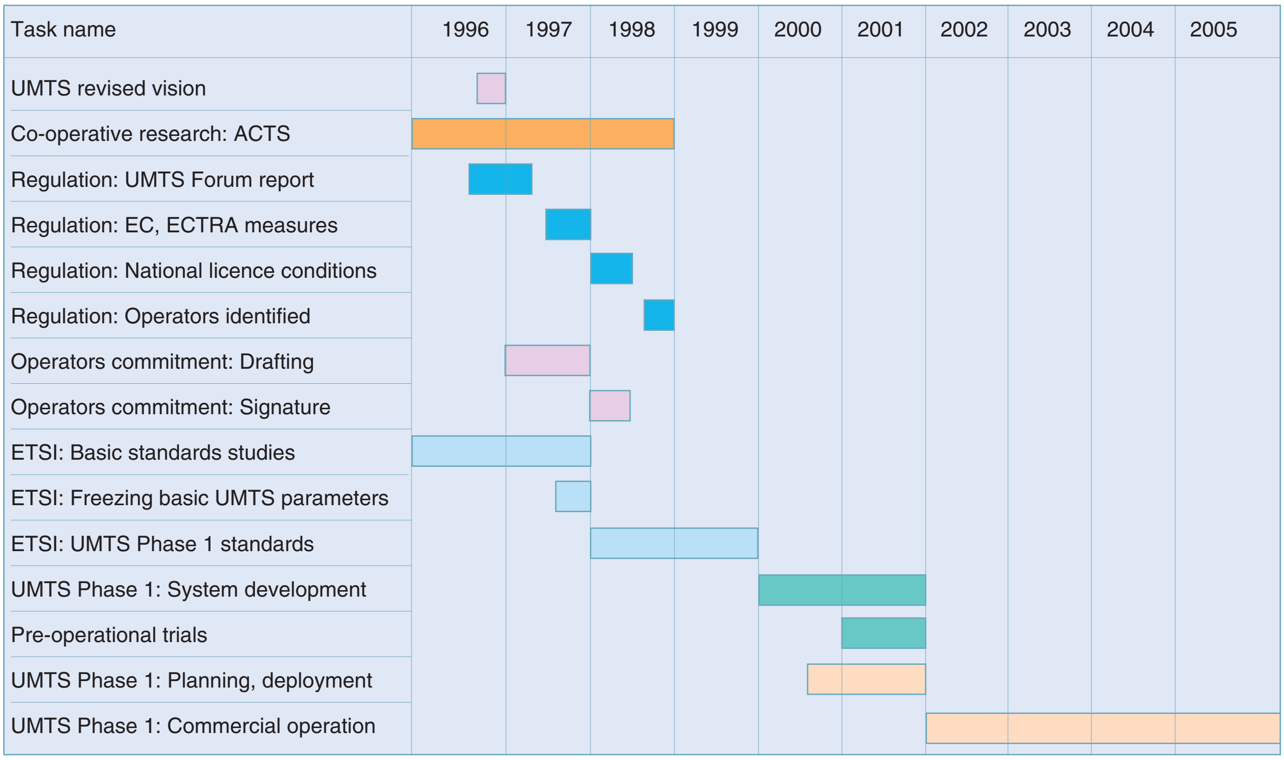
4 The phased approach

The introduction of UMTS will proceed through a number of pre-operational and operational phases taking place over the years 2002 – 2005. The aim of this phased approach is to reduce risk and cost for operators and ensure early adoption of services by end users. A UMTS Phase 1 development schedule as envisaged in [8]. It represents the consensus on the timetable at that time. Backlogs in some tasks are already visible today and may require revision of the schedule.

Many people within the industry believe that an important step along the way will be the widespread deployment of packet radio services being developed for second generation systems, such as GPRS (general packet radio service) for GSM. These systems will give valuable experience for the operators with connectionless systems and could provide a platform for the development of service interworking functions and service provider interfaces as well as a core of mobile multimedia services. This can be done with less initial investment than is necessary for UMTS, where a completely new radio infrastructure and terminals will be needed. Customers can be attracted onto these intermediate networks by the provision of attractive services from new content and service providers. These customers will then be willing to invest in new UMTS terminals on the anticipation of better and more efficient delivery of enhanced services. In turn, this provides the incentive for network operators to invest in UMTS infrastructure in order to satisfy the need for capacity demanded by a successful mobile multimedia mass market.

The current situation is less than optimal, particularly with regard to licensing certainty. The EU Proposal envisages publication of procedures for UMTS licencing in all member countries by 1 January 2000. This represents a significant delay with respect to the schedule originally proposed by the UMTS Forum in [8], while maintaining the commercial deployment phase beginning in 2002. The primary phases of the development of UMTS are:

Table 2 UMTS timeline [8]



- *Extension of GSM's capability* to include packet and high speed data operation, as described above;
- *Pre-UMTS Trial Phase,* during which prototype UMTS base stations will be tried out either in subsets of real GSM networks, or in isolated trial packet-based networks;
- *Basic deployment phase* beginning in 2002, which includes the first incorporation of UTRA base stations into 'live' networks and the launch of satellite-based UMTS services; new services based exclusively on UTRA's capabilities; and support of both narrowband and broadband services over the same UTRA interfaces;
- *Full commercial phase,* beginning shortly after 2002 and approaching fruition in 2005 incorporating enhancements to its performance and capability, and involving the introduction of new, sophisticated UMTS based services.

5 Conclusions

Until now the main cellular service has been speech, even though data services have been present in the operational networks for several years. However, in later years the focus of the mobile society has changed from speech to data services due to the tremendous growth in the demand for information services and Internet access.

The next step will be integration of the different fixed, cellular and Internet services. Mobility functions in both wireless and fixed networks, and flexible service creation and management make the differences between fixed services, cordless telephony and cellular diminish. Introduction of packet switched data into the GSM network, like the General Packet Radio Service (GPRS) is turning the original circuit switched GSM network into a hybrid network.

The standardisation of a third generation cellular system – Universal Mobile Telecommunications System (UMTS) has been going on for several years. In addition, real broadband mobile systems offering bit rates of up to 155 Mbit/s are being developed.

UMTS is aimed at giving access to multimedia applications. It predominantly evolves from GSM, and will interwork with GSM. In the longer term, integration between UMTS and IP networks offering differentiated quality of service will be the next evolutionary step. UMTS may then give global access to multimedia services across platforms like mobile, fixed and satellite-based networks.

Mobility across terminals, locations and infrastructure together with tailoring of high quality services will make the vision of *communicating anytime, with anyone, anywhere* come true. The availability of broadband wireless access will substantially affect the lives of individual citizens as well as the functioning of society.

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Satellite networks and stratospheric platforms

AGNE NORDBOTTEN

This paper presents the network concepts and operational principles of new broadband satellite networks based on GEO and LEO platforms and the stabilised stratospheric platforms proposed for operation from 20 km altitude.

1 Introduction

Satellite systems operated from the geostationary orbit are today used for communication to remote areas (represented by the Arctic island Spitzbergen, ferries, and oil installations in the North Sea), communication to mobile vehicles (land and sea), business type communication (VSAT) and first of all broadcasting, which up to now has been the killer application. Entirely new and improved satellite networks are now under development and introduction. The ongoing development involves a multiplicity of systems, new services, new operator groups, new technological solutions and the use of higher frequency bands to increase available capacity.

A new system group based on the use of stratospheric platforms has many similarities with the satellite systems, but operate in more local areas with a higher capacity per km^2.

The new systems which are expected in operation during the period 2000–2005, represent a total renewal of satellite communication and broadcast and take the full step into the world of multimedia offering possibilities for broadband communication all over the world regardless of previous infrastructure. In this article the focus will be on the potential, possibilities and development trends of the new generation satellite and stratospheric networks.

2 Satellite networks

Satellite systems have some important advantages:

- They offer total coverage and may operate without any terrestrial infrastructure. However, for most new systems interoperability with other networks is a strong requirement;
- They are very cost effective on point-to-multipoint connections and broadcast.

The capacity of these systems is however limited which means that they are not suited for servicing of a high number of individual users per km^2. Within the satellite domain there are now three important areas for broadband and multimedia access under rapid development:

- Broadband multimedia satellites operating from a GEO position. The first ongoing phase of this development is a consequence of the development of more general interactive digital platforms from the digital broadcasting systems already in operation. The second phase includes new systems with on-board processing operating also at higher frequencies.
- High capacity LEO systems for multimedia services under development and production and ready for operation in 2002 – 2003. Teledesic and Skyway typically represent them.
- Satellite systems for UMTS services operated from LEO, MEO and GEO orbits are now being specified and developed in close co-ordination with the ongoing development of terrestrial UMTS with a focus on obtaining world-wide coverage for UMTS.

The present status is that some tests are running on the GEO systems, and services will be gradually offered.

2.1 Broadband multimedia GEO satellites

The next generation GEO systems are follow-up systems of the VSAT and broadcast systems of today. The basis for the rapid development is the success of the satellite broadcast systems in combination with the digitalisation of moving pictures and digital satellite broadcasting made possible through the work of MPEG (Moving Pictures Expert Group) and DVB (Digital Video Broadcasting). The new broadband digital broadcast services now introduced form the background for development of digital interactive services. Digital TV transmission normally operates at bitrates of 4 – 8 Mbit/s. The programs are time division multiplexed into the MPEG-2 transport stream with a capacity of 34 Mbit/s for the bandwidth used for a PAL or D2MAC transmission. The satellite transmits in the frequency band 10.7 – 12.75 GHz. The RF unit at the receiver antenna converts the input to the IF frequency range 950 – 2050 MHz which is the input frequency range of the integrated receiver detector (IRD) commonly called a set top box, which interfaces to the normal TV receiver. The set-up is illustrated in Figure 1. In this way 4 – 8 digital TV channels are transmitted per transponder with a capacity of one analogue TV channel.

Transmission of TV channels is the dominant satellite application today, and it illustrates the strength of satellite transmissions in broadcast and point-to-multipoint applications. The total transmission capacity at K_u-band from a satellite position in the geostationary orbit using QPSK modulation is approximately 5 Gbit/s corresponding to 1,000 digital TV programs. If this capacity is divided among 1 million households in Norway on an individual basis, they would have 5 kbit/s per family on average. With

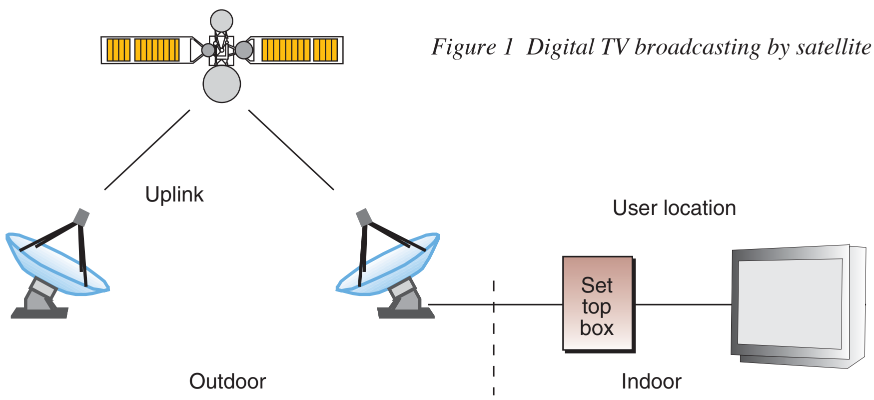

Figure 1 Digital TV broadcasting by satellite

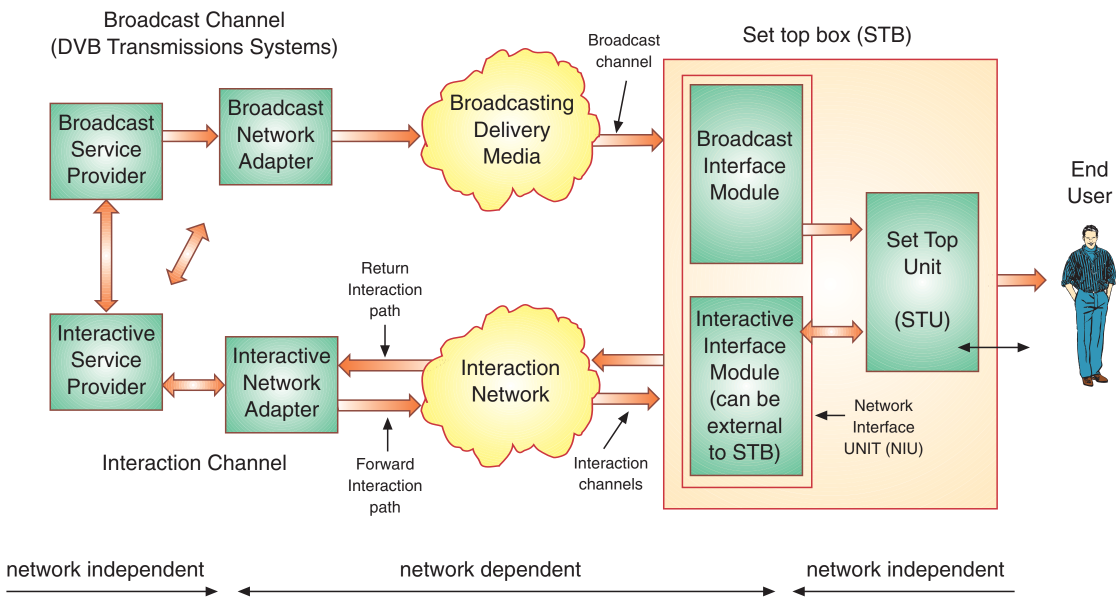

Figure 2 Generic model for a broadcast based interactive system used by DVB and ETSI

100,000 households as users on a 10 % basis the available capacity per household increases to 500 kbit/s on average. This is still low for broadband communication. This example illustrates that the satellite technology has its strength in broadcasting and point-to-multipoint applications. The capacity from a satellite position in the geostationary orbit is increased through the use of higher frequency bands and more efficient modulation methods.

Digital broadcast systems are converted into interactive systems by functionally adding an interactive point-to-point communication channel as illustrated in Figure 2, which shows the generic interactive model adopted by DVB and ETSI.

This model is based on the use of the DVB/MPEG-2 based digital broadcast channel with a capacity of approximately 34 Mbit/s for the down link. The MPEG-2 transport multiplex may contain digital TV or data including ATM or IP type of data transmissions. The satellite delay of 250 ms does represent complications for protocols like TCP, reducing the trans-

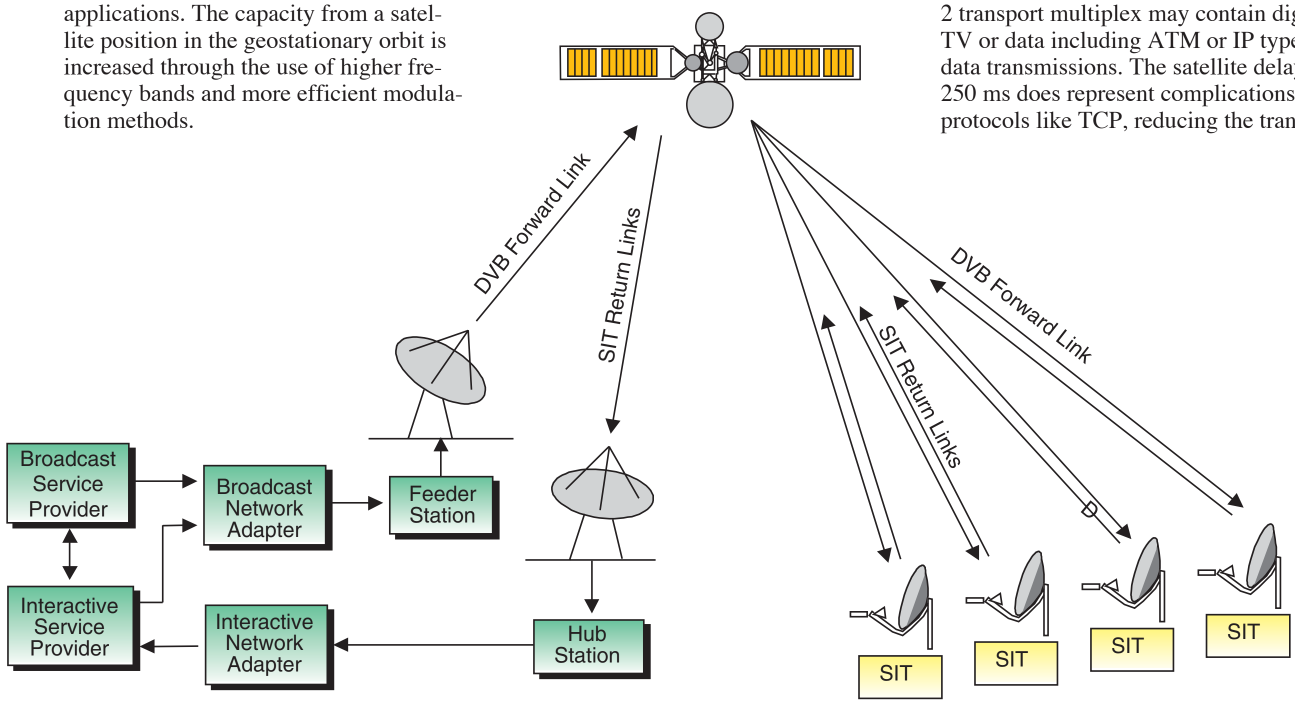

Figure 3 Interactive satellite system

mission capacity to some hundreds of kbit/s if proper precautions are not taken.

The choice of return channel is more flexible, different technologies and capacities may be used. The interactive channel consists of an up link part and a down link part. It is used for signalling and ID purposes, service request and up link information transfer. Today ISDN is commonly used for the return channel.

The preferred solution is return by satellite, and this is now being tested and implemented. A proposal for standardisation has been worked out by a group of European satellite operators co-ordinated through ESA [1]. In the proposed system, which is referred to as a Satellite Interactive Terminal (SIT), the up link is proposed for operation in the frequency band 29.5 – 30.0 GHz. The total interactive system is referred to as a K_a/K_u-band solution. An illustration of the system is shown in Figure 3. This proposal has been taken up by DVB and the finalisation of the standard will hopefully take place in 1999.

The main reason for the combined solution is the more favourable link budget obtainable at K_a-band allowing for 2 Mbit/s with reasonable antenna size. The tentative requirements set for the standardisation work were as listed in Table 1.

The proposed solution is based on ATM for the up link. The access system of the interactive channel is based on MF-TDMA with a high degree of flexibility with regard to up link bitrate. The SIT will operate at bitrates up to 2 Mbit/s with an output power not exceeding 2 W and an antenna diameter less than 1.2 m in diameter. The MF-TDMA multiplex, however, should have a capacity of at least ATM-25, preferably ATM-50.

The first generation of interactive systems will be based on the use of transparent satellite transponders. For the next generation it is expected that on-board processing will be used allowing for direct communication between users in different antenna beam areas. An option for K_u-band return preferred by some operators is included in the specification proposal. This option is preferred for installations with a large number of users (like SMATV). The first generation interactive satellite systems based on transparent transponders will operate in a star network. The first systems will be in operation late 1999 / early 2000. The next generation system with on-board processing will have a mesh capability allowing for direct communication between users.

The down link capacity of the broadcast type GEO platforms focused on in Europe is limited to 34 Mbit/s per transmission beam. Downloading of videos and movies will require much higher capacity, at least 155 Mbit/s. This may lead to development of systems where the TV programs are included in high capacity ATM or IP based transmissions. The new GEO systems proposed by different US companies may move in such directions in particular since they are not TV based. Broadcast or point-to-multipoint operation will however be the efficient mode of operation for satellite networks. The increased storage capacity of PCs used for home servers will favour this development.

Market penetration depends on the cost of user equipment, the number of users sharing the transmission costs and a higher transmission capacity per satellite. It has been estimated that a geostationary gigabit satellite with on-board switching can be realised with a capacity of about 4–5 Gbit/s corresponding to 80,000 64 kbit/s circuits [2]. The transmission cost is highly dependent on the capacity of the satellite. For the high capacity system with a space segment cost of 400 million euro the cost per minute per 64 kbit/s can be less than 0.01 euro which would then also be the cost for a 2 Mbit/s circuit shared by 30 users located in the same down link beam spot.

Table 1 Tentative requirements for standardisation of interactive terminal

Parameter	Value
Antenna diameter	Less than 1.2 m
Output power	Less than 2 W
Modulation	QPSK
Max data capacity	2 Mbit/s
Access system	MF-TDMA

2.2 Broadband LEO satellite systems

Broadband LEO satellite systems are under development and are expected into operation in 2002 – 2005. The high capacity LEO systems are typical multipurpose satellites not dedicated for TV broadcasting. Transmissions may be IP- or ATM based. Their interoperability with terrestrial networks is less complicated than for GEO systems since the time delay over the satellite hop is negligible. While the emphasis for GEO satellites is on modest interactivity, LEO satellite constellations represent more efficient solutions to highly interactive services with a short round trip time over the satellite. The low propagation delay has a strong impact on response times using protocols such as TCP/IP and simplifies interoperability with terrestrial networks. For more local traffic the LEO system can be considered as a RLAN or an integrated radio based part of a terrestrial network.

Table 2 Some characteristic parameters for Skybridge and Teledesic

Parameter	Skybridge	Teledesic
Satellite constellation	2 x 32 LEO	12 x 24 LEO
Total coverage area	± 68°	± 90°
Altitude	1,457 km	1,400 km
Down link frequency (DL)	10.70 – 12.75 GHz	18.9 – 19.3 GHz
Up link frequency (UL)	12 – 18 GHz (part of)	28.6 – 29.1 GHz
Max DL capacity per user	60 Mbit/s	64 Mbit/s
Max UP capacity per user	2 Mbit/s	2 Mbit/s

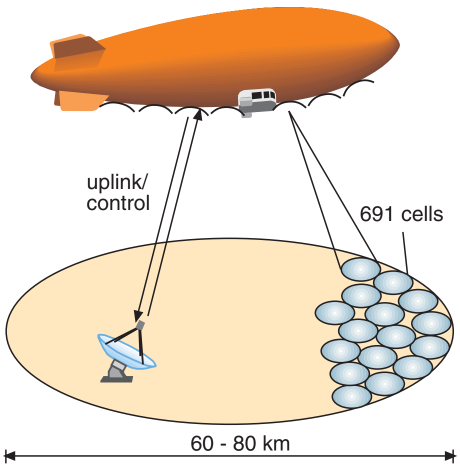

Figure 4 Basic principle for balloon borne multimedia platform

At present satellite Internet access seems to be the market focused on by these systems. Problems associated with handover and line of sight blockage may complicate for the user. Electronically steerable antennas are required and they are not available at an acceptable cost yet. The Teledesic system operated over a 500 MHz band in K_a-band has been considered the most ambitious of these systems. The number of satellites has recently been reduced to 256. The spot beam area of 3,000 km^2 will have a communication capacity of approximately 300 Mbit/s. Frequency resources for operation of new satellite systems is a problem. A European LEO system, Skybridge, planned for operation at the K_u-band frequencies of the GEO satellites, will have to turn off transmissions in the direction of a GEO system to avoid interference. Table 2 gives a comparison between the two systems Skybridge and Teledesic. The parameters are very similar, but Teledesic has a better coverage towards the polar regions.

2.3 Multimedia mobile satellite systems

The strong focus on UMTS also includes mobile satellite systems; S-UMTS. In UMTS, the satellite part of the network has been foreseen to provide mobile multimedia services up to 144 kbit/s. It may be discussed however whether this could be increased to at least 384 kbit/s, possibly 2 Mbit/s. Some standardisation work still remains.

The main types of terminals discussed for S-UMTS are hand-held, vehicular, transportable, fixed and paging receivers. The different terminal types will normally provide a bit rate which is lower than the maximum S-UMTS bit rate typically obtainable using fixed transportable terminals. Standardisation must specify the bit range and services offered by each type of terminal. The portable terminal must be cheap, compact and lightweight with low power consumption. The first generation of this group of terminals is the Iridium terminal. They will exist both as dual mode (multi-mode?) and for satellite use only.

For all terminal types handover terrestrial/satellite and between satellite beams are a requirement. These problems are now being studied in several ACTS projects (SINUS, SUMO, THOMAS) and the main conclusions from these projects will be made available during 1999. Preliminary tests, which are now performed by operators, indicate problems with connections over several minutes using the IRIDIUM, which is in a pre-operational phase of testing, and system evaluation.

The mobile satellite systems under development are mainly of the personal communication type. A system like Inmarsat Horizon will have higher capacity, but is not so far meant to become compliant with the UMTS standard. For services requiring higher capacity than voice / low rate data using hand held terminals, the terminals fall into two categories; portable and mobile. The mobile terminals will be mounted in vehicles and trucks, on-board ships and aeroplanes, while the portable terminal typically represented by a laptop will be personal.

3 Stratospheric platforms

The philosophy of the stratospheric platforms is to find a solution for providing high capacity broadband services, which can be preferable to satellite and radio solutions. Platforms kept in stable positions 16–24 km above the surface of the earth are claimed to represent very attractive possibilities. They will cover an area of approximately 3000 km^2 without line-of-sight problems and thus represent a solution with coverage advantages relative to terrestrial radio based solutions like LMDS. The up- and down link power requirements will be much lower than for a satellite system even when it is operated in a LEO orbit. Table 3 shows a comparison between different radio systems based on spot beam numbers and sizes.

In addition the available frequency range and its reuse potential are important parameters when discussing capacity. In general a system based on small cells with a high reuse potential will have the highest capacity which means LMDS, stratospheric platforms, LEO satellites and GEO satellites as shown in Table 3. This is however a simplification not taking into account the traffic between cells and the amount of broadcast/multicast traffic.

A stratospheric platform may be established in different ways; the proposals, which today seem reasonably close to realisation, are based on the use of stabilised balloons at an altitude of 23 km or aircraft circling at an altitude of 16 – 18 km.

Table 3 Capacity of different radio based systems for broadband distribution

Technology	Spot beam capacity	Spot beam area	Capacity per km^2
Terrestrial LMDS	4 – 6 beams per tower	3 – 15 km^2	500 Mbit/s
GEO satellites	Regional spot	Up to semi-global	Low
LEO satellites	1 spot beam per town	3000 km^2	100 kbit/s
Stratospheric platforms	700 spot beams per platform	5 – 10 km^2	1 Mbit/s

3.1 Balloon borne platforms

A Washington DC based company, Sky Station International, promotes the system consisting of balloon borne platforms [3]. Several European companies are contributing to the system by making both balloons and electronic equipment. The concept is illustrated in Figure 4.

The main data for the balloon borne platform are listed in Table 4.

The platforms will be stabilised and operated using power from solar cells and storage in fuel cells. This requires the platforms to be operated in areas somewhat to the south of the polar circle to produce energy enough from the solar cells. The first platforms are planned for operation over Rome, Lisbon and Singapore in year 2000. The critical issues, which are not too well documented, are the problems of stabilisation and the amount of energy required for keeping the platforms in a stable position. The total communication capacity may be quite large; approximately the same as for a K_u-band satellite position while the cost of the platform is approximately 80 million euro. It may be taken down for repair and there is a possibility for reuse of equipment. Thus the system may represent a success if stable operation is established. This type of system has obtained its own frequency allocation at the WRC 97 conference. The main electrical and operational parameters for the platforms proposed are listed in Table 5.

The data in Table 5 indicate that this is a system which can be used for telephony, Internet access, conferencing and more general data exchange. It seems to be a very flexible system. Since only local areas are covered however, it is strongly dependent on other networks for connections outside the coverage area. The system as presented is not well suited for broadcast or point-to-multipoint delivery. That would involve a large number of antenna beams. Introducing an overlay antenna beam covering the whole area would solve this problem.

Table 4 Some characteristic platform parameters

Parameter	Value
Height of operation	21 – 23 km
Platform length	150 –160 m
Diameter	≅ 50 m
Volume	170,000 m^3
Weight	11,000 kg
Payload	1,000 kg
Coverage area	5,000 km^2 max

Table 5 Electrical parameters for proposed platform payload

Parameter	Value
Allocated frequencies	47.2 – 47.5 and 47.9 – 48.2 GHz
Frequency reuse factor	9
Total capacity	7.68 Gbit/s
Number of beams	691
Covered area per beam	7.3 km^2
Capacity per cell	11.114 Mbit/s
Capacity per household*	3 kbit/s
Number of channels	100,000
Available user rates	64 – 2048 kbit/s
Up link access	MF-TDMA
Down link	TDM

* With 500 households per km^2

3.2 Aircraft based platforms

Another system is based on the use of manned aircraft circulating in orbit above the coverage area at a radius of 3 – 8 km at an altitude of 16 km which is well above the corridors for commercial air traffic [4]. The concept is based on known and proven aircraft technology, but cost effectiveness may become a critical issue. The High Altitude Long Operation (HALO) Aircraft will operate for 8 hours before it is replaced by another aircraft and another crew consisting of two persons. Figure 5 illustrates the principle of operation. It is obvious that the moving platform automatically leads to handover or antenna steering problems.

The system has not been allocated any frequency bands for operation, but it is assumed that it may operate anywhere from 2 GHz up to at least 50 GHz and in particular in the LMDS bands at 30 (US) and 40 GHz (Europe). The name of the company, Angel Technologies, is somewhat ambitious.

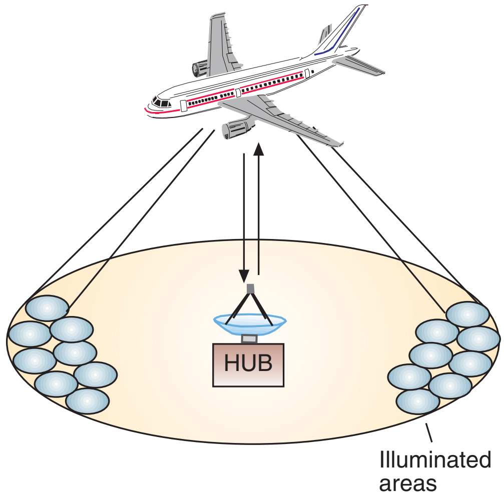

Figure 5 Principle of operation for HALO Network

4 Concluding remarks

The increasing need for efficient broadband access has led to the proposal and development of different types of new access systems. The capacity of the different systems referred to area or population density decreases with increasing cell size, resulting in low individual capacity for satellite systems with semi-global coverage. However, the larger the cell, the better the broadcast ability of a system. The different systems are complementing each other more than competing.

Total coverage globally, as required in UMTS, favours the use of satellite networks for most regions of the world from an area point of view.

The stratospheric platforms are focusing on densely populated areas with insufficient infrastructure for their first generation. With operational success during this introductory phase, they may represent strong competition for terrestrial networks in southern parts of the world. They have also been discussed for use as base stations for high capacity mobile networks.

Several types of interesting and promising types of platforms are now being developed and introduced. Some of them will be winners, other losers. Good business concepts and cost effective user equipment will be important factors. Standardisation of equipment and basic operational principles are definitely required.

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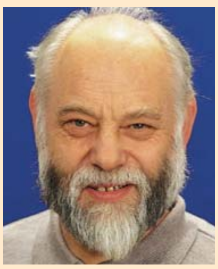

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The passive optical network (PON)

DAVID FAULKNER

This paper presents passive optical network (PON) concepts, architecture options and key components for narrowband PONs and broadband PONs. It traces the history of PONs, relates experiences from field implementations, and examines the future role of PONs.

Introduction

In the early 1980s, the technology for long-haul fibre networks made the transition from multi-mode to single mode. This opened up the possibility of almost unlimited bandwidth. Not only was fibre dispersion low enough now to allow gigabit transmission on one wavelength but also seemingly unlimited bandwidth could be made available by wavelength division multiplexing. At that time, costs were too high to justify extensive use of fibre in the local loop, nevertheless the potential of single mode fibre as a ubiquitous high capacity transmission medium was appreciated. What was needed was a way of reducing the costs so that all users of the local loop could benefit. The approach taken at BT Labs was to maximise resource sharing so that the most significant cost per customer was the customer drop and terminal. Until then the local loop had relied on point-to-point metallic pairs with origins over a century ago. A typical topology for the existing access network is shown in Figure 1 with flexibility points, lengths up to 90 % of the cumulative distribution function of cable lengths, and cable sizes, into which fibre access networks would need to fit.

Loss and bandwidth constraints offered little scope for multiplexing and shared lines had not been popular because of the lack of privacy. Even though the distribution network already exhibits sharing of the cable duct in a physical tree topology, the wiring inside the cable and duct routes is point-to-point. Introducing both a shared access architecture and fibre transmission was going to be a major culture shock for traditional telcos. However, the term 'passive' could be seen as one way of softening the blow since the local loop has always been passive to ease whole-life maintenance costs. Fibre could then be offered as a multi-service delivery system, which avoids problems of electrical surges, EMC and water ingress.

Broadband passive optical networks

Cable TV networks on the other hand have traditionally been broadcast in nature and exploited the greater bandwidth of coaxial cable and line fed amplifiers to enable a very high degree of resource sharing. If the same architectural approach could be applied to fibre then the potential for the loop would be enormous, at least for broadcast services.

Work was focused on the design of single-mode star couplers as a step forward from those developed for multi-mode LANs, which tended to suffer loss variability due to mode selectivity. Much of the credit for this pioneering work on single mode couplers goes to my colleague Dave Payne and his team [1, 2]. His idea was to use WDM as a means of gaining independence of transmission format from one channel to another and to use WDM to enable other logical topologies to be set up over the network by wavelength routing. It was therefore necessary to produce some experimental HDWDM components to maximise the number of channels available.

My approach was to investigate a somewhat less ambitious solution by maximising the use of digital transmission and TDM, which was already successful for core transmission but had yet to gain acceptance for TV or telephony applications. This called for less innovative optical component technology except for the passive power divider. Our first experiment in 1986 was the demonstration of cable TV with 8 channels of 140 Mbit/s TV, which led to a multiplex line rate of 1100 Mbit/s [3, 4]. This was fed through a 64-way power divider to the receivers.

Telecommunications over a passive optical network

This and other experiments led to more interest in the technology and it was Keith Oakley of BT Network Strategy who set the challenge of building an experimental telephony system. None of us thought that we would achieve a cost-effective solution for single lines but maybe for multiple line services, ISDN and cable TV the technology could prove itself.

Our first experimental telephony system over a passive optical network was carried out with existing primary multiplexers (PMUXs), which were intended for point-to-point transmission as shown in Figure 2 [5]. Whilst the downstream multiplex of 30 telephony channels could be broadcast easily over a PON even with the standard ternary (HDB3) line code, a certain amount of reverse engineering was needed to enable point-to-multi-point transmission in the upstream direction. The problems were to

- prevent signals from separate upstream channels from overlapping with each other;
- ensure channels arriving at the head-end demultiplexer were in separate byte-wide time slots.

HDB3 encoded signals from separate PMUXs would interfere. It was therefore necessary first to revert to un-encoded binary transmission on the passive optical network by picking off individual NRZ telephony channels from the back plane to drive the laser at the customer-end. These channels were found conveniently in separate time slots of one byte duration with 2.048 Mbit/s line rate.

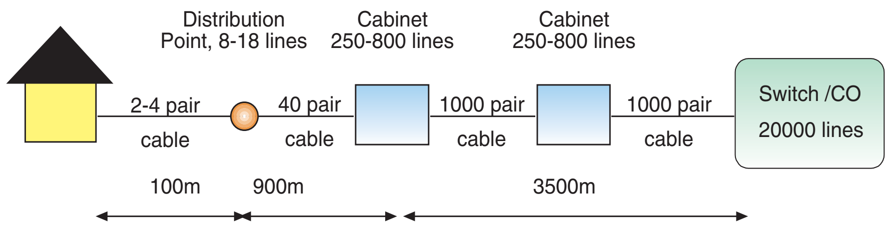

Figure 1 Layout of a typical service area

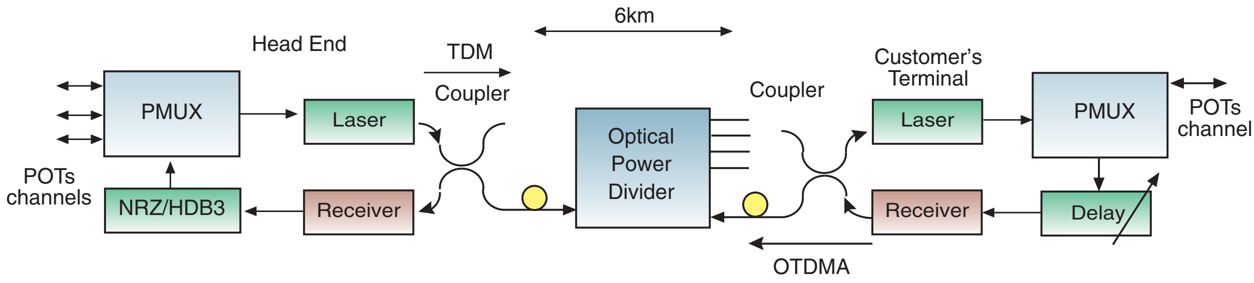

Figure 2 Experimental system using PMUXs

Secondly, since the round trip delay was not compensated for at this experimental stage, a variable delay line was needed to enable bytes to be delayed at the customer ends. This is explained below. A simple bit-stepping circuit was used to move the bytes into a valid time slot in the multiplex as seen at the output of the head-end receiver. A further expediency was the use of a NRZ to HDB3 encoder after the head-end receiver to ensure that the input signal appeared normal to the head-end primary multiplexer. Using this arrangement a number of two-way calls over the passive optical network were demonstrated.

Following this demonstration, ambitious plans were put into place to purpose-build a telephony system and it was at this time that the acronym TPON was coined to describe telecommunications over a passive optical network. The new system would have an automatic ranging system, 256 bi-directional telephony channels, sufficient power budget for 128 way splitting and would be implemented in CMOS technology to save power [6]. This system was designed and built under the supervision of John Balance who was responsible later for the first ATM over a passive optical network (APON) system running at 155 Mbit/s [7].

Outline of TPON ranging and pulse amplitude control

The need for an automatic ranging system is illustrated in Figure 3, which shows a typical TPON system with byte interleaving. Nearer customers will receive the downstream multiplex earlier than more distant ones. In the TPON specification a range of 0.1 – 10 km was specified. In the diagram the difference in round trip delay between farthest and nearest customers is $2(T_{max} - T_{min})$. If the same time slots are to be used for both upstream and downstream channels, this delay needs to be added to the variable delay line in each customer terminal to build out artificially the round trip delay so that the upstream data arrives in its correct time slot. A description of the automatic ranging system used to measure and compensate for the round trip delay is given in [6].

The diagram illustrates the optical time division multiplex in the upstream direction as having channel number 3 inactive. Hence in NRZ form, the head-end receiver detects zeros in this time slot. The absence of an upstream line-code and the variability of upstream pulse amplitudes

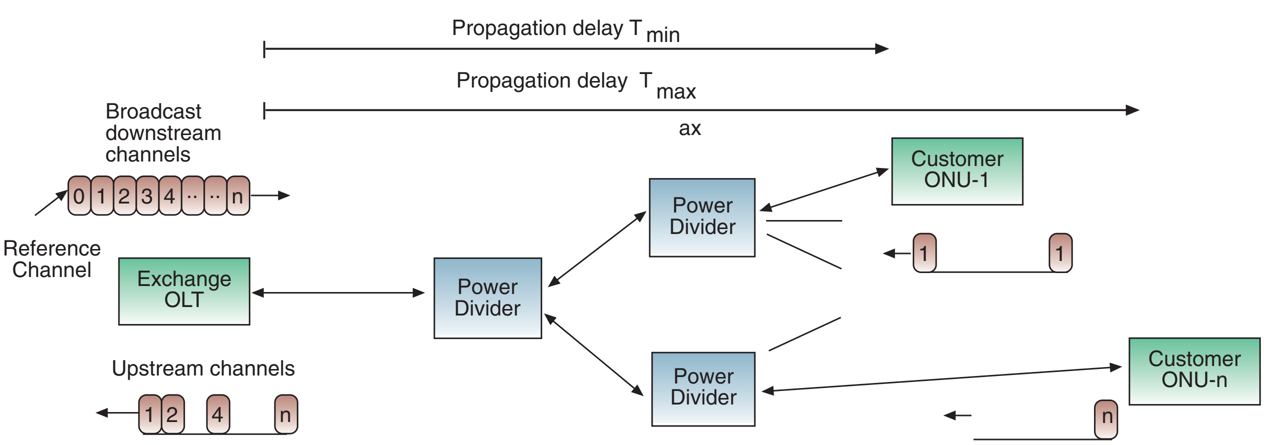

Figure 3 Diagram showing the need for ranging

according to distance put special constraints on the design of the head-end receiver. The receiver design chosen used a zero voltage restoration circuit and referenced the binary decision threshold from this. In the system design, provision was also made to control the amplitude of the upstream pulses by remote control from the head-end receiver, which also included 'too high' and 'too low' thresholds.

Technology for FITL

Single mode fibre is preferred over multi-mode because it has lower dispersion and is therefore capable of higher bit rates for a given reach. The lowest dispersion on G652 fibre is in the 1300 nm band. Although the need for low dispersion in the access network is not paramount, the need for minimum cost is. By choosing an initial operating wavelength of 1300 nm costs of fibre and lasers were minimised. Products were easier to make and more plentiful at this wavelength. A step index profile with 8 μm core and 125 μm cladding characterises single mode fibre. A broad emission bandwidth was chosen to suit simpler, and hence cheaper, buried heterostructure lasers. An emission band between 1285 – 1330 nm, 1 mW power output is specified in ITU-T Recommendation G981. Transmitters such as light emitting diodes as used for point-to-point access networks could be even cheaper but do not launch sufficient power into single mode fibre to allow power dividers to be used with adequate margin and dynamic range.

Receivers for fibre in the loop have been specified with less than state-of-the-art sensitivity to allow low cost technologies such as PIN-bipolar to be used although most suppliers have opted for PIN-FET which can achieve higher sensitivity. The large power budget available (40 dB or more) on optical systems operating at bit rates of 155 Mbit/s or less can easily make the short reach from the central office with sufficient budget to allow power distribution to a large number of customers.

Single mode optical power dividers are available from two family types: fused bi-conical taper and monolithic. A simple two-by-two port fused bi-conical taper coupler has the same functionality as an electrical reflectometer, hybrid transformer or return loss bridge in electrical transmission systems. The device is fabricated from two or more fibres [1].

During construction the aim is to bring the cores into proximity so that the fields interact. A furnace with a pulling and twisting rig is used in the fabrication. Upon stretching, the fibre cores come close together and the evanescent fields begin to couple. At a certain distance, power transmitted into port 1 or 2 appears at ports 3 and 4, split by 50 %. Further pulling causes total cross coupling at certain wavelengths. The component then forms the basis of a wavelength division multiplexer. Advantages of this technology are ease of jointing to transmission fibre and low excess loss (less than 1/2 dB). A disadvantage is the tendency for the power ratio to be wavelength dependent.

Monolithic Power Dividers have waveguides formed on the surface of a glass substrate by ion deposition using fabrication methods similar to silicon integrated circuits. Using this technology 1 by *n* devices can be fabricated (depending upon substrate length). These devices exhibit good wavelength flatness and triple window operation. Reliable fibre jointing, polarization sensitivity and high excess loss have been the chief drawbacks.

The power budget available in a typical fibre system is 40 dB. Access networks are typically up to 5 km long and fibre exhibits an installed loss of around 5 dB over this distance. Allowing for 5 dB transmission margin, there is around 30 dB power budget available in the access network for passive power division.

Experiences with TPON

The first experimental TPON systems showed that it was relatively straightforward to design and build narrowband PONs and produce the necessary optics and electro-optics for the local loop. The field trial and subsequent use of TPON in quantities of approaching 40,000 lines has also shown no technical problems. The key benefit found in practice has been the ability of the PON to act as a single multi-service access network offering flexible service delivery of POTS, as well as basic and primary rate ISDN. Both public and private circuits can be delivered. Prior to this, separate solutions existed for different services.

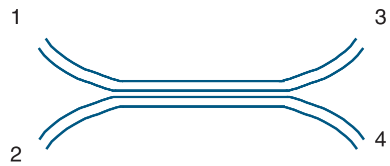

Figure 4 Fused bi-conical taper showing ports and core interaction region

A further benefit has been the ability of the PON to survive adverse weather conditions, such as water ingress and lightning damage, at times when the metallic network is returning a higher than normal fault rate.

Although PONs have proved themselves technically in the field and user reports on TPON have been favourable, some practical issues remain which have limited their widespread use:

- The cost of civil works and technology restricts their use except in new-build situations where a number of narrow band channels are required such as might be found in new business parks.
- Services requiring 2 Mbit/s can often be met with HDSL, which is a more recent technology not available at the time TPON was developed. TPON is more suitable if the distance to be covered exceeds the range of HDSL.
- Demand for broadband services often comes from isolated businesses on a piecemeal basis. This demand is more obviously met with point-to-point systems. The PON architecture is point-to-multipoint.
- Although TPON can carry 8 primary multiplexes if used as a point-to-point system, PDH or SDH technology is usually chosen, probably because the management systems match that being used with existing core and private networks. This may change with FSAN APONs [8], which will enable greater capacity to be delivered more flexibly than TPON or SDH.
- Some customers need alternative access paths. SDH has already solved this problem using dual self-healing rings and two alternative paths. Although expensive, it works. The parenting of customer units on two

head-ends is possible with PONs via alternative routes. This adds to the overall complexity of planning a PON system, which then becomes multi-point-to-multi-point.

- Systems now require more capacity than TPON offers.

APON trials and deployment

The APON system is similar to a TPON system from an optical transmission viewpoint. It has the same power budget but runs at 155 Mbit/s. The system is designed to transmit ATM packets which are 53 bytes long bi-directionally to allow broadcast interactive broadband services. These may be variable bit-rate or constant bit-rate within the constraints of the system capacity.

BT ran a successful trial of interactive TV to 2000 homes in and around Colchester using either ADSL links or 155 Mbit/s APON technology. Video and audio signals were digitally encoded and compressed prior to storage on 6 very large multiple access disk drives. Customers used a remote control hand set to navigate around the menus appearing on their TV set. The trial offered a range of education, communications, information, entertainment, home shopping and banking services and has enabled BT to learn about both the potential market for interactive TV services and the ability of the network to support these services.

The trial enabled marketing information to be obtained through the billing of a variety of services. Video on demand did not provide sufficient revenue alone to justify the costs but other services included in the trial such as: tele-shopping, education and other on-line services coupled with fast Internet access may be cost effective in the future as the cost of ADSL technology falls.

The feeder system included SDH (synchronous digital hierarchy) equipment to bring the broadband services within reach of the central office. This was configured as a bi-directional ring to give resilience. An ATM (asynchronous transfer mode) cross-connect allows customers to be connected to broadband services. Upstream signalling was routed via the same cross connects.

Service was provided with a mixture of PON and ADSL technology for the final drop. In the case of APON the system was connected directly to the ATM switch, whereas ADSL required an additional SDH demultiplexer to spit off the signals to the ADSL cards.

NTT in conjunction with several suppliers are developing APON systems [9]. These systems can provide bi-directional switched broadband services and with additional fibres or WDM can provide telephony services (TPON), interactive broadband, and broadcast services (BPON). As systems evolve, the APON system should be able to offer all services in the same multiplex. NTT has carried out multimedia trials of FTTH using PON systems in three areas where 900 customers are connected. TPON with BPON is installed in Tachikawa and APON is installed in Yokosuka and Urayasu. Leased service of ATM was introduced commercially using APON in June 1997 for business users.

Optical amplifiers in combination with passive power dividers

The emergence of fibre amplifiers opened up new possibilities for both access and core networks. Broadcast networks with fibre amplifiers, power dividers, WDM and TDM led to some very impressive experiments demonstrating the possibility of national coverage from a single cable TV head-end with huge numbers of channels [10]. The experimental system offered 40 Gbit/s (using 16 wavelengths) over 44 million way split and 527 km range. Using today's MPEG2 video codecs the number of 2 Mbit/s video channels would be 22,000.

Whilst cable TV systems of this sort are possible, they are not yet competitive with satellite or conventional cable TV. What might tip the balance in favour of fibre would be the presence of a corresponding upstream path.

Experiments and analysis revealed that noise-funnelling [11] led to a signal to noise ratio degradation, which was dependent on the number of amplifiers feeding the upstream power divider. This limited the upstream split ratio to that achievable on a single PON with no amplification. The presence of a fibre amplifier would only offer the benefit of extending the upstream range of the PON to enable it to transmit to a distant head-end receiver.

The search for more range, split and upstream capacity has now moved a stage further with work on the ACTS PLANET project at Alcatel Central Research Labs. The aim has been to make a 2.5 Gbit/s downstream and 310 Mbit/s upstream amplified-PON [12]. An optical split of 2048 and range of 100 km is achievable. Such networks are often referred to as superPONs or transparent optical networks. To allow amplifiers to be cascaded in the upstream direction semiconductor optical amplifiers (SOAs) are used which can be turned on only when traffic is flowing. SOAs can switch on and off rapidly but fibre amplifiers do not. The upstream media access protocol ensures that only one upstream amplifier attached to a passive splitter is operating at a time.

The future role of PONs

The future of PONs may be in the use of the FSAN/APON in situations where the capacity of ADSL and HDSL is insufficient and access SDH is uneconomic. Narrowband PONs would then be superseded by broadband PONs which can deliver both cell based (ATM) and circuit switched capacity at primary rate or higher. For this technology to become widespread it will be necessary for planners to move actively from expedient point-to-point solutions to target clusters of customers. Both incumbent and second operator networks could be served using this technology. One of the key determining factors will be the expected penetration and density of customers within a given geographical area and the ability of alternative technologies such as broadband radio to offer similar service at lower cost.

Apart from direct fibre entry systems, PONs may also find application in fibre feeder systems for other forms of customer drop such as hybrid fibre twisted pair (HFTP), coax (HFC) or radio (HFR). Of these HFTP is of interest to incumbent operators with a large twisted pair legacy network. HFC appeals to cable operators and HFR could find a range of applications for new entrant operators if both narrowband and broadband access are required. By choosing a suitable fibre feeder system the option may be available for future direct-entry fibre systems using PONs.

Achieving end-to-end transparency with fibre systems has remained an ultimate goal for many operators who recognise WDM as a very powerful service enabler. Whilst this has been achieved for undersea or core systems, access remains a problem because of cost. What is needed is either an evolutionary or a revolutionary approach. At present, evolution seems to favour point-to-point and hybrid-fibre solutions, whilst revolution can be associated with PON. Although TPON, APON and BPON have great appeal, no one entry-system or combination has yet succeeded in driving investment hard enough to offer ubiquitous solution in the UK although APON is going ahead for business customers in Japan.

Within the UK, there has been massive investment in broadband access by cable operators with HFC passing almost 50 % of homes. At the outset of the construction of cable networks, in the mid 1980s, PON technology was immature and the anticipated new market could be more economically served by twisted pair and coax in the final drops in 'Siamese' cables. Cable companies have struggled to see return on this huge investment because their broadband services are competing with satellite and their narrowband services are competing with fixed and mobile access.

Incumbent operators would like to enter the mass broadband market but are unwilling to invest heavily in another access infrastructure against an uncertain market. DSL offers a much less risky approach.

Second operators may find a use for PONs in the future. Strategically, owning an access network is important and fibre, rather than metallic transmission, offers better future proofing. However, radio systems represent an attractive alternative to PON for narrow-band services because no civil works are required and bi-directional broadband may soon be possible for mass deployment via satellite, high altitude aircraft and broadband cellular systems.

Whilst second operators favour fibre and radio systems as separate technologies now, fibre and radio technology together in a single system could make a powerful claim for second operator traffic in the future. The ACTS FRANS project [13] has explored the use of hybrid fibre-radio systems with PONs feeding a number of base stations. This brings together two flexible technologies for broadband point-to-multi-point access. With further development, a choice of fibre or radio drop could be offered according to the market demand. Radio could fulfil the requirements for a profitable entry-system, which could later be overbuilt with fibre to reduce the demand for radio spectrum and offer an economical dual access system for those customers requiring additional reliability [14].

Whether or not PONs will find a place in the forthcoming data-wave still remains uncertain. The FSAN APON promises the next step. If successful, amplified successors could follow to give greater economy and bandwidth flexibility. Versions with WDM could also be expected at that time.

Stones left unturned

In the hunt for a cost-effective fibre access network, a number of technical features of PONs have been passed-by to enable focused solutions such as TPON and APON to prove themselves. In the future ideas, which have been shelved, could later prove advantageous if significant investment in fibre takes place. As already mentioned, there are many possibilities for new services via WDM, especially cable TV. Other technical possibilities are outlined below.

- *PONs with active loop-back*
  Experiments were performed at BT Labs with TDM PONs, which allowed loop-back at the head-end so that the upstream channels could be reflected back into the downstream direction. This topology can turn the PON into a distributive switch, which is controlled by time slot selection at the customer-end [15, 16]. Although these experiments were successful, the drive for ATM centralized switching has been very strong and the use of this technique probably depends upon centrally switched PONs appearing first. An isolated LAN has been demonstrated but further work at BT Labs was shelved in favour of industry solutions.
- *PONs in LANs*
  Distributed switching has been the territory of LANs with technology such as Ethernet being capable of addressing different nodes on the network. PONs, perhaps using plastic optical fibre (POF), may find a place in a future generation of LAN using the power of PCs rather than centralised routers to achieve fast file transfer. However POF needs further development to achieve adequate range, power budget and improved practicality.
- *PONs with high-power upstream lasers*
  As the split ratio of a PON increases, the duty-cycle of the upstream transmitters decreases. This could allow transmitters to operate at higher peak power whilst maintaining the same average power and so compensate for the loss of the power divider. This benefit could allow more power budget and more ambitious split ratios in the future without the need for upstream amplifiers. The same principle is used in TV remote control handsets. This arrangement could also allow larger switches of the type described above.
- *PONs with concentration and/or by statistical multiplexing*
  When large split-ratios PONs are sought, the power budget and capacity requirements also increase. These effects conflict. To make better use of the available bandwidth, concentration and/or by statistical multiplexing may be used.

In a circuit switched network such as that used with TPON concentration requires call by call capacity assignment and possibly more user ports than the pre-provisioned approach would allow.

The issues with a cell based ATM system are even more complex because of the statistical nature of the cell-based system, which could be studied further. Early experiments with APONs at BT Labs made use of the 'Orwell' protocol for this purpose [7].

Conclusion

Point-to-point fibre access technology is already well established for businesses and buildings requiring in excess of 2 Mbit/s capacity. For users requiring 2 Mbit/s or less, technologies such as HDSL can offer a lower cost alternative if the twisted pairs are available. For new-build situations, point-to-point fibre and PON offer capacity for future-proofing but more rapid deployment and lower costs may be achieved with radio if suitable radio spectrum is available and adequate coverage can be achieved.

The FSAN APON in the future should support both existing narrowband and broadband services efficiently at a low cost relative to point-to-point alternatives. The future of PONs now depends upon the successful deployment of this technology in a market segment demanding capacity which is unsuitable for DSL.

For new-entrant operators, fibre and radio systems offer a good technical starting point now, although HFC has been used in the UK in recent years. The evolution of these networks towards second operator status with full service capability may be served with HFC or a combination of PON and radio systems, perhaps in a new generation of HFR.

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Flexible wavelength multiplexing techniques for broadband fibre access networks

TON KOONEN

After having reached an established position as the transmission medium of choice in core transport networks, fibre is penetrating ever deeper into the subscriber access networks. Today's access networks are mostly of a hybrid nature. Fibre is used in the feeder part of the network, but in the last drop to the residential user there is a variety of media, such as twisted pair, coaxial cable, and wireless drops. As the capacity demand by the subscriber grows, the capacity in the fibre feeder part has to keep up with it. Wavelength multiplexing is a powerful technique to upgrade the fibre network capacity without having to resort to (expensive) new fibre plant installation. Wavelength routing techniques are receiving much interest for path restoration in core transport networks. Similarly, in access networks wavelength routing provides higher network availability. But even more powerful, by dynamic wavelength routing fibre feeder capacity can be directed to those spots in the access network where there is a temporally high traffic demand. Thus network resources can be optimally deployed in response to traffic conditions, and the operator can maximise the efficiency of these resources. Moreover, different independent wavelength channels offer independent transmission paths for hosting a multitude of service providers and/or different types of services in one single infrastructure. The concept of 'wavelength leasing' thus provides another way of getting maximum benefits out of the infrastructural investment.

In this paper, two hybrid subscriber access network architectures applying flexible wavelength routing will be introduced. Firstly, the application in fibre-coaxial CATV networks will be described; this has been developed and put into a field trial in the ACTS project AC028 TOBASCO. Secondly, the application in fibre-wireless networks will be discussed, which offers even more fertile opportunities for network reconfiguration. The concepts being worked on in the ACTS project AC349 PRISMA will be introduced.

1 Introduction

The introduction of new telecommunication services as well as the increasing usage of existing ones requires a continuous increase in the capacity of networks. In core transport networks, optical fibre provides ample bandwidth for digital signals. A single wavelength may carry a data stream of 10 Gbit/s or more, and by deploying multiple wavelengths this capacity can even be stretched beyond 1 Tbit/s. Ultra-wideband optical fibre amplifiers are able to handle more than 100 wavelength channels in an 80 nm band in the 1.5 μm wavelength window [1]. Commercially available systems offer 80 wavelength channels with an aggregate capacity of 400 Gbit/s. The data streams are commonly built according to the digital Synchronous Digital Hierarchy (SDH), by multiplexing into transport modules as high as STM-64 (9.95 Gbit/s). To increase the network reliability and availability, wavelength routing techniques by means of optical crossconnects and add-drop multiplexers are being explored for fast path restoration; thus failing or congested links can be circumvented.

The growing need for capacity is similarly felt in access networks. As compared to the core transport networks, there is a huge variety in information signal formats and transport media: copper twisted pair networks for telephony, coaxial cable networks for CATV distribution, wireless GSM and DECT networks for mobile telephony, etc. In each of these networks, both the number of users connected and the range of services offered are growing steadily. The demand for more capacity pushes fibre ever deeper into access networks, closer to the customers. Justification of the installation of optical fibre up to the home still requires considerable cost reductions in optical components and fibre installation practices to be made [2]. However, in hybrid access network architectures fibre has established its position in the feeder part of the network; from there the signals are handed over to the variety of media in the last drop to the customer. In this way Hybrid Fibre-Coax (HFC) networks are delivering CATV broadcast services, augmented with narrowband interactive services (voice telephony, ISDN). In wireless networks, fibre is making its way towards the base antenna stations. Without affecting the installed fibre plant (in which huge investments have been made), the increasing demand for capacity in the feeder network can be met by introducing multiple wavelength channels. Like in core transport networks, wavelength multiplexing techniques may also provide alternative paths to route the data streams, thus increasing the network's availability. The most pronounced advantages, however, emerge when the wavelength routing can be done dynamically in response to varying communication needs. Feeder capacity can be directed to those locations in the network where there is a temporally high traffic demand, ie. to the so-called 'hot spots'. Thus the network operator can most efficiently exploit the network resources, and hence maximise his revenues. Moreover, the wide variety of services and affiliated transport requirements can be adequately met by carrying those services via different wavelength channels. Separation at the wavelength level by 'wavelength leasing' allows independent service providers and different types of services to be transported in the same fibre network, thus maximising the exploitation benefits of this infrastructure.

In this paper, two novel hybrid access network architectures deploying wavelength multiplexing will be described. In the European R&D programme ACTS [3a], project AC028 TOBASCO has studied the application of WDM in fibre-coax networks; the project AC349 PRISMA [3b] is addressing WDM in fibre-wireless networks. The basic concepts of these projects will be outlined, as well as some experimental results and future prospects.

2 WDM in fibre-coax networks: the TOBASCO project

The project TOBASCO (Towards Broadband Access Systems on CATV Optical networks) aims at upgrading fibre-coax CATV networks in order to provide broadband interactive services with speeds in the order of 2 Mbit/s bidirectionally at the customer. The user applications foreseen are tele-working and tele-learning, by LAN emulation, fast Internet access, video conference, etc. The project started in September 1995 and finished in October 1998.

2.1 TOBASCO's system architecture

The CATV fibre-coax infrastructure taken as the starting point is shown in Figure 1. The CATV distributive services (DS) are put on a wavelength λ_0 in the 1.55 μm wavelength window. The ana-

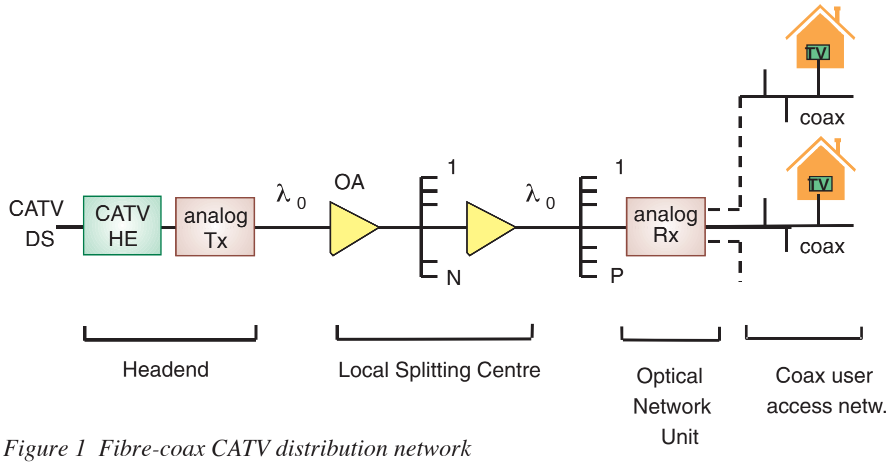

Figure 1 Fibre-coax CATV distribution network

logue optical signal is split at several stages, using unidirectional optical amplifiers (OAs; preferably erbium-doped fibre amplifiers, EDFAs) to overcome the splitting losses. Typically, the split factors *N* and *P* are 4 to 16. At each Optical Network Unit (ONU), the analogue optical signal is converted to an electrical one. This RF signal usually lies in the range of 42 to 900 MHz, and is fed via a coaxial cable plant with electrical amplifiers to the customer residences. The modern mini-fibre node networks may have a number of users as low as 40 per ONU; together with $N = 4$ and $P = 16$ this yields at least 2560 users to be fed by a single fibre from the headend. In Hybrid Fibre Coax systems, the unused spectral bands are deployed for conveying data upstream from the customer homes to the headend. Because of the limited amount of spectrum available, and the huge number of users, the upstream capacity is limited to narrowband services like Plain Old Telephone Service (POTS) and ISDN.

To enable broadband interactive services (BB-IS) delivery to the customer, the TOBASCO project has proposed the system concept shown in Figure 2 as an upgrade of the CATV distribution network in Figure 1. Clearly, the fibre plant installed in the field remains the same, thus protecting the infrastructure investments. Also the analogue CATV distribution system on wavelength λ_0 is still in place. But on top of that, a number of multi-wavelength optical transceivers have been added at the headend in the Optical Line Terminations (OLTs). Each OLT supports a bidirectional 622 Mbit/s ATM-based BB-IS communication channel, for which two wavelengths carry the data in up- and downstream direction across the tree-and-branch split optical fibre network. ATM-PON technology from the ACTS BAF project and its successor BONAPARTE is used [3a]. Eight wavelengths are deployed, with four in downstream and four in upstream direction. The wavelengths are chosen in the lower part of the EDFA operation window (1.53 – 1.54 μm), in order to allow easy multiplexing with the CATV distribution wavelength in a coarse wavelength demultiplexer (CWDM). The lat-

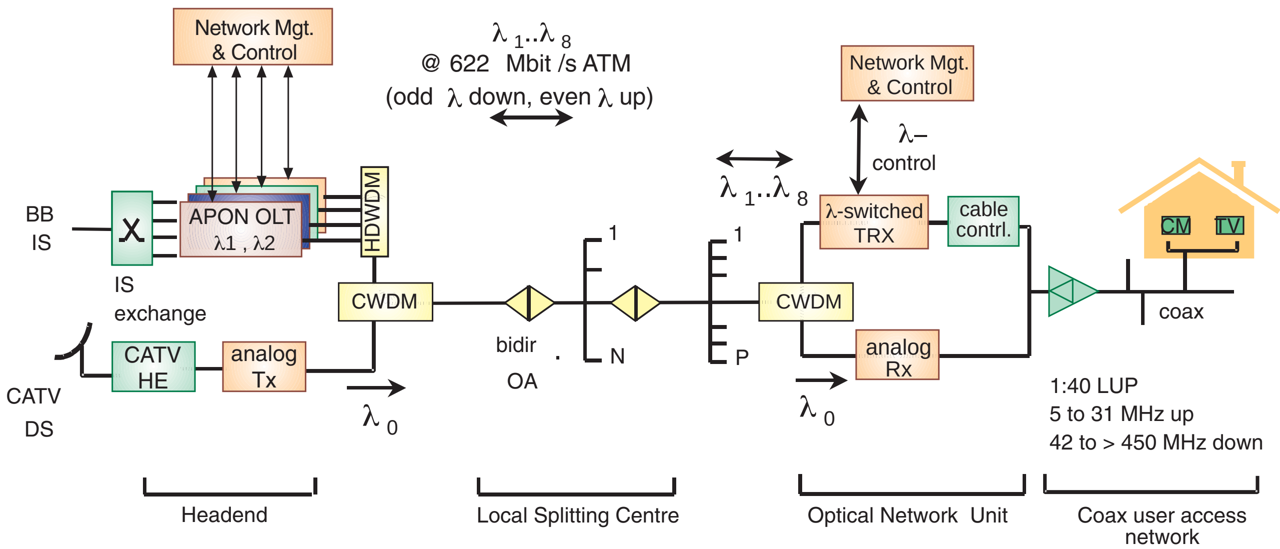

Figure 2 TOBASCO's multi-wavelength upgrade scenario

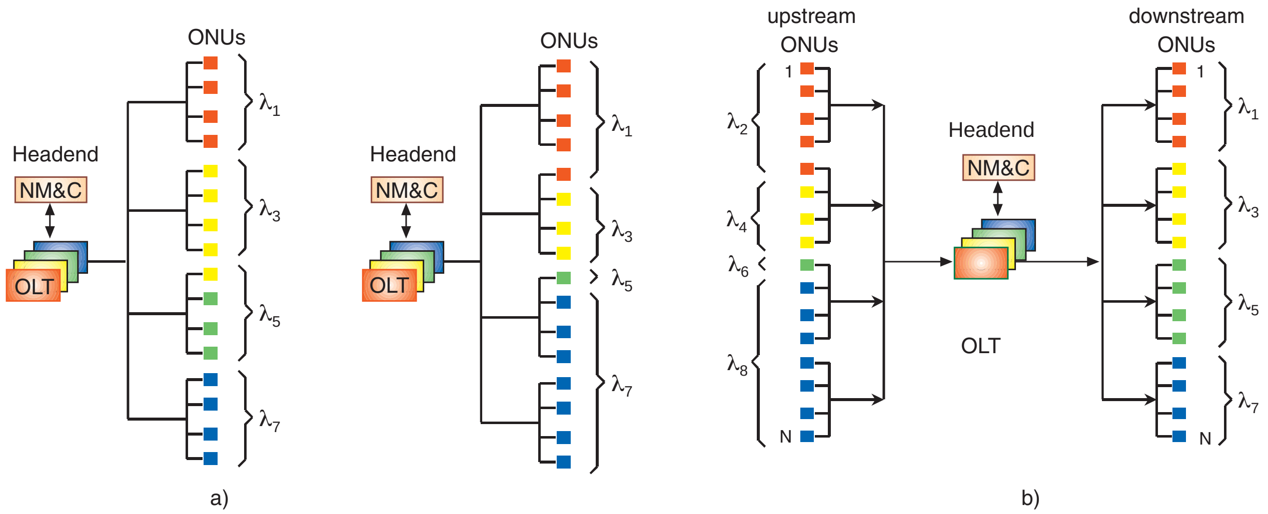

Figure 3 Network reconfiguration
a) rearranging the wavelength allocation for symmetric services
b) different virtual topologies for the up- and downstream directions of asymmetric services

ter wavelength is preferably put in the higher part of the EDFA window, in the range 1.55 – 1.56 μm. The BB-IS wavelengths travelling in the same direction are spaced at 200 GHz. The upstream wavelengths are interleaved with the downstream ones; wavelengths travelling in opposite directions are spaced at 100 GHz. In the field, the original unidirectional optical amplifiers in the CATV distribution-only network obviously have to be replaced by bi-directional multi-wavelength ones. At the ONU, the analogue CATV distribution services are firstly separated from the interactive services by a coarse wavelength demultiplexer (WDM). The analogue signal is treated in the same way as in the original CATV network. The BB-IS wavelength channels are fed by the CWDM device to a wavelength-switchable transceiver. Which of the channels is to be processed by this transceiver can be chosen via the network management and control (NM&C) system. By providing the wavelength selection signal from the NM&C system at the headend, the network operator can remotely control the wavelength selection at each ONU.

In the coaxial cable user access network, the cable infrastructure also remains largely the same when upgrading the CATV distribution system. The electrical amplifiers obviously need to be replaced by bi-directional ones. Advanced cable modems (CMs) enable broadband interactive data streams to be transported via the coaxial cable plant. Up- and downstream data traffic streams are positioned in different spectral bands. The upstream traffic is usually put below the lowest CATV channel (so mostly below 40 MHz), and the downstream traffic in the empty frequency bands between the CATV broadcast channels.

2.2 Dynamic wavelength assignment

By flexibly assigning the wavelength channels to the ONUs, the operator is in control of the virtual topology of the fibre network, without intruding the fibre plant. He can thus optimise the wavelength grouping of the ONUs such as to optimise the network operation efficiency. As shown in Figure 3.a, each wavelength channel may feed the same number of ONUs in case the traffic load is equally spread among them. If, however, the load is heavier at particular ONUs, the wavelength allocation can be rearranged in such a way that these ONUs have to share the wavelength channel capacity with less other ONUs. For instance, in Figure 3.a wavelength λ_5 is dedicated to a single ONU, thus providing it with the full 622 Mbit/s ATM capacity. As the wavelength setting for the transmitter at the ONU may differ from that for the receiver, even a deliberate asymmetry in capacity between up- and downstream direction may be introduced, as shown in Figure 3.b. This may be useful for asymmetric services; eg. for static downstream video broadcast in combination with irregular upstream customer-generated traffic.

The flexible allocation of wavelengths to the ONUs allows to provide capacity on demand. Each wavelength channel can handle 622 Mbit/s on an ATM packet basis. As illustrated in Figure 4, when a certain ONU requires more capacity than actually available within its currently assigned wavelength channel, it may be moved, by changing its wavelength setting, to another channel where enough spare capacity is still available. Several strategies may be followed for the wavelength reallocation [4]: a semi-static one (for failure circumvention or maintenance), a long-term one (for deterministic user behaviour patterns), and a short-term one (for randomly varying user behaviour). The latter strategy needs to assign bandwidth on demand; it considerably reduces the blocking probability of the overall network when compared with a fixed wavelength allocation. The results from a traffic analysis are shown in Figure 5, where the system blocking probability is plotted versus the average traffic intensity (ie. the total traffic load normalised on the total available network capacity of 4 x 622 Mbit/s

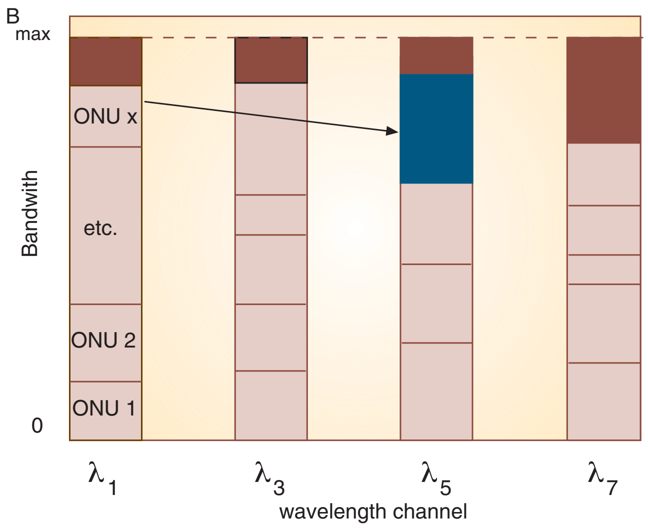

Figure 4 Bandwidth according to need

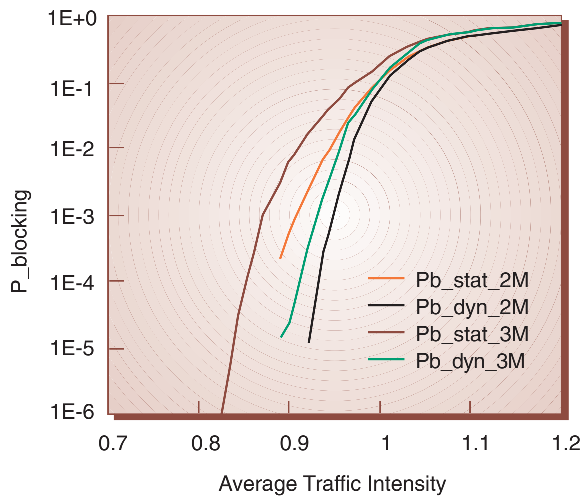

Figure 5 System blocking probability

= 2.5 Gbit/s). It has been assumed that each subscriber generates calls requiring either 2 Mbit/s or 3 Mbit/s. The call arrival process follows a Poisson distribution, where the call duration is exponentially distributed. Each ONU connects 40 subscribers; in total there are 64 ONUs, fed by 4 wavelengths in either direction which each can handle 622 Mbit/s on an ATM basis. When the wavelengths are statically assigned to the ONUs, with each wavelength feeding 16 ONUs, the blocking probability for 3 Mbit/s calls is obviously worse than the one for 2 Mbit/s calls. With the dynamic wavelength assignment strategy, however, the blocking probabilities are significantly lowered. As shown from the graphs, by using this strategy the blocking probability for 3 Mbit/s calls is even lower than the one for static wavelength assignment with 2 Mbit/s calls. Thus it may be concluded that the dynamic wavelength assignment strategy extends the capacity available to the subscriber by more than 50 %; or in other words, for a given subscriber capacity demand fewer wavelength channels will suffice for the operator.

2.3 Novel system modules

A number of optical modules has been developed within the TOBASCO project. In Figure 6, the circuit layout of the bi-directional optical amplifier is shown. It is composed of two branches. In one branch, the CATV signal (positioned in the 1.55 – 1.56 μm range) is amplified in downstream direction only in a relatively long erbium-doped fibre, yielding a high output power and a low noise figure. In the other branch, the interactive signals (in the 1.535 – 1.542 μm range) are amplified in a short erbium-doped fibre; together with a gain-equalising filter, a relatively flat gain over the wavelength range is obtained. Two pump laser diodes emitting 120 mW at 980 nm are deployed. In this so-called Two-Window Optical Branching Amplifier (TWOBA), coarse WDM devices (CWDM) separate the CATV signal from the interactive signals, and a 1 : 4 splitter distributes the signals to four outlets. The net gain of the TWOBA is 11.5 to 12 dB for the CATV signal (at –5 dBm input level), and 17 ± 1 dB for the interactive signals.

Figure 7 shows a multi-wavelength receiver, which uses a phased-array waveguide grating for demultiplexing up to eight wavelength channels; the photodiodes have been integrated on the same indium-phosphide (InP) chip. The wavelength-switchable ONU transceiver module pictured in Figure 8 contains 4 wavelength-specific DFB laser diodes and the control electronics. The use of multiple fixed-wavelength lasers instead of a tuneable laser allows a make-before-break procedure when switching to another wavelength; this eases the data buffering problems during switch-over. A phased-array demultiplexer integrated in planar glass and four individual photodiodes are used for the receiver functions; the performance of this configuration is still somewhat better than that of the integrated InP multi-wavelength receiver.

Advanced cable modems have been developed deploying synchronous CDMA techniques, for optimum robustness against ingress noise, in combination with QAM-16 (or -64) techniques

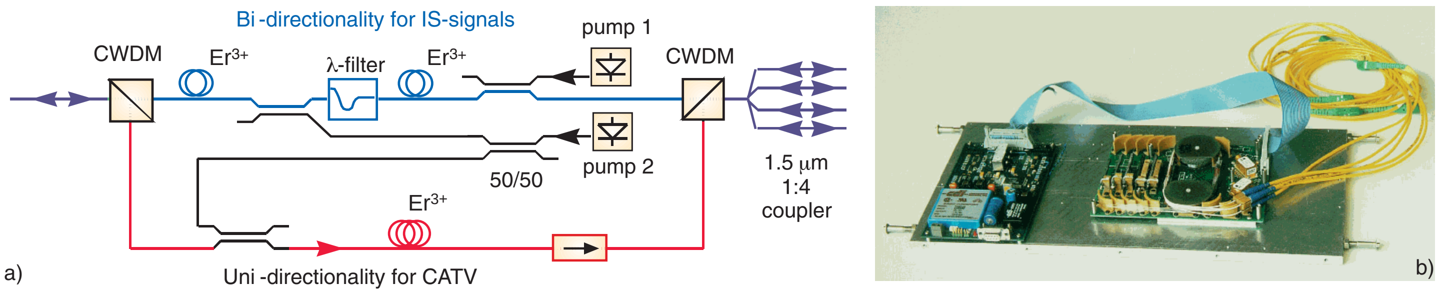

Figure 6 Two-window optical branching amplifier
a) circuit layout, b) module with control electronics and optical parts

for better spectral efficiency. Per 6 MHz frequency slot a data signal of net 8.2 Mbit/s can be accommodated.

2.4 Cost analysis

In co-operation with the ACTS OPTIMUM project, a first cost comparison of the TOBASCO system with alternative system architectures has been made. These alternatives were a Space Division Multiplexed (SDM) architecture, and a static wavelength multiplexed (static WDM) architecture. In the SDM one, multiple fibres are used instead of multiple wavelengths. In the static WDM one, the ONUs were not wavelength-flexible, and hence were only equipped with a single laser diode. The installed first costs have been assessed, and their evolution in time, under the assumption that the fibre network is already in place and that the prices of the various modules decrease due to growing market volumes. The study results are shown in Figure 9. Although at the present price levels the TOBASCO solution is clearly the most expensive one, the cost difference with the other solutions will tend to diminish within the next ten years, mainly due to the growing market volumes and the price erosion of optical components expected. Note, however, that the TOBASCO solution is the most versatile one.

2.5 Field trial

The TOBASCO system was put into a field trial in the city of Ghent, Belgium, for six months (from 15 April to 15 October 1998). The system was installed in a part of an operational fibre-coax CATV network run by TeveOosT, the regional CATV operator. The network

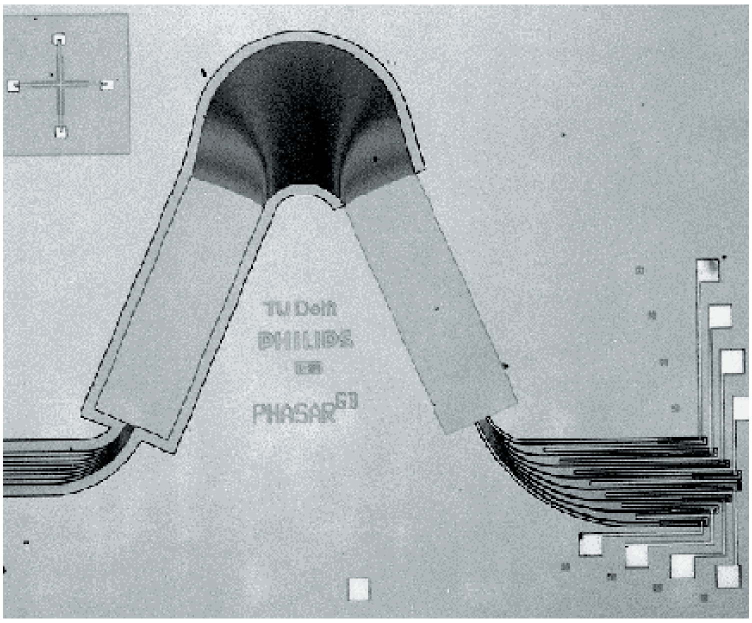

Figure 7 Integrated multi-wavelength receiver

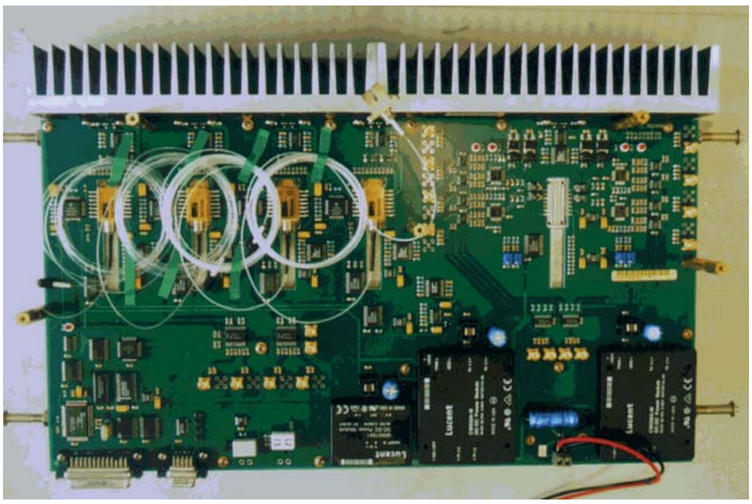

Figure 8 Wavelength-switchable transceiver at ONU

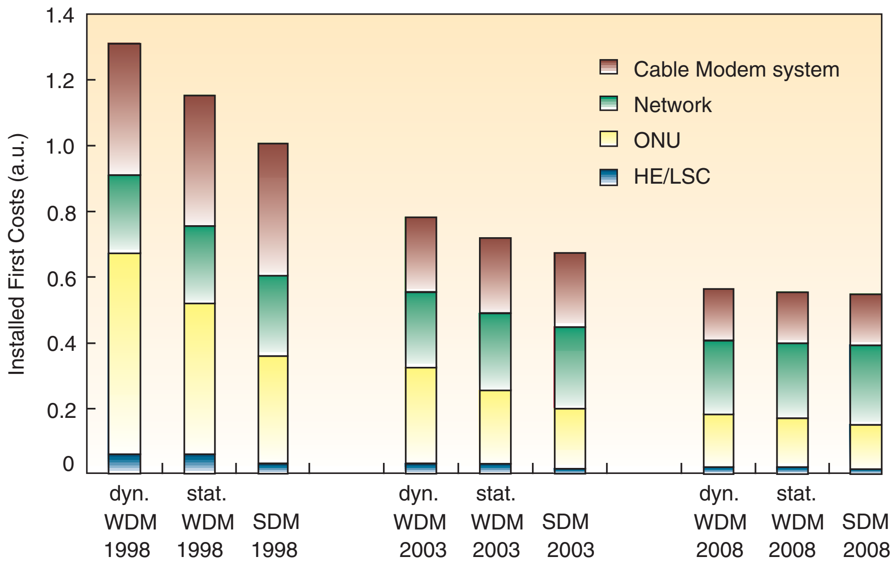

Figure 9 Evolution of Installed First Costs per user, estimated at five-year intervals

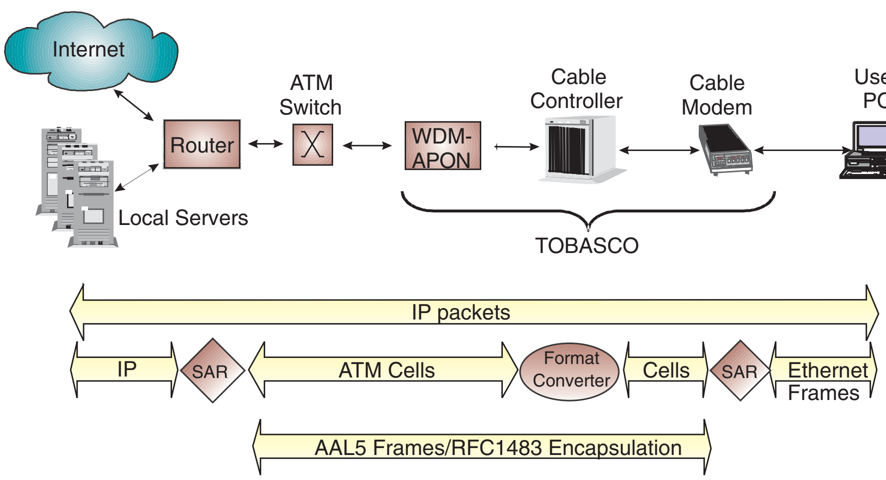

Figure 10 IP bridging over ATM (according to IETF RFC 1483)

management and control information was transported via some spare fibres in the cables. The interactive services (fast Internet, fast file transfer, video conferencing, etc.) were offered by the University of Ghent, where an ATM switch connected to file servers and to the Internet was located. Via the coaxial cable modem system and the multi-wavelength ATM optical network (WDM APON), IP packets could be transferred as shown in Figure 10. The system was used by students, university staff members, sales persons in a travel agency, and visitors at a local Internet café. The operation of the system was quite successful. Monitoring of the performance showed IP peak rates of 6.2 Mbit/s downstream and 3.6 Mbit/s upstream per subscriber. Measurements of the round-trip times for 64-bytes packets showed that the TOBASCO system performance is close to that of a 10 Mbit/s Ethernet LAN. The user experiences with the system were evaluated by means of questionnaires. The results showed that about 80 % of the users were very satisfied with the speed of the system, and would favour it above their own PC connections at home or in the office.

3 WDM in fibre-wireless networks: the PRISMA project

In wireless access networks, the users with their mobile terminals are connected to antennas at the base stations via microwaves. The information transport to and from these base stations is carried via a fixed wired network, in which fibre is steadily penetrating ever deeper. The traffic load at the base stations may fluctuate even stronger than at the ONUs in the fibre-coax network considered before, as users not only vary their communication needs in time but also in space when moving around. Having the advantages of flexible wavelength allocation in fibre-coax networks in mind, the ACTS project AC349 PRISMA (Photonic Routing of Interactive Services for Mobile Applications) studies the aspects of flexible multi-wavelength techniques in fibre-wireless networks. The project started in April 1998, and will finish end of January 2000.

In general, two types of mobility can be discerned:

- Nomadic services, where connections are set up from a certain location, run for some time and are subsequently torn down; the user moves to another location and sets up a connection again, etc. These services usually have a broadband nature, such as wireless LAN applications for nomadic computing, and do not employ in-travel communication with its associated call hand-over issues.
- Mobile services, where users roam throughout the network while staying in connection; this entails call hand-over processing.

Roughly speaking, mobility is traded against capacity. For nomadic services, high information transfer rates (several

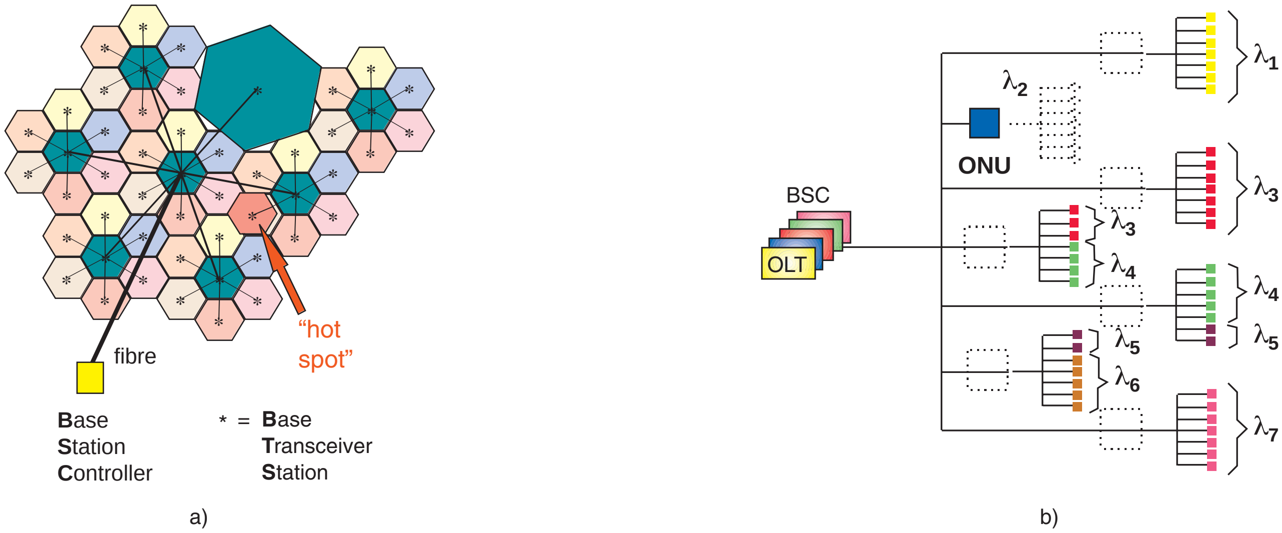

Figure 11 Wiring a microwave cellular network with optical fibre, using multiple wavelengths
a) feeding the Base Transceiver Stations (BTSs)
b) wavelength allocation among the ONUs of the BTSs

Mbit/s) are needed, which implies a smaller cell size. Also hand-over processing gets more difficult, and hence mobility is limited to low speeds. In contrast, mobile services requiring lower bit-rates (10 kbit/s for GSM, up to 2 Mbit/s for UMTS) allow a much larger cell size. Hand-over processing is easier, and as the hand-over frequency is reduced by the larger cell size at a given user movement speed, the mobility is higher.

The PRISMA project is mainly targeting nomadic applications, run from eg. portable PCs. Three user scenarios are being explored: university campus (eg. group exercises), hospital (eg. bedside diagnostics, remote X-ray pictures retrieval), and industrial park (eg. flexible office rooms).

3.1 PRISMA's system architecture

Basically, a similar fibre feeder network as in TOBASCO is considered to feed the Base Transceiver Stations (BTSs) [5]. The mapping on a microwave cellular network is illustrated in Figure 11. To avoid interference problems, each cell needs to use a microwave frequency which differs from the one used at the

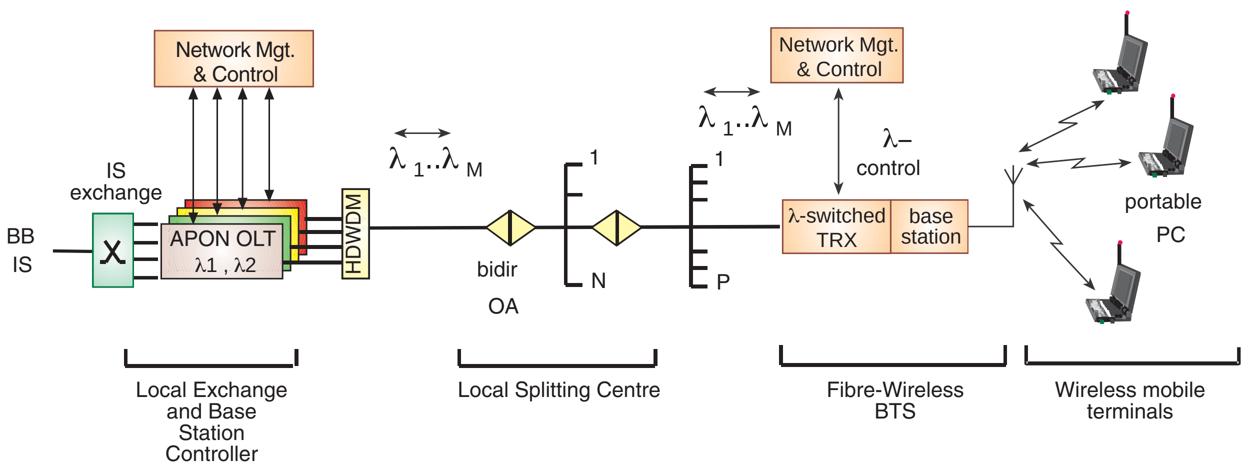

Figure 12 PRISMA's system architecture

neighbouring cells, which implies that at least 7 different frequencies are needed (indicated by different colour shadings in Figure 11.a). The frequency pattern of a 7-cells cluster can be repeated to cover a larger geographical area. The fibre network feeding the BTSs can be laid out as a split fibre network, where the BTSs are accessed via their Optical Network Units. When the traffic load in a cell becomes very high (ie. if a cell becomes a 'hot spot'), an extra microwave carrier may be switched on to handle it. At the ONU extra feeder capacity needs to be made available, and for this a flexible wavelength allocation strategy like in TOBASCO can be deployed. In contrast, a larger region with less intense traffic may be covered by a macro-cell, served by a single microwave carrier and BTS. As shown in Figure 11.b, the wavelength channels can be allocated among the ONUs in such a way that the varying demands are adequately met.

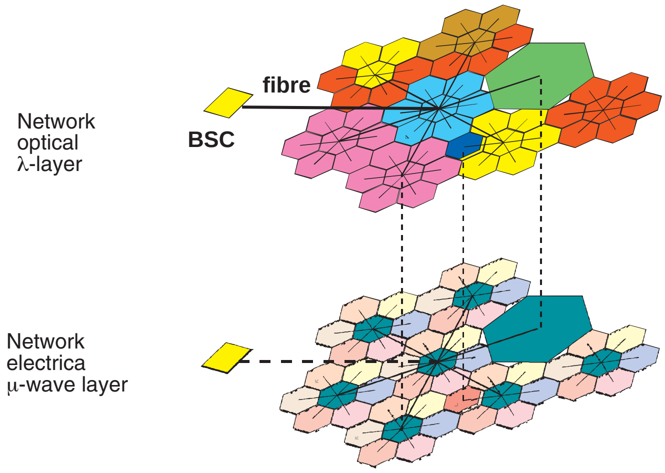

Figure 13 Mapping microwaves to wavelengths

The architecture of the PRISMA system is depicted in Figure 12. In a similar way as in the TOBASCO system, the wavelength allocation at the BTSs can be remotely controlled from the central local exchange/base station controller site. This allows the operator to optimally direct the network's capacity resources to the BTSs in such a way that the locally offered traffic load is adequately met. The total splitting factor in the optical network, enabled by the bidirectional amplifiers, may be as high as $7^3 = 343$, corresponding to three stages of 1 : 7 split (the factor 7 allows easy mapping on the cellular network topology). $M = 8$ wavelength channels are to be used, of which 4 are for the upstream and 4 for the downstream direction. Per wavelength, 622 Mbit/s ATM-based data can be transported. At the wireless end, the system from the ACTS project AC085 WAND [3] is used. This system provides 20 Mbit/s capacity per microwave carrier on an ATM basis (total of up- and downstream traffic), to be shared by the mobile terminals connected. It can support as much as 5 carriers in the 5 GHz region, and deploys Orthogonal Frequency Division Multiplexing (OFDM) technology.

The mapping of the microwaves in the individual cells to the wavelength channels in the fibre network is flexible, and can be changed by reallocating the wavelengths at the BTSs. For example, a particular wavelength allocation may yield the mapping as shown in Figure 13.

Depending on the traffic load per cell, the mapping can be adjusted. The interposition of application filters, mobile-aware agents and proxies at the wireless-fixed network interface may even lead to higher traffic loads at the ONUs, affecting the mapping choices.

3.2 System performance analysis

Traffic studies have been made to assess the impact of the wavelength reallocation strategy on the blocking performance of the system. In principle, the same allocation strategy as depicted in Figure 4 can be followed. The results of a first analysis are shown in Figure 14, where the system blocking probability has been plotted versus the normalised traffic load, assuming 7 wavelength channels in the fibre network in either direction (ie. the total traffic load offered at the BTSs, normalised on the total available network capacity of 7 x 622 Mbit/s = 4.35 Gbit/s). The call arrival process is assumed to follow a Poisson distribution, and the call duration a uniform distribution and band-

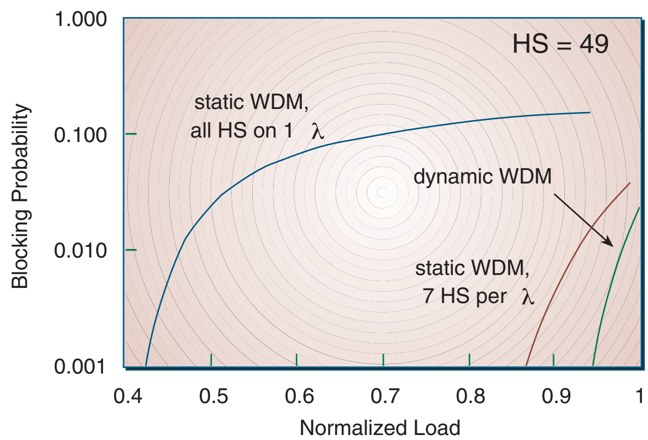

Figure 14 Impact of wavelength reallocation on the system blocking probability in the presence of hot spots (HS)

width. Hot spots (HS) are defined as cells where the call arrival rate is twice that of a normal cell; it is assumed that there are 49 of these hot spots in the network. When the allocation of the wavelength channels to the BTSs is fixed, the blocking probability is obviously the highest if all hot spots are located such that they are served by the same wavelength. The blocking probability is the lowest if the hot spots are evenly spread among the wavelength channels, ie. 7 hot spots per wavelength. In reality, it is unknown where the hot spots will occur, so for a fixed wavelength allocation the blocking probability may vary anywhere between these two extremes. Following the dynamic wavelength allocation strategy, however, the capacity is directed to the locations where traffic loads demand it. This results in the blocking probability curve labelled 'dynamic WDM'. Clearly this strategy yields the lowest blocking probability, independent of the actual location of the hot spots, and thus allows the network operator to employ its capacity resources with optimum efficiency even for unknown hot spot distributions. The graphs also suggest that a second best strategy is to equalise the traffic load over the various wavelengths, in such a way that the hot spots are equally spread among the wavelength channels. The latter strategy ('load balancing') may imply a less complicated wavelength allocation process, and thus may be easier to implement.

3.3 System trials

The PRISMA project builds on the flexible multi-wavelength ATM PON system realised in the TOBASCO project, and the wireless ATM system for nomadic computing from the WAND project. In a first laboratory set-up, a successful integration of both systems has been accomplished. In a LAN emulation (Ethernet over ATM) set-up, error-free transport of data packets has been achieved between a server PC at the headend and a user PC at the wireless mobile terminal, at data rates of 4 Mbit/s downstream and 2 Mbit/s upstream. Later on in the project, a more comprehensive laboratory system is planned, with a network management and control system overlooking the end-to-end IP-in-ATM connectivity using the flexible wavelength allocation strategy. This set-up will integrate a number of novel and adapted optical modules, including the wavelength-switching functionality, and will be the basis for the field trial.

The project is planning to have a small-scale field trial during the last three months of 1999 in Ghent, Belgium. Facilitated by the IMEC group at the University of Ghent, the potential of the system will be assessed in a realistic user environment. The layout of the trial network is shown in Figure 15. Within the university premises in the new Urbis building complex, network interconnections will be made with students, researchers and other university staff members via an IP-in-ATM LAN testbed, which comprises an ATM switch and a router providing fast Ethernet access to the backbone network of the university. The university network (RUG

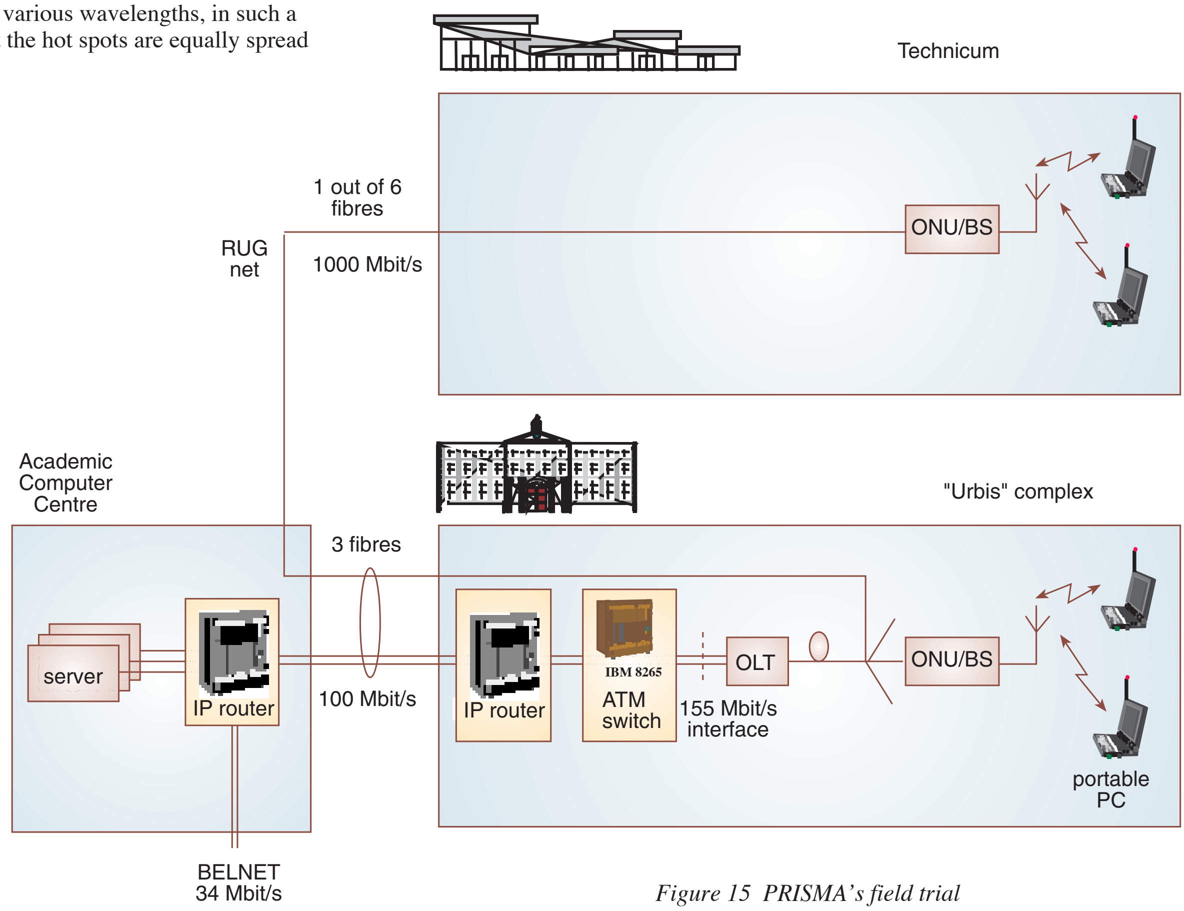

Figure 15 PRISMA's field trial

Net) has a high-speed connection to the Internet via the BELNET national research network. In the Urbis complex, a number of lecture halls and laboratory rooms will be connected, providing broadband wireless access to the university's network. By means of a fibre running via the Academic Computing Centre, the same access capabilities are offered to students and university staff at the Technicum building. A number of businesses are also located in the Urbis complex, such as a computer hardware/software supplies shop, music/video shops, a supermarket, and some other traditional mall shops. In addition, a consultancy company has moved in and more companies are expected to follow. The services planned to be offered in the trial network are fast Internet access, video conferencing, remote access to the university's Academic Computing Centre, etc.

4 Conclusions

After having proven the benefits for capacity increase and traffic routing in core transport networks, wavelength multiplexing techniques have a large potential to extend the capabilities in optical access networks also. Flexible wavelength multiplexing allows the network operator to deploy his resources in the most efficient way, by adapting his network's virtual topology in order to provide capacity on demand; he may also provide wavelength channels as independent transport pipes in order to offer a wide variety of services and to host other independent operators ('wavelength leasing'). Both in the laboratory and in the field, the TOBASCO project has proven the technical feasibility of the flexible multi-wavelength concept for upgrading a hybrid fibre-coax CATV network towards the provisioning of broadband interactive services. A number of novel system modules have been realised and successfully tested. Traffic studies have pointed out that a significant increase in network efficiency can be obtained by deploying flexible wavelength assignment to the optical network units, whereas a first analysis of the economics shows that the extra costs incurred in comparison to alternative (less flexible) network architectures are only marginal. In fibre-wireless networks, as studied in the PRISMA project, even larger increases in network utilisation can be gained with the flexible wavelength allocation strategy. First traffic studies show that local temporal concentrations of traffic load ('hot spots') can be handled very effectively with a limited set of resources. The project's focus is on nomadic broadband applications (such as nomadic computing on portable PCs); the scope of the studies will be extended to mobile UMTS applications shortly.

Acknowledgements

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Inverse multiplexing

EINAR EDVARDSEN

This paper describes a new alternative for transforming the existing telephone access network into a real broadband network. The objective is to introduce a low-cost network evolution scenario, which makes maximal use of the huge investments connected to this kind of networks. The existing network is subdivided into small cell networks, each covering an area with an approximate radius of 1 kilometre. Inverse multiplexing of xDSL systems is used to aggregate bandwidth in the 100 to 1000 Mbit/s range between nodes in the network. VDSL modems able to carry about 25 – 50 Mbit/s, are used on the last section from the node to the customer premises. These modems provide all households within each geographical cell with real broadband access to a large common bandwidth.

1 Background

At the present time there is a common understanding that the vision of Fibre-To-The-Home (FTTH) still belongs to an undefined future scenario. This is both due to the fact that the demand for broadband services has not yet matured, that the related investments are supposed to be very high, and that such huge civil works will take a long time to accomplish. Other intermediate solutions have therefore been looked upon as more realistic.

Various adaptions to the Fibre-To-The-Xx (FTTX) architectures have therefore been given more attention. FTTC (Fibre-To-The-Cabinet) is one of the approaches adopted by the FSAN (Full Service Access Network) group. The idea behind FTTC is to utilise the existing telephone access network from the cabinet to the customer, but use optical fibre cables on sections between the cabinets and the broadband switch. By doing it this way, optical fibre cables will only be installed on sections were the costs can be shared by large numbers of customers, while the existing infrastructure will be used in the other parts. In practice this means that ADSL or VDSL technology is supposed to play a major role in the access network in order to make available the necessary bandwidth on the sections between the cabinets and the customers.

Even if an FTTC architecture is flexible and less expensive than the FTTH architecture, it still involves significant investments. In areas were cable ducts do not exist, optical cables will have to be buried in the ground. Even in cases were such ducts do exist, the cost of fibre cables and related installation work may be considerable and it will take time to accomplish – time that telecom operator companies possibly might not have. New competitors entering the market are offering broadband access over powerlines, radio, satellites and CATV networks. To maintain their market shares, the owners of the telephone cable network will have to meet this challenge by upgrading their networks.

2 The capacity of telephone cables

Though each single twisted pair in a telephone cable has a limited bandwidth, the total capacity of a telephone cable can nevertheless be very large. This is due to the fact that telephone cables contain large numbers of copper pairs, each of which by utilising xDSL technology may provide a relatively large bandwidth over a certain distance. If the capacity of each single pair could be added up, the aggregated capacity would be huge, as seen from Figure 1. Inverse multiplexing is the technology that enables such aggregation of capacity from a number of lower bandwidth digital channels.

The figure shows the bandwidth of a telephone cable with 100 twisted pairs as a function of line length. A telephone cable with one hundred twisted pairs is in this context a small cable. The graphs indicate that within reasonable cable lengths, the capacity of one hundred twisted pairs is in the range of several gigabits, ie. a capacity that today is far beyond what is needed in residential access networks. The lower curve indicates the capacity of 100 copper pairs using the performance of standard modems. The upper one indicates the theoretical upper value for the aggregated capacity.

These brief calculations are of course not exact. Noise and cross talk influence on the obtainable bandwidth, resulting in less performance. Nevertheless do the results indicate that the telephone cables are much more powerful than we are used to believe. The question is whether the bandwidth of this network can be exploited in an efficient way, thus opening a new possibility of how to provide real broadband access to the general public.

3 Inverse multiplexing

Inverse multiplexing is used to aggregate bandwidth from a number of 'lines with smaller bandwidths'. The principle of inverse multiplexing is shown in Figure 2.

Figure 2 shows the basic principle behind inverse multiplexing. The incoming traffic stream from the left is sequentially distributed over a number of lower bit

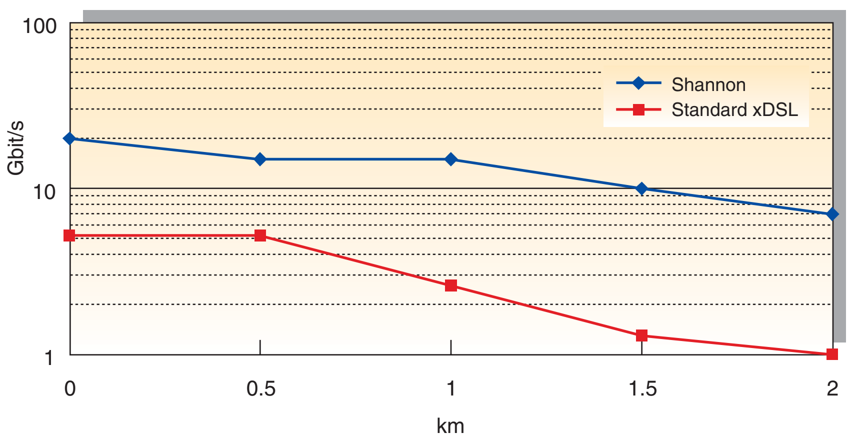

Figure 1 Capacity of a telephone cable as a function of its length

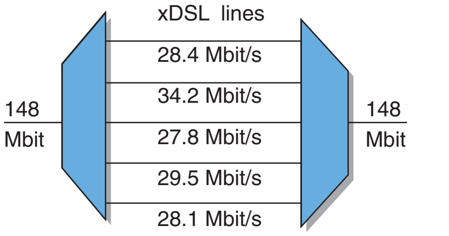

Figure 2 The principle of inverse multiplexing

rate lines and reassembled at the other end. Inverse multiplexing is standardised by a number of standardisation organisations, such as ITU, ETSI and ATM Forum. The available standards cover inverse multiplexing of channels with equal bandwidth, for instance inverse multiplexing of four times 2 Mbit/s to form a channel of 8 Mbit/s. Although from a technical point of view it is also possible to multiplex lines/channels running various bit rates, it is not covered by any official standards yet. Inverse multiplexing of xDSL modems is therefore so far not standardised. There are several methods for performing inverse multiplexing of packet based traffic (ATM), for instance by the use of sequence numbering, as illustrated in Figure 3.

Each cell arriving from the left is given a sequence number before it is transmitted over one of the available lines. The bandwidth of each line may differ from line to line. One line can perform 13 Mbit/s, while another can perform 19.3 Mbit/s. The cells will therefore arrive out of order at the receiver end, and have to be intermediately stored in the buffer on the right side in order to re-establish the sequential order. Since it is mandatory for inverse multiplexers to be transparent for traffic streams, and the ATM cell itself does not contain any field useful for carrying the sequence number, it must be transferred as a tag to the cell. The cell length will therefore deviate from the ATM standard (53 bytes). However, the interface between the two terminals of the inverse multiplexer can be looked upon as an internal interface, and a deviation from the standards is therefore acceptable. Mixing of lines with different bandwidths may create delay and cell delay variation (CDV), which are unacceptable for certain types of traffic. To meet requirements from the various traffic types, each of them may have to use dedicated line groups with properties that match their demand. As mentioned above, the method of using sequence numbering to perform inverse multiplexing of lines with different bit rates is only one way to do it. Other methods also exist. A method called Deterministic Inverse Multiplexing is illustrated in Figure 4.

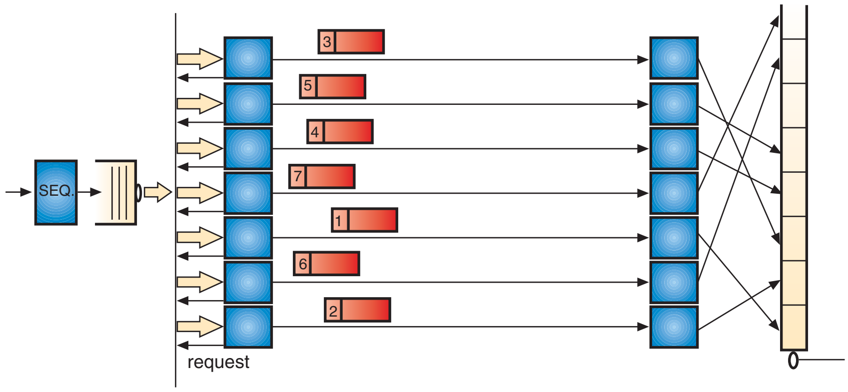

Figure 3 Inverse multiplexing by use of sequence numbering over xDSL lines

The traffic coming from the left is distributed over the four included lines in the same relation as their bit rates. In the above example, two units of data are sent over the 2 Mbit/s line, six units over the 6 Mbit/s line, 18 units over the 18 Mbit/s line, and nine units over the 9 Mbit/s line during the same period *T*. The method requires that the lines are phase-locked to each other. Compared with the first described method, the latter one is independent of data format. It can transfer ATM as well as bit synchronous traffic.

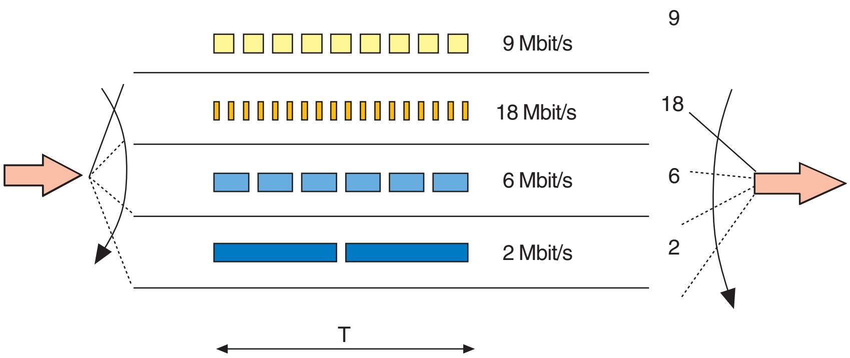

Figure 4 The principle of Deterministic Inverse Multiplexing

4 The network concept

The network concept is based on using the existing telephone access network infrastructure. In the general structure of the new network, new nodes (Figure 5) will have to be installed in connection with the street cabinets. These network nodes must perform both inverse multiplexing and statistical multiplexing. Figure 5 contains a functional description of such a network node.

Figure 6 shows the principal structure of the new network. The nodes in the network are placed geographically close to the cabinets in the old telephone network in order to have easy access to the necessary copper pairs. The distance between the nodes should not be more than about two kilometres. Each node covers an area with an approximate radius of one kilometre, which makes it possible to provide 25 – 50 Mbit/s to each of the customers. Inverse multiplexing over a number of copper pairs running VDSL modems, is used to aggregate the requested bandwidth between the main ATM switch located at the telephone exchange building, and nodes in the network. With access lines of 25 – 50 Mbit/s the needed bandwidth between the nodes will be in the 100 – 1000 Mbit/s range. 100 – 1000 Mbit/s can be obtained by inverse multiplexing up to a few tens for lines. Each network node performs both inverse multiplexing and statistical multiplexing of traffic flows from the individual users. The users are connected to the nearest node by VDSL modems, thus giving them access to a large aggregated bandwidth, which has to be shared among them. The nodes will be equipped with signalling according to standards, thus enabling SVCs (Switched Virtual Connections) with QoS (Quality of Service) as defined by relevant standards.

The structure of this network is more or less identical with the recommendation from the FSAN (Full Service Access Network) consortium. The difference is that FSAN recommends optical fibres between the nodes, while this approach is based upon copper. However, due to the similarities between the two concepts, it is easy to adopt the technology that best fits the need in each case. On sections were optical cables can be installed at low cost, fibre cables are the natural choice. But on sections where optical cables cannot be installed at a reasonable cost, inverse multiplexing is the choice. The two approaches go hand in hand – they will complement each other in a way that both the operators and the public may profit from.

5 The ACTS project AC309 ITUNET

To promote the network concept and to pave the way for commercial products needed to implement this kind of network, the ACTS project AC309 ITUNET was initiated. The project started in March 1998 and will continue for two years. One of the main objectives of the project is to study how the existing access network infrastructures can be upgraded using xDSL technologies to form a cost-efficient integrated service network providing the necessary capacity and functionality for broadband services. By conducting field trials the project seeks to prove the viability of the adopted network topology for the realisation of an end-to-end ATM network providing a selection of broadband applications. Through the trials, ITUNET will gain valuable experience, both with regard to installation and operation of the proposed platforms, and to the end-user's perception of the supplied broadband services.

One key component in the proposal is the development and evaluation of a network node being able to perform both inverse multiplexing and statistical multiplexing. The equipment will be used in various field trials aiming to visualise the potential usage areas of the technology. Three areas are identified:

- In a Full Service Access Network based upon the existing telephone access network;
- As above, but in combination with other fibre technology;
- In corporate networks.

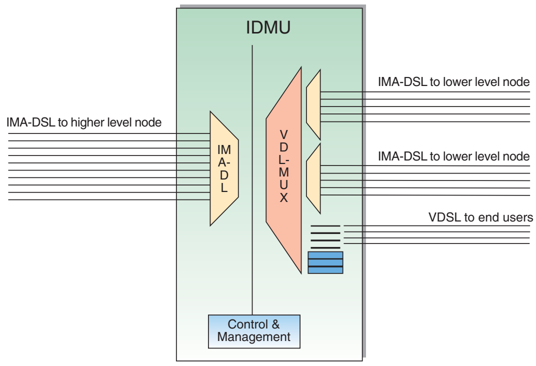

Figure 5 A network Node

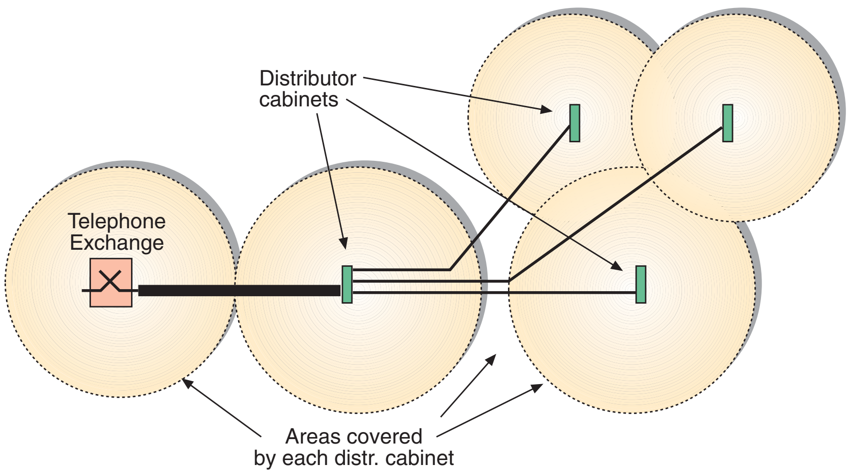

Figure 6 The architecture of the new network

In order to demonstrate services in the network, ITUNET has chosen two services that will be partly developed in the project:

- Switched broadcast TV (SBC-TV) based upon use of the UNI 4.0 signalling protocol (multi-cast);
- Video Surveillance enabling a number of video channels to be multiplexed and transferred over the network.

The new network concept will be a rather complex network. Signalling and resource management may have to be implemented further out in the network than today's recommendations prescribe. The technology also makes it possible to utilise Adaptive Asymmetrical Systems (AAS) – a method of adapting upstream and downstream capacity to the actual traffic profile. The management of Floating Transmission Capacity (FTC) is also an important issue to manage. FTC is a consequence of using bit rate adaptive modems. The capacity of the physical lines may vary over time due to varying line conditions. The project also aims to perform in-depth calculations and evaluation of the cost related to establishing an access network based on DSL. An evaluation with regard to service provision in the proposed access network will also be performed.

6 Evaluation

The general complexity of a network node is comparable to what is implemented in existing ATM switches and multiplexers. The concept does not involve unknown technology. All the basic technology is more or less available. VDSL modems and inverse multiplexing technology are key elements in the network concept. The present status for these elements is:

VDSL modems, which are a basic component both in this concept and in the FSAN recommendation, are under standardisation and partly available today.

Inverse multiplexers adapted to the standardised transmission systems (T1, T3, ...) are available. With regard to inverse multiplexing over DSL technology, this kind of equipment is not available today. However, work has begun to find industrial partners being interested in making commercial products.

A case study is being performed in order to have a rough evaluation of the implementability of such a network and the cost to establish it. A local network in a residential area (NorVillageA) has been chosen for this purpose. Figure 7 shows an overview drawing of the converted network. NorVillageA has 728 telephone subscribers. 384 of them live closer to the telephone exchange building than

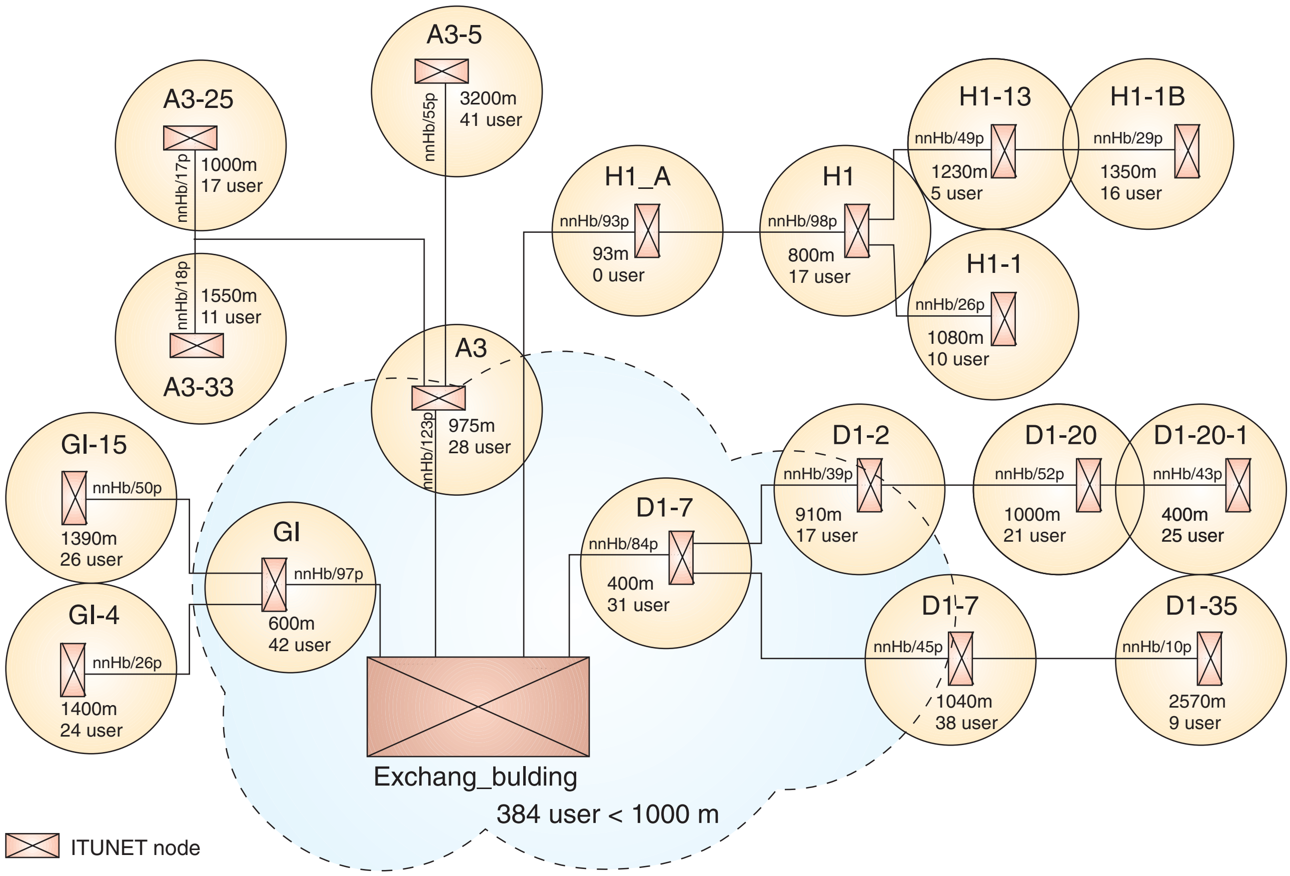

Figure 7 An overview drawing of the converted network

1,000 metres, thus one can provide 25 – 50 Mbit/s to each of them with single user VDSL modems. The remaining subscribers, 244, must be connected via inverse multiplexed equipment. The case study revealed that:

1 It is not possible to place the new nodes at optimal locations. The nodes have to be installed at central points in the cable network, ie. at cabinets which form 'distribution' points in the cable network structure. As a result of this, the number of network nodes will be higher than expected.

2 Relatively few users will be connected to each network node, ie. less statistical gain.

3 Due to non-optimal location of the network nodes, the case study shows that one needs up to 4 cascaded nodes in order to reach the most distant users.

7 Comparison of the FSAN and the ITUNET concepts

The technology and the network concept of ITUNET are introduced as an independent strategy for building a broadband access network. The concept is well adapted to other approaches, such as the FSAN approach. These two strategies are complementary in the sense that one easily can combine sub-nets based on the two technologies without large influence on the planned network structure. Both of the two approaches rely on utilisation of the existing telephone network. Optical fibres can supplement a network based upon the ITUNET ideas, as well as inverse multiplexers can supplement a network based on the FSAN concept. Since there are a number of similarities between the FSAN and the ITUNET concept, it is of special interest to compare them. The principal structure of the two networks are shown in Figure 8.

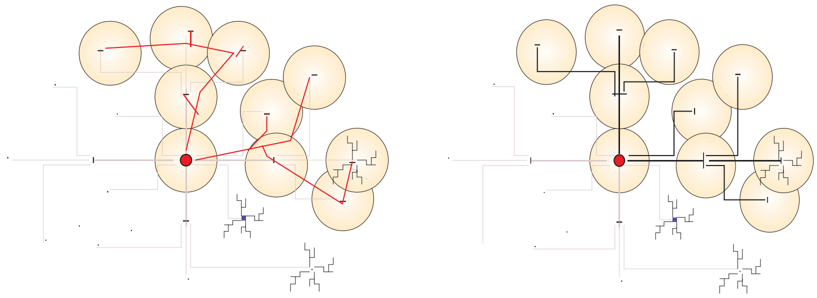

Figure 8 The FSAN (left) and ITUNET (right) network structures

In summary, here is a very brief overview of the two concepts:

- The FSAN concept is based upon fibre optic communication between network nodes. Installation of optical cables often involves large investments both in optical cables and civil work. The operation, administration and maintenance costs however, are assumed to be very low for fibre compared to copper.
- The ITUNET concept uses the existing local telephone cables between the network nodes. Investments as mentioned above are not relevant, but inverse multiplexers (an integral part of the remote node) are used to establish the needed bandwidth between the nodes.
- The number of VDSL modems – an often heard objection against the ITUNET approach. The modems used for inverse multiplexers are a common resource for a number of users, and in total it is expected that the ITUNET concept only will use approximately 10 – 15 % more modems than the FSAN strategy.
- An optical cable has more capacity than a telephone cable, but the bandwidth of the latter will in most cases be sufficient. Bandwidths in the range of Gbit/s can relatively easily be achieved.
- None of the concepts need to influence on the telephony service. Both analogue and digital telephony can be transmitted in a separate frequency band on the twisted pairs.
- The complexity of the remote network nodes in the two cases will differ slightly since inverse multiplexing will have to be integrated in the ones used for the ITUNET concept.

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Transmission on power line cables

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1 Introduction

Transmission on power line cables is currently the subject of much research and development activity, constituting a potentially very attractive alternative access technology as the power utility companies are considering to enter the residential telecommunications market. Power Line Communications refers to the transmission of data over the low voltage electricity distribution network. This is achieved by injecting the data signal at the low voltage transformer via a power line modem. Another modem in the customer premises extracts the signal. The transformer serves a number of houses and consequently, the data signal is shared between that number of customers. Two types of transmission capabilities are distinguished, namely, Power Line Communication (PLC), which operates in the range of kbit/s and Power Line Telecommunication (PLT), which is able to transmit data in the range of Mbit/s [1].

2 Power network structure

The architecture of the electrical power network is one of the most important factors in determining whether it is suitable for data transmission. Figure 1 shows the generic European power network structure.

Power is transmitted to customers via the high voltage transport network at 220 kV – 800 kV and the low voltage distribution network at 220 V – 240 V. The low voltage distribution network is used for PLT. In urban areas in European countries approximately 200 homes are served by the final transformer and the distance from each house to the transformer is usually from 50 m to 400 m. The distribution network is a mixture of overhead and underground cabling with a majority of underground cable in urban areas.

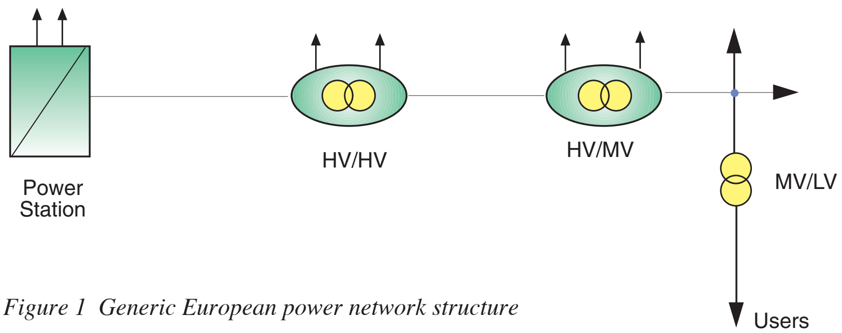

Figure 1 Generic European power network structure

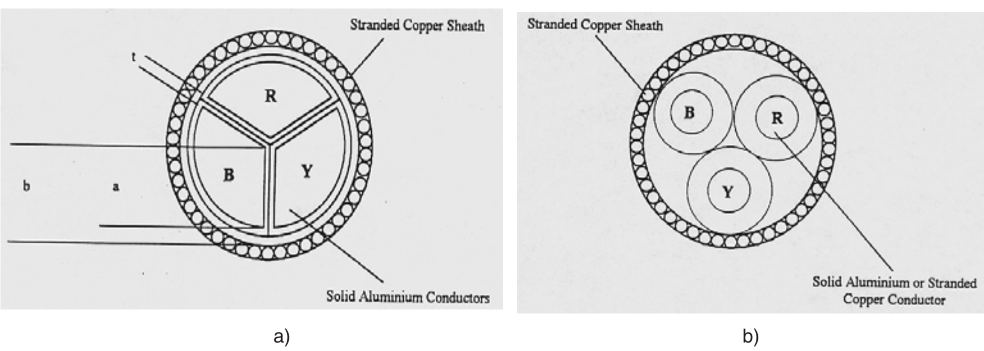

Figure 2 Typical modern electricity distribution cable structure; (a) sector-shaped conductors, (b) circular conductors

3 Power cable characteristics and transmission techniques

The suitability of a power distribution network for PLT use is affected by the physical characteristics of the cable. A number of different cable types may be found. Typical cable construction for two types of modern distribution cable is shown in Figure 2. Figure 2a shows a cable with sector-shaped conductors and Figure 2b shows a cable with circular conductors.

Practical testing on low voltage distribution networks in the UK has shown that for the frequency range 1 to 10 MHz the attenuation can vary anywhere between 30 dB and 90 dB for a network of length 250 m. The variation in attenuation is caused by reflections from impedance mismatches at the end of each spur and from any point on the cable where its electrical parameters change. The distribution cable size reduces as distance from the transformer station increases – typically being 185 mm^2 on leaving the station and reducing to 95 mm^2 after some distance.

There are several obstacles to be overcome in attempting to transmit high bit rate data signals over the electrical power network. Its bus architecture is heterogeneous (in electromagnetic terms) and the impedance is not well defined. In addition, the noisy nature of the network between the transformer and the customer premises, and inside the home, requires sophisticated but feasible techniques. Among the most promising are Coded Orthogonal Frequency Division Multiplexing (COFDM) and Spread Spectrum techniques such as Direct Sequence Spread Spectrum (DSSS), and Frequency Hopping Spread Spectrum (FHSS).

4 Electromagnetic Compatibility standards

Power line telecommunication technologies use frequencies above 1 MHz (up to 30 MHz) to deliver broadband services over not dedicated cables. So it is important to consider EMC (Electromagnetic Compatibility) issues. At the moment no standards exist regarding this specific subject over power lines. The only existing standard concerning the power lines is the CENELEC 50065 that takes into account “Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz”.

Electromagnetic Compatibility concerns the ability of electronic equipment to function correctly in a disturbed environment (immunity), while limiting the disturbing effect (emission), of the equipment on its environment. The evaluation of EMC performance should include equipment, cabling, outlets, connecting hardware, electrical interfaces and cable termination at the equipment.

5 Digital power spectral density

In order to make a comparison with the Digital Power Line technologies, it is useful to collect the values of the different digital technologies that have been already standardised. Here, the Power Spectral Density (PSD) for copper digital technologies such as ISDN, HDSL, ADSL and VDSL are presented. Figure 3 shows the PSD for copper digital technologies.

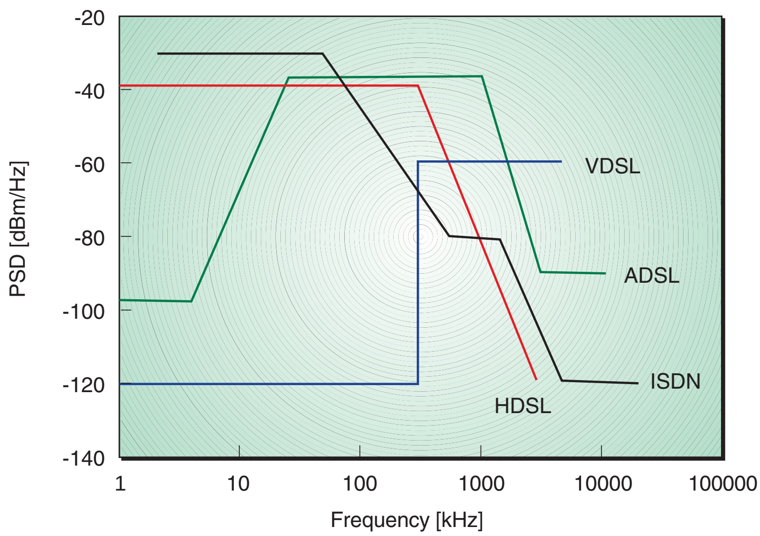

Figure 3 PSD for digital technologies

6 Services and Applications

Services and applications fall into two general classes. Firstly, low speed (kbit/sec) telemetry applications and secondly, new high speed (Mbit/sec) applications for telecommunications. Another distinction to be drawn is that between indoor and outdoor applications where the power meter is the boundary since it blocks the PLT signal. These two networks are illustrated in Figure 4.

Indoor applications refer to the use of the indoor power network for communication with household appliances. Outdoor applications are those which use the low voltage distribution network between the customer premises and the electricity company transformer station. This is currently considered a low bit rate field of application and includes such tasks as power supply load management, tariff switching and remote meter reading [2, 3, 4, 5, 6, 7]. Telecommunications services which could be provided are voice telephony and data services such as Internet provision. The latter, in particular, is seen as the ‘killer application’ for PLT. Table 1 compares access technologies in terms of limitations and functionalities.

Current field trials suggest that a capacity of about 1 Mbit/sec per final transformer may soon be available. It is indicated that a penetration rate of about 10 % will be necessary to make the service commercially viable. Then, with 200 customers

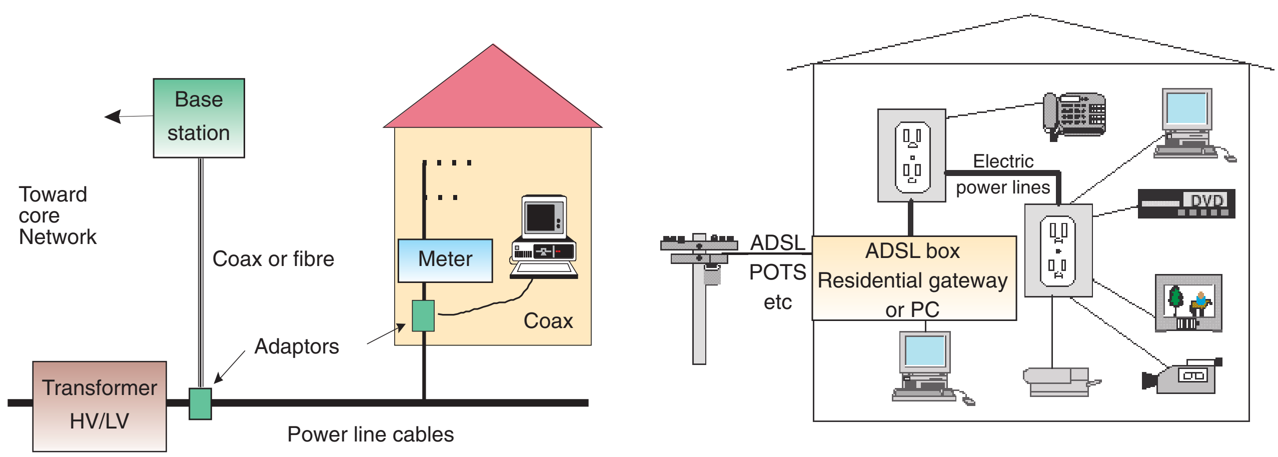

Figure 4 Indoor and outdoor powerline networks

Table 1 Comparison of technology features

Media	**Twisted pair**				**Coaxial cable**	**Power line**
Method	POTS	ISDN	ADSL	ADSLlite	Cable Modem	PLT
Media type	point-to-point				shared	
Switching type	circuit		packet		packet	to be determined
User interface up (kbit/s)	33	144	~ 640	512	2000	to be determined
User interface down (kbit/s)	56	144	≤ 8000	1500	25000 (shared)	1000? (shared)
Point of access	phone plug	S interface	specific cabling	phone plug	cable plug	power meter, specific cabling
Required upgrade from POTS other than POP access	--	NT, digital line card	modems	modems, distributed filters	modems, access to cable network	modems

per transformer and an activity rate of 0.1, a customer could have up to 500 kbit/sec available. This would, clearly, represent a substantial improvement over current PSTN-based access bit rates. However, at the moment dedicated cabling from the electricity meter to the modem is required.

7 Power line products

A number of products are available which use the power line for communication. Most are intended for low bit rate telemetry applications such as automatic meter reading and power supply management. Some products are intended for voice communication but also at low bitrates. For telecommunication applications, products are available for indoor use which are designed to communicate between household appliances and between computer equipment in the home. The only known outdoor high speed product is the Nortel/Norweb power line modem.

8 Field trials

Independent verification of field trial information is very difficult to obtain and the information presented here is taken largely from the press and press releases of the companies involved. Nortel/Norweb have conducted field trials in the UK using their Digital PowerLine technology to provide voice and Internet services [8, 9, 10, 11]. The Internet trial connected 12 computers using a shared 1 Mbit/sec power line link. A larger Internet trial is planned. Additional field trials are in progress, planned or under consideration in some European countries, such as ENEL Spa in Italy (planned Internet access trial) and Tesion Communications in Germany/Switzerland (meter reading, Internet access). Meter reading field trials are in place in Spain and Italy.

9 Conclusions and open questions

The message for the Network Operator is one of 'wait and see'. The number of power line products available is now quite limited and in the case of outdoor Power Line Telecommunication (PLT) services there is only a single product. Power line technology is not now a competitive threat to the incumbent operator.

The low voltage electricity distribution network is not now an alternative to the Network Operator's access network for telecommunications services. This is due to the immature nature of PLT technology.

The PLT infrastructure is owned by an actual or potential competitor in most European countries. Consequently, it is difficult for a traditional Network Operator to trial or properly measure the performance of PLT products.

There are currently no published standards for PLT. The CENELEC 50065 standard will not cover PLT since it specifies a maximum transmission frequency of 140 kHz. High bit rate PLT applications will require a spectrum of 1 to 20 MHz or more. Electromagnetic Compatibility at these high frequencies may be problematic. The Radio Society of Great Britain believes EMC targets for PLT will not be met and so it opposes PLT completely.

The role of the domestic power meter in the power line communications circuit is unclear. Currently, it acts as a barrier to PLT signals and consequently there exists separate products for outdoor and indoor use. The need to access the PLT signal from the meter is inconvenient for the consumer and the PLT service provider. However, there is no obvious reason why this situation should continue and the development of a power meter which does not block PLT signals can be foreseen.

There is no inherent physical barrier to the further development, improvement and commercialisation of PLT technology. It can be expected that PLT will be driven by business needs and that if it is seen as viable, then higher performance PLT systems will surely appear. For this reason and due to its near-ubiquitous customer coverage, PLT technology has the potential to being a serious competitor to traditional Network Operators.

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Component technologies for wireline broadband access networks

DANIEL LECROSNIER

Infrastructure costs represent one of the most important factors in the global cost of an access network construction. Advances in this field can strongly influence the practical feasibility of new network deployment. The purpose of this paper is to address the basic elements – including key components, installation techniques and powering – needed for the construction of wireline FTTx infrastructures supporting broadband services. Up to now, most optical technologies used in access networks have been developed for the long haul application for which cost is not a prominent factor. However, in the last few years, the specific access network requirements have been stressed and made clearer both in the framework of the FSAN initiative and in EURESCOM P614 project "Implementation Strategies for advanced access networks". As a result, the maturing of optical technologies is in rapid progress to meet access network requirements. A few examples will be presented indicating how technical and economical barriers should be overcome in the near future.

1 Introduction

With the explosion of Internet-based services, there is an increasing demand for access networks supporting high bandwidth. This demand is now clearly identified for business customers and will appear in the near future for professionals, and later for residentials. For network operators a broad diversity of implementation is becoming available to meet the great variety of customer demands.

On the one hand, the full exploitation of existing infrastructures, ie. re-use of copper pairs, coaxial cables and, under certain circumstances, even powerlines only need new electronic-based equipment to be installed at the local exchange and at the customer premises. Considering ADSL as an example, a technology analysis of currently available modems reveals that they rely mostly on conventional CMOS circuits, therefore no major technical barrier has to be overcome for their fabrication. Modem cost evaluation can be easily predicted using the well known silicon industry economic trends, and the low cost target will be achieved if a high volume (above 1 million pieces) market is reached. However, this approach of upgrading copper networks presents limitations with respect to bandwidth, distance and quality performances.

On the other hand, the laying of fibre rich infrastructure appears as the most promising solution to overcome the above mentioned copper limitations and for serving new-built areas. Optical fibre is now widely used for long distance trunks, and in the access network it is assumed that fibre could also be the basic medium to construct a core infrastructure supporting full wideband services. At present, the real implementation of optical infrastructures require heavy investments, not only due to the use of opto-electronic equipment but mainly due to fibre deployment. As a consequence, cost evaluation of fibre-based infrastructures is a very relevant issue for network planners.

In the following sections the various elements needed to construct an FTTx infrastructure are reviewed and discussed with the main emphasis on recent advances and cost reductions in optical technologies.

2 FTTx infrastructure for access networks

Figure 1 shows a variety of ways to build broadband access networks based on fibre deployment. Today, the basic architectures under study in most countries are:

- FTTF/O: Fibre to the floor/office;
- FTTB: Fibre to the building;
- FTTCab: Fibre to the cabinet;
- FTTH: Fibre to the home;
- HFC: Hybrid fibre coax;
- HFR: Hybrid fibre radio.

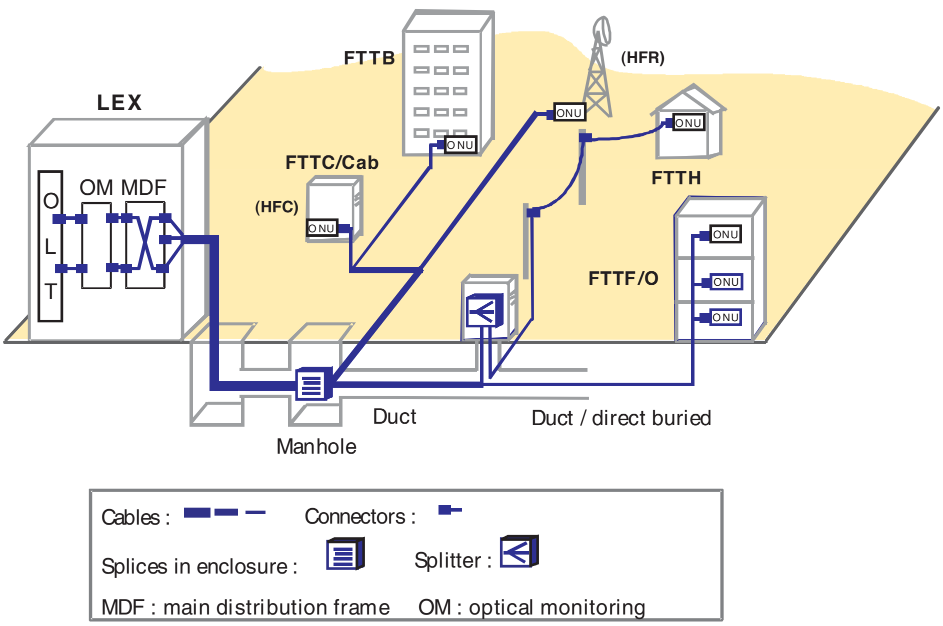


Figure 1 FTTx infrastructure

The construction of a fibre rich access network relies on the implementation of several major building blocks. In the local exchange, the OLT (Optical Line Termination) ensures the interface between the switching equipment and the ODN (Optical Distribution Network). The OM (Optical Monitoring) module of which the functionality is to survey the ODN quality and an MDF (Main Distribution Frame) which provides a connection point between equipment and outside cables. For outside plant construction, it is necessary to consider the hardware parts (cables, splices, splitters, connectors and enclosures) together with civil work and installation techniques. The optical network terminates at the ONU (Optical Network Unit) whose location depends on the chosen architecture. Finally, powering equipment is needed to supply all active equipment.

3 Optoelectronic conversion modules

For both OLT and ONU equipment, the optoelectronic conversion is a critical functionality with regard to cost. As large volume production is a prominent factor for cost reduction, common physical media layer requirements have recently been agreed on within the FSAN initiative [1] and ITU-T [2]. Table 1 indicates basic parameters for ATM/PON systems. From the FSAN study it has been demonstrated that bi-directional transmission over one fibre using 1.5 μm (downstream) and 1.3 μm (upstream) windows is more cost-effective than two fibre transmission [3].

The presently available technology for production of O/E modules is generically called micro-optics. It relies on assembling several individual parts as sketched in Figure 2: a laser diode, a photodiode, a wavelength dichroic filter, etc., which all need to be mechanically assembled with lenses and fibre with less than a micrometer tolerance with respect to optical axes. This requires the use of high precision materials and components and time consuming operator assembling. As a consequence, automation of the assembling process is limited, which severely impacts fabrication costs.

To reduce the cost, a new generation of modules is under development in many companies. It is based on hybrid integration of optoelectronic chips with passive optical components (splitter, filter) implemented with the Planar Lightwave

Table 1 Optical access network requirements

Optical transmission	**2 fibres** **1.3 μm**	**1 fibre** **WDM** **1.3↑ 1.5↓**	1 fibre WDM 1.3+↑ 1.3–↓
Bit rate (Mbit/s) between OLT and ONU	Downstream		Upstream
Symmetric 155	155.52		155.52
Asymmetric 622	622.08		155.52
Optical path loss	10 – 15 dB (G.982 Class B) 15 – 30 dB (G.982 Class C)		
Differential path loss	15 dB		
Overall reflectance at S/R points	32 dB		
Temperature FTTH ONU	0 to 60°C (case temperature) –40 to +85°C (storage)		

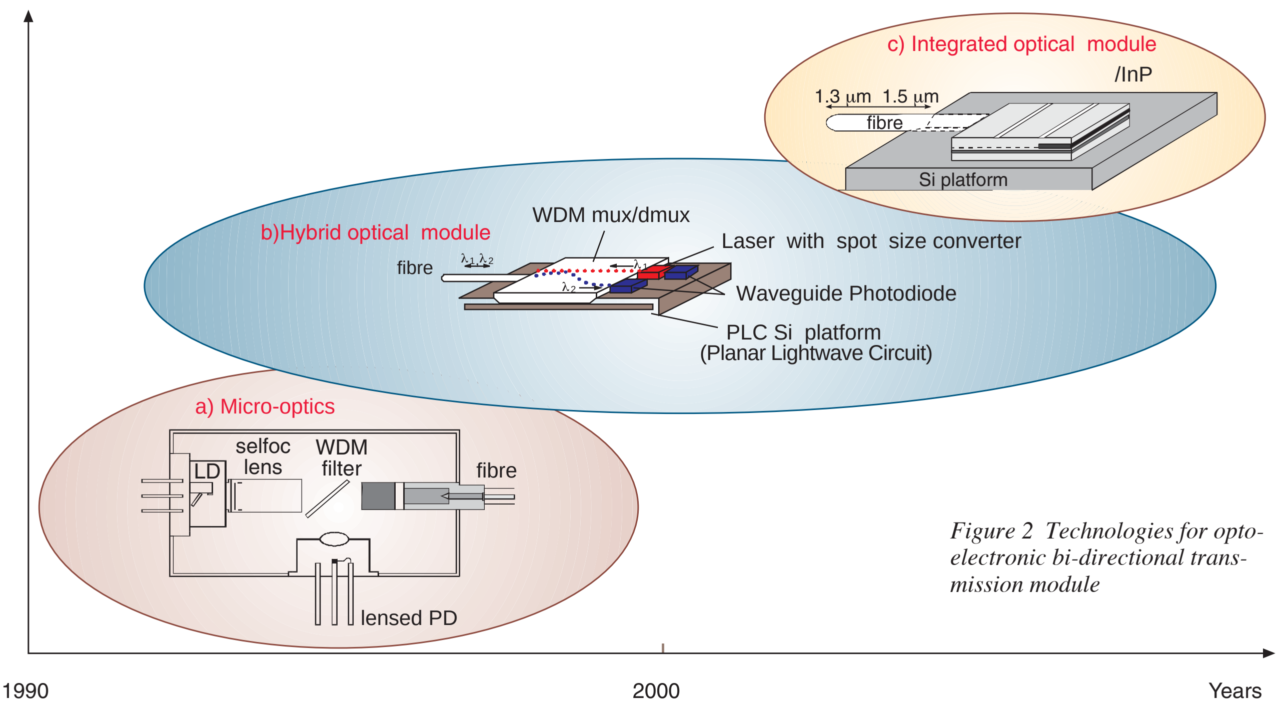


Figure 2 Technologies for opto-electronic bi-directional transmission module

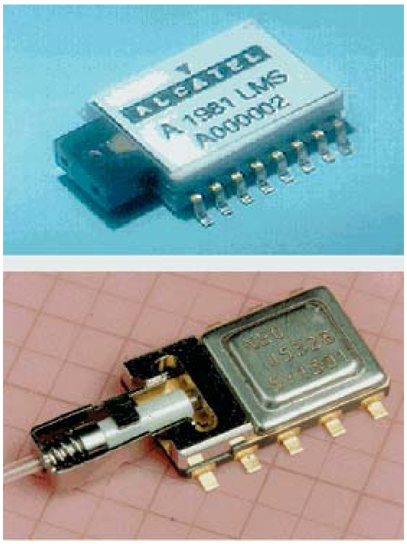


Figure 3 Detachable pigtail packaging for automated board mounting

Circuit (PLC) technology. PLC technology uses dielectric waveguides (Silica on Silicon) deposited on the same silicon motherboard that performs chip and fibre self alignment. In addition, the planarity of this assembly technique permits a packaging suited for automated surface mounting on printed boards. Examples of a detachable pigtail device are shown in Figure 3.

Finally, monolithic integration of the optical and optoelectronic functions in a single semiconductor chip is at a research stage and could lead to further cost savings. Yields and material compatibility for different functions are the main issues at present. A production status is unlikely to be reached before year 2000.

Prices of optical modules produced with different technologies for different production volumes are presented in Figure 4, taking as a reference a bi-directional transmission at 155 Mbit/s for G.982 class B standard. Cost evolution over the last two years clearly shows a dramatic decrease for the so-called micro-optic technology while PLC hybrid integration is still at prototype level. For mass production level (one million pieces a year) a target value as low as USD 40 seems realistic both with micro-optic and hybrid technologies.

4 Optical cabling

4.1 Access network requirements

During the last ten years, optical fibre has demonstrated great qualities for the long-haul applications; among them capability to transmit very high bit rates, insensitivity to electromagnetic perturbations leading to very low bit error rates, and a reliability better than coaxial links. In comparison to the long distance network, the access network has several specific requirements:

- In urban areas, the topology presents many bends and the ducts are usually occupied by other cables, therefore installation of a new infrastructure is often contracted in small volumes leading to a small bending radius for fibre and cable;
- Cables are installed in various conditions: outside, underground (in duct or buried), aerial, indoor (in operator building and in customer premises). Consequently many thermal, mechanical and other stresses have to be taken into account such as humidity, temperature variations, UV exposure, wind, frost, snow and shots;
- The links usually comprise many connections, so it is desirable that installation does not require specially trained technicians; easy preparation of fibre for splicing and for connector mounting is recognised as a critical issue;
- The cost of the global link has to be low.

4.2 Low diameter, low weight, high density optical cables

Figure 5 presents geometrical and weight characteristics for typical copper and optical cables of a quite similar capacity. It clearly shows that optical cable technology leads to a tremendous reduction in weight as well as in diameter parameters when compared to the copper cables and therefore offers large potentials for lower installation costs. Small diameter and high density cables really open the door to a re-use of existing civil work in case of overlay fibre deployment. Moreover, ultra high density cables can be realised by using the newly developed multicore fibre [4].

From recent cost analysis it appears that today's price of bare G.652 standard fibre is quite uniform world-wide: it ranges from USD 40 to USD 60 per kilometre. It is about twice the copper pair price. Following the fibre prices, which have been continuously dropping during the last years, quite similar values for fibre and copper pair prices are expected in the short term.

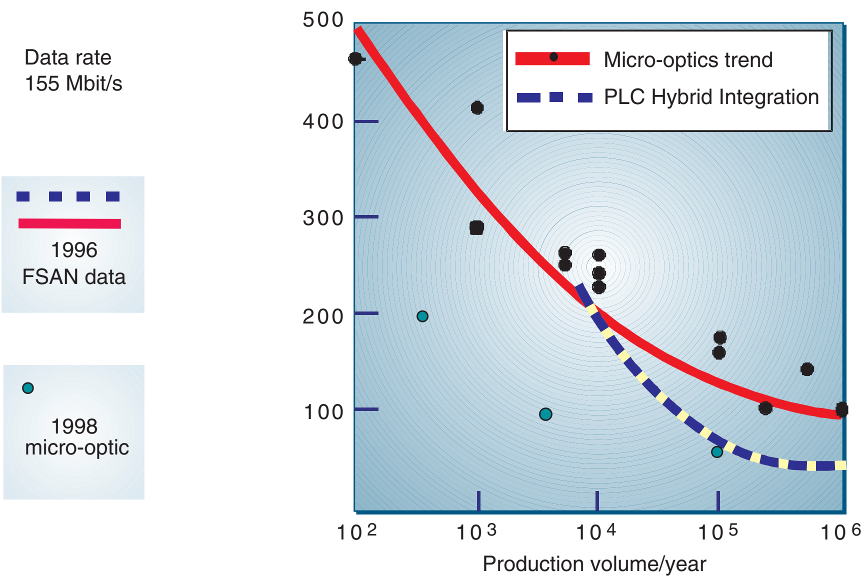


Figure 4 Optical module cost dependency on volume

4.3 New installation techniques

In addition to the usual pulling and pushing methods, the blowing technique is now recognised as a technology breakthrough for low cost installation of optical cables. Taking advantage of the tiny nature of fibre, British Telecom researchers first proposed this method. The fibre unit is placed in a machine where it is pushed forward by a little caterpillar or by a series of wheels. On the fibre unit two kinds of pushing forces are therefore present: the concentrated force due to the caterpillar and the distributed force along the duct due to the compressed air. The distributed force limits the effects of the curves on the maximum installation length, so that air blowing techniques could be particularly useful if the installation route is quite tortuous.

Significant improvements have been added to the initial blowing concept allowing the installation of a great variety of cables over long distances. To the head of the cable a small piston is connected (see Figure 6) in order to produce an additional pulling force. If the piston is an airtight one, the compressed air pushes it and consequently the cable is pulled by the piston inside the duct. In this case, the flow of compressed air does not produce a distributed pushing force along the cable length because it is stopped by the piston, but it contributes to reduce the friction between cable and duct.

If the piston is not an airtight one both contributions are present: a small pulling force on the head of the cable and a force due to the pressure drop along the conduit, distributed along the cable. Recent improvements in the piston design called 'sonic head' [5] allows the extension of the trajectory of the cable.

With both techniques, according to cable weight and installation route, it is possible to install cable lengths with a maximum of 1500–2000 m in one step. This technique is applicable for both outdoor and indoor installations.

For buried cables, a Micro Cabling System concept has recently been proposed by Siemens [6] in order to reduce installation costs and installation time. This is achieved by means of a simple but rugged design cable which is laid in a very low depth groove dug into the asphalt of road or pavement (see Figure 7). As a result the cable is required to meet exact demands as to crush resistance and, in particular, temperature resistance which is needed when sealing the cable in the groove with hot bitumen. This new technique is significantly more cost effective and more rapidly deployable than a standard solution.

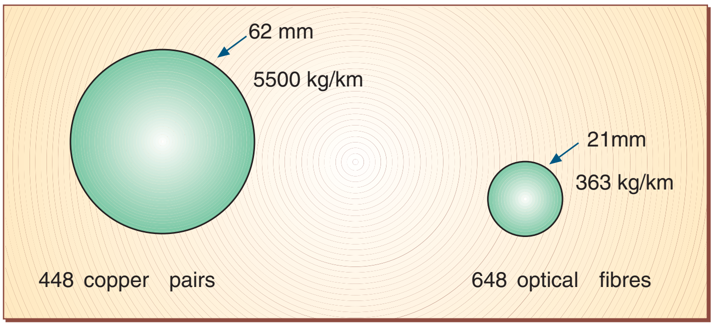


Figure 5 Comparison of currently available copper and optical cables

4.4 Connecting technologies

4.4.1 Connectors

Connectors used in access networks could be installed in the outside plant as well as at the customer premises, therefore, in addition to the general requirements of optical links, some specific features become critical. For example, the connectors set up inside the customer home must be secure, robust and friendly to be handled by unskilled people.

As many optical devices which have initially been designed and produced for the long haul transmissions, connectors have to be hardened and adapted to fulfil access requirements. The main specific requirements are:

- Reliable coupling mechanism both between the plug and the pigtail and

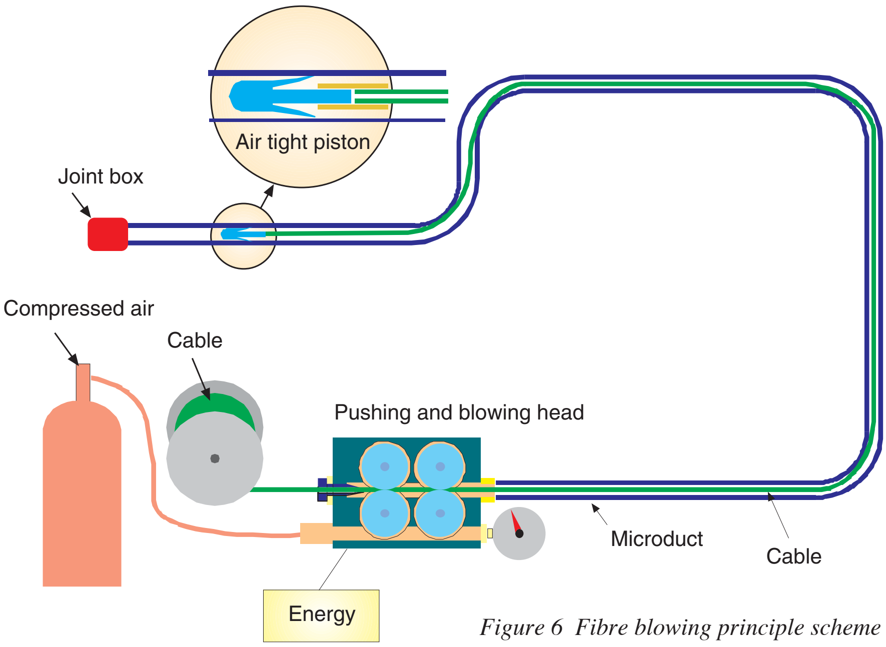
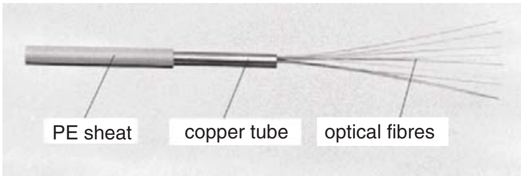


Figure 6 Fibre blowing principle scheme



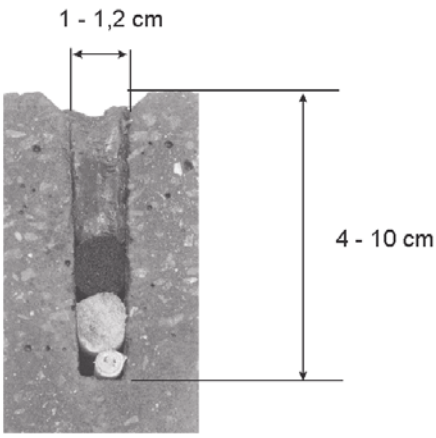


Figure 7 Low depth buried cable

between the plug and the adapter in order to face accidental pulls;

- Reliable optical performances;
- High mechanical strength against accidental crashes or drops;
- Good endurance to the temperature changes (above all for connectors set up in outside plants);
- Easy and quick field installation;
- Protection against eye-damaging laser radiation;
- Low cost.

One major critical point has been stressed by EURESCOM P614 members: connector field assembly capabilities appear not yet ready for true mass application. Fibre preparation, fibre positioning into the plug, fibre ending still require well-trained technicians and expensive tools. In fact, at present, most operators buy pigtailed connectors and splice the tails in. Significant improvements in connector and fibre technology are expected to solve this problem in the very near future.

In addition, to reduce cost some innovations are also desirable:

- Ceramic ferrule replaced by glass or plastic;
- Ferrule-less connector;
- Multi-fibre connectors allowing miniaturisation.

With present technologies, prices range from USD 8 to USD 25 depending on basic performances (insertion loss and reflection). A cost target in the range of USD 4 to USD 10 seems within reach at high volume production.

4.4.2 Splices

The installation of a future proof and stable infrastructure could represent a key factor in a competitive market. The splices and the enclosures as joint elements have a strong impact in this environment as they must guarantee high quality, low maintenance and low installation cost.

Concerning splices, two technologies are still competing at present: fusion and mechanical. At present, fusion splice using ribbon fibre arrangement appears as the preferred jointing technique. This technique provides very low losses (0.1 dB) and low reflected light (50 dB) in the whole temperature range for outside operation. Cost investigations of fibre splicing have revealed a high sensitivity to specific factors such as field labour cost and splicer amortisation which are liable to strong variations from country to country.

Mechanical splices are usually related to the temporary situation, as in the case of emergency restoration. From a technical point of view the mechanical splices have some weaknesses as compared to the fusion splicing: lower tensile strength, higher return loss and the use of index matching gels which are temperature sensitive and less suitable for multiple fibre arrays.

4.4.3 Enclosures

The purpose of an enclosure in communications systems, whether employing copper or fibre-optic cables, is to protect the splices and all other components of a cable at a jointing or branching point. General requirements for optical cable splices have been proposed for enclosures:

- *Mechanical strength:* The enclosure must have sufficient mechanical strength to withstand external forces acting on the laid cables, such as vibration, tensile and compressive forces. Its lifetime should be at least as long as that of the cable.
- *Pneumatic seal:* Generally the enclosures are installed by placing them in manholes. So the device must be tightly sealed to prevent the effect of water or moisture which would damage fibres.
- *Enclosures function:* In order to easily maintain and upgrade the network the enclosures should be readily accessible and simple to use (no special training, short intervention time, no special tools).
- *Chemical resistance:* The enclosure material should have a strong capacity to resist the attack from chemicals, such as acid, base, solvent, etc.

With today's technologies, the above requirements are usually fulfilled by manufacturers. However, large cost variations are found mainly due to small volume production. Fully standardised products will be beneficial for the operators.

5 The splitter

The splitter is a basic device for PON systems, since it permits not only a sharing of the fibre in the network but also a sharing of optoelectronic converters in the central office. Three basic technologies exist today:

- *Fused fibres (a):* This technology appears well suited for low splitting ratios (up to four) but suffers from a rather large package when splitting ratios increase. This is mainly due to the splicing technique used for concatenation of 1:2 couplers. Example: 1:16 splitter, dimensions 150 x 100 x 20 mm.
- *Planar glass (b):* Waveguides are obtained by diffusion techniques into glass substrate.

- *Planar Lightwave Circuits (PLC) (c):* Waveguides are made of silicon oxide layers deposited either by flame hydrolysis (which was initially developed for fibre fabrication) or by plasma techniques. Substrates commonly used are silicon or glass.

Both b) and c) technologies apply some of the well matured silicon microelectronic processes (eg. lithography, etching) to delineate the various branches of a splitter; devices with ratios up to 16 (and even 32) are now fabricated in a very compact package. Example: 1:16 splitter, dimensions 90 x 10 x 6 mm. The cost is about USD 50 per port for 5,000 pieces, which is quite a high figure. By contrast to connector or splicing devices which serve only to joint fibres, splitters have a higher functionality. They have a strong impact on network implementation; their installation requires a careful analysis taking into account many parameters such as installation planning, impact on maintenance, network upgradability. One basic point is its location: in the field or in the central office. These two options have been studied in EURESCOM P614 together with point-to-point links as sketched in Figure 8. This comparison highlights the advantage of point-to-point solution when considering network functionality (O&M, service provision, quality and upgradability) as a strategic parameter [7].

6 Hardware maintenance – optical monitoring

ITU-T gives the following definition of maintenance: *"Maintenance involves the whole of operations required for setting up and maintaining, within prescribed limits, any element entering into the setting up of a connection"* [8]. Starting from this generic definition, EURESCOM P614 proposes the concept of hardware maintenance: *"Hardware maintenance covers all the means to guarantee the performances of the physical carrier (fibres, twisted copper pairs, coaxial, splices, connectors, passive components, enclosures), and specifically to detect and locate any fault in the access network"*. Some guidelines have been established and a procedure is given based on three parts: acceptance of components, network qualification and network monitoring. As regards the optical infrastructure, monitoring should identify problems such as slow and uniform degradation as well as abrupt fault (for example cable break). To implement the monitoring of an optical infrastructure three methods can be envisaged: use of a dedicated branched fibre monitoring, 'dark fibre' and on-line monitoring [9]. On-line techniques refer to the monitoring of every transmission fibre while the services are running and consequently allowing a high quality of service offer. However, the implementation of on-line monitoring based on OTDR (Optical Time Domain Reflectometry) as sketched in Figure 9 needs a heavy investment which should be justified when high quality transmission guarantees are required.

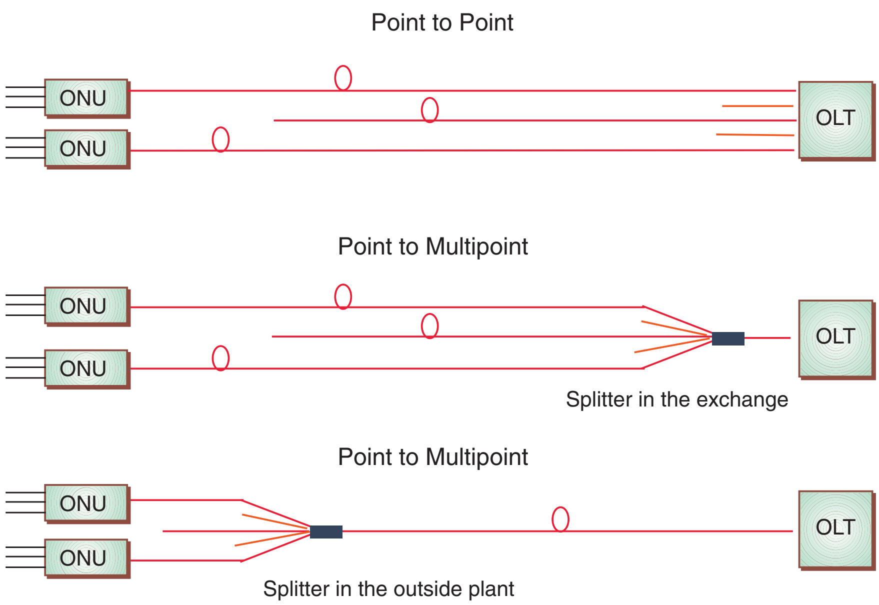


Figure 8 PON and point-to-point network topology

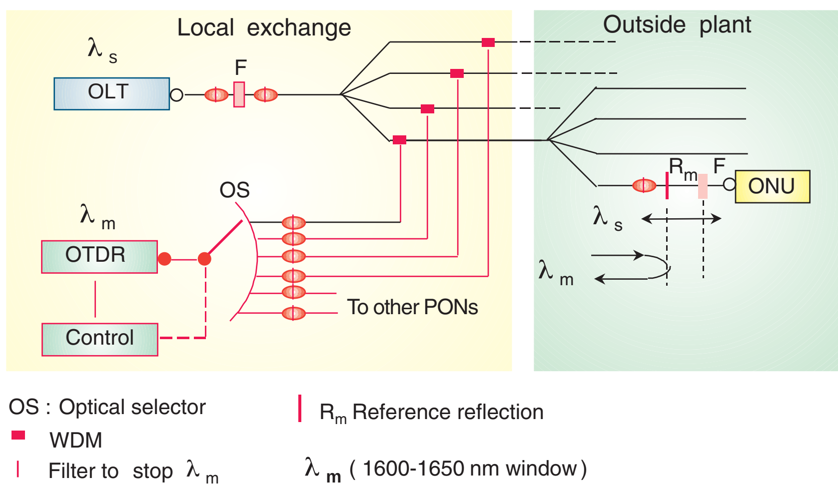


Figure 9 Optical maintenance scheme based on reference reflection and optical selector

7 Powering

Contrary to the copper pair, the fibre does not transport energy, therefore the powering of ONUs is a hot topic in the network planning due to the use of active equipment in the field. To solve the problem some solutions exist based on two major architectures, namely local or remote powering. The decision to opt for a particular powering architecture relates not only to its cost. Field constraints of a non-technical nature mean that very difficult decisions have to be taken regarding the place where the powering equipment is installed. Experience with installing classical CATV networks has shown all the difficulties of performing maintenance on equipment in the access network, especially for installations in private buildings. Although no specific solution can be rejected *a priori*, each option has its own particular difficulties, mainly in heavily populated urban areas:

- *Installing equipment in a private building:* This is the preferred solution for equipment environmental conditions. However, many old buildings do not have plant rooms; moreover, installing equipment in one building to supply other buildings raises problems of accessing the building 'playing host' to the equipment if maintenance needs to be carried out.
- *Installing equipment in a street box:* The equipment environment conditions are much less favourable (reduced capacity for the batteries at low temperatures and reduction of battery life at high temperatures). Furthermore, operators of various networks find it difficult to obtain permission to locate more street equipment in major conurbations for aesthetic reasons.
- *Installing equipment in a telecom manhole:* Active equipment must be placed in costly leakproof cases requiring civil works to widen existing manholes. Problems of heat dissipation mean that power concentration is impossible unless Controlled Environmental Vaults (CEVs) are developed, but these are difficult to install in heavily populated urban areas.

A cost analysis of powering reveals extremely large variations according to the chosen architecture and to the customer requirement with regard to service quality. In case of an FTTH architecture with local powering, a value of about USD 60 for ONU powering equipment with three hours battery back-up has been estimated.

8 Conclusions

Major building blocks needed for the construction of fibre rich infrastructure have been addressed in the scope of this paper, and the main conclusions drawn are:

- Recent advances in optoelectronic module technology show great potentials for dramatic cost reductions in a short term time scale.
- For outside plant construction, basic hardware parts (cables, splices, connectors and enclosures) are in progress in order to meet the specific access network requirements.
- Very significant innovations (blowing technique, micro-civil work concept) are now providing cost effective installation techniques, which in turn makes the construction of fibre rich access networks more and more attractive as a means of providing full wideband services to a large spectrum of customers.

Acknowledgement

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Management of access networks – trends and challenges

TOR BREIVIK AND HÅKON LØNSETHAGEN

This article provides an introduction to telecommunications management technologies, also identifying emerging technologies and solutions challenging the traditional ones. From a broad management perspective, important properties and challenges related to the introduction of modern access network technologies are identified.

1 Introduction

Access network operators are facing many questions, challenges and opportunities in their effort to remove the bandwidth bottleneck of the access network. The future success of an access network operator will largely depend on how successful his telecommunications management solutions become. Whereas management[1)] of network resources largely is a non-issue in relation to old access network facilities, the forthcoming access network resources fully depend on management interfaces to accomplish the management functions integral to the corresponding network technologies.

Several network technologies will enter the access network in the future. A paramount goal will be to enable management of the network resources in an integrated fashion. If operations systems operators must learn and handle several different management systems and user interfaces, the added costs induced by inefficient operational procedures will significantly reduce the competitiveness of the network operator. Likewise, maintenance of numerous but similar management applications and systems must be avoided.

The management infrastructure should be suited to the needs and characteristics of the access network architecture. Knowledge and insight related to the access network technologies as perceived from a management perspective is important to make the right judgements related to the design and choice of management interfaces to network elements. Furthermore, the management frameworks of IETF[2)] and OSI respectively both have strengths that must be considered carefully with respect to the network technology and architecture they are best suited to.

Operations, administrations and maintenance of network resources is only one area of telecommunications management. The scope of telecommunications management (or TMN) also covers service management. That is, in our case, management of access network transport (bearer) services. Efficient and reliable service provisioning is a key goal in this area. Clever management systems must make their service provisioning activities based on adequate network level resource models. These information models must be able to support multi-service and multi-technology networks. Moreover, user-friendly customer access enabling on-line management of services may very well become the facility distinguishing the successful operator from the others.

Along with the emerging management systems for new access network technologies, integration and architectural challenges also appear regarding integration with and migration of legacy operations and administrative systems. Strategies to handle these challenges must also cope with evolving and changing business processes and the uncertainties related to the choices, timing, and the evolution of new network technologies.

Emerging and maturing software technologies for distributed computing, like object request broker platforms (eg. CORBA)[3)] and component based technology and corresponding middleware, provide a means of handling the challenges identified above.

This article will address the issues identified above and provide insight to the underlying challenges. The following section will introduce TMN and related management infrastructure technologies, also covering some emerging technologies. Section 3 will identify some of the main characteristics related to the future role and architecture of access networks, which represent major shifts upon management architectures. While section 4 provides an overview of a few important generic standards, section 5 identifies management information and functionality related to the ADSL and PON network technologies. Software technology trends, opportunities and issues are further discussed in section 6, whereas section 7 presents issues related to integration of management systems and interworking among management technologies.

2 Telecommunications management

The concepts and ideas behind telecommunications management have been around for quite some years, first being introduced in the mid-1980s. Standards providing the setting for basic management technologies have been stable for several years. Still, however, the community of telecommunications management does have several interesting issues to address, as will be discussed below. This section gives a brief introduction to the basics of telecommunications management technologies, and provides an overview of OSI[4)] Systems Management (OSIsm), TMN from ITU-T and SNMP[5)] from IETF. Important differences between the IETF approach and the OSI approach will be addressed.

2.1 The manager-agent paradigm

Some way or another, the various solutions available for telecommunications management are based on the manager-agent paradigm. A system or an application in the *manager* role communicates with an application in the *agent* role being managed by the manager application. Thus, the system containing the agent (the application in the agent role) is taking the *managed* role. The agent provides a representation of the system or resource being managed, and performs the management tasks as instructed by the manager. These ideas are illustrated in Figure 1. A fundamental goal is to

1) *In this article, the term management is used analogous to telecommunications management, and with the same scope as adopted by TMN (see below). Unless otherwise noted the term* management *of network resources assumes interworking between managers and network elements (their agents) across management interfaces involving a data communication facility.*

2) *Internet Engineering Task Force.*

3) *Common Object Request Broker (ORB) Architecture.*

4) *Open Systems Interconnection (jointly from ISO/IEC and ITU-T). In this article, only the ITU-T recommendations numbering will be used.*

5) *Simple Network Management Protocol.*

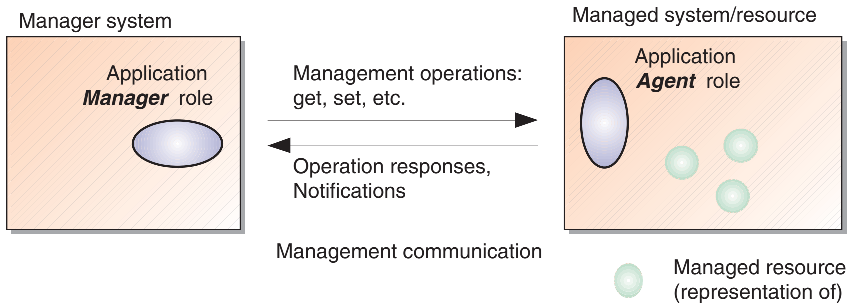

Figure 1 The Manager-Agent Paradigm

provide a means for specification of interfaces between manager systems and managed systems in a complete and well-defined way to enable vendor independent interface specifications. The specification should only constrain what is necessary to ensure interoperability, leaving a considerable amount of freedom regarding the implementation. Furthermore, hierarchical structures of management systems may also be possible. This implies that a management system that takes the agent role with respect to one interface may take the manager role with respect to another interface.

A few essential aspects can be associated with this paradigm. First, the capabilities of the protocol enabling management communication between the manager (the application in the manager role) and the agent will to a great extent settle the basic properties of a management solution. Secondly, the capabilities of the management information specification language further determines additional important properties on which the management solution will be based. A third aspect relates to architectural issues and choices, both with respect to structures of system internal functional entities as well as possibly hierarchical structures of related management systems. In this section, the first two aspects will get more attention.

Telecommunications Management Network (TMN) from ITU-T, have adopted the core standards from OSIsm [1, 2]. Thus, before giving an overview of TMN, we will first take a closer look at OSIsm, addressing the capabilities of the management protocol and the management information specification language.

2.2 OSI systems management

The OSIsm solution was developed for the management of complex OSI data networks (OSI systems) and telecommunications facilities. Reliable management communications has been emphasised, thus the choice of a connection-oriented solution. To handle the complexities of the resources to be managed as well as to keep the management traffic low a powerful management protocol has been developed as well as an expressive specification language. However, this results in complex functionality in the agent increasing the cost and the processing load of the managed system.

The specification language of OSIsm is GDMO (Guidelines for the Definition of Managed Objects [3]). GDMO is a powerful object-oriented specification language supporting classes, inheritance, and allomorphism (see below). A class specification identifies properties such as the attributes (data elements), actions (operations relating to the object as a whole) and notifications associated with objects (instances) of that class. Notifications are an effective capability of OSIsm-based solutions allowing the agent to spontaneously report events related to the managed object. Operations on the attributes (get, set) as well as actions may be associated with result or error information as a response to the operation. Inheritance allows a class to inherit the properties of possible multiple parent classes, provided by the *derived from* construct. Unlike object-oriented programming languages, GDMO allows attributes, actions and notifications to be identified as self-contained specification pieces outside the scope of the class definition. The same is true for *packages,* which may contain a set of the just mentioned properties. The aim is to increase the potential reuse of specification pieces. The properties associated with a class are specified via the identified set of packages constituting the class definition. The GDMO language consists of a set of templates such as the Managed Object Class template, the Package template, and the Attribute template. The semantics associated with the specification templates is explained in a separate recommendation describing the Management Information Model [4] associated with GDMO.

The syntax associated with GDMO templates has a mapping to ASN.1[6)] syntax [5]. ASN.1 enables abstract specification (independent of a specific transfer syntax) of the structure and type of data elements to be communicated across a network. GDMO may utilise the full power of the ASN.1 language allowing for instance an attribute to be of a complex structure. Furthermore, each specification element (of a standard) is registered with a unique value whose type is the Object Identifier (OID) ASN.1 type. This is used by the management protocol ensuring that the management information is properly typed.

Managed object instances controlled by and clustered under one agent constitute the Management Information Base (MIB). Each instance has a name and to ensure an efficient and unique naming of managed object instances, they are organised in a tree structure referenced as the Management Information Tree (MIT). Naming is based on the containment relation specified relative to Managed Object Classes using the name-binding template. In this fashion, every (subordinate) instance is named relative to and contained within a superior instance, where the root of a MIT is associated with a directory object[7)] representing the agent.

The Management Information Model identifies rules for compatibility, that is, how one class can be a compatible extension of another. A subclass derived from a superclass is compatible with the superclass. However, a class may not be a subclass to be a compatible class. The notion of allomorphism is related to and based

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6) *Abstract Syntax Notation One.*

7) *OSI Directory Service X.500.*

on that of compatibility, and is provided for by OSIsm. If an instance of a class can be managed as an instance of another class, such other classes are termed its allomorphic classes. By using allomorphism, an agent may support both an old and a new 'version' of a class, thus allomorphism may be considered as a means to support systems evolution.

A more in-depth tutorial of GDMO and information modelling related to OSIsm may be found in [6].

2.2.1 CMIS/CMIP

The application layer protocol supporting communication between manager and agent, and closely related to GDMO, is specified in a pair of standards. That is, the Common Management Information Service Definition (CMIS) [7] defining the service elements and the capabilities of the protocol; and the protocol itself, the Common Management Information Protocol (CMIP) [8]. This protocol allows reliable asynchronous message passing and an elaborate set of capabilities. It provides means for basic operations associated with single objects as specified by GDMO, such as *Get* and *Set* attribute, *Action, Create* and *Delete* object instance, and *Event-report,* the later supporting notifications. In addition, these protocol services (except *Event-report* and *Create*) can be used with an expansion or query mechanism known as scoping and filtering. These mechanisms allow an operation to be performed on a selected set of objects. Thus, the functionality of the agent is expanded. Scoping provides various ways of identifying a subset of the MIT 'below' a given base object. The selected set of objects may further be narrowed or filtered using logical constraints. When using this facility of performing an operation to a set of objects, the manager must choose either the *best effort* or the *atomic* synchronisation property. The protocol provides means to handle multiple replies resulting from this kind of operations.

This set of protocol services results in powerful capabilities, which keeps the network traffic at a minimum, however, at the price of increasing the complexity and cost of the agent. SNMP, on the other hand, has chosen the other end of the spectrum. This will be discussed below.

Operations Systems Function (OSF) block:
related to the telecommunications management manager role, for the purpose of monitoring, co-ordinating, configuring and controlling telecommunications resources as well as the TMN itself.

Workstation Function (WSF) block:
provides means to interpret TMN information for the human user (operator), and vice versa.

Network Element Function (NEF) block:
a function block representing telecommunications equipment (or parts of equipment), communicating with the TMN for the purpose of being monitored and controlled.

Mediation Function (MF) block:
mediates and/or processes information passed between an OSF and NEF (or QAF). An MF block may store, adapt, filter, threshold and condense information.

Q Adapter Function (QAF) block:
translates between a TMN and a non-TMN reference point. For example between non-TMN network elements and TMN (MF or OSF).

Box 1 TMN function blocks

2.2.2 Generic management information and functions

OSIsm defines a set of generic managed object classes that can be used and refined by other standards. Of particular importance is the *top* managed object class. Every other class must inherit this class, which identifies properties that every managed object must support, for example an attribute telling which class it belongs to. Furthermore, classes such as Log, Log record, Alarm record, Event record and Object creation record are defined, representing generic capabilities useful in many contexts.

Systems Management Functions[8] represents another group of standards. These define generic functionality and corresponding managed object classes useful in many settings. Examples of this kind of general functionality are object management function, state management function, event forwarding discrimination function, alarm reporting function, log control function, and security audit trail function, to name a few.

[8] *The X.73x to X.75x series of ITU-T recommendations.*

2.3 TMN – Telecommunications Management Network

The principles for a TMN [9] are related to four main topics or classes of architectures, that is functional, information, physical, and logical layered architecture. The TMN functional architecture identifies and defines function blocks and their content in terms of functional components. Several solutions exist regarding which functional components the various functional blocks contain. Reference points between relevant pairs of function blocks are also identified. The TMN function blocks are shown in Box 1.

The *q* class of reference points identifies the association between NEF and OSF or MF, and between OSF and MF or QAF, and between MF and QAF. The *f* reference point identifies the association between WSF and OSF or MF. The *x* reference point identifies the association between OSFs of TMNs belonging to different administrative domains.

The information architecture describes an object-oriented approach for transaction-oriented information exchanges. In essence, this is covered by the adoption of the OSIsm means of information exchange (ie. GDMO, CMIS/P). However, it is noted that other concepts supportive of location transparent fully distributed management applications are being considered. This is further discussed in [10]. In addition, the information architecture also considers the notion of *shared management knowledge* and context negotiation to establish this. Naming and addressing of TMN resources is also considered.

The TMN physical architecture identifies various options for configurations of physical systems or equipment (TMN building blocks), in terms of Operations System (OS), Mediation Device (MD), Q Adapter (QA), Data Communication Network (DCN), Network Element (NE), and Workstation (WS). These physical entities contain the corresponding functional block. Optionally however, they may also contain some of the other functional blocks as well. As an example, the OS may contain MF, QAF and/or WSF.

Interfaces between physical entities are identified by capital letters corresponding to the letter identifying the reference point between the functional blocks contained in the respective physical entities. For example, the interface between NE and OS is Q (or more specifically Q_3). Further requirements regarding communication protocols are also identified.

The TMN logical layered architecture (LLA) was developed as an attempt to deal with complexity. LLA implies grouping specialised OSFs including clustering of related management information into layers. TMN has identified the following layers (in addition to the network element layer:

- *Element Management Layer (EML)* Manages individual network elements possibly on a group basis. As an objective, this layer will provide a vendor-independent view of network elements to the layers above.[9)]
- *Network Management Layer (NML)* Manages and controls (abstract) resources associated with the network view related to the network elements within a domain. Must provide an appropriate view of the network level resources (services) to the service management layer.
- *Service Management Layer (SML)* This layer is responsible for the contractual aspects of services provided to customers, such as service order handling, co-ordination of services, complaint handling, QoS data, and invoicing.
- *Business Management Layer (BML)* This layer has responsibility for the entire enterprise. It may relate to all the other layers. It should support the decision-making process for optimal investments and use of new resources. Management information in this layer is not subject to standardisation.

The transition from one logical layer to another will often occur inside an OS. Correspondingly, an interface between OSs will often address one logical layer, although one still has to consider the manager (client) vs. the agent (server) side of the interface.[10)]

2.4 IETF management and SNMP vs. OSI systems management

The management solution from IETF, the set of SNMP standards, is also based on the concept of manager-agent (management station and management agent respectively), as well as management information base (MIB) and management protocol. It was first issued in 1988 and designed to provide a low complexity cost efficient solution for vendor-independent management of IP-based networks and related equipment such as routers, servers, workstations and other network resources [11].

The following provides a brief overview of SNMP, identifies enhancements in SNMPv2 and SNMPv3, and comments upon major differences compared to OSIsm. A more in-depth coverage of SNMP can be found in [12], and [13] provides a more in-depth comparison of SNMP and OSIsm (as well as CORBA).

The SNMP MIB specification language [14, 15] is significantly simpler than GDMO. It does not provide the notion of class nor inheritance. Thus, it is not possible to specialise one class from a generic class. An SNMP *object* is a simple data value or row entry whose number of elements is fixed and the elements are of simple types. ASN.1 is also used by SNMP; however, only a subset of ASN.1 is used. Ultimately, object values or row elements are of the ASN.1 basic types INTEGER, OCTET STRING and OBJECT IDENTIFIER [13]. Although tables can be specified as part of the MIB, whose lengths can dynamically be varied, SNMP does not provide any notion of composite object of several attributes manageable as a whole. As such, a table is not a named and manageable object as such. SNMP objects are singly instantiated. Multiple instantiated 'objects' can only be achieved through tables and multiple table entries.

SNMP registers MIB object types using ASN.1 OIDs in a similar fashion as OSIsm. However, naming of objects (instances) is significantly different from OSIsm, as the OIDs are also used for naming. Thus, naming of a singly instantiated object is sufficiently distinguishable by the OID itself. Table entries are named by the OID of the table suffixed typically by the value of one or more elements whose fields can be considered as the table 'key'. This registration and naming strategy prohibits the opportunity to define generic objects that can be 'imported' and used in different contexts.

The SNMP protocol [16, 17] does not provide create, delete or action operations. This limits the possibility to specify complex operations with precise semantics. In addition, SNMPv1 was limited by the maximum packet size of the protocol data unit (PDU). This can be a problem with respect to atomic table entry 'creation'. SNMPv2 has a more elaborate interaction scheme to remedy

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9) *It is interesting to note (considering the q_3 reference point between the NEF and the Element-OSF of figure 18/M.3010 [9]) that the previous goal of providing a vendor-independent view related to the management interface to network elements, has been relaxed.*

10) *It is stated in M.3010 [9] that a management information model is associated with a management layer, and may furthermore be used for the exchange of information at the* inter-layer interface. *We note that this last part is a matter of definition. It is clear, however, that the translation of information corresponding to the transition from one management layer to another does not occur as part of the management protocol. Management information exchange is only concerned with establishment of shared state knowledge between the manager and agent (ie. synchronising the knowledge of the state of the same information entities at both sides of the interface).*

this limitation. In addition to *get* and *set* operations, a *get-next* operation is provided to ease the access to greater amounts of information. The order information related to the naming scheme and the column-by-column ordering of table entries, is used by the *get-next* operation. The lack of support of the scoping and filtering facility also limits the power of the protocol. SNMPv2 does however support a *get-bulk* operation. It uses ordering knowledge to read more than one object. This get-operation allows multiple variables or objects to be requested. In SNMPv1, this must be an atomic operation. In SNMPv2 however, non-atomic responses are allowed [11].

The *trap* facility provides a means for the agent to notify the manager. In SNMPv1, this facility is associated with the agent itself rather than with objects. This limits the use of this facility. SNMPv2 allows a notation to associate traps with objects. In addition, SNMPv2 extends the limitation of having just one manager-agent level. A middle level of hybrid manager/agents has been appointed. In addition, multiple top-level management stations (management servers) may exist in one management domain. This hierarchical structure distributes and makes the processing burden on each manager node lower, as well as reduces the total management network traffic. Corresponding to this scheme, an element manager taking the manager as well as the agent role, can send *inform* messages to the management server. The management server must provide a *response* to the *inform* message, making this a reliable notification. A manager-to-manager MIB has been developed for the support of manager-to-manager communication.[11)]

Due to the goal of achieving low cost simple agents, the choice of the connectionless unreliable user datagram protocol (UDP) as required protocol has been made. The unreliable nature of the transport protocol increases the burden on the applications as well as the total network traffic. Considering that *traps* are unreliable, the manager must still resort to polling to ensure that problems have not occurred. Furthermore, network traffic is increased due to the lack of support of multiple replies, in combination with limited packet size. The increased network traffic can be a significant drawback when the communication resource is shared and the distances between managers and agents are long.

The proposed SNMPv2 standards of 1993 did not get the anticipated acceptance [11]. The functional enhancements have been welcomed, however, the security mechanisms were found too complex. The SNMPv2 workgroup was not able to resolve this problem, and as SNMPv2 was progressed to draft Internet standard as of 1996, no security solution was part of it. The result has been delayed acceptance of SNMPv2. An SNMPv3 working group was charted in 1997, and a less complex and a more accepted solution to the security challenge has been provided, as well as a few minor fixes related to general SNMPv2 functionality.

2.5 Trends

The primary focus thus far has been various aspects relevant to specification and communication related to the manager-agent interface and interworking. Solutions in this area contribute to the basic management infrastructure. However, the Web-Based Enterprise Management (WBEM)[12)] initiative also provides an interesting set of solutions, with their web-based management infrastructure.

Before taking a brief look at WBEM, we will note that advances in distributed object technology also play an important role. While TMN and SNMP are focused on the communication interface between the manager and agent, the ORB-based distributed object technology is focused on APIs between applications. The CORBA architecture and related specifications from OMG[13)] provides the basis for a set of important technologies, technologies considered important for telecommunications management [18, 19]. Characteristic aspects and interesting topics related to these technologies will be identified and discussed further below. The work by ITU-T related to the Open Distributed Management Architecture (ODMA) [20] will exploit these opportunities. ODMA is further based on the concepts from RM-ODP [21].

A primary goal of the WBEM initiative is to facilitate integrated management of an enterprise wide range of resources, from user applications, desktop systems and servers, to systems, network devices and networks, as well as corresponding services. Solutions are based on cost efficient general purpose computing platforms and engines (eg. web-browser, web-server). Last summer, the ownership to WBEM was transferred to the Desktop Management Task Force (DMTF),[14)] who will be in charge of issuing WBEM standards. Currently, the only WBEM standards are the Common Information Model (CIM) standards, partly originating from the Microsoft Hyper Media Management Schema (HMMS). The CIM standards cover a notation for specifying management information in a UML-oriented way, as well as a specification of a core set of management information and furthermore, some general domain specific models. Currently, WBEM is focused on developing an XML[15)] vocabulary for CIM, enabling XML-based encoding and communication.

When considering relevancy for access network management, WBEM technology can be used for several reasons and in various architectural contexts. It can provide a low cost solution for user interfaces and uniform access to heterogeneous management applications and information. Thus, it is particularly relevant between a client and the middle tier of a multi-tier architecture. Furthermore, it can provide means for applications and systems management related to management of the access network management systems and applications. A more open question however, is whether WBEM or XML technology are also suitable for system-system interworking and management communication with NEs.

The idea of a platform supporting the facility of deploying and delegating management functionality to agents in a dynamic fashion, have been considered

[11)] *It is not clear form [11, 13] if these facilities are general in the sense that they also support communication 'horizontally' between mid-level managers, or between top-level managers.*

[12)] *http://www.dmtf.org/wbem/index.html*

[13)] *Object Management Group. An industry consortium of more than 800 companies, spanning a variety of businesses from IT vendors to telecom operators. http://www.omg.org*

[14)] *http://www.dmtf.org/*

[15)] *eXtensible Markup Language, developed and specified by W3C. http://www.w3c.org/XML/*

by the research community for several years. The Java solution and the recently announced JMX[16)] may provide a viable solution in this direction and deserve close consideration.

[16)] *Java Management Extensions. http://java.sun.com/products/JavaManagement/*

Above, we have pointed out that efficient use of network resources for the purpose of management is an important goal, in particular as communication distance increases. This is however somewhat debatable as network bandwidth continues to increase. The related topic of DCN design and technologies is anyhow important, although not getting much attention here.

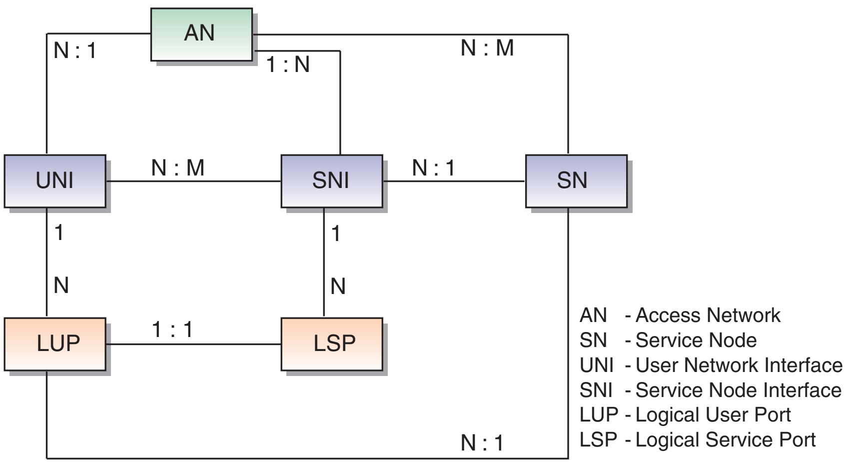

Figure 2 Access network related entities and relationships

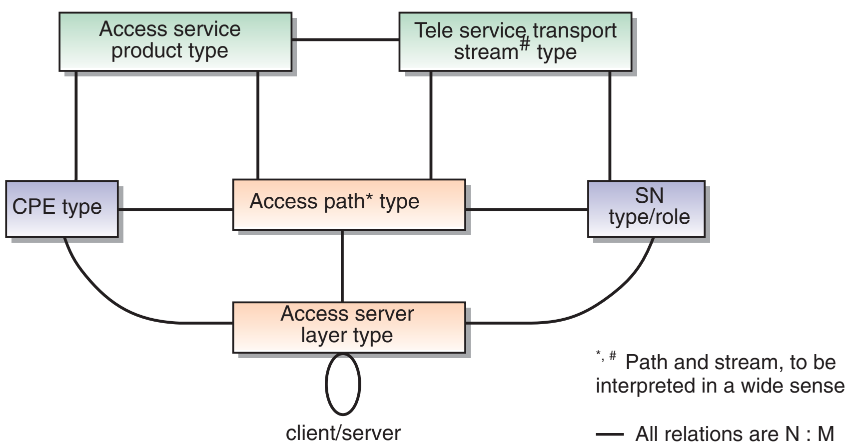

Figure 3 Relationships among access network resource types and service types

3 Evolving access network architectures

The adoption and introduction of modern access network technologies represents a giant change for the (access) network operator. This section will identify a few characteristic factors related to administration and management of access networks, considering the transition from yesterday's technology to the future access network technologies and services. Although access to leased line services is an important area that also involves management, here the focus is the provisioning of access to end-user telecom services. However, it should be considered whether provisioning and management of leased line services should be more integrated with management of access network resources supporting on-demand telecom services.

The access network of today or yesterday consists of passive twisted pair copper wires, their cables and distribution frames at various sizes and levels throughout the local loop. Provisioning of a telephone service can be associated with an instance of a switch port and its associated pair of wires manually cross-connected in the distribution frames to reach the customer premises equipment (CPE). The administration of this physical infrastructure is a challenging task in itself, but this network architecture does not involve active network management via management interfaces to network elements (NEs). The introduction of extended concentration nodes does not change this picture as this kind of NE is managed as part of the switch (Service Node) itself.

This situation is not significantly changed as self-contained multiplex systems are introduced to free copper pairs part of the way between the customer and the extended concentration node. The multiplex system will require remote management; however, its basic configuration is static and requires manual intervention to change. Likewise, the one-to-one 'physical association' between the switch port, the telephone service and the copper pair at the customer premises is still valid.

The introduction of new technologies like PON and VDSL, and for instance related ATM technology, implies introduction of new types of entities and relationships, and the vanishing of the one-to-one relationship between the service port and the physical infrastructure. The introduction of several technologies and network layers and corresponding logical user ports and service ports makes a more complex picture. This is illustrated in Figure 2. Figure 3 illustrates the multitude of possible technologies and service combinations. While it is a great challenge to decide the network architecture, it is an equally great challenge to come up with the best systems architectures to support administration and management of this complex setting. An essential objective should be to provide for each service node type (role), a consistent and integrated high level view of the access network, hiding differences in technologies and technology specific details. Performance issues and load balancing will become important issues as dynamic configuration changes of the access services and network will be possible. On-line user access to such configuration management services will result in a high volume of configuration transactions.

These changes result in a need for the introduction of a new network level management system keeping track of the associations and connectivity (eg. VPCs) between the LUPs and LSPs of the access network. This system must interface with subordinate management systems for the particular technology specific subnetworks and corresponding NEs, including management of SNIs, the later co-ordinated with the management systems of the SNs.

This new network level management system(s) will be the system to inquire for access network resources and status, and furthermore, to request for configuration operations, in the case of service provisioning. These systems must also provide essential information to the access network planners. The system administrating the physical resources will most likely be separate from the former, and must be augmented to cover administration of the new physical resources including PON and xDSL physical resources, to provide a user friendly view of the physical network infrastructure.

The strategic introduction of new management systems as well as the transition of the role of the system administrating the physical infrastructure, represent a significant challenge. The access network operator must develop a strategy to enable a step-by-step introduction of new technologies. Mechanisms and strategies supporting systems evolution and flexibility will be important in order to handle the uncertainties associated with which network architecture to adopt.

4 Generic architectures and models

Although different technologies are available for offering broadband solutions to end users, these have a lot in common concerning management. In the following, central standards are described that are suitable for handling the resources of different technologies in a uniform way. G.902 [22] provides a general architecture of access networks while G.805 [23] provides a generic functional architecture of transport networks. In addition to these general network architectural models, common models within specific management areas are also available and will be briefly described. Management solutions based on these standards will help in achieving a common view of the network resources and parameters to be managed, and thus, providing a basis for integrated management solutions.

4.1 Generic architectures

G.902 provides an architecture of an Access Network from a high level perspective by identifying and defining the functions and requirements above the transmission media layer. A network layer is defined independently of the other layers and each is decomposed into three basic functions: Adaptation, Termination and Matrix Connection, and may have its own operations and maintenance capabilities. The model is useful in defining the managed objects related to the management interface of the access network, and the goal is that different technologies from different vendors can be managed in a uniform way. Although being focused toward OSIsm by identifying a Q_3-interface, G.902 can still be considered as general with respect to management if one allows other management paradigms as well.

G.902 establishes a functional architecture and how each of the functional groups are interconnected (see Figure 4). The AN is broken down into functional groups (some examples of functions are given). They are: User Port Function (UNI termination, signalling conversions), Service Port Function (protocol mapping, testing of SNI), Core Function (bearer channel concentration), Transport Function (physical media functions, multiplexing, cross connect), and AN-System Management Function (FCAPS[17)]). Q_3 Agent and MIB are located in the

[17)] *Fault, Configuration, Accounting, Performance, and Security management. Defined in X.700 [1].*

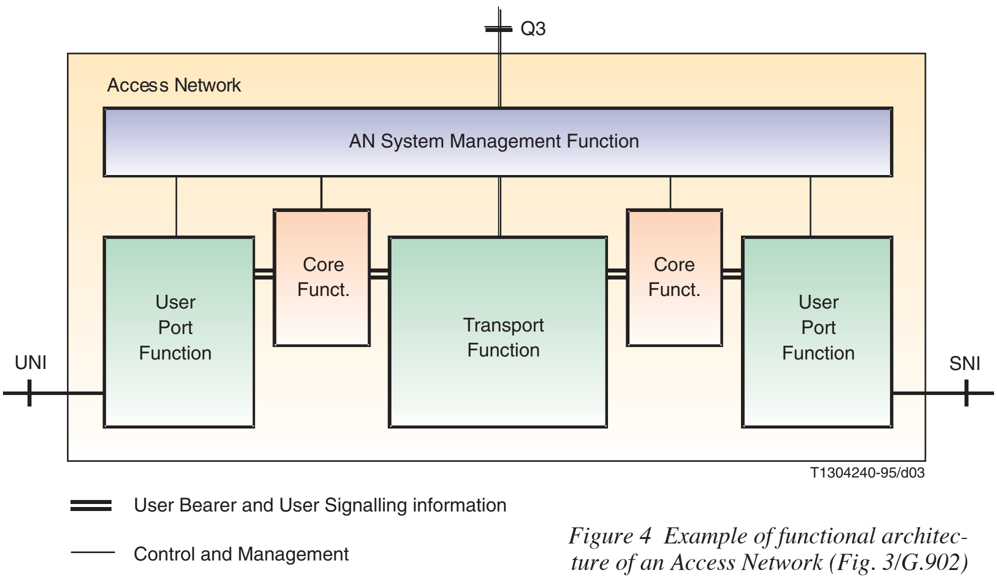

Figure 4 Example of functional architecture of an Access Network (Fig. 3/G.902)

AN-SMF. The AN-SMF acts as an Agent to the TMN and as a Manager to the AN functions such as UPF, CF, etc. However, G.902 does not advice a management architecture within the AN domain.

A user port function has a fixed association with one and only one SNI through provisioning. This concerns all the bearer capabilities at the user. In case of shared UNI, which may support more than one logical user port function at the same time, eg. using ATM, more than one SN may be accessed through a single UNI (eg. one VP for each logical access).

The objective of this Recommendation is to describe an access network concept that provides flexibility towards future access types, eg. for interactive video services. It is VB5 focused, deals with semi-permanent connections, and connects logical ports at Service node to their peers at the customer.

Access networks with many technologies from a mix of vendors may constitute a rather complex network. G.805 describes networks from the perspective of the information transfer capability. For transport networks, this recommendation describes the functional architecture in a technology independent way. It provides means to describe network functionality in an abstract way in terms of a small number of architectural components. These are defined by the function they perform in information processing terms or by the relationships they describe between architectural components.

The client/server relationship is fundamental and described as the association between layer networks that is performed by an 'adaptation' function to allow the link connection in the client layer network to be supported by a trail in the server layer network. The transport processing functions, adaptation and termination, give relationships between topological components that give an abstract description of the network.

A port is given as the representation of the output of a trail termination source or unidirectional link connection, or the input to a trail termination sink or unidirectional link connection. This could fit into the G.902 port concept, but it seems like G.902 defines functional components for AN covering all layers at the same time.

G.805 describes how to decompose a network into specific path layer networks which are likely to be independently managed and where paths across the specific path layer network will be set up independently from the set-up of paths in other specific path layer networks. A network can be decomposed into a number of independent layer networks with a client/server association between adjacent layer networks. Each layer network can be separately partitioned in a way that reflects the internal structure of that layer network or the way that it will be managed. The actual decomposition used to generate the specific path layer networks is dependent on the technology. While G.902 asserts adoption of the G.805 principles, the latter does give valuable additional input to the modelling of access networks. G.805 presents diagrammatic conventions for producing graphical models.

4.2 Common models

The Systems Management Functions from OSIsm provide useful functionality generally applicable to many areas. The standards identified in the following also provide common facilities, although each dedicated to a specific management functional area. These are alarm surveillance, performance management, and physical resource management. These standards all define Q_3 interface information models and thus are based on OSIsm. While it is not always feasible to require the use of the CMIP protocol, the adoption of these standards provides a basis for easier integration of vendor-specific element managers.

The ITU-T Recommendation Q.821 [24] on Alarm Surveillance specifies the Q_3 interface requirements for communication between an OS and an NE and is a generic framework for the management information and functions related to alarm handling. It supports the TMN management service component described in M.3200, Management Services [25], and defines a generic information model for alarm surveillance. It provides a set of application messages and associated support objects for the support of management communication. It covers alarm reporting and logging, management of alarm severity profiles, alarm summary reporting and management operations scheduling. It defines classes such as 'currentAlarmSummaryControl' which is used to specify the criteria for the generation of the summary reports (eg. included alarm objects, alarm status, severity, or probable cause), and 'managementOperationsSchedule' to allow the reporting of alarm summaries to be performed periodically.

Alarm report notifications as defined in X.733 [26] are used to indicate that an exceptional event or condition has been detected in the NE. These notifications are emitted from objects that represent the affected resources or model the detecting resource. The alarm reports provide a very detailed alarm event description (eg. event type, perceived severity, probable cause, physical location of the affected resource, and additional specific information on the event) according to the information specified in the object classes representing the resources and their associated attributes.

Examples of events are detection of transmission data errors, the crossing of a performance threshold, and the detection of faulty equipment. Alarm reports may be stored in alarm logs represented by specific X.735 [27] Alarm Log objects. The default severity, which is assigned to each alarm by the NE, may also be modified from the OS.

The purpose of Q.822 [28] on Performance Management is to provide a set of application messages and associated support objects for parameter collection and thresholding aspects of Performance Management (PM). Q.822 provides definitions of managed objects and attributes and associated functionality, and furthermore, specifications of the services, functional units, and protocols related to PM. The PM functions supported are 'data storage', 'thresholding' and 'data reporting'. The supporting object classes are 'currentData', 'historyData' and 'thresholdData'. Examples of monitored parameters described in Q.822 are:

- Slip second;
- Code violation;
- Errored second (of various types);
- Loss of signal second;
- Protection switching count;
- Protection switching duration.

The duration of the performance interval can be set, and Scanner objects may be used to aggregate measurements from a number of Current Data objects into summary reports or to perform statistics on the measurements.

The described generic information model for performance management will be useful for manager/agent communication between OSs and NEs in TMN Management solutions, and also for SNMP managed NEs using QAs/MDs.

ES 201 097-1 [48] on the other hand, is part 1 of a series of ETSI Resource Management standards to come. It provides a generic model for the management of NE resources (hardware and software). It defines the managed objects to be applicable at both the OS-NE and OS-OS interfaces. The functional descriptions of physical resource management (functional requirements and management functions) are based on M.3400 [29]. All applicable OSI Systems Management Functions (X.730-X.750 series) are reused. The information model is fully aligned with M.3100 [30].

This standard covers the configuration management and the fault management areas (based on Q.821), including testing, timing, protection and inventory. Within each management view, the standard addresses the management of physical resources (hardware) comprising a network element. This includes the peripheral/accessories parts (eg. disk, power supply, fan equipment, etc.) subject to management actions.

5 Management of specific access network technologies

The identification of management aspects and needs associated with two important access network technologies, ADSL and PON, will be the subject of this section. ADSL is the most standardised xDSL technology also regarding management. Even if parameters will be different for other xDSL technologies, the management regime for these technologies will be similar to the one established for ADSL.

However, management issues related to several other network technologies and equipment are also important for management of access networks. While not covered in this article, we will just mention that the following issues are important; operator management of CPEs, ATM cross-connect and multiplexer management, and VB5 management. Management related to IP is also relevant in the case of IP technology being used as an access network technology. Accounting management is not relevant with respect to xDSL and PON technology as such. However, it may be an issue related to the usage of client layer resources, such as IP or ATM resources.

5.1 The Full Service Access Network (FSAN) initiative

A group of telecommunication network operators and equipment manufacturers have undertaken an international initiative to create requirement specifications for access systems. Although FSAN is not a standardisation activity, it has produced valuable results concerning AN through development of a set of requirements specifications.

An ATM Passive Optical Network (APON) was identified by the project as the most promising approach to achieve large-scale full service access network deployment that could meet the evolving service needs of network users. It has been shown that this APON approach could support a wide range of 'FTTx' access network architectures – Fibre-to-the-Building, Cabinet, Curb, or Home. PON was combined with copper technology meaning that the ONUs are equipped with Very-high speed Digital Subscriber Line modems.

The FSAN initiative has produced a set of requirement specifications for Operation, Administration and Maintenance where it has attempted to incorporate applicable standards where they exist. The Optical Access Network workgroup in FSAN has created an APON specification. It has been presented to several standardisation bodies, eg. ITU, ATM Forum and ETSI. The first draft of the ITU G.983 [12] specification was based on this specification.

5.2 ADSL technology

An ADSL system consists of modem pairs and some associated equipment necessary to offer ADSL as a customer access. All development of ADSL modems is based on the standard T1.413 [31], that describes transmission related details like line code, receive signals, organisation of transmitted and received signals into frames, and electrical and mechanical specifications of the network interface. Further, the interface between the telecommunications network and the customer installation in terms of their interaction and electrical characteristics. ITU-T is preparing a set of standards for

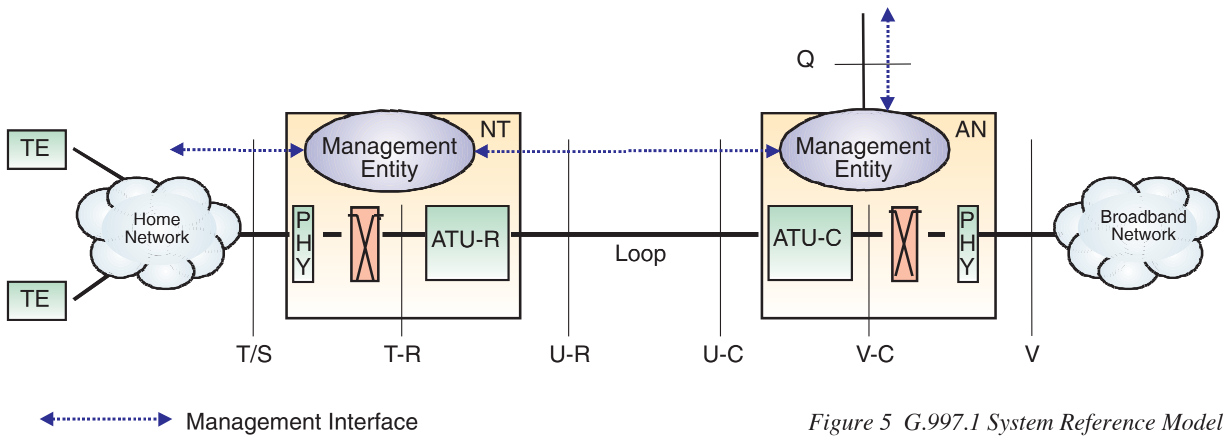

Figure 5 G.997.1 System Reference Model

ADSL (eg. G.992.1 [32]) for discrete multitone encoding for transmission rates up to 8.192 Mbit/s downstream and 640 kbit/s upstream.

5.2.1 Embedded Operation Channel

The modem at each end of the copper line, ATU-C and ATU-R (see Figure 5), communicate with each other over embedded operations channel (clear eoc), well documented in T1.413 and G.992.1 [32]. The latter describes eoc organisation and protocol, eoc message structure, eoc message sets, data registers in ATU-R, eoc protocol states, ADSL line related primitives, STM data path related primitives, ATM data path related primitives and many other parameters. The defined ATM data path related eoc primitives cover Cell Delineation and Header Error Check.

The eoc may also be used in the future to extend maintenance and performance monitoring to the service module(s) at the customer premises. G.997.1 [33] prescribes for use the eoc:

- A data link layer based on byte oriented HDLC;
- Message passing via SNMP on HDLC;
- One MIB in the ATU-R and one MIB in the CO/LE;
- The MIB in the ATU-R should be accessible from the TE (Terminal) as well as the Network.

5.2.2 ADSL management functions

ADSL Forum Technical Report TR-005 [35] describes parameters, operations and protocols that are subjects for network element management, and covers configuration, fault and performance management. Management includes five elements according to ADSL reference model: communication protocols over V interface, communication protocols over U interface, parameters and operations within ATU-C, parameters and operations within ATU-R and the ATU-R side of the T interface. How information over T and V is treated depends on the client layer services.

Configuration management provides functions for installation and provisioning and to collect status and control. Accounting Management for ADSL has not been much focused in the standardisation work. Some ADSL Forum proposals state that the ADSL NE shall collect usage data at the SNI and UNI for billing purposes.

5.2.3 Example ADSL management parameters

The ADSL technology is depending on copper lines with varying quality, and therefore threshold settings, threshold crossing alarms for bit errors, s/n ratio and attenuation are all important parameters. *Noise Margin parameters* are defined to control the noise margin to assure acceptable BER ($<10^{-7}$). Based on the set noise margins the output power and bandwidth will automatically adjust to optimum level. *Upshift Noise Margin* and *Downshift Noise Margin* is supported only for Rate Adaptive Modus. *Bit Rate Parameters* are used to set maximum and minimum line rates, to enable alarms at excess and provide a good division between fast and interleaved capacity when line rate is to be altered. Threshold values for *15 min/day counters* enable alarms in case of threshold crossover.

Examples of mandatory ATU-R registers:

- ATU-R Vendor ID;
- ATU-R Revision Number;
- ATU-R Serial number;
- Self Test;
- Line attenuation;
- SNR Margin;
- ATU-R configuration.

5.2.4 Standardisation and management information

Several tasks are ongoing to develop information models for management of ADSL transmission systems, and the ones listed here cover medium specific layers only:

ADSL Forum WT-025: *CMIP Specification for ADSL Network Element Management (9/98)* [34]. This document specifies a CMIP based management framework.

The TR-005 [35] and TR-006 [36] MIB definitions suggest an SNMP agent localised in ATU-C and acting as proxy for ATU-R. ADSL Forum WT-022 [37] and WT-023 [38] support and complement these with code specific details necessary to define a complete MIB.

G.997.1 defines parameters and functions within the ATU-C and the ATU-R at their local ADSL interfaces (ie. T1.413, G.992.1 and G.992.2 [39]). The document identifies how these parameters map to a set of managed objects.

G.997.1 describes physical layer operations administrations and maintenance and gives service providers the ability to manage and provision DSL systems. It describes parameters (line, physical, path, inventory, thresholds, status, failures) for configuration, fault and performance management. Furthermore, G.997.1 identifies ATU-C parameters to be available at the S/T interface. These parameters must be retrieved across the U interface via the ATU-R. G.997.1. Operations and procedures described are SNMP-based.

ADSL Forum99-048 [40]: This contribution provides guidelines for DMT-based systems to implement element management in a common way by mapping primitives identified by the PHY layer standards, T1.413, G.992.1 and G.992.2, to the "network management elements" identified in TR-005 and G.997.1. It specifically identifies the means for

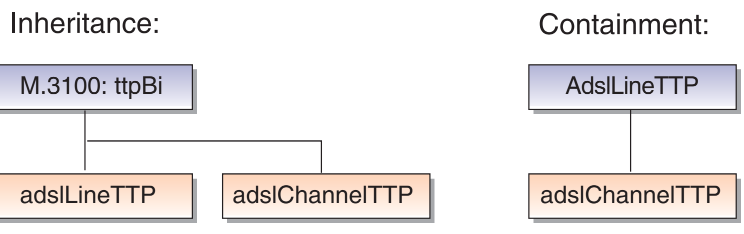

Figure 6 From ADSL Forum CMIP model

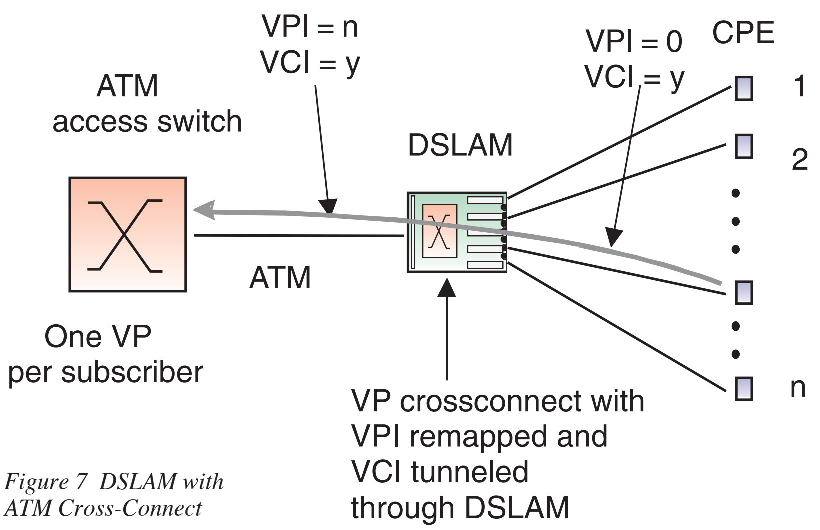

Figure 7 DSLAM with ATM Cross-Connect

transferring the required information across the U interface for presentation to the Q or S/T interface.

IETF is also making an effort at ADSL management developing an ADSL MIB in line with the SNMP v2 standard.

An ADSL system and subnetwork can be modelled according to the G.805 architecture. So far, no model is presented in standards. This is perhaps due to the fact that both DSLAM and ATU-R realise rather advanced network functions. ADSL Forum WT-025 [34] contains a CMIP Specification for ADSL Network Element Management. This document suggests an adslLine (trail) containing adslChannels (connection). AdslLineTTP and adslChannelTTP objects are defined. The adslChannel is serving the client layers (eg. ATM).

Other ADSL Forum contributions have slightly different suggestions for an architecture. Common for the contributions are that adslTTP shall cover physical matters such as lineCoding, supportedChannelTypes, attenuation, rate, s/n margin, output Power, etc. AdslChannel shall contain information about how the line is used concerning type, id, rate, etc. Five types of *ADSL Line Type* are defined:

- No channels exist;
- Fast channel exists only;
- Interleaved channel exists only;
- Either fast or interleaved channels can exist, but only one at any time;
- Both fast and interleaved channels exist.

5.2.6 DSLAM and DSLAM management functions

To interconnect multiple ADSL users to a high-speed backbone network, the AN provider uses a Digital Subscriber Line Access Multiplexer (DSLAM). DSLAM might connect to an ATM network that can aggregate data transmission at transport network data rates. At the downward end of each transmission, a DSLAM demultiplexes the signals and forwards them to appropriate individual ADSL connections. ADSL can be combined with ATM, SDH and Ethernet. G.992.1 describes how ATM and SDH are used as clients for ADSL.

The typical DSLAM might perform a VP cross-connect function and will be transparent to VCI values (Figure 7). PVCs from each customer are effectively tunnelled through the DSLAM to the serving ATM switch. A unique VPI is assigned to each customer for the link between the DSLAM and the ATM switch. The DSLAM is effectively an ATM cell multiplex in the upstream direction and a VP based cell router in the downstream direction.

ADSL Forum TR-002 [41] identifies and defines the functional blocks of an ATM-based ADSL access network, which are formally referred to as B-ISDN Network Termination (B-NT) for the ADSL modem and Access Node for the access multiplexer system. The report addresses the layer 2 protocols and specifically describes the implementation of ATM transport over ADSL links.

TR-002 also addresses the control and management planes related to supporting ATM in the user plane. It includes the ATM PVC support, signalling for SVC support and operations and maintenance functionality to support ATM over ADSL. Concerning ATM Layer Management, ADSL Forum suggests that ATM management of the CPE shall be based on ILMI 4.0 [42].

A management system should be able to manage the entire ADSL network. DSLAM management interface must therefore handle;

- Subscriber line (VPI/VCI/port no/customer id);
- NE IP address;
- WAN port (no/type);
- Master profiles and service profile.

5.3 Passive Optical Network – PON

A likely configuration of a PON is shown in Figure 8, with a single OLT at the exchange side and a number of remote ONUs. OAM functions that are relevant for PONs are: Configuration, Performance, Fault and Security Management.

The Optical Distribution Network (ODN) provides the optical transmission medium for the physical connections and consists of passive optical elements; optical fibres and cables, optical connectors, passive branching components, passive optical attenuators and splices. Individual ODNs may be combined and extended using optical amplifiers.

When modelling a simple PON without amplifiers and multiplexers, the transmission can be split into network layers according to G.805. Using one *Optical Medium Layer* and one *Optical Section Layer*, the latter to support the *Client Layer*, this can be sufficient for modelling purposes. The association of an OLT with its ONU will then be modelled through the association with the fibres. In such a simple model a PON object represents the one or two fibres of the bi-directional point-to-multipoint link between the OLT and its ONUs, each located at a specific fibre, including the associated splitters and other passive components.

Furthermore, one single object may be used for the OLT (oltTtp) and one for each of the ONUs (onuTtp) to represent

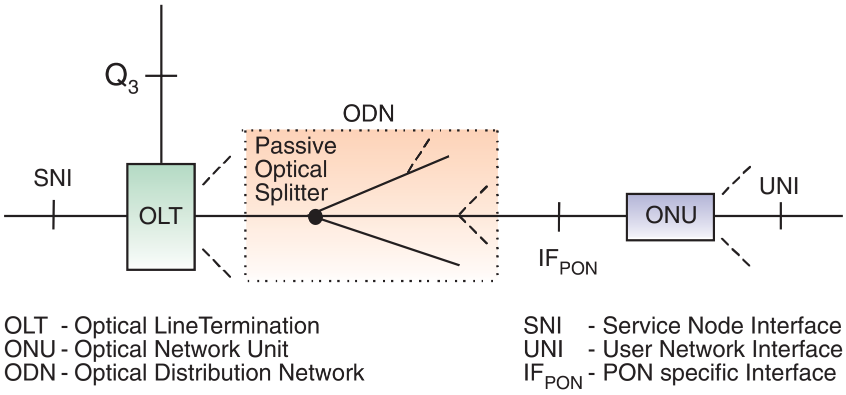

Figure 8 PON configuration

all the functionality of these locations avoiding the need for vendor specific detailed modelling of the sublayers. Each onuTtp object is in turn associated with a number of userPortTtp objects, which represent user ports. Each ONU may have a number of user ports. The user ports interface over UNIs to a terminal (CPE).

Future ODN may have NEs that are all optical and have signals that are processed in the optical domain. Use of various forms of wave division and subcarrier multiplexing may be assumed, allowing several subgroups of ONUs to share the same fibre. Then a model using a wider division of the optical layers should be applied. ITU-T has several recommendations relevant for optical networks management. G.982 [43] deals with the characteristics of an Optical Access Network (OAN) based on 64 kbit/s bearer capabilities up to and including ISDN primary rate services. G.983 [44] focuses on a network to support services with bandwidth requirements greater than ISDN basic rate and is concentrating on ATM over PON. G.872 [45] deals with optical transport network functionality described from a network level viewpoint using the modelling mechanisms from G.805.

G.983 describes capabilities of an ODN and related OAM functions that must exist, and parameters that should be detected in OLT and ONU. It also defines the messages that must be available in the PLOAM[18] channel. The model suggests the PON to be managed as one element, through a Q_3 management interface. The information defined for the PLOAM provides the basis for the management functions available through the Q-interface.

There are several ongoing efforts on modelling optical networks, but the models are not yet stable and consistent. Even if the models are describing slightly different functionality in their layers, the managed objects realised for these layers must cover functions for termination, adaptation and supervision. Management functionality that must be covered for the PON is, eg.:

- Frequency and bandwidth allocations;
- Supervision of optical signal power level;
- Monitoring of optical signal/noise ratio;
- Alarm by loss of optical signal;
- Signal detection and frame alignment.

An ODN may be made more reliable using redundant fibre up to first splitter, thus making protection switching possible. A dedicated wavelength may be used for test/management purposes. To support management, sometimes an extra fibre is deployed, running continuously along with all the fibres that constitute the ODN, thus enabling testing and supervision. Faults that may occur in an ODN are fibre breakage and loss/reduction of optical signal. Fibre breaks can be localised by supervision of reflected signals. Loss/attenuation in fibres is supervised by monitoring received optical signal.

Regarding the equipment fragment, ONUs and OLTs are represented by racks, shelves, slots with field-replaceable units, etc., just like equipment of other technologies. Parameters especially relevant for ONUs and OLTs are:

- Temperature/temperature threshold;
- Bias current/Bias current threshold;
- Optical power/optical power threshold;
- Output frequency/threshold (outside pre-set operating frequency window);
- Line width broadening;
- Tx BER/threshold;
- Optical signal/noise ratio.

A main role of the alarm management functionality is the long term proactive prevention of failures, and monitoring is performed to control transmitter stability and component degradation. Frequency stability depends on the temperature, and statistics made on monitored data can identify failure trends. Attenuation must be monitored also to avoid introduction of additional splitters.

6 Management platforms and component based SW technologies

Although OSIsm and SNMP are focused on the interface between the manager and agent, software platforms for development as well as for run-time use, has always been an important topic related to management systems. In general, platforms provide ways of making the job for the application developer easier. For instance, software services (eg. middleware[19] services) provided by a platform can be utilised by an application developer, and so he does not have to develop that piece of software. Another facility of a platform can be to provide half-made skeletons or solutions that can be further specialised and completed by the developer.

[18] *Physical-layer OAM.*

[19] *Middleware – a loose term for software and corresponding services, layered between communications-and-operating systems facilities and the applications. Middleware constitutes much of the application development environment.*

X/Open and TMN (previously NMF) have developed API[20] standards for access to OSIsm or SNMP middleware. These standards are programming language dependent and for OSIsm they are for instance categorised into ASN.1/C++, CMIS/C++, and GDMO/C++ API standards.

The CORBA initiative by OMG (see above) also provides a basis for platforms, but is even more general as its focus is specification of programming language independent APIs for middleware and ORB services. The ORB-based solution enables full distribution of applications where access and location transparencies are supported. The CORBA Interface Definition Language (IDL) and the CORBA services, specified in IDL, enable portability of applications and provide a basis for interoperability between applications. Based on these properties, the CORBA technology is promoted as an excellent distributed systems technology and the future technology for heterogeneous systems and application integration. Thus, many of the challenges identified above concerning integration of systems in the network and service management layer, can possibly best be handled using CORBA technology.

Since the CORBA technology addresses many of the challenges experienced with the development of large complex and integrated TMN solutions, two issues appear: How to integrate CORBA technology with OSIsm or SNMP technology, and, can OSIsm or SNMP technology be replaced by CORBA technology in an advantageous fashion? The first issues will be addressed in the next section. It should be noted that TMN does not in itself exclude CORBA technology, and ITU-T SG4 currently focuses on how to harmonise CORBA and similar technologies within TMN to take advantage of what these technologies have to offer. While SNMP and OSIsm can be considered as being at opposite ends of a complexity scale, the CORBA technology has the potential to be profiled and appropriately suited for a range of settings.

While Java and Java RMI[21] and Microsoft DCOM[22] represent technologies challenging CORBA (ver.2), the appearance of transaction based server-side component models like Enterprise Java Beans (EJB), and the CORBA Components Model[23] go one step further. By formalising the notion of components and hiding more software details from the application developer, software development is made more efficient and the support for assuring component (application) interoperability is improved.

Based on these emerging trends in distributed software technologies, one can hope that a better basis is provided for to enable integrated management, than what we have experienced so far in the realm of TMN. Several issues are unsettled. For instance, are NE providers willing to deliver element managers with well specified component interfaces, and thus let their element manager be integrated in an operators integrated element management system? Are operators willing to take greater responsibility themselves in developing integrated solutions based on integration of subsystems and software components from NE vendors and management platforms providers? Will a combined 'buy and build' approach like this give greater freedom of choice and better control of the operators management systems portfolio? In any case, it is likely that an operator will acquire an increasingly complex management systems portfolio to manage the access network, and the management of systems and applications as well as providing support for systems evolution will become more important. Application server technology as well as systems and application management solutions will become correspondingly important.

7 Integrated management and interworking

The development of systems plans and systems architectures to enable integrated telecommunications management is a great challenge to network operators. Issues relevant to this challenge have been identified above. Although just being one other part of the challenge of integrated management, the issue of interworking between different management technologies will be addressed briefly in this section.

In general, the mapping from one technology to another can be done at the manager-side or the agent-side by embedding a gateway in either the manager or the agent respectively. The gateway can also be located in a standalone (mediation) device. On the other hand, one could translate an interface model from one language to the other, and likewise use the corresponding technology at both the manager and the agent side. However, the more likely situation involves a gateway, to let investments in existing solutions carry through. Yet another solution is to let the application developer take care of the mapping, by having him program against several management technologies. This does make the burden on the application developer considerably greater. While this is not effective for programming against APIs representing similar interfaces, it may be a reasonable strategy if the technology mapping also involves a conversion from a model and interface at one management layer to another. For instance, if the application realises a mapping between an NE-level to a network level model, one can envisage that the NE-level interface is based on CMIP, while the network level interface is based on CORBA IDL.

Due to the simplicity of the SNMP management information model, automatic specification translation from OSIsm- or CORBA-based models to SNMP is not possible without losing important semantic information. Mapping from SNMP to OSIsm or to CORBA IDL on the other hand, is achievable. By locating for instance a CMIP/SNMP gateway near the SNMP agent, it is possible to 'extend' the functionality of the SNMP agent and introduce event reporting, logging and summarisation functionality closer to the NEs. However, the mapping of SNMP table entries to separate CORBA IDL interfaces may result in a significant overhead if the number of interfaces becomes large.

Due to the popularity of CORBA, enabling interworking between CORBA based environments and OSIsm based environments is of particular relevance. Both modelling notations are based on an object-oriented modelling approach. This provides a good starting point for translating models. However, while translation from CORBA to OSIsm is rather

[20] *Application Programming Interface.*

[21] *Remote Method Invocation.*

[22] *Distributed Component Object Model.*

[23] *Supported by CORBA 3.0, becoming available in 1999.*

straightforward, the translation in the opposite direction is more difficult. The latter case is also more relevant to access network management scenarios. Most of the difficulties due to the differences have been resolved and a standardised way of achieving specification translation has been suggested by X/Open [46]. Still, there is semantic information associated with GDMO conditional packages that may have to be manually resolved. While based on the specification translation from X/Open, the final submission to the OMG's CORBA/TMN interworking RFP [47] provides a gateway solution for dynamic conversion between the protocols and associated behaviour of the two technologies. To support all interactions possible in CMIP, this solution relies on previously specified CORBA services like naming, life cycle, event, property, and collection services.

Although the just mentioned specification efforts represent a significant step in the integration of these two technology domains, there is much experience to be acquired before one can be sure what architectures and technologies to go for, considering large scale management solutions.

8 Conclusion

Several technologies are challenging the GDMO/CMIP-based solutions from OSI Systems Management. SNMP-based solutions will play an important role regarding management of network elements. However, trade-offs must be assessed to choose between the two. CORBA-based solutions will become more relevant at the network and service management layers, and technology interworking solutions will be required. The WBEM initiative may also provide interesting solutions within specific areas.

The development of systems plans and systems architectures to enable integrated telecommunications management is a great challenge. Emerging component based software technologies provide a basis for application integration. However, great challenges prevail in the area of the network and service management layers where new kinds of network and service resources must be managed in an integrated and efficient fashion.

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Home networks: New challenges for network operators

MARKUS WYSS AND FRÉDÉRIC PYTHOUD

1 Introduction

You are at home, sitting in front of your desktop, quickly reading the news on the web. Suddenly, the phone rings. As you are used to, you click your mouse and get the conversation with your friend. He is very keen on the football match that is being played now. In order to share his enthusiasm, you display the corresponding TV channel on your screen. At this moment, you notice that you have forgotten to switch off the light in the living room and a warning on your screen informs you that the electric cooker is ready to explode. By another two mouse clicks you perform with simplicity ... all necessary actions.

This imaginary story is certainly not for today. But it may typically represent tomorrow's home network features. The home network represents the last drop of communication networks by which the information gets to or from the user. It is thus a domain with a high degree of complexity that is in touch with different areas of telecommunications.

2 Home Network scenarios

The Home Network (HN) does not simply deal with a transmission system, or a management system, as the last drop of the telecommunication network covers all OSI layers. This makes the subject quite complex. Moreover, it is located at the customer premises so that the ownership issue, responsibility issue, and interface definition between operator and customer are problematic.

HN is the 'termination' of the broadband network infrastructure. Many different areas are touched by the Home Network as shown in Figure 1 and discussed in the following sections.

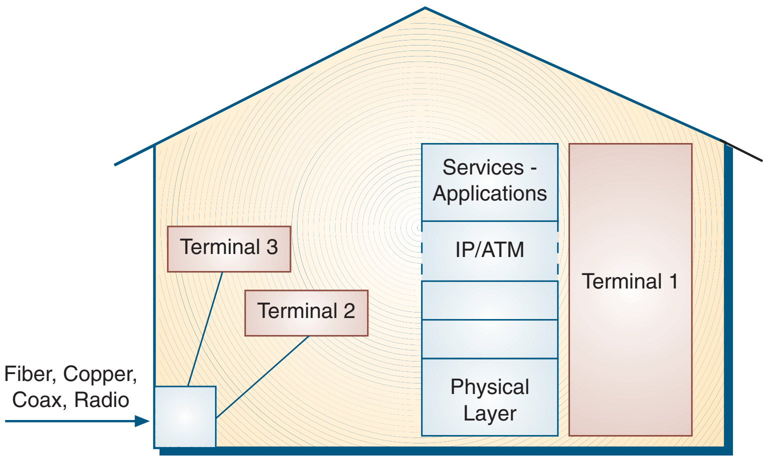


Figure 1 Representation of the different domains and problems touched by HN

3 Media types

Twisted pair, plastic optical fibre (POF), power lines, air (for wireless infrared or radio) are the most known media types that may be used for home network applications. Each of these media types has some advantages and disadvantages that are briefly mentioned hereafter:

- Twisted pair is a medium that is very popular for business LAN (Ethernet, ATM 25). The standards available specify twisted pair to be able to carry up to 100 Mbit/s over several tens of metres (cat. 5). More often than not, the actual cabling used for POTS distribution inside buildings is not adapted for such bitrates. The cabling thus has to be newly installed.
- POF (Polymer Optical Fibres) also offers the possibility of carrying 100 Mbit/s over several tens of metres. POF is younger than twisted pair, but may typically compete with twisted pair in the future. POF offers the advantages of high flexibility, easy handling and processing, EM immunity, low cost components, high bandwidth, and low attenuation.
- Power lines is a very interesting medium for communication inside the home since it is already deployed in every room, and sometimes in every corner of the room. However, this medium is electronically contaminated and has a prohibited frequency band (different in Europe than in the US). It is still for the time being a very good candidate for typical home automation applications.
- Wireless infrared and radio offer the very nice advantage that they do not require extra cabling. However, the reach of these systems is most of the time limited to the room except for some radio systems operating at adapted frequencies. For radio wireless communication in the customer premises currently unlicensed spectrum is used. For available wireless LAN systems in the ISM-Band (2.4 GHz) and future HIPERLAN (High Performance Radio LAN) systems in the 5 GHz band house coverage can be achieved.

4 Low bitrate transmission systems – home automation

The imaginary scenario mentioned in the introduction requires access to many appliances and consumer electronic equipment in the house, like the oven, lights, heating, air conditioning, TV, the video, security systems, which typically require low bitrate. One could think, for this so-called smart house, of connecting all these systems to a broadband transmission network for all applications inside the home like a twisted pair of optical fibre network. However, a set of existing technologies is already available to connect the different house equipment together:

- X10 is currently the most widely deployed technology for home automation. It transmits over powerlines using the zero crossing of the AC sinusoid to transmit information bidirectionally. The bitrate is typically a few bits per second.
- CEBus (Consumer Electronic Bus) is a communication standard for home networks developed by the Electronic Industry Association (EIA) and the Consumer Electronics Manufacturer Association. The standard covers communication via many media like twisted pair (TP) cable, coax cable, RF, Infrared, and AC powerline carrier. The bitrate is typically a few kbit/s.
- LonWorks is a proprietary local operating network communication

technology introduced in 1990 by Echelon Corp. LonWorks can typically work at 4–5 kbit/s over powerlines, twisted pair, coax cable, fibre optics, and wireless RF and infrared.

- EIB (European Installation Bus) is a transmission system optimised for each medium: twisted pair, powerline, and radio frequency (RF).

5 High bitrate transmission systems

The candidates generally accepted for use in home environments are briefly listed below:

- ATM25 is a transmission system able to transmit 25 Mbit/s on twisted pair category 5 cables. ATM25 is a PTP system that is normally used in star architectures. However, the use of small switches allows tree-like architectures.
- ATM 50 is a transmission system able to transmit 50 Mbit/s over twisted pair (category UTP5) and POF.
- Ethernet 10 Mbit/s is for twisted pair cat. 3 or 5 (10 BaseT) as well as for fibre optic (10BaseF).
- Ethernet 100 Mbit/s can also be used on twisted pair cat. 3 (100Base T4), cat. 5 (100BaseTx), or optical fibre (100Base Fx).
- IEEE1394 (or Firewire) is an interface originally made for consumer electronics (TV, VCR) and requires a special cabling where 2 pairs are used for transmission and 1 pair for powering. The bandwidth available is 100, 200, or 400 Mbit/s. Its flexibility makes it a good candidate for computer and telecommunication applications.
- IEEE802.11 is an Ethernet interface specially developed for wireless applications (both infrared and radio). The available bandwidth is now 1–2 Mbit/s and should be increased in the future to 10 Mbit/s.
- IrDA is a standard developed by the Japanese manufacturer of computers, communication equipment, and semiconductors for short range half duplex bitrates up to 4 Mbit/s using infrared wireless transmitters.

Other wireless systems are being considered to increase the bandwidth to several tens of Mbit/s like UMTS, MBS, HIPERLAN, HRFWG, Bluetooth, COMMEND projects. These systems are not available at the moment but are planned for 2000 and later.

6 Architectures for the home network

FSAN (Full Service Access Network), DAVIC (Digital AudioVisual Council), VESA (Video Electronics Standards Association), HAVi (Home Audio/Video Interoperability Architecture) are different international groups that have their view on the home architecture. The concept of a residential gateway is able to cope with many different home networks and access network interfaces.

6.1 GX-FSAN

The Network Termination – Home Network Group of GX-FSAN has produced a few different reference configurations based on the general architecture. Figure 2 represents the general architecture according to GX-FSAN for xDSL based access. It is assumed that the cabling carrying the broadband signals and the cabling carrying the narrowband signals inside the home are separate, although they can run in parallel. One option of the market deployment reference model is shown in Figure 3.

6.2 DAVIC

DAVIC has provided Home Networking specifications in its last 1.4 specification.

DAVIC's Home Networking tools have been developed to support the following functional requirements:

1 Secure tunnels (ie. authentication and encryption), secure home owner resources (eg. select video content, financial data);

2 Multiple consumer appliances per home (eg. VCR, STU, PC);

3 Multiple service providers (eg. HFC, FTTC);

4 Inter-room and intra-room communications;

5 Capabilities for uncompressed or 'lightly compressed' video transmissions between consumer appliances;

6 Target at least 100 metre runs;

7 Target at least an aggregate bandwidth of 200 Mbit/s;

8 Target at least eight simultaneous isochronous streams (eg. MPEG2 TS, lightly compressed video stream);

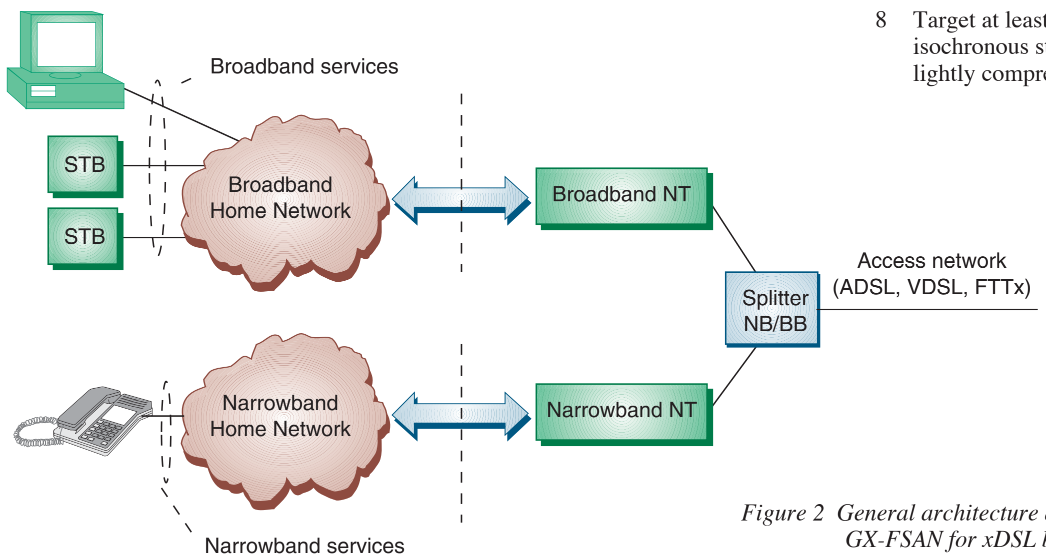


Figure 2 General architecture according to GX-FSAN for xDSL based access

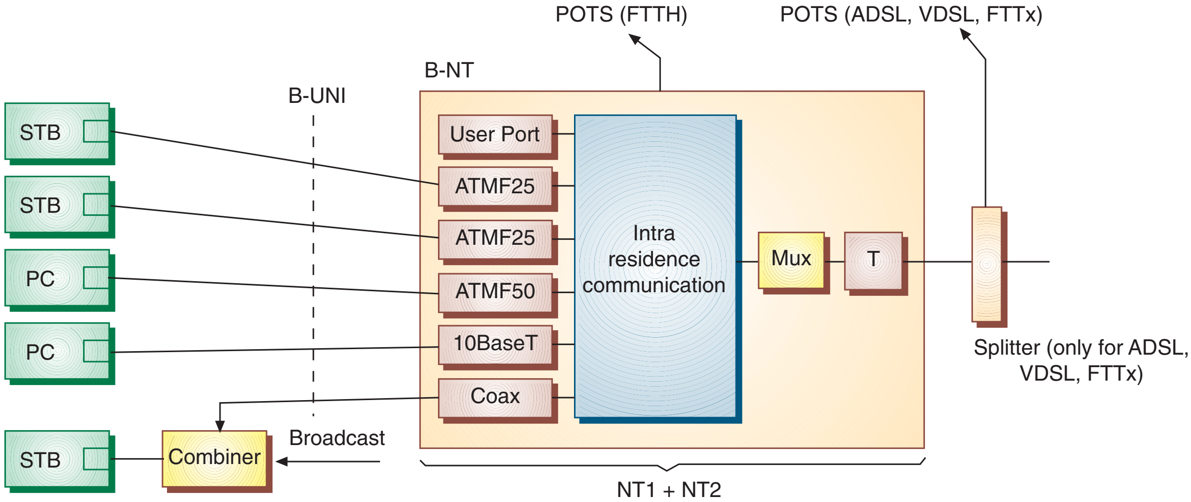


Figure 3 One of the FSAN models: Modular B-NT, with integrated NT2 for Market Deployment

9 Target ease of use for average home owner;

10 Target evolution from simple to complex networks;

11 Simple to install and maintain;

12 Must meet local EMC and be fit for purpose requirements;

13 Must meet local safety and regulatory requirements.

Figure 4 provides a general overview of Home Network Architectures. The DAVIC Home Network systems are functionally divided into Home Access Networks, and Home Local Area Networks. These architectures represent the full range of architectures to facilitate detailed specifications of home network devices, topologies and technologies.

This reference model introduces many new different concepts like:

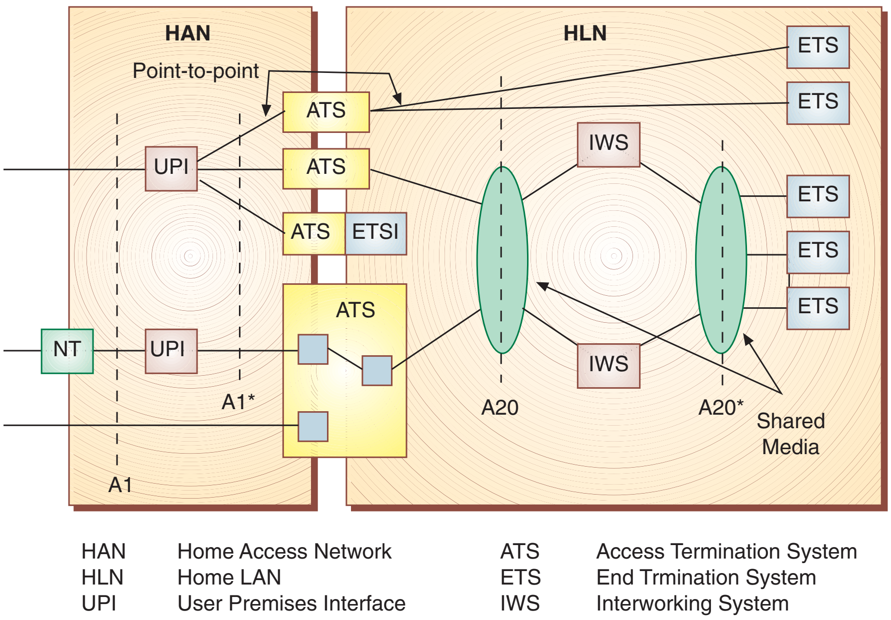


Figure 4 DAVIC Home Network Overview

- User Premises Interface (UPI) provides connectivity from the DAVIC Access Network to the Home Access Network (HAN) by connecting the A1 to one or more A1* interfaces. The UPI may be passive or active.
- Access Termination System (ATS) provides several functions. It may be an end consumer device, such as a set-top box, that uses all S-flows provided by the Delivery or HAN system. It may also be a gateway device between the Delivery or HAN system and the Home Local Area Network (HLN). Examples of IWS include copper to optical repeaters, bridges, and routers.
- Interworking System (IWS) provides a similar functionality to the HLN as the UPI does to the HAN. It may act in a passive or active mode to translate between physical and mid-layer protocols for ETS and ATS devices on the HLN. Examples of IWS include copper to optic repeaters, bridges, and routers.
- End Termination System (ETS) devices represent end user equipment that may be used for a DAVIC application. Examples of ETS devices are camcorders, PCs, VCRs, television, Internet appliances, and security systems.
- Home Access Network (HAN) is an extension of the DAVIC Delivery System access network to multiple devices within the home. The User Premises Interface provides separation between the HAN media at the A1* reference point.

- Home Local Area Network (HLN) functions much like a traditional LAN environment, with the ATS devices acting as gateways to the DAVIC service provider applications. The HLN may also support separate applications with no dependencies to service provider resources or content.

6.3 VESA (Video Electronics Standards Association)

The VESA Home Network committee is formed by hardware, software, PC, display and component manufacturers, cable and telephone companies, and service providers. It has several goals:

1 Provide an interoperability specification which will allow the transfer of information from any device to any other device in the home;

2 Allow interoperability between different home networks from low to high bandwidth;

3 Provide a common interface on the home side for Access Devices, such as the Residential Gateway;

4 Be able to make a transition from analogue distribution to totally digital distribution;

5 Provide directory services for devices in the home.

The VESA committee feels that there will continue to be several types of networks in the home. Today many houses have a copper wire telephone network and a coaxial cable TV network. These networks will stay in the home for a long time and the new digital networks will be put in place in addition to them. The VESA Home Network architecture (Figure 5) has the benefit of allowing low bandwidth low cost devices to stay on their own network and not have to handle high speed data and decode complex protocols.

The Backbone network spans the whole house so that devices located anywhere in the house can communicate with each other. The backbone provides sufficient quality of service for the applications and devices that communicate over it.

The Component network enables devices connected to it to communicate with each other. Examples of important Components Networks are IEEE1394, Ethernet, Powerline CEBus, and RF Wireless LAN.

An Access Device is a device that connects an external access network to the home network. A POTS modem, an ISDN adapter, a cable modem, Residential Gateway and DBS decoder are all examples of Access Devices.

An End Device is a digital device connected to a network whose purpose is to provide some utility (other than network service) to the end user. Examples of End Devices are printers, TVs, audio speakers, security sensors.

A Network Device is a device whose purpose is to provide network services to End Devices. Examples of Network Devices include repeaters, bridges, routers, brouters, and network management stations or any device that serves such a purpose, such as a PC.

6.4 HAVi

The HAVi Architecture is defined by companies like Sony, Philips, Hitachi, Sharp, Matsushita, Thomson, Toshiba, and Grundig. The HAVi Architecture is intended for implementation on consumer electronics (CE) devices and computing devices; it provides a set of services which facilitate interoperability and the development of distributed applications on home networks. HAVi is intended for, but not restricted to, CE devices supporting the IEEE 1394-1995 and IEC 61883 interface standards.

The HAVi Architecture is intended for networks based on the IEEE 1394 standard. IEEE 1394 is a powerful technology that meets many of the requirements of home networks (see Figure 6).

Since a goal of the HAVi Architecture is to be future-proof, interoperability is more than a common command set. It is a software architecture that allows new devices to be integrated into the home network and to offer their services in an open and seamless manner.

The HAVi Architecture provides:

- A set of software elements with their protocols and APIs needed to achieve interoperability (Figure 7);
- Device abstraction and device control models;
- An addressing scheme and lookup service for devices and their resources;
- An open execution environment supporting visual presentation and control of devices, and providing runtime support for third party applications;
- Communication mechanisms for extending the environment dynamically through plug-and-play capabilities;
- A versioning mechanism that preserves interoperability as the architecture evolves;
- Management of isochronous data streams.

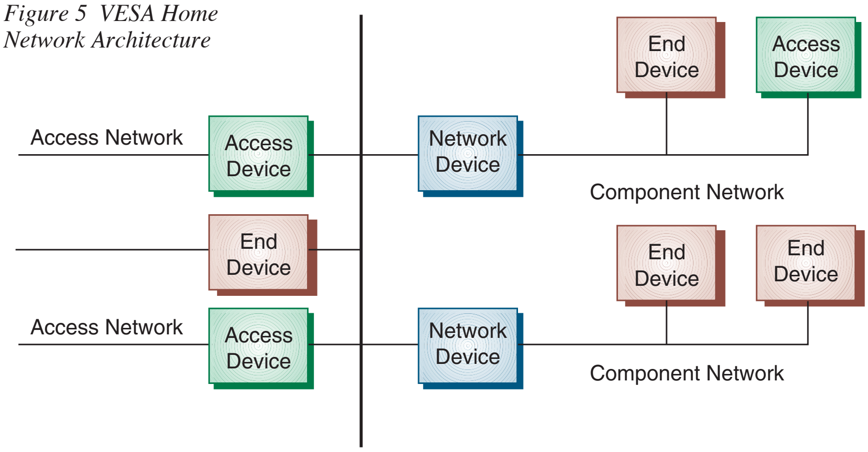
6.5 Residential gateway

The Bellcore concept

The concept of residential gateway has, according to Bellcore, the following key attributes:

- The ability to provide efficient interfacing of one or more access network

Figure 5 VESA Home Network Architecture



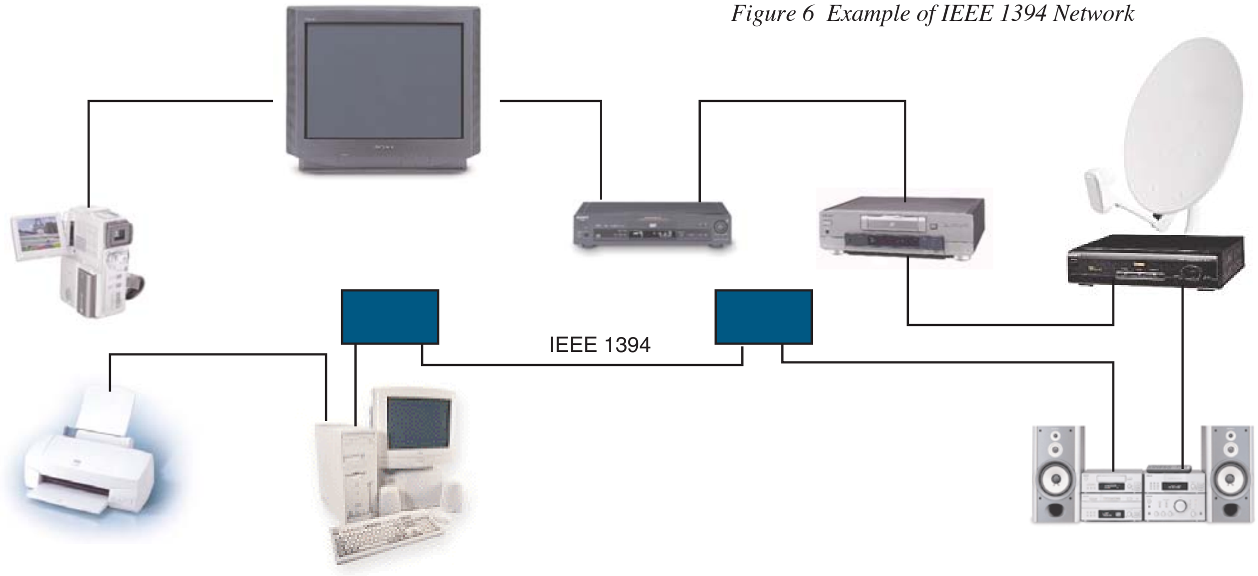


Figure 6 Example of IEEE 1394 Network

interfaces with multiple home networks and devices;

- Low cost, perhaps using a modular, incremental expansion strategy to accommodate additional interface, networks and devices;
- Power management, with power-down or standby capabilities, and either power back-up or passive coupling features for some critical services.

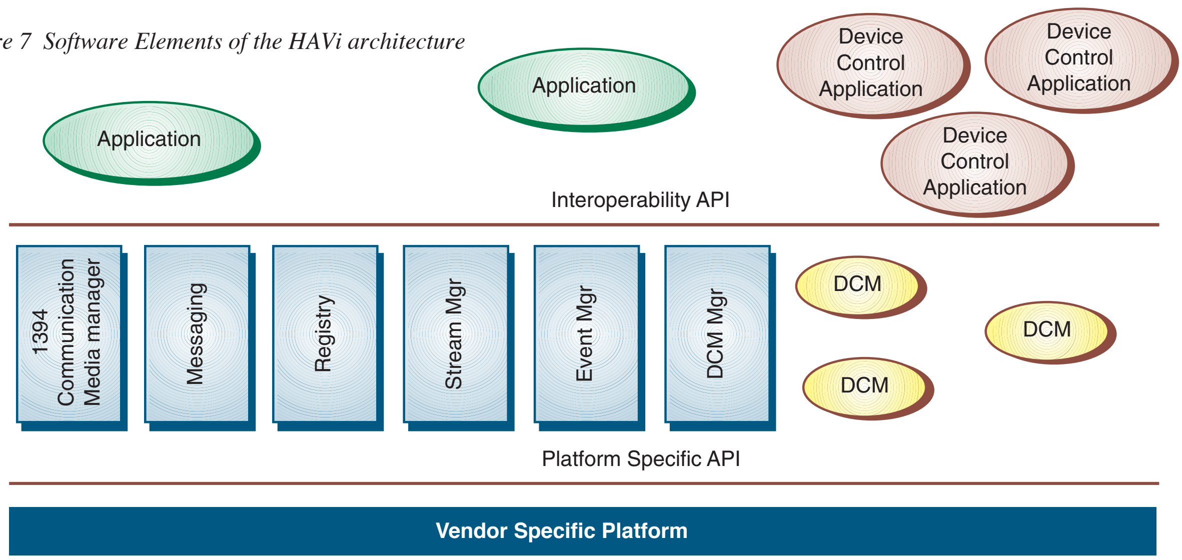
Figure 8 shows a Residential Gateway concept.

There are many functions that could be integrated in the RG (residential gateway), but the core required function may be protocol and format conversion, intelligence within the RG to enable features such as remote provisioning and maintenance. The RG allows network technologies to be reliably terminated, with well-defined network provisioning, monitoring and loop-back capabilities. Similarly, internal home networks can be more reliably installed and maintained if they are not extensions of outside plant networks, such as is currently the case for cable modems. The RG provides an important middleware interworking flexibility point, for example interworking between an access network delivering ATM cells, and separate home networks using the TCP/IP protocol on 10Base-T Ethernet, and IEEE 1394 network supporting isochronous digital video.

CENELEC concept

The working group WG5, under the responsibility of the CENELEC TC205 ‘Home and Building Electronic Systems’ started early 1998 a new work. The objective of this is to specify a standardised interface between telecommunication networks and home networks to satisfy the need of the service providers (functionalities) and of the customers (cost and usability) in the area of the home automation services. Liaisons have been established with many other groups (ETSI, CEN, CENELEC, TIA, DAVIC, VESA, EIBA) in order to ensure a system compatible to all of these future applications. The WG5 aims to get a first set of documents end 1998.

Figure 7 Software Elements of the HAVi architecture



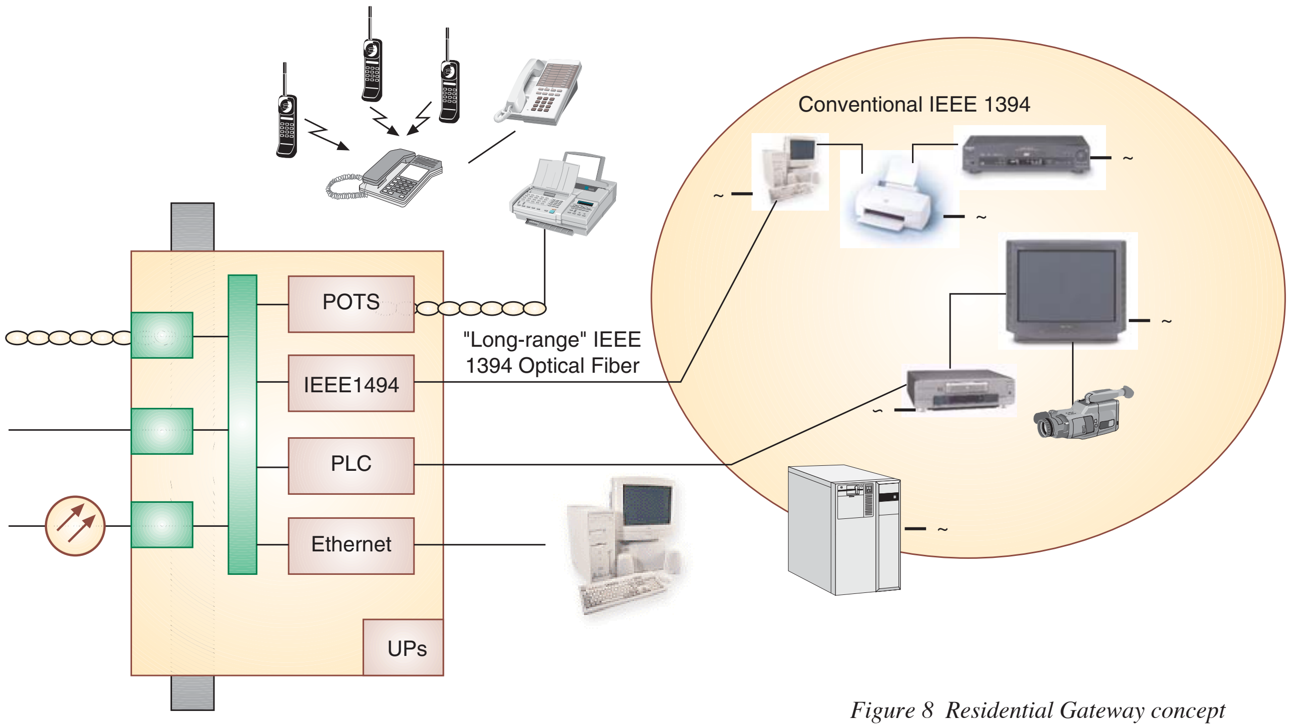


Figure 8 Residential Gateway concept

PLC: Power Line Communication
UPS: Uninterruptible Power Supply

It seems that the generic interface will be able to support several kinds of home bus with different protocols as well as ISDN, POTS, and GSM. The capacity in terms of Mbit/s of this bus, as well as its ability to handle ATM and IP traffic, are still not clear.

7 Challenges

This contribution illustrates the number of possible interfaces, transmission systems, and possible architectures that may be used for Home Network applications, today available. Network Operators should not ignore this status and leave consumer electronics companies to this market. Network operators are active partners in the deployment of end-to-end solutions for telecommunications. Their choices, their strategies, like for example to sell ATM to the desktop, may deeply influence the choice of the architecture, of the transmission system, and of the interfaces. A good strategy for Home Networks may also increase the demand for broadband and thus directly impact on the core network. The youth of the Home Network market shows the huge potential for new developments in the future that may make the imaginary story of the introduction become real.

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Achieving global consensus on the strategic broadband access network: The Full Service Access Network initiative

ALAN QUAYLE AND JEFF STERN

The Full Service Access Network (FSAN) initiative represents over half of the world's telephony lines. They have agreed upon a common broadband access system that can be applied to both the business and residential market sectors. The FSAN initiative has been responsible for harmonising the broadband requirements of many telcos, for example it has produced the world's first asynchronous transfer mode passive optical network (ATM PON) specification which is being adopted world-wide. This paper describes the current activities within FSAN, the application of FSAN components and where FSAN can go in the future.

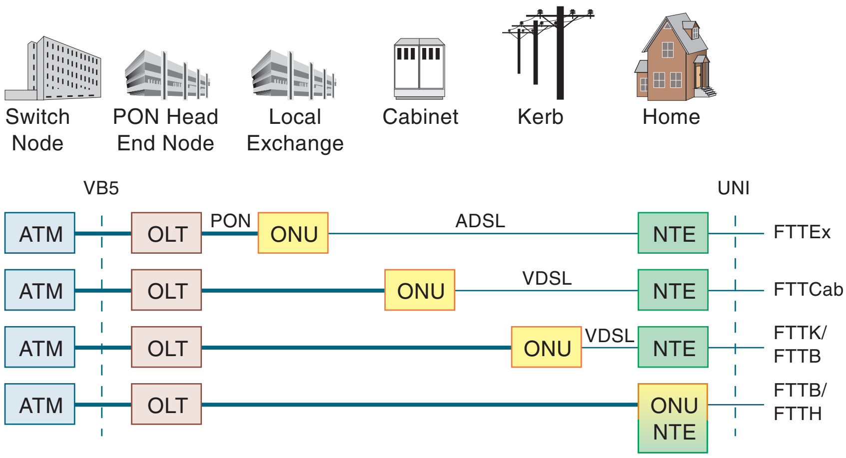

Figure 1 Common network elements

Table 1 The telecommunications operator's position in the emerging broadband environment

Strengths	**Weaknesses**
Existing ubiquitous infrastructure. Organisation, eg. sales, marketing, maintenance, able to support new broadband services.	Existing infrastructure with ongoing depreciation charges necessitates re-use.
Reputation.	Capital constraints limit investment.
Excellent brand awareness.	POTS is devaluing so need new revenue streams.
	Market will be strictly regulated.
Opportunities	**Threats**
New revenue streams – teleworking, Internet and multimedia.	Uncertainty in demand and regulation.
Lower cost of providing POTS.	Competitors already providing broadband.
Technology enabling broadband multimedia delivery to the home.	Low service take-up.
	High churn.

1 Introduction

Imagine how much cheaper broadband networks could be if their components could be mass produced, say in the quantities needed for tens of millions of access lines, rather than today's typical few thousand line trials. This is the vision behind the Full Service Access Networks (FSAN) initiative; a three year old project, that involves nineteen of the leading telecommunications network operators, supported by many of the major telecommunications equipment manufacturers. The aim is to create a common requirements specification for an access system supporting a full range of narrowband and broadband services for a market that covers nearly four hundred million lines of telephony.

The aim of this paper is to communicate the achievements of the FSAN initiative, describe the common access system and explain the potential application areas of this technology. The telcos currently involved in the initiative are: Bell Canada, Bell South, BT, Chungwa (Taiwan) Telecom, Deutsche Telekom, Dutch PTT, Telecom Eireann, France Telecom, GTE, Korea Telecom, NTT, SBC, SingTel, Swisscom, Telecom Italia, Telefonica, Telia, Telstra, and USWest.

Within FSAN it was recognised that the needs of individual telecommunication operators differ due to different regulatory, business, and structural environment in each country. But sufficient similarities exist in requirements for future access networks to enable significant benefits to be achieved through adopting a common requirements specification. The common system is based around a broadband fibre feeder system, ATM PON (Passive Optical Network), and a xDSL (Digital Subscriber Line) system, shown in Figure 1. The exact DSL system used depends upon where the optical system is terminated, eg. in the local exchange, cabinet, kerb or home. Hence this broadband access system can support a range of access architectures; this flexibility is fundamental to the consensus achieved in FSAN. [1] describes the use of Asymmetric Digital Subscriber Line (ADSL), one of the topology options shown in Figure 1.

2 The need for broadband

It is anticipated that FSAN will provide a broadband solution to both the residential and small/medium enterprise markets. Table 1 captures the incumbent operator's position in the emerging broadband environment. The existing revenue streams are under increasing pressure, and the nature of network usage is also changing, n.b. the rapid growth of the Internet. FSAN provides a broadband access solution that builds upon the operator's strengths through using the existing infrastructure, this also tackles some of the weaknesses by minimising capital investment. FSAN is flexible in its topology through a range of re-use options, thus managing the threats. FSAN is enabling operators to jointly take advantage of the broadband opportunity through minimising the risks associated with the investment.

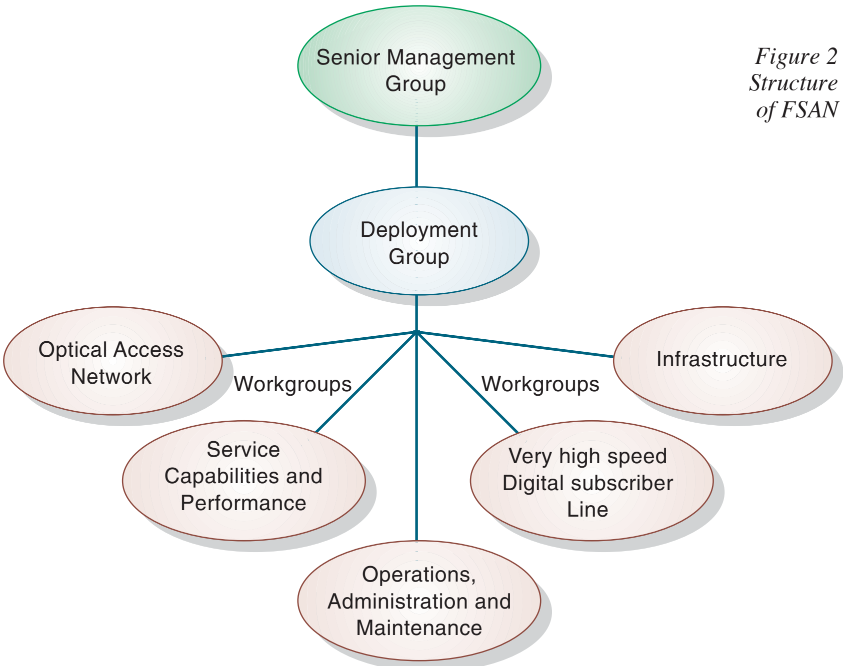

Figure 2 Structure of FSAN

3 FSAN structure

The FSAN initiative has been through four phases, each lasting roughly one year, the results being presented to the industry at public conferences, they are also available on the world-wide web [2]. Initially the initiative focused on identifying how cost reduction could be achieved. Several important system components were identified, and with a common specification it was believed that cost reduction would be possible. The global access product achieves cost reduction through two effects; competition in supply which reduces margins, and each supplier produces a greater volume of the common system so the learning curve effect has a greater impact on production costs.

As the initiative has progressed the focus has moved away from bit level specifications to management/control plane issues and service specific aspects, eg. how fast channel changing is done for switched digital broadcast TV, see section 5.1.

Figure 2 shows the relationship between the different groups within FSAN. The workgroups are focused on adding technical content to the specification, their work will be discussed in later sections. The deployment group is developing a clear business opportunity statement for FSAN deployment and communicating this to the industry. It is also responsible for ensuring any specification gaps are completed by workgroups.

The objectives of FSAN are to:

- Complete the outstanding technical issues by the end of 1998, and provide a milestone upon which the manufacturers can focus their development programmes, particularly for the APON system;
- Sell the business opportunities from using FSAN components in extending broadband to the wider market;
- Share trial and deployment experiences to encourage the adoption of FSAN systems.

4 The Deployment Group

The Deployment Group is formed from the merged FTTCab and FTTH chapters. Its aims are to:

- Identify and develop clear business opportunities for FSAN deployment and sell these opportunities to the industry;
- Assemble complete packages of specifications for each deployment scenario driven by the early mover telcos.

5 FSAN workgroups

5.1 Service Capabilities and Performance Workgroup

The mandate of the Service Capabilities and Performance (SCP) workgroup is:

- To define and specify the capabilities required of FSAN access network to support the required services;
- To determine dimensioning/sensitivity and performance requirements of a FSAN;
- And because FSAN is access-centric, the focus is on bearer services, ie. transport-related.

The current work areas of the group are:

- Switched Digital Broadcast (SDB), which covers the following issues:
  - fast channel changing (zapping) protocol;
  - replication in the access to conserve capacity;
  - customers having access to multiple broadcast content providers simultaneously.
- Real-time control of access network resources, which covers the following issues:

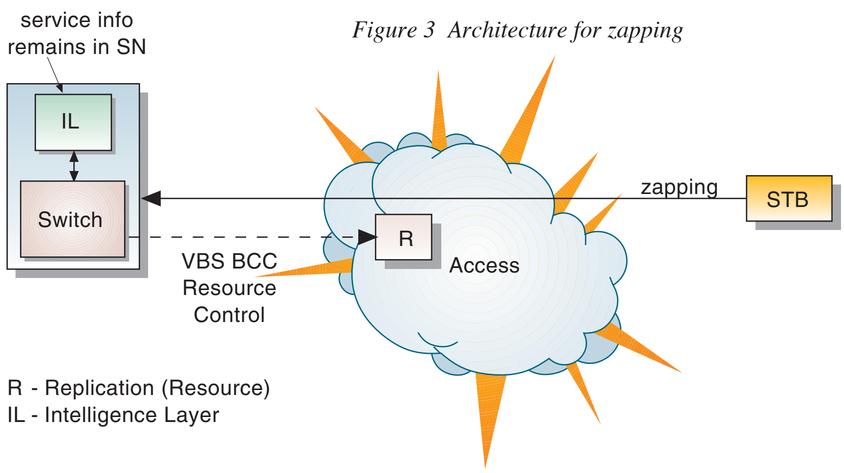

Figure 3 Architecture for zapping

– full signalling (Q.2931) versus possible new streamlined low-level protocols;

– resource management of network termination is a key issue.

- Integrated POTS/voice, multi-line voice, for example:

– lifeline, toll quality;

– non-lifeline, lesser quality;

– other classifications based on availability.

- Handling of IP capabilities and Ethernet/10BaseT user interfaces, with a focus on:

– multi-service, multi-terminal support;

– concentrating on determining operator requirements for input into standards bodies.

- The Home Network group has been merged into this group and is described in the following sub-section.

Taking the switched digital broadcast issue as an example, the group has decided not to provide a special solution for zapping between TV channels provided over the access system, but follow the VB5 architecture, as is used for all other services over the access system. Figure 3 shows the architecture for zapping. A channel change request, zapping, comes from the STB (Set Top Box). It is not terminated in the access, for many operational and commercial reasons, eg. this avoids the need for the access network to contain customers' personal information. It enables the zapping protocol to be independent of the access network. Only the service provider and STB need to be aware of the protocol. Through the bearer channel control (BCC) protocol the access receives the instruction for the channel change.

5.1.1 Home network aspects

The work of FSAN is very much service driven. Since services are by definition end to end, then FSAN must ensure that it considers a complete end to end system description, which includes the customer environment. This is something of a change from the traditional telco view, where responsibility (and possibly interest) ended at the NT. Although there may still be a limit to which operators can dictate what occurs in the customer environment, they can at least ensure that suitable customer systems are specified. Three aspects of the customer environment need be considered:

- The home network;
- The customer interface;
- CPE functionality.

5.1.1.1 Home network

The basic problem that the home network needs to address is how to distribute the Access Network services throughout the home, and provide multiple simultaneous attachment to different services, while retaining the quality of each service. The solution to this problem involves issues that range from architecture to infrastructure. The basic FSAN HN architecture is shown in Figure 4; two key features are shown. The Access Network is decoupled from the HN by means of an active NT; the HN is essentially a LAN rather than simply being an extension of the Access network, however, it must be a LAN that can support the required service mix. This decoupling means that different and appropriate transmission systems can be used in the Access and Home environments, and that the same HN can be used with a variety of Access Network types. The second main feature is the separation of the broadband home network from the existing narrowband one.

After consideration of all the existing and developing technologies, the following solution was agreed:

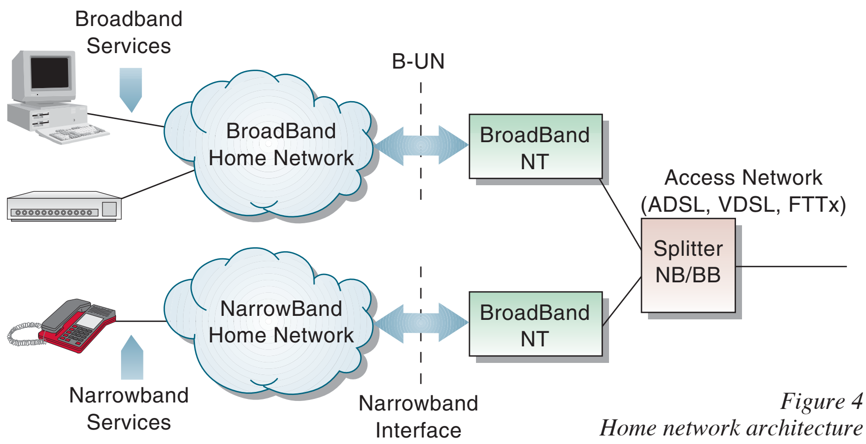

Figure 4
Home network architecture

- A point to point star, architecture;
- Newly installed Category 5 twisted pair cable;
- 50 m reach between nodes;
- Basic network functionality incorporated into the NT;
- Enhanced functionality provided by means of a separate hub.

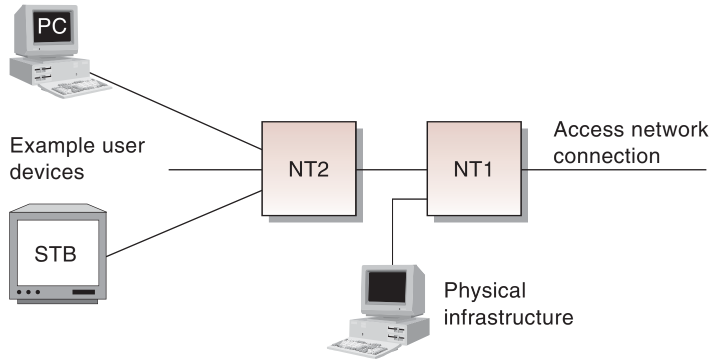

Figure 5 Basic functional elements

The basic functional elements of the home network are shown in Figure 5. The NT1 terminates the Access line system (xDSL or fibre) and may contain other functionality, in particular basic multiplexing and demultiplexing. Multiple (customer-side) interfaces may be presented by the NT1. The NT1 functionality will be physically located in the B-NT. Full switching requires the addition of an NT2. This may be located in a separate physical device, or could be incorporated into the B-NT; however the degree to which this incorporation is allowed may be the subject of local regulation. A separate NT2 would generally be regarded as CPE. The CPE end devices can connect directly to the NT1, NT2 or both, depending on the implementation.

5.1.1.2 The customer interface

The general framework of FSAN is based on the fact that the transfer mode of the access network needs to be based on ATM to provide the controlled, full service mix. In order to retain this full service capability to the user, ATM needs to be continued right through the home network to the CPE. This also avoids a complex interworking function in the NT. The problem is that the home environment is rather different from the business environment with regard to the required transmission and EMC performance. However the ATM Forum have developed a PHY standard specifically designed for the residential environment. This is based on (and backward compatible with) the original ATM25, but provides:

- A higher line rate mode (51.2 Mbit/s);
- Improved EMC properties;
- Physical layer OAM.

This is the chosen FSAN customer interface. It provides sufficient bandwidth to support future HDTV services as well as allowing for more extensive customer networks. The 51 Mbit/s mode of this PHY must be supported in FSAN systems, but it will automatically interoperate with devices that conform to the original ATM25 specification, thereby providing backward compatibility with some early, existing deployments.

However for some specific services, there may be a case for terminating ATM before the CPE (eg. in the B-NT or a separate terminal adapter) and providing interworking to another network type. The only example of this alternative approach considered by FSAN is Ethernet interworking. A key issue with Ethernet presentation is where the (layer 2) Ethernet protocol is terminated, ie. where the initial routing functionality is carried out. The preferred FSAN approach is to do this in the home for reasons of scalability and security; this functionality could either be incorporated in the NT or as a separate, conventional small router. 10BaseT was not designed for the residential environment and does not have desirable EMC properties. The FSAN preferred Ethernet interface type is therefore 100BaseTX. However in order to provide compatibility with 10BaseT PC interface cards, where 100BaseTX is implemented in the B-NT it must support dual mode 10/100 Ethernet operation.

5.1.1.3 CPE functionality

A range of appropriate broadband CPE must be available, together with attractive service offerings, to ensure that a new access network is fully utilised; lack of CPE and services inhibited the early take-up of ISDN. An objective of the FSAN members is to gain consensus on the core requirements for Customer Premises Equipment (CPE) and thus ensure compatibility and interoperability with FSAN networks and services. This would also enable the member companies to leverage commercial advantage in the supply of CPE either through the normal retail chain or via direct procurement. The term CPE embraces PCs with Network Interface Cards (NICs), Network Computers (NCs) and Set Top Boxes (STBs). The Consumer Electronics industry will be invited to comment and input, as necessary, to these core requirements since FSAN's goal is to influence their 'roadmap' for future products. Key CPE features already identified which need to be addressed include:

- User friendly CPE which is truly 'Plug and Play';
- User to network flows terminating in the Access Network;
- User to user flows terminating beyond the Access Network;
- Traffic shaping;
- APIs / middleware;
- Standardised software download;
- Configuration management;
- Security.

For residential services, the intention is that the core CPE requirements developed by FSAN may be added to next generation consumer electronic equipment such as digital satellite receivers, digital terrestrial TV receivers, DVD players and games consoles. This would then enable the consumer to access multiple services from a single STB.

5.2 Operations, Administration and Maintenance

The Operations, Administration and Maintenance (OAM) group was set up to look at the operational aspects of the FSAN and to agree on a common set of management functions. A framework for developing a common set of require-

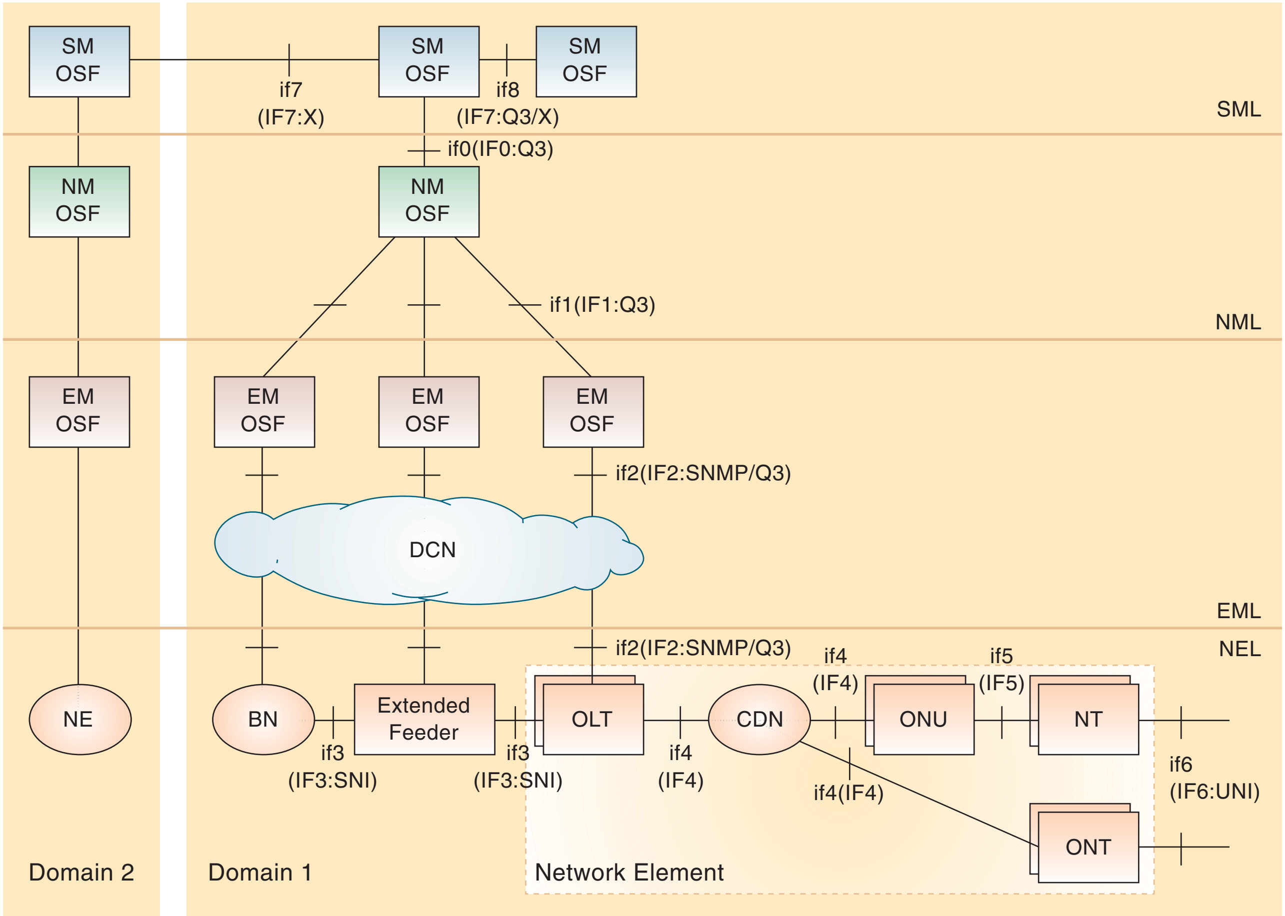

Figure 6 FSAN target management architecture

ments was quickly established which included the following steps:

- Understand the operational and service requirements (what are we trying to deliver);
- Derive the management requirements and develop a reference architecture (how it is to be managed);
- Develop specifications to ensure standardisation in the supplier industry.

A key decision of the group was to look at the problem from an end to end perspective which led to the group adopting a set of high level processes from which it was possible to agree on a set of common operations functions. A number of high level processes are described in the FSAN OAM requirements document [3] which include Service Provision, Network Repair, and Planning and Engineering. Each of these contain elements of customer handling, work management, installation, billing and so on.

Another key agreement of the group was to re-use as many existing standards as possible in order to make rapid progress. When it was clear that an architecture was required to progress discussions on the requirements, the basic architecture described by the Telecommunication Management Network (TMN) was adopted and extended to develop an FSAN target architecture as shown in Figure 6.

Over the first three phases of the FSAN initiative the group has defined requirements on the following aspects of operations and management:

- High level processes;
- Operational requirements of the equipment
  - modular design, simple visual indications, self configuration, accurate fault diagnosis;
- Management requirements
  - management architecture, interfaces and functions;
- Platform requirements
  - scalability, throughput, performance, operating system, security, availability;
- Data Network Communications
  - types of data networks to be supported;
- Test Equipment
  - automated testing, reduction of reliance on network testing;
- VSDL
  - operational requirements of VDSL link (management of physical layer);
- ATM layer requirements
  - OAM flows;
- Information Model
  - based on ATM Forum M4 and ITU-T models.

Most of this work has been completed in nine meetings since work began in late 1995 and is entirely due to the commitment and support from both the operators and suppliers involved.

In the next phase the OAM group will be progressing the following areas of work:

- Define information model details;
- Collaborate with the Optical Access Network (OAN)-WG on management requirements for the management channel on OLT to ONU/ONT interface;
- Support programme to standardise FSAN requirements; and
- Explore common management requirements for higher layer functions. The current sets of requirements cover the NE and EM layers of the Telecommunication Management Network (TMN). Further work is needed to extend the FSAN management requirements to the Network Management (NM) and Service Management (SM) layers.

The FSAN requirements have been discussed at a meeting of the appropriate ITU-T work group in March 1998 and a draft ITU-T document containing the FSAN requirements has been produced. The OAM group is currently working on the definition of an information model for interface IF1 (see Figure 4) which will be available in July 1998. In addition it is proposed to input both the requirements and information model in to ETSI in September 1998. The aim is to have agreed recommendations by end 1999 following the normal procedures of the ITU-T and ETSI. The group is also looking at adoption of the FSAN requirements as an ANSI standard but discussions are at an early stage.

It has only been possible to give a high level view of the work of the OAM group in this section. The reader is referred to the OAM requirements document [3], including past papers [4, 5, 6] for more details of the areas described above.

5.3 Optical access network

This group has created the world's first ATM PON specification. It has been presented to and accepted by the ATMF [7], ITU G.PONB [8] and ETSI [9]. The specification focuses on physical layer and transmission convergence layer, shown in Table 2, following the reference configuration of ITU-T Rec. G.PONA (G.982) [10]. The system has been designed to support all configurations shown in Figure 1.

There are two PON options, a symmetric 155 Mbit/s, and an asymmetric 622 Mbit/s down to the customer and 155 Mbit/s from the customer. The PON also has a minislot capability to cost effectively support voice, STM (Synchronous Transfer Mode) services or dynamic capacity over the PON. The PON's dimensions are a 20 km reach, and a maximum optical split of 32. The system can operate on either 1 fibre using WDM, or 2 fibres.

Figure 7 shows the frame structure of the APON. It is ATM cell based. A downstream frame is made of 56 cells, this includes 2 PLOAM (Physical Layer Operations, Administration and Maintenance) cells. The PLOAM cells contain the grants for the upstream slots, and messaging for physical layer functions, eg. to instruct an ONU to start ranging. The upstream cell has a 3 byte header, to cope with the multiple access nature of the upstream transmission path. Because of the overhead, the upstream frame is made up of 53 upstream slots. The mechanism for allocating the slots, the media access control protocol, is not defined. This was left open to enable vendors to innovate. The OLT is the controlling device. The ONU responds to the OLT's commands, hence the PON interface can still be manufacturer independent.

5.4 Very high rate Digital Subscriber Line

VDSL technology can deliver data at multi-Mbits/s over the unscreened, twisted telephone wires originally intended for bandwidths of between 300 Hz and 3.4 kHz. This is due to remarkable advances in digital signal processing technology which allow the implementation of sophisticated digital modulation and equalisation schemes. In fact, the challenges are now mainly of an analogue nature: channel attenuation, noise and spectrum management. More details on the use of DSL in the access network can be found in [11].

It is important to note that VDSL is required to operate on underground as well as overhead distribution cabling. This imposes some difficult requirements in order to control unwanted RF emissions, particularly for overhead distribution cabling. VDSL will also be required to operate in the presence of Bridged Taps – principally a problem for North American telcos.

Table 2 PON layers and functions

Circuit layer			Translation and maintenance
Path layer			I.732
Transmission media layer	Transmission convergence layer	Adaptation	I.732
		PON transmission	Ranging
			Cell slot allocation
			Capacity allocation
			Privacy & security
			Frame alignment
			Burst synchronisation
			Bit/byte synchronisation
	Physical media layer		E/O adaptation
			WDM
			Fibre connection

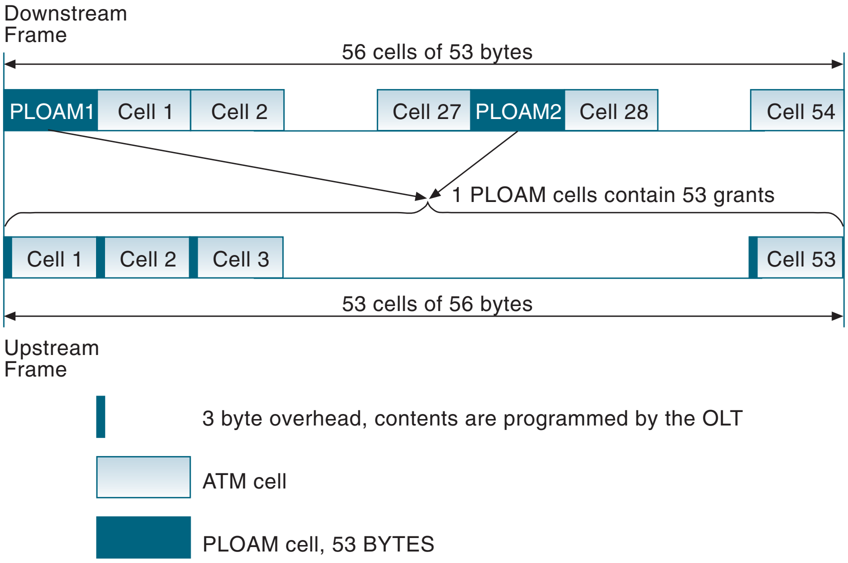

Figure 7 APON frame structure

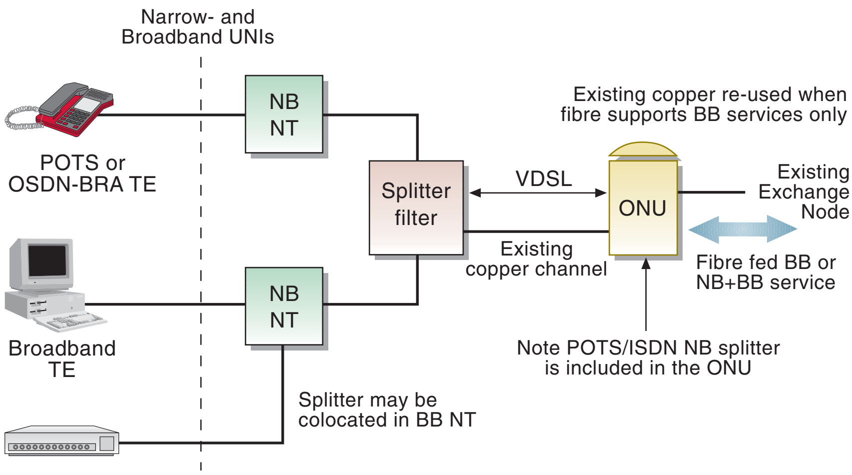

Figure 8 VDSL concept

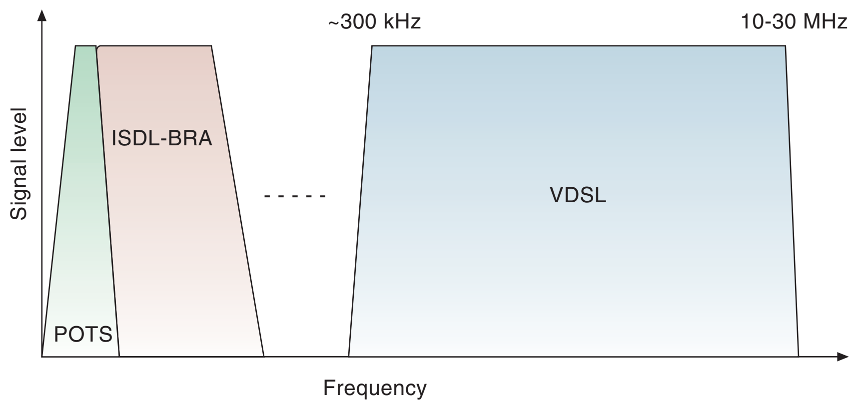

Figure 9 Frequency separation of VDSL

5.4.1 General description of VDSL

Figure 8 shows a simple architectural model of VDSL.

Since the broadband and narrowband services should be able to share the same metallic distribution cable, the broadband services are introduced at frequencies well above POTS or ISDN-BRA. Figure 9 shows the VDSL signal placed well above the band occupied by POTS or ISDN-BRA.

5.4.2 The VDSL standardisation process

The introduction of VDSL transmission systems is dependent on harmonisation of Network Operators' requirements to produce a large common market. The remit of the FSAN VDSL Working Group has therefore been to identify the key requirements which are common to all telcos, and downstream these requirements to the standards fora, notably the European Telecommunications Standards Institute (ETSI), the American National Standards Institute (ANSI), and more recently, the VDSL Study Group within the ADSL Forum.

5.4.3 The FSAN VDSL Working Group

The FSAN VDSL Working Group has made a significant contribution to the VDSL Standards process by achieving telco consensus on the key systems requirements for VDSL. This work was published in some detail at a workshop in Atlanta in March 1997 [12]. The work has now been successfully downstreamed such that the current version of the ETSI Draft Technical Specification for VDSL [13] should be viewed as the primary reference source for FSAN VDSL requirements at this time.

The ANSI standards process for VDSL is less advanced than ETSI but is catching up. ANSI is adopting much of the ETSI work, with the FSAN requirements being actively progressed by the North American members of FSAN, notably GTE and Bell Canada.

During 1997–98, the group has been addressing the complex technical issues of noise model and spectral compatibility for VDSL. Spectral compatibility is a fundamental issue for telcos – to ensure that different xDSL systems can co-exist in the same cable infrastructure, maximising their performance, while minimising their impact on neighbouring systems due to crosstalk. Because spectral compatibility is a systems issue which is network dependent and which transcends the boundaries between xDSL systems, the group has remained telco-only to date.

5.4.4 VDSL noise model

A major achievement of the group has been the definition of a noise model for VDSL that was derived during a telco-only meeting in Paris in November 1997. The noise model is required to enable telcos to benchmark vendor implementations and to verify that systems will work in real networks.

At the Paris meeting, different telco xDSL deployment scenarios and cable topologies were modelled in real time to identify a small set of noise profiles that could be applied to all telcos. A powerful enabler for consensus at the meeting was the availability of two independent laptop computer models which could be used to check results in real time. It was found from modelling that all basic telco scenarios could be fitted to only four noise profiles; a result that was not obvious beforehand. These profiles have been accepted by ETSI [14] and have been provisionally adopted for inclusion in the ANSI standard.

This is believed to be the first time that a consensus noise model has been defined so early in the standards lifecycle for an xDSL system; demonstrating the value of this method of reaching consensus.

A key insight from the noise model work was confirmation, previously highlighted by Nortel [14], that the spectral mask for ADSL required modification to minimise impact on VDSL capacity. This has been progressed in ANSI by GTE on behalf of the FSAN telcos. It was also noticed that existing standards relating to the spectral masks for ISDN-BRA were not adequate to prevent new systems polluting the VDSL spectrum above 1 MHz. Fortunately, measurements on installed ISDN-BRA systems (both 2B1Q and 4B3T) have confirmed that existing systems are VDSL friendly. But the ISDN standard is currently under review in ETSI, and vigilance needs to be maintained to prevent any relaxation of the mask, which would open the door to spectral pollution from future variants of ISDN-BRA systems.

5.4.5 VDSL spectral compatibility

More work is now required by the FSAN telcos to define the spectral bounds and duplexing scheme for VDSL before vendors have sufficient information to develop spectrally compatible systems.

Although spectral masks for VDSL have been agreed in ETSI, these only detail the major features such as notching and maximum power. To ensure that systems are developed which are spectrally compatible with installed xDSL systems such as ADSL, telcos must provide more detail to vendors on the spectral bounds for upstream and downstream VDSL transmission, and evaluate the systems implications of the different duplexing techniques.

This is an extremely complex problem to resolve because VDSL capacity is a complex function of topology, duplexing scheme and crosstalk. The final choice will depend on which engineering compromises telcos are willing to adopt, and this depends on the ability of the telcos to model their scenarios for VDSL upstream and downstream capacity.

To resolve this problem, a common formula and methodology for calculating VDSL capacity in different telco scenarios was agreed at a meeting in Bern in February 1998. The models have been verified using a single common scenario and will be used by individual telcos to evaluate their own xDSL scenarios in order to develop a group insight into this complex problem. With group insight, it is hoped that a consensus solution will be adopted at a meeting to be held in London in May, 1998.

5.4.6 Next steps

If, as is hoped, the group achieves consensus on the spectral bounds and duplexing scheme for VDSL, it will have achieved its primary aim of defining the spectral parameters and systems requirements for VDSL. Vendors will then have enough information to confidently invest in development of FSAN compliant VDSL equipment. If consensus is not achieved, a degree of additional flexibility will be required in vendor equipment to guarantee that a particular VDSL implementation will operate reliably in all telco networks world-wide – the overall aim of the FSAN initiative.

Telcos ultimately require that systems are not just spectrally compatible, but that a modem from one vendor will interwork with that from another vendor. This is primarily the task of international standards.

5.4.7 Alleviating the standards burden

The world spotlight is on xDSL as the technology that will provide universal broadband access as we enter the next millennium. This has significantly increased the pressure on xDSL technical experts to attend meetings all over the world. The FSAN initiative provides an opportunity to alleviate some of this pressure (and save costs) by sharing technical perspectives, and co-ordinating attendance at meetings.

Following the FSAN summit in Venice in March, 1998, the remit of the VDSL Working Group has been extended to encompass general liaison on all xDSL issues of common interest to the telcos. In particular, to maintain vigilance, and cooperate to ensure that xDSL systems are spectrally compatible with each other, and through technical dialogue, resolve the difficult engineering issues presented by for example the Splitterless ADSL concept.

5.5 Infrastructure

The implementation of VDSL Fibre-to-the-Cabinet has traditionally taken the form shown in Figure 10. The VDSL electronics are housed in an above ground cabinet, and positioned close to an existing copper Primary Cross-Connection Point (PCCP) in the network. The VDSL Access Point (VAP) is linked to the exchange via fibre. Copper 'Tie' cables are used to link the VAP to the PCCP in order that broadband service can be overlaid on the existing D-Side copper network.

Placing active electronics in a hostile external environment presents major design challenges. The combined requirements for line capacity and the associated power dissipation, plus the auxiliary facilities for copper, fibre and power can result in a physically large VAP cabinet with a complex and expensive cooling system. These issues have been the focus of in-depth discussion for the FSAN Infrastructure Group, where telcos and suppliers are endeavouring to reach a common consensus on the design

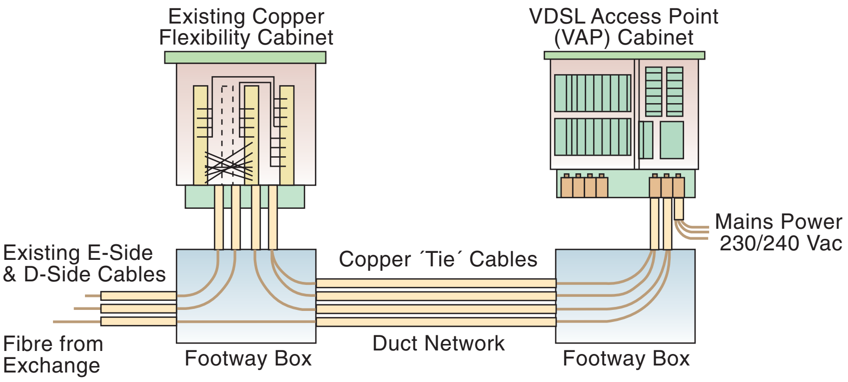

Figure 10 Traditional above ground VAP FTTCab scenario

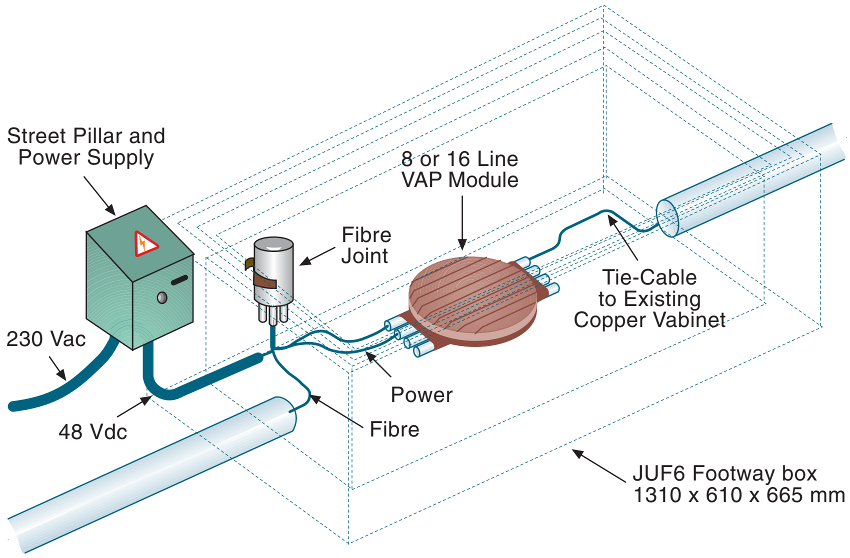

Figure 11 Underground modular VAP proposal

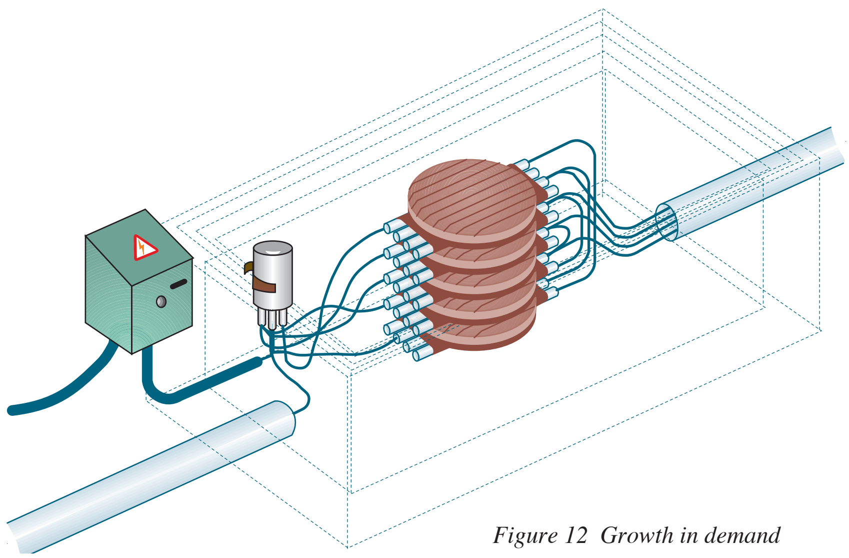

Figure 12 Growth in demand

requirements for an FTTCab solution. These discussions are progressing well, but have clearly highlighted that the various telcos have significantly different requirements and constraints on the design and use of active street furniture. Generic requirements for an above ground solution are well advanced and are expected to be issued shortly. However, restrictions on certain telcos not to use physically large, or in some cases any, above ground cabinets have resulted in FSAN also proposing an underground solution.

Figure 11 shows the underground concept that employs 8 or 16 line, sealed-for-life modular VAP enclosures which can be located in existing underground footway boxes. Each VAP module should provide suitable connections for primary power, fibre, copper 'tie-cables' and the option for battery back-up. The advantages of an underground system have been identified as:

- Less hostile environment for temperature extremes. Improved electronics and battery reliability;
- Less prone to EMC radiation damage and emissions;
- More aesthetically pleasing;
- Less vulnerable to accidental or deliberate damage;
- Savings in enclosure costs compared to cabinets.

The underground system is designed to be highly modular allowing extra modules to be added to satisfy growing demand, as demonstrated in Figure 12.

The underground system is intended to be highly flexible to satisfy variations in telco requirements, and has the potential to be significantly less expensive than a cabinet solution. The proposal is attracting major interest from the telcos and suppliers within FSAN who are currently discussing the development issues and potential applications.

6 Next steps within FSAN

The latest results in FSAN were presented at Globecom'98. FSAN is a temporary body. After the initial trials are complete, and the FSAN specification is updated to reflect the learning of the trials, and the FSAN specification [2] reflects the systems for commercial deployment, FSAN's job is complete.

The systems are available to all, because the specification is public, hence volumes are up and prices are down. This is the FSAN vision.

7 Conclusions

The keys to FSAN's success are a political will to facilitate the creation of a common access system specification to enable vast economies of scale, and a highly flexible technology, PON and xDSL, that can meet the disparate requirements of the telecommunication operators involved in the initiative.

The FSAN deployment group is building a business opportunity statement to sell the benefits of FSAN systems to the commercial people in the industry, and are accelerating the availability of FSAN systems, through a co-ordinated approach to testing and trials.

The SCP group's mandate is to identify capabilities in the FSAN access network to support a full set of services.

The FSAN VDSL Working Group has established a powerful discussion and modelling methodology for resolving the complex problem of xDSL spectral compatibility, and rapidly achieving consensus through mutual insight. This forum is unique in the world in that it contains xDSL technical experts from the core development teams of the major telcos, working harmoniously together to resolve telco-specific transmission problems, thereby accelerating standards through advance consensus.

The OAN group has created the world's first ATM PON specification. It has been presented to and accepted by the ATMF, ITU and ETSI. The system has been designed to support the requirements of all telcos.

FSAN has specified the world's first truly global broadband access system through the dedication and expertise of the people involved in the initiative. The challenge is now on how to realise the benefits of the consensus achieved within FSAN.

8 Acknowledgements

We would like to thank the many members of FSAN and colleagues within BT for their help and support in creating this paper.

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Towards broadband access in Europe – the view from EURESCOM

UMBERTO FERRERO

The access network is the portion of the telecommunication infrastructure linking every single customer to the closest local exchange: Traditionally dimensioned to deliver telephony, it now calls for a thorough upgrade to accommodate new midband and broadband services, exploiting the extensive range of available technologies. EURESCOM[1)] P614 "Implementation strategies for advanced access networks" represents the third generation of access network related EURESCOM Projects, after P306 "Access network evolution and preparation for implementation" [1, 2] and P413 "Optical Networking" [3].

The paper focuses on four main areas: broadband radio systems, broadband fixed systems, technologies and installation techniques, and techno-economics.

1 Introduction

The Project started in late 1996 and involves over 50 experts from 12 European telecommunication operators; the objectives are illustrated in [4]. The project completed its activities in November 1998, releasing the 14 Deliverables listed in Table 1.

Broadband access network deployment is strongly influenced by capital investment and regulatory boundaries, with technical matters in the background, often underestimated.

P614 focused on three main ideas developed during the previous projects. First, the future access network will feature a number of alternative implementations and several architectures, and will extend its domain towards longer reach allowing for node consolidation: European PNOs need to understand and cope with a number of architectures and systems with a single, comprehensive overall network perspective to assure the effective exploitation of the heavy investment involved. Second, the access network evolution is moving towards real deployment (as witnessed by the number of market trial and roll-out programs announced in most European countries), and co-operative projects have to focus on practical issues, such as specifications, outside plant technologies and interoperability of new and old technologies. Third, the monitoring and contribution to standardisation bodies, together with the techno-economic appraisal of technical implementation need to be carried out on an ongoing basis by EURESCOM members, to quickly and effectively react to the changing access network scenario.

The European operators' declared strategies tend to swing between the idea of doing nothing or everything as far as broadband access network is concerned. P614 results recommend what to do (something), when to do it (with specific phasing, following the maturity of different technologies), and where (in areas of well defined technical and service characteristics). The uncertainty becomes even greater with the increasing competitive pressure.

P614 tries to spot, and tackle, some areas that have been insufficiently taken into account so far, or at least little discussed, increasing the awareness of their potential and giving answers to outstanding, much discussed questions, or to counteract the easy enthusiasm on technical capabilities and trends.

Table 1 EURESCOM P614 Deliverables

	Title	Planned issue date
D1	An analysis of the relative benefits of proposed SNI standards	April 1997
D2	Target B-ISDN access network architectures	December 1997
D3	Techno-economic analysis of major factors of B-ISDN/ATM upgrades	September 1997
D4	Opportunities for broadband radio technologies in the access network	January 1998
D5	Optical technologies for advanced access networks: early results	December 1997
D6	Evolution paths towards target B-ISDN access networks	July 1998
D7	Optical technologies for advanced access networks: final results	September 1998
D8	Elaboration of common FTTH guidelines	July 1998
D9	Contributing to standardisation bodies and other fora	April 1998
D10	Techno-economic evaluation of B-ISDN access networks architectures, scenarios and business cases	September 1998
D11	Evaluation of Broadband Home Networks for residential and small business	September 1998
D12	FTTH: Definition of the suitable powering architectures	February 1998
D13	FTTH: Definition of access network quality and cost	February 1998
D14	FTTH: Definition of related service offer strategies	February 1998

1) *EURESCOM (European institute for research and strategic studies in telecommunications) was founded in 1991 by European telcos (fixed network operators), as an instrument to perform collaborative precompetitive research and development. In December 1997 the Institute had 23 active Shareholders from 21 European countries.*

2 Broadband radio access: opportunities and limitations

Broadband radio technologies are becoming more and more close to real field deployment, and are offering very promising applications for both incumbent operators and new competitors [5]. The potentially large cost savings stimulate a big hype of interest, boosted by an aggressive marketing campaign. P614 reviews the radio access network architectures and technologies giving access to residential and business customers; a Request For Information was issued. P614 also reviewed ongoing research and standardisation activities and estimated the type of technologies available in the long term.

P614 highlights the truth on time for available systems and technical capabilities. Many systems are in their infancy and the wide diversity of technical implementation and regulatory constraints is making the successful exploitation of such technologies more difficult. The need for common air interface and radio-to-fibre interfaces has been identified as a key enabler for a real and extensive use of broadband radio solutions; the visions elaborated are now being downstreamed in the appropriate bodies (see Deliverable 4).

2.1 Short term wireless technologies

Wireless technologies have been around for quite a while and at the turn of the millennium there is strong evidence indicating that wireless solutions are about to become a viable means for providing broadband access to the majority of customers, at least in developed countries. Broadband communications in this context refers to end-user capacity in the range 2 Mbit/s up to 155 Mbit/s in both directions.

There is a broad range of wireless technologies available or predicted to be available in the short term and they are mostly *terrestrial* and *satellite technologies*. Satellite technologies have been delivering broadband broadcasting services for some time already with a special focus on the residential market.

Satellite technologies are very much capacity limited and their main competitive feature is the regional or global coverage. Current systems are located in geostationary orbit (GSO) which prevents them from offering a full service due to the inherent transmission delays and consequently only limited services for residential users are offered. To achieve full service access, satellite technologies must migrate to low-earth orbit (LEO) which is beyond the short-term perspective.

Stratospheric fixed platforms consist of one or more high altitude (20 to 30 km kilometres) platforms located at fixed points in the stratosphere, serving a limited geographic area compared to the satellite technologies. HALO and Skystation are two such systems, with operation expected to commence in 2000 at the earliest.

Terrestrial technologies are by far the most interesting alternative among the wireless technologies. They offer a variety of technologies, which may be arranged according to very specific Operator needs.

The *wireless telecom* services have up to now been provided by point-to-point (P-P) radio-relay technology. Capacity available is typically 34 Mbit/s (optionally 155 Mbit/s) and symmetrical services are usually offered. Primarily, P-P technologies target the business market and there are no widely adopted Common Air Interface (CAI) standards available. Recently several manufacturers have launched so-called point-to-multipoint (P-MP) technologies. They are in most aspects an extension of the P-P technologies and the P-MP feature is traded for lower capacity, typically 2 Mbit/s (optionally higher), and shorter range in order of 5–10 km. Preferred frequency bands are 3.5 and 10.5 GHz and there are no widely adopted CAI available.

Wireless broadcasting technologies are developing along several different paths. In the field of terrestrial broadcasting, the DVB-T standard is widely followed but does only offer digital broadcasting at about 20–25 Mbit/s per channel. Another development path is represented by the multiservice multipoint distribution system (MMDS) type technologies. They emerged as a wireless extension of the cable technologies and are as such often related to the contradictory term *wireless cable*. They are primarily deployed in the spectrum below 10 GHz and typically in the 2.5 GHz band and offer highly asymmetrical services due to the small amount of spectrum available. The channel capacity is comparable with the DVB-T technology and the range is several tens of kilometres.

As for *satellite broadcasting*, terrestrial wireless networks redistributing satellite TV services have been in operation for some time, known as multipoint video distribution systems (MVDS). However, the MVDS systems will most likely be surpassed by the local multipoint distribution system (LMDS) technologies which offer true multiservice broadband capabilities. They are offering asymmetrical services with a capacity of up to 3 Mbit/s uplink and 52 Mbit/s downlink with a typical range of 1 to 5 km. Generally, they are related to the frequency bands above 10 GHz. More specific, the 28 GHz and 40 GHz band are the probable candidates in most countries. No widely supported CAI is currently available but several standards targeting parts of the LMDS systems exist or are under way.

The *wireless datacom* technologies have emerged as an extension of the wired LANs. They were primarily intended for indoor use, but have evolved to cover outdoor services as well. For the time being radio LANs (RLAN) or wireless LANs (WLAN) are the most adequate terms and the preferred frequency band is the 2.4 GHz band. The capacity is a couple of Mbit/s in Europe with an achievable range of approximately one kilometre due to restrictions on transmitted power. Limited mobility is offered by some systems and a standard is evolving named IEEE 802.11.

Next Generation cellular mobile. It is also worth keeping an eye on the UMTS technologies, which are the evolutionary successors to the cellular mobile systems, like GSM. They may offer near broadband capabilities and will be highly standardised.

A summary of the target deployment scenarios and time-scale of the different technologies are shown in Table 2.

2.2 Going wireless: main conclusions

The main findings of this study may be summarised as follows:

- Terrestrial LMDS systems will be available within 1 to 2 years. They will be able to support asymmetrical trans-

Table 2 Potential deployment scenarios

Wireless technologies		**Residential** Limited service			**Residential** Full service			**Small and med. business**			**Large business**		
Now	P-P							*	*	*	*	*	*
	MMDS	*	*	*									
	DVB-S	*	*	*									
< 2 yrs	RLAN				*	*		*	*				
	DVB-T	*	*	*									
	P-MP							*	*	*	*	*	*
> 2 yrs	UMTS	*			*								
	LEO	*	*	*	*	*	*	*	*				
	LMDS		*	*	*	*	*	*	*				
		Urban	*Suburb*	*Rural*	*Urban*	*Suburb*	*Rural*	*Urban*	*Suburb*	*Rural*	*Urban*	*Suburb*	*Rural*

port services (typically 25 Mbit/s downstream, 1 to 2 Mbit/s upstream). They will be most useful in urban and suburban areas, although the study could not rule out their use in certain rural areas as well. Full coverage of all potential users by terrestrial microwave systems will not be feasible in many areas. LMDS is therefore most suitable for competitive environments where full coverage is not an essential requirement for obtaining a significant market share.

- UMTS targeted for 2002 will offer fast mobile data up to 2 Mbit/s for *some* users and N-ISDN equivalent mobile services to many users. It seems unlikely that UMTS could be an alternative to broadband wireline or wireless access solutions.

- Future broadband satellites (LEOs) may support broadband wireless access and can be a solution for cost-effective broadband access networks for millions of users *globally*, but unfortunately their broadband user capacity will be negligible *locally*. Stratospheric platforms have theoretically more capacity and may thus be able to solve some of the coverage problems of terrestrial wireless networks.

- Operators using broadcasting type systems (digital satellite, terrestrial UHF and microwave MMDS) will also be able to compete with established operators, but in highly asymmetrical services only.

- *For business users* broadband point-to-point and broadband point-to-multipoint radio systems may be an attractive alternative to optical fibre access systems due to lower cost and/or speed of implementation.

ETSI BRAN and ATM Forum are working towards new broadband solutions. Operators and manufacturers should promote standardisation of common air interfaces in order to lower the costs of user radio terminals. Compatibility with fibre based access networks should be ensured by also defining common network interfaces. Harmonisation of frequency bands in Europe should also be encouraged.

As the mobile networks are spreading globally, operators should seriously consider the potential synergy and cost benefits of using a common infrastructure (transmission to base stations, towers, etc.) for both mobile and fixed wireless access networks.

3 Broadband fixed access: interim and target solutions

The dramatic technological evolution and the regulatory changeout are leading to the installation of a variety of broadband access systems.

On the one hand, operators look at target solutions: a wider time frame scenario enables the investigation of fibre rich implementations, taking advantage of potential benefits in terms of global network rationalisation and optimisation. The overall access network optimisation potentially enables significant cost savings, improved service quality and eventual integration of services for business customers, provided that specifications and standard solutions are being developed. The target solutions encompass both ATM PON and ATM point-to-point (Deliverable 2); one or several evolution paths from a set of existing access network architectures to the identified target architecture are addressed (Deliverable 6).

On the other hand, the compelling need to enter new markets and provide new services requires the full exploitation of existing infrastructures, re-using twisted pairs, coaxial cables and, under certain circumstances, even powerlines. The broad diversity of the technical implementation is able to match the diversity of service offering and acceptance, existing infrastructures and other local constraints, enabling the investment optimisation (Deliverable 6, Deliverable 3 and Deliverable 10). The results offer the Operators the possibility to identify the relevant parameters to be considered when planning an upgrade of its own access network, understanding the capability and limits of the existing initial architectures and giving full knowledge of the established target solution.

3.1 Target broadband access network architectures

From the work already produced in the former EURESCOM Projects, as well as from the results of the Full Services Access Network (FSAN) initiative [6], it is taken as formal input that the architecture towards which fixed access networks are going to evolve is ATM-PON, and in some cases ATM on Point-to-Point links (ATM-PP). Since at this moment there is a variety of different access network architectures, and Operators would wish in some cases to reuse part of their infrastructure, this Project analyses how (if possible), an existing architecture might evolve towards ATM-PON or ATM-PP.

These two architectures have much in common; for instance, the services they are intended to support, the Customer Premises Networks (CPN) to which they can be connected, and their external interfaces. On the other hand, the aspects which are linked to the use of optical splitting, like Medium Access Control (MAC) mechanisms, are certainly different.

One problem when defining these architectures is that currently they practically do not exist. Certainly there is almost no deployment of ATM-PONs, and while ATM-PPs do exist, they are intended for business customers only, and they incorporate network elements which suppliers have produced mainly out of their own entrepreneurship, without relying on a solid body of backing standards. It should be kept in mind that at the time of writing even the much expected Service Node Interfaces (SNI) VB5.1 and VB5.2 are not officially approved. This lack of physical existence produces network definitions which are mainly theoretical, without the advantage of a feedback experience.

For the definition of the ATM-PON architecture the following two main assumptions have been adopted:

- The architecture is that defined by FSAN.
- Broadband (BB) and narrowband (NB) service integration is mandatory as a target solution, though only broadband services might be offered at a first stage.

The following main conclusions can be highlighted:

- BB access networks offer a broad range of functionalities which have to be mapped in their constitutive network elements, at a price. A comprehensive set of functionalities is conceivable, but only one subset of it will be included in a real deployment. Which subset to incorporate depends on the Operator's business case.
- The BB access networks described in this document are intended for the mixed residential and small businesses market.
- ATM-PON and ATM-PP networks offer very similar functionalities. In general, ATM-PONs make a more efficient use of network resources, like fibre sharing and traffic multiplexing at distribution network interface level, while ATM-PP networks may be more flexible in terms of geographic diversity.
- Concerning BB residential access networks there are currently two significant issues which are far from being understood. One of them is how to integrate telephony and ISDN within an ATM stream. Another is the subject of BB CPNs. Both issues are being addressed in a number of fora, but lack market experience.

In summary, when currently the deployment of interactive BB services for residential users is proceeding slowly, both because of a lack of a clear market and for regulatory reasons, it is necessary to raise the awareness of the intricacies of BB networks, which are a long way from the access networks in use today.

3.2 Evolution from existing access networks to the target solution

The evolution studies start with a statement of their market and regulatory drives, describe their starting situation, ie. the existing access network, and chart a path towards the target network through a small number of intermediate steps. Each needs to be marked with a cost analysis. The evolution studies performed are the following:

- From HFC to ATM-PON;
- From existing fibre networks to ATM-PP/PON;
- From existing copper networks to ATM-PP/PON;
- From existing copper to ATM-PON through LMDS.

An extensive cost analysis of network evolution from existing access networks to target solutions has been performed in Task 6 (Deliverable 10).

3.3 Interim solutions

The regulatory changes which have taken place in the last few years, together with the emerging demand for new services often developed in the Information Technology area, require a rapid and economical deployment of new infrastructures. Therefore, beside the target solutions, a number of short term implementations allow the quick provision of new services.

Several technologies are being developed for this purpose, and all of them put leverage on the possibility of bypassing part of the network deployment exploiting the installed copper/coax network, power cables or radio transmission. The use of similar systems in some areas will lead to an increasingly complex overall network: the integration of interim solutions is likely to become the main challenge to be handled at a later stage.

Some of these solutions are likely to be exploited by competitors: as an example, joint ventures between local power utilities and foreign telecommunications operators are very common and will benefit from the powerline transmission technologies, if sufficiently mature and economical.

Table 3 Areas of applications for interim systems

	Incumbent	Newcomer
Low-cost DSL	Yes	Yes (with unbundling)
Powerlines	No	Yes
Radio	Yes	Yes
HFC networks	Yes (if available)	Yes

The success of these solutions is strictly related to the evolving regulation:

- Exploitation of radio spectrum is strictly regulated and rather non-homogeneous across Europe;
- The copper access network unbundling, with copper pair rental to competitors, may trigger the success of low cost DSL technologies;
- The use of CATV networks and local networks in building needs settlement of possible ownership problems;
- Transmission over powerline has very complex safety and regulatory implications.

All the described interim solutions do not fully support the envisaged set of services: they cannot be considered as full service options, at least with the current maturity. Therefore, there is little scope comparing them with the systems analyzed in previous sections: interim solutions have their own economic viability and support very specific business cases. Table 3 summarizes the possible application of the technologies described in the chapter; more details can be found in Deliverable 6 and other P614 documents.

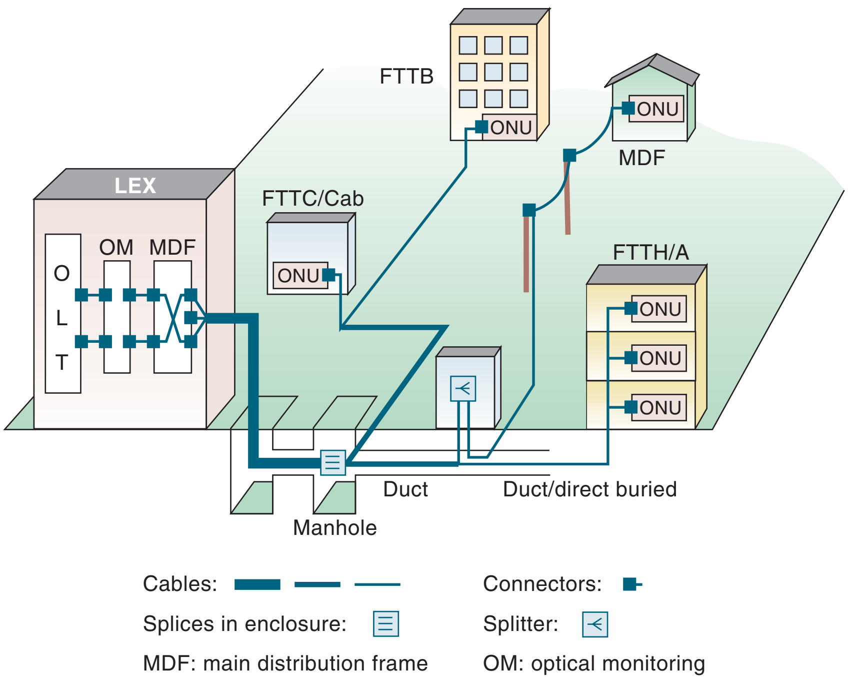

Figure 1 Main FTTx optical cabling elements

4 Basic technologies and practical implementation aspect

Among the six tasks of project P614, one is devoted to enabling technologies in which major building blocks have been investigated with main emphasis on the state of the art and near term evolution of technologies as well as cost figures and standardisation issues.

The contents of the first report (Deliverable 5) are: optical cabling technologies (hardware), optoelectronic modules, electronic functions, xDSL techniques, alternative fibres for low cost cabling, powering, civil work, installation techniques. The second one (Deliverable 7) will be focused on three major items: point-to-point link, measurements and maintenance of the hardware and opportunities for WDM technologies in access networks, together with a study on feasibility of powerline communications.

Civil work and installation represent the most important factors in the global cost of a new access network. Advances in this field can strongly influence the practical feasibility of network deployment, affecting both direct and indirect cost.

Moreover, the use of new techniques allows reduction of the social and environmental impact of road works, especially in urban areas.

4.1 Optoelectronic modules for ONU

The optoelectronic converter (O/E) has been recognised as a major stumbling block for large scale optical fibre deployment in the access network. Bearing in mind the above specifications, present and near term technologies will be presented with main focus on one fibre transmission system since this approach leads to cost effective cabling infrastructure investment.

Today, commercially available bi-directional O/E modules are mainly based on micro-optics technology: in a single package, the module contains the laser diode equipped with its monitoring detector, a photodiode and a WDM dichroic filter. All these elements are mechanically assembled with lenses and a fibre by using precise and time consuming alignment techniques resulting in a high cost (around USD 200 for 10^4 pieces).

To reduce the cost a new generation of O/E modules is under development in many laboratories, it is based on hybrid integration of optoelectronic chips with passive optical components (splitter, WDM). The passive components are implemented on a silicon platform which contains a V-groove for fibre positioning. To further lower the cost this hybrid module will be packaged into a surface mountable case for easy soldering on printed board.

This new O/E generation still requires many technical challenges to be overcome, for example: expanded beam laser, edge photodiode, passive alignment soldering techniques, detachable pigtail, plastic encapsulation. Finally, as a third step, monolithic integration on InP material of O/E converters appears as a long term target.

In a short time scale, advanced devices incorporating the above mentioned innovations are expected to generate significant changes in cost.

4.2 Optical cabling technologies

These technologies mainly include: fibres, cables, connectors, fibre splicing and enclosures, fibre termination modules, main distribution frame, splitters. A few examples will be given showing that significant innovations are still needed in this area.

Fibres/cables. Cables are installed in various conditions: outdoors, underground (in duct or buried), aerial, indoors; consequently many thermal, mechanical and chemical constraints have to be taken into account. In urban areas and for indoor cabling, the topology presents many bends leading to small curvature radius for fibres and cables.

One driving force of today's cable development is to reduce the installation costs. Compared to copper, optical cables offer tremendous potentialities in terms of weight and diameter, then allowing the use of cost effective laying technique such as air blowing in ducts.

Connectors. Field assembly capabilities appear not yet ready for true mass application. Improvements in fibre preparation and positioning into plugs are needed. Fibre ending still requires well-trained technicians and expensive tools. Innovations are foreseen to solve this problem in the near future. Other technology breakthroughs are related to glass or plastic ferrule, ferrule-less connectors, multi-fibre connectors and miniaturisation.

Splitters. As a basic component for PON systems, splitter technology analysis reveals quite a high cost figure of about USD 50 per end or port; in addition some extra cost should be added for field installation and maintenance. The location of splitters – in the outside plant or at central office – still remains an open question.

Optical monitoring. Several solutions are envisaged: dark fibre and in-service monitoring. In the latter case, the wavelength could be 1625 nm, key components will be embedded filters in connectors, optical switches with a high number of ports at low cost and WDM.

4.3 The ANCIT Workshop

Beside the survey and appraisal activities, P614 organised an international workshop on access network cabling and installation techniques [7]. The following main points emerged:

1 There is a need to develop and use new techniques to reduce the costs related to the deployment of a broad-band access network;

2 There is a need to improve the flexibility of the installation techniques;

3 There is a growing attention for the environmental and social impacts related to civil work and installation.

The second point is strictly related to the ever higher constraints that Local Authorities impose on Operators and companies working in urban environment.

Starting from the network design, new CAD systems allow optimisation of the design itself but also help the operators to perform quicker maintenance and updating operations. Improvement in site investigation can avoid drawbacks due to digging or drilling works for the construction of underground infrastructures. On the subject, a New Ground Penetrating Radar system for the detection of underground existing utilities allows a direct link with CAD and GIS systems for an automatic output of utility maps, updating existing digital cartography.

New construction methods alternative to traditional digging techniques are strictly related to the need to reduce th social and environmental impact of civil work.

The so-called No Dig techniques allow installation of underground ducts performing small tunnels without digging long and deep trenches which, especially in urban environments, cause many inconveniences to traffic and pedestrians. No Dig techniques, mainly used in Japan and Italy, sometimes represent the unique solution to work in urban environments, where Local Authorities do not allow opening of new trenches, in order to avoid traffic jam and damages to artistic and historical areas.

The installation of telecommunication cables in sewer ducts is a possibility: even in this case the final aim is to reduce social and environmental impact by avoiding new civil works. Another interesting alternative to digging is to install small optical cables in shallow and narrow trenches along roads or pavements.

There are several new techniques for installing optical fibres. Using appropriate materials and equipment it is possible to install directly in small underground ducts, single fibres or fibre bundles by blowing or by pulling. Field results and economic evaluation show the main advantages offered by these techniques in comparison with traditional cable installation: design and installation flexibility and global cost saving.

5 Broadband upgrade economics

In Task 6 of the EURESCOM P614 project an extensive techno-economic assessment has been carried out, in order to assess the overall economics of broadband access network upgrades and identify economically viable implementation strategies for the broadband access network technologies and strategies studied in the project. Several migration alternatives for access network providers downtown, urban, suburban and rural areas in Europe have been examined, including the different options available for traditional telephone operators, cable operators and new entrant operators. The methodology and tool initially developed

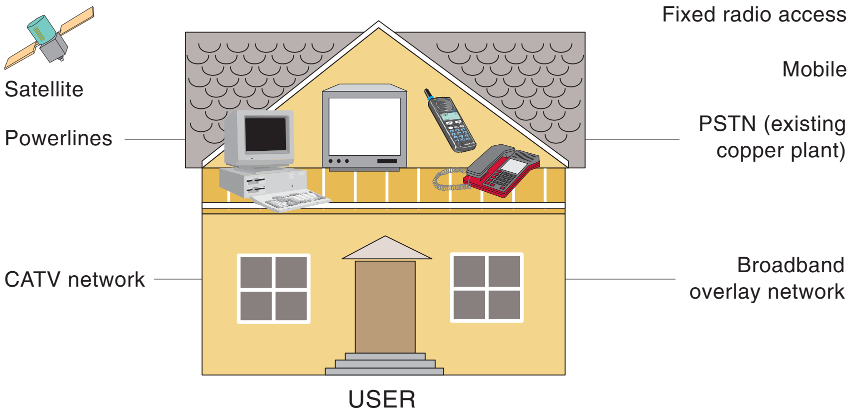

Figure 2 Several access techniques reaching the end user: is access going to turn into a commodity?

by the RACE[2] 2087/TITAN[3] project, and further developed in the ACTS[4] 226 OPTIMUM[5] project have been applied in the techno-economic analysis [8].

Broadband service scenarios for the next ten years have been defined, based on results from international studies. The analysis of the provision of services from the surveys covers upgrades in four network area types, which have been segmented and characterised according to average copper loop length in the existing access network (also reflects the density of living units in the area), availability of existing ducts and surface conditions with corresponding cable deployment type and civil works costs. Representative ranges of the characteristic parameters have been assigned to each network area segment.

Starting from the pure Installed First Cost (IFC) and Life Cycle Cost (LCC) analysis of the selected Evolutionary Paths (EPs), the business opportunities of the network roll-out projects in the defined area have been examined, taking willingness to pay, revenues and competition effects into consideration. The business risks associated with the upgrade strategies have been quantified, including market introduction risk, revenue risk, technology risk and overall network evolution risk. The financial analysis carried out with OPTIMUM has been complemented by an industrial cost assessment, in which the production cost per service has been calculated for different evolutionary paths.

The analyses confirm that the cost of increased bandwidth in the access network for interactive broadband delivery is high, independent of the operator's existing network situation, area type and broadband technology choice. Telephone operators, cable operators and new entrant operators are likely to face broadband upgrade investment levels per connected user similar to or higher than the overall costs of establishing the existing access network. Moreover, the node configuration and corresponding degree of fibre penetration has a great impact on the cost level. Thus, the fibre penetration and the location of the optical nodes in the network is a key strategic decision.

6 Conclusions and future work

Broadband access network introduction has been extensively discussed during the last ten years within all the research programs in Europe. The search for common and ultimate strategies, guidelines and technologies somehow hampered the real field deployment.

As a matter of fact, a number of advanced access networks are likely to emerge, relying on technologies under fast development. From a technical point of view the challenge for Operators is the full exploitation of a range of technologies in their own network, and effectively interoperating legacy and new systems.

Beside the technology specific issues, successful broadband access network deployment requires enabling and supporting development in mobile and fixed networks convergence and broadband home network installation practices [9], favouring the customers' acceptance of new services.

And finally a provocative statement to highlight a different point of view: is access becoming a commodity? The number of alternative access systems and techniques exploiting existing infrastructures (copper pairs, CATV network, power distribution), coupled to wireless solutions, stimulates tough competition.

This statement stimulates a new vision of access network evolution: the initial competition in the transport network and in the business market segment, where the margins are shrinking, will later shift to access and residential market. Operators prepared to deliver a full range of services will be in a better position in the access competition against players able to offer just few services with limited performance.

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[2] *RACE: Research in advanced communications in Europe.*

[3] *TITAN: Tool for introduction scenario and techno-economic evaluation of access networks.*

[4] *ACTS: Advanced communications technologies and services*

[5] *OPTIMUM: Optimised network architectures for multimedia services.*

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http://www.cselt.it/Cselt/euresc/P614/welcome.html

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Towards broadband access in Japan – ATM access for Mega-Media Services

KENJI OKADA

The number of telephone circuits provided by NTT (Nippon Telephone and Telegraph) slightly decreased in 1998, which is the first time since NTT was started. Present telecommunication networks have been constructed to optimize for telephone services for over a hundred years. A narrowband but a constant path is required for telephone services and especially a small transmission delay is needed for analog telephony. The deployment of fibreoptic cable in the access network has now started from the central office to the access point for telephone services, that is near FTTH (Fibre To The Home). However, the provided service is still POTS (Plain Old Telephone Service).

On the other hand, there have been remarkable increases in high-speed digital services for computer communication. Computer communication may undoubtedly occupy the telecom services instead of telephone services and it may require broadband and peaky path. Notable extensions of computer communications force the telecom network to evolve. An ATM backbone network has already been constructed in Japan. However, it is essential to establish an end-to-end path without bottlenecks, not only in the core network but also in the access network. ATM-PON (Asynchronous Transfer Mode over Passive Optical Network) systems have been deployed as broadband access in order to satisfy these requirements. FTTH/B (Fibre To The Home/Building) will be accomplished by deploying ATM-PON systems. At the initial stage, ATM-PON systems will be deployed for business applications, especially in order to target the SOHO (Small Office, Home Office) market.

The FSAN (Full Services Access Network) Initiative has been established in order to obtain cost effective access systems based on a *de facto* standard. Specifications of the ATM-PON have been standardized in FSAN and are expected to be determined soon in ITU-T (International Telecommunications Union – Telecommunication Sector). This paper presents the trend of telecommunication services in Japan and describes the broadband access systems now under development.

1 Introduction

The environment surrounding telecommunications has been changing rapidly. One of the big trends is the growth in data telecommunications such as Internet, whose volume obviously will exceed the volume of telephone traffic. Another trend is the explosive expansion of mobile telecommunications. In Japan, the number of mobile phones has grown beyond 40 million. There are 65 million fixed telephone lines in Japan. Voice telecommunication has been changed from a family to a personal basis. While LANs (local area networks) have been installed in all business offices, LANs have also been installed at the premises of advanced residential customers. The introduction of LAN at home results in the expansion of ISDN, and finally the 10/100 Base-T interface will be provided directly to the residential customer. These trends confirm the broadband service demand.

2 Trends of telecommunication services

Telecommunication service trends must be reviewed since access networks are designed according to the telecommunication service demands. It is essential to determine the direction of access networks and applied access systems after not only reviewing the trend of current telecommunication services, but also anticipating the future telecommunication services when shifting from POTS (Plain Old Telephone Service) to the broadband services. The most remarkable trend in NTT is that the market for POTS has been saturated for the last ten years, and moreover, the number has decreased by one million subscribers in March 1998, as shown in Figure 1. During the 100 years since NTT started telephone services this is the first time that NTT experience that the number of POTS has decreased.

The telephone service has dominated telecommunications up till now. Therefore the current telecommunication network has been optimized to the telephone service. In short, NTT have aimed at a constant speed and short transmission delays for the telecommunication network.

On the other hand, digital telecommunication services such as ISDN (Integrated Services Digital Network), HSD (High-Speed Digital Leased Service), FR (Frame Relay), OCN (Open Computer Network, a connection-less mode telecommunication service), and ATM Megalink (ATM virtual path service) have shown a remarkable growth (Figure 1). These digital telecommunications are used for Internet access and telecommunications between computers, and these services have a great possibility to occupy the telecommunication network instead of telephone services. For reference, the number of Internet users are

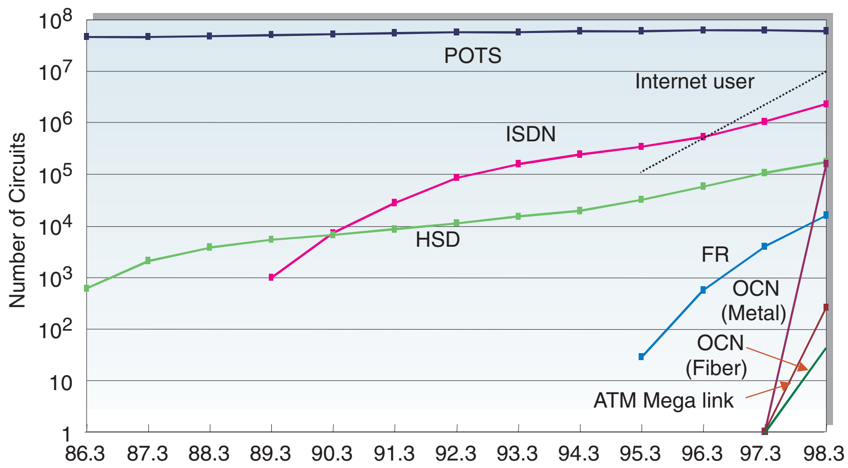


Figure 1 Telecommunications service trends

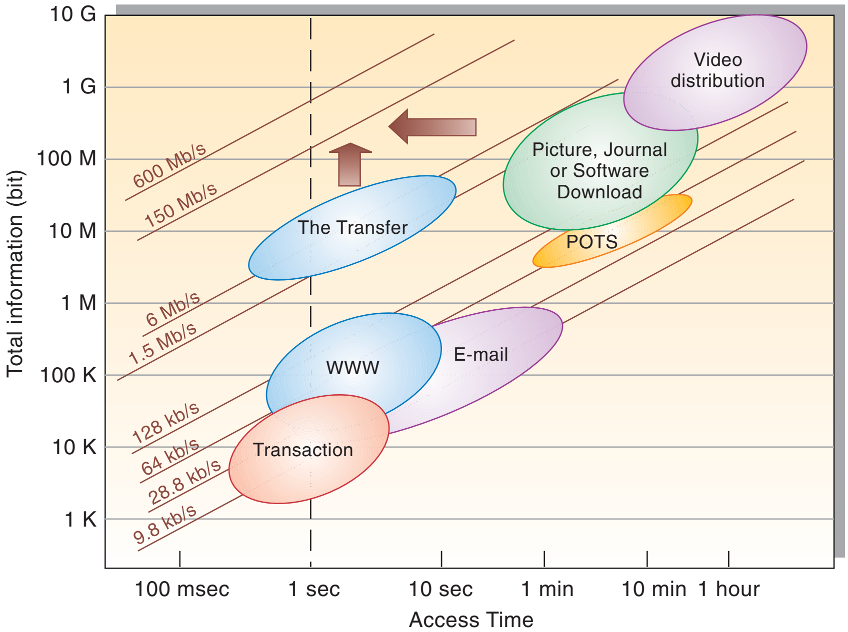


Figure 2 Categorization of telecommunication contents

also shown in Figure 1. The Internet subscribers use ISDN or OCN for their Internet access. HSD, FR or ATM Megalink are used by business customers. These computer telecommunications may have a significant impact on the evolution of the structure of telecommunication networks.

Requirements for telecommunication networks may be extracted from the characteristics of telecommunication contents. Telecommunication contents are categorized by the *total information of contents* and the *access time*, as depicted in Figure 2.

The slant line indicates transmission speeds, which are derived from the total information per access time. The POTS requires 64 kbit/s of telecommunication speed and the access time from several tens of seconds to several tens of minutes. Speeds in the range from 10 kbit/s to 100 kbit/s are applied for access to WWW, due to the speed limitation of metallic access systems. On the other hand, the capacity of WWW files is increasing year by year. Video distribution signals must be transmitted in a short time interval due to the expensive server cost. Broadband access systems are needed if a short access time is required.

3 Telecommunication service line-up

NTT already has various kinds of broadband services as shown in Figure 3.

The HSD service, the ATM-Megalink service, the Cell Relay service and the OCN service are all available as broadband services. In Figure 3, the virtual path type of services are found in the upper part of the figure, whilst the virtual circuit type of services are found in the middle of the figure. Initially, HSD was the only broadband service. This is an STM based service which provides broadband leased line services at a speed from 64 kbit/s to 150 Mbit/s. The CR (Cell Relay) service started as a broadband service with speeds from 6 Mbit/s to 135 Mbit/s on an ATM network. However, the take up has been somewhat slow, possibly due to the relatively high price. Therefore, the ATM-Megalink service has been taken into consideration. This service provides an ATM virtual path service at a speed of 500 kbit/s – 135 Mbit/s. This service is growing rapidly, as seen from Figure 1. At the end of last year a best effort type of service was offered with the ATM-Megalink, using a GFR (Guaranteed Frame Rate) function.

4 Access system toward FTTH

At present there is a bottleneck of telecommunication in the access part of the network, as depicted in Figure 4.

The introduction of optical transmission systems has greatly increased the transmission capacity in the core network. SDH (Synchronous Digital Hierarchy) systems with a few Gbit/s capacity

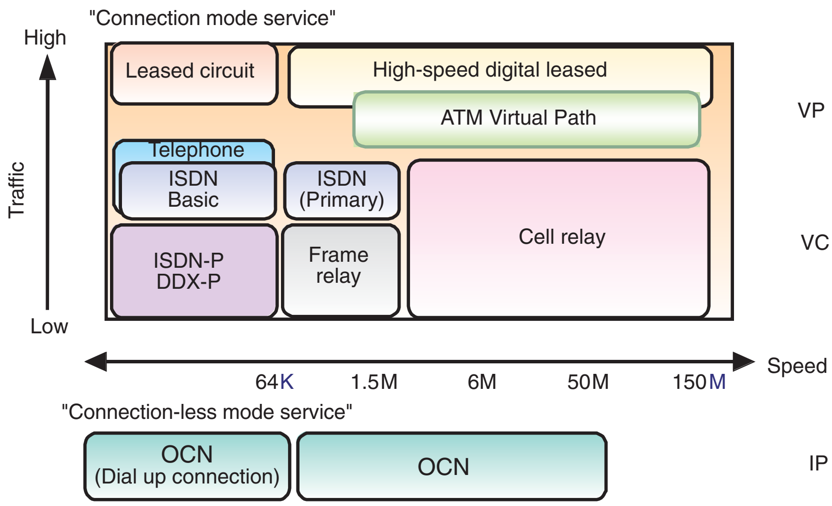


Figure 3 Telecommunication service line-up

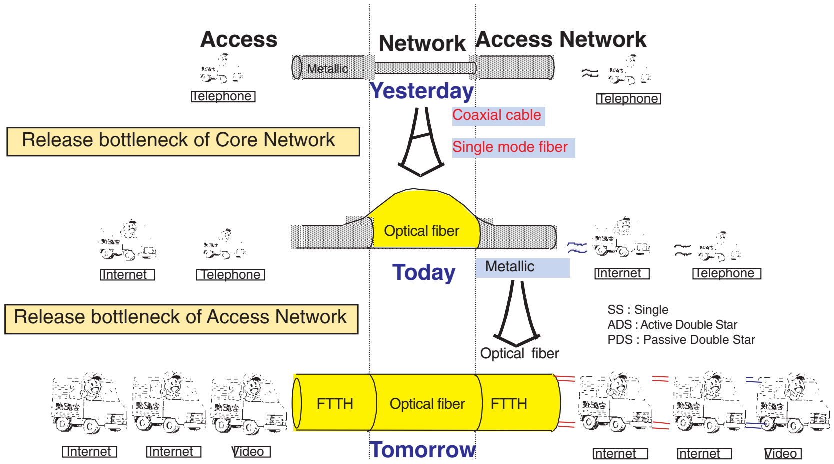


Figure 4 Status of the telecommunications infrastructure

have been deployed in the core network. However, metallic systems are used in most of the access network, and this causes a bottleneck of telecommunication.

But the bottleneck in the core network has been released by introducing optical systems instead of metallic systems. This is also the key issue for FTTH. If optical access networks are constructed with reasonable cost, these will enable the provision of broadband services in a flexible and rapid manner. Especially for high speed Internet access broadband access networks will be needed. A narrowband but constant path network was required for the telephone service. However, computer communication may require a broadband and peaky path optimised network. It is essential to establish an end-to-end path without any bottlenecks, neither in the core network nor in the access network.

There are many kinds of access systems providing broadband services, such as ADSL (Asymmetric Digital Subscriber Loop) systems, HFC (Hybrid Fibre Coaxial) systems, FTTC (Fibre To The Curb) systems, and FTTH systems. ADSL is good for providing broadband services fast, but limits the transmission quality, the applied distance, and the number of provided subscribers. Especially, there are some problems of cross talk in the Japanese network, since NTT applies TCM (Time Compression Multiplexing) technologies for the ISDN metallic systems. It is advantageous for HFC that cable TV companies optimize the existing coaxial cable. However, it is not so advantageous for telecom operators to install new coaxial cable. FTTC is good for the telecom operators who have direct buried infrastructure, since it is very expensive to replace direct buried metallic cable with new optical cable. FTTH is good for the telecom operators who have an aerial section or duct section in the access network. FTTH is also suitable in green field areas. Fortunately, NTT has a good availability of ducts at the feeder section and distribution section in business areas, and has aerial cable at the distribution section in the residential areas. Thus, it is relatively easy for NTT to deploy an FTTH architecture.

It is important to decide on the strategy for FTTH in the initial stage when the demand for broadband services has developed. There are two approaches towards FTTH, as illustrated in Figure 5. One approach is a network-oriented approach, and the other is a service-oriented approach.

In the network-oriented approach, the services provided by the optical access systems are the same as the services provided by the metallic access systems. This approach is applied by NTT in order to improve the existing infrastructure. However, optical access systems for narrowband services must be realised with the same cost as the metallic system alternatives. In this approach, the ONU (Optical Network Unit) for narrowband services is installed at the access point (point at user side closer than feeder point), which is near the customer premises (near-FTTH: n-FTTH). The ONU accommodates about ten subscribers.

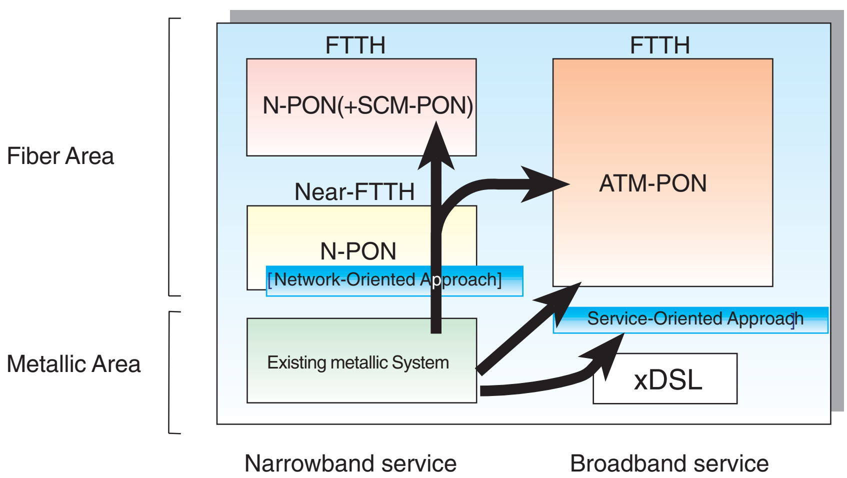


Figure 5 Approach to FTTH in NTT

In the case of near-FTTH, it is easy to extend from an n-FTTH architecture to FTTH, since there are additional fibres in the optical cable from the central office to the access point. If a customer requires a broadband service, and an optical cable recently has been installed between the customer premises and the access point, an additional fibre is connected. If the customer requires both a narrowband service and the CATV service, a narrowband PON (N-PON) and a SCM (subcarrier multiplexing) PON (SCM-PDN) are applied by the use of WDM (wavelength division multiplexing) technology. The N-PON and SCM-PDN uses the 1.3 μm and 1.5 μm wavelengths, respectively.

In the service-oriented approach, when broadband services such as the ATM service are demanded, an FTTH architecture will be realized by the use of an ATM-PON system. The FTTH architecture includes FTTB (Fibre To The Building) in this paper. As a first step business users are provided with broadband services through FTTH. If broadband services are demanded in an area dominated by a metallic cable based infrastructure, xDSL technologies will be applied in order to obtain fast provisioning of services. However, xDSL is considered to be a temporary solution, as discussed previously. It should also be noted that both the operator and the user need an opportunity to stimulate broadband services raised from user demand in order to break the ‘chicken and egg’ challenge.

5 Field trial of ATM-PON system and acquired understanding

NTT conducted the field trial of the ATM service applying an ATM-PON system in order to investigate the demand of future broadband services and the applied system technology. Since early 1996, field trials of ATM-PON systems have been conducted in Yokosuka and Urayasu city, as shown in Figure 6.

In these field trials, CATV, VoD and ISDN services were provided for up to 300 customers in each city (Figure 7). These systems had NTT proprietary interfaces, but had interoperability between the OLT (Optical Line Terminal) and the ONU, which were manufactured by different suppliers. This made the maintenance easy.

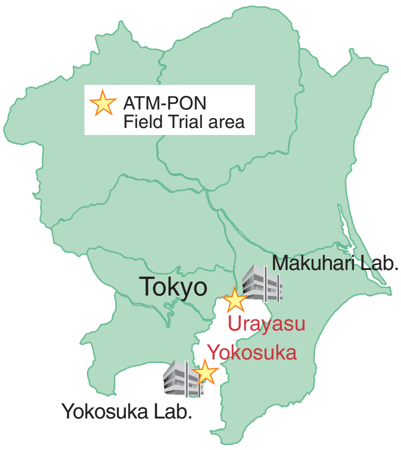


Figure 6 Field trials of ATM-PON systems for FTTH

Many good features of the ATM service have been envisaged through these field trials. There are many advantages for a network operator if an ATM network is constructed. The network cost reduction is led by simple multiplexing with non-hierarchical multiplexing and easy maintenance using cell-base multiplexing. From the viewpoint of the customer there are many attractive features, such as lower price, various classes of speed, and quality control. Of course, the basic concept of ATM is service integration, and the network operator can provide various kinds of services, which have even different speed class or quality, through his ATM network.

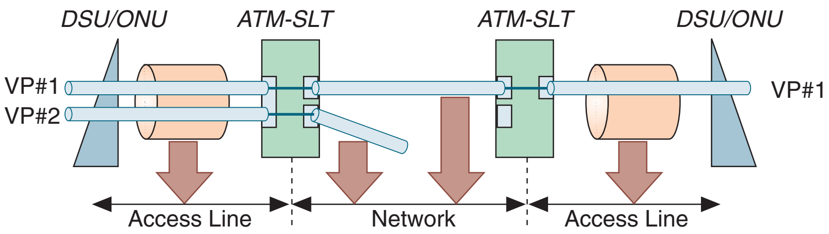
Through these field trials, it has been clarified that users – business users in particular – require ATM services at a reasonable price level. Therefore, NTT has deployed ATM-PON systems in the commercial networks in order to provide ATM services and utilise this experience. NTT was afraid to miss an opportunity to introduce the ATM service if we were to wait for the standardized ATM-PON system to become available. NTT decided to provide the ATM service as soon as possible by applying the same ATM-PON system as used in these field trials. This is the so-called *ATM Megalink service* as described above.

6 Outline of ATM service and access system

In the present commercial network, there are only a few speed classes in the STM based HSD service. However, by applying cell-based multiplexing as in the ATM Megalink service a huge class of speeds ranging from 0.5 Mbit/s to 135 Mbit/s is available, ie. every 1 Mbit/s pitch. The optimal speed may satisfy the users’ request. Up to 44 Mbit/s (equivalent) services are provided through the ATM-PON systems and up to 135 Mbit/s (equivalent) services are provided through conventional STM-1 single star (SS) systems, since the ATM-PON system was optimized for service speeds up to 44 Mbit/s (see Figure 8).

	Urayasu	Yokosuka
Test Period	1st quarter of 1996 - March 199	1st quarter of 1996 - March 199
Number of Subscriber	About 300	About 300
Service	Cable TV VOD (MPEG2) ISDN	
Network	ATM-PON	

Figure 7 Outline of the field trials



ATM Virtual Path		
	Network	(1) protected CBR VP [Dual]
VP cell rate 0.5Mbit/s 1.0Mbit/s 2.0Mbit/s 134Mbit/s		(2) protected CBR and UBR VPs [Extra]
		(3) non-protected CBR VP [Single]
	Access line	(1) ATM-PON (0.5Mbit~44Mbit/s)
		(2) ATM-SS (45Mbit~135Mbit/s)

Figure 8 Outline of the ATM services

In the core network, there are three reliability levels depending on the service price. Customers who make much account of economy will choose a core network without protection (*'Single'*), and customers who request the best reliability will choose completely duplicated core network (*'Dual'*). CBR (Constant Bit Rate) technology is applied for *'Single'* and *'Dual'* in the ATM Megalink service. In *'Extra'*, half of the cells which are required to be highly reliable are transmitted using guaranteed CBR, and the rest of the cells are transmitted through another path by using UBR (unspecified bit rate). Customers can choose service reliability level depending on their requirements and economy.

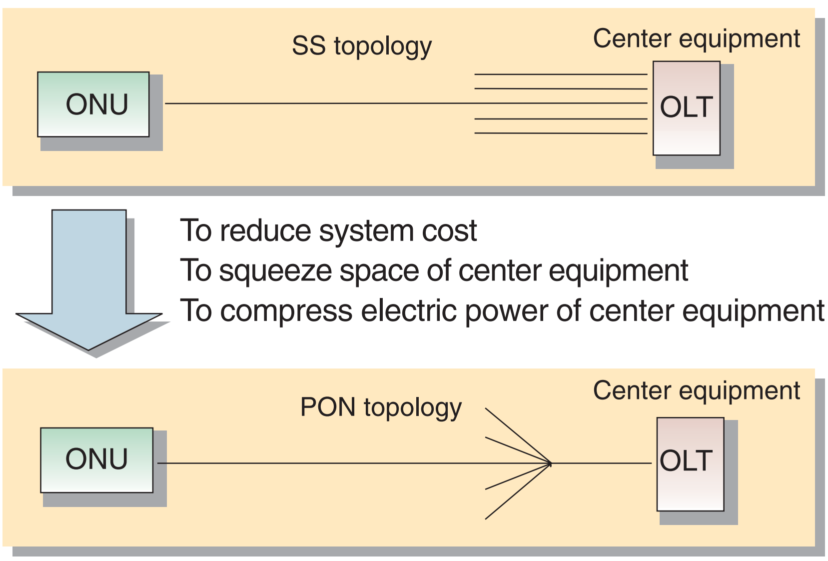


Figure 9 Features of the PON technology

NTT has started to deploy ATM-PON systems due to their good features, as illustrated in Figure 9.

The PON topology has many advantages compared to conventional SS (Single Star) topology. The first advantage is the lower system cost, due to the sharing of the OLT between multiple ONUs. The second advantage is the space reduction due to the fact that the OLT can accommodate many ONUs simultaneously. For example, SLICs (Subscriber Line Interface Cards) of switching systems occupy much space in central offices because a large number of SLICs is needed for each customer. Optical circuits need much more space than metallic systems if the conventional SS topology is applied. The third advantage is the low power consumption. The overall power consumption for the PON system is less than for the SS topology. However, there is cost limitation in ATM-PON systems if proprietary interfaces are applied in the existing ATM-PON system. NTT decided to introduce a standardized interface in order to achieve a cost effective ATM-PON system.

7 The FSAN initiative

Each telecom operator has different network architectures, system configurations, or deployment plans in the access network. This is because each of them has different geographical conditions, development strategies, or service requirements. However, every telecom operator targets the cost reduction of optical access system and aims at broadband service provisioning.

In 1995 a consortium named G7, consisting of seven large operators, was established in order to work towards common system specifications. Later on, the name was changed to FSAN (Full Service Access Networks), as more companies joined the initiative. The structure of FSAN is shown in Figure 10.

Operators who have their own access networks and exhibit their requirements to access networks can be members of FSAN. 19 operators are members as of February 1999. The aim of FSAN is cost reduction of optical access systems for early deployment. In the beginning of FSAN there were discussions on introduction strategies for optical access systems for broadband services. The discussions led to the consensus that the most cost-effective way to provide broadband services is to share common system specifications. During the discussion the ATM-PON system has been defined as the common target for each operator. FSAN aims at finding cost-effective solutions by defining a multi-vendor interface in the ATM-PON system. Service requirements from operators and technologies from suppliers have been harmonized in order to specify the interface between the ONU and the OLT of the ATM-PON system. The concept of FTTx is produced to overcome the diversity in geographical circumstances and the existing infrastructure, so that the ATM-PON system can be applied in any architecture, ranging from FTTH, FTTB, FTTC to FTTCab, as depicted in Figure 11.

At present the standardisation bodies are trying to decide on the standards for the systems already developed. Therefore, the systems do not always fit the requirements of the operators, and several systems have been standardized at the same time. Moreover, it takes a long time for the standardisation work to reach completion. FSAN decided to study some unique and what was considered the best system specifications which satisfy the requirements of the operators. The first step is to clarify the requirements from the operators, and the second step is to examine the technologies from the suppliers which satisfy these requirements. Unified interface specifications of ATM-PON systems have been completed in a short time. After completing the unique and best solution, the operators may, according to these specifications, procure the system from any supplier. Suppliers can sell the system to any operator demanding requirements satisfying these specifications. FSAN is not a standardisation body, so the results are often input to existing standardisation bodies such as ITU-T or ETSI (see Figure 10). At present, the specifications of the access line interface have been recommended as G.983.1 at ITU-T. Specifications of the management channel defined between ONT/NTE and OLT have been completed at FSAN and are planned to be frozen as G.983.2 at ITU-T. The Q3 interface is also discussed and planned to be input to ITU-T quite soon.

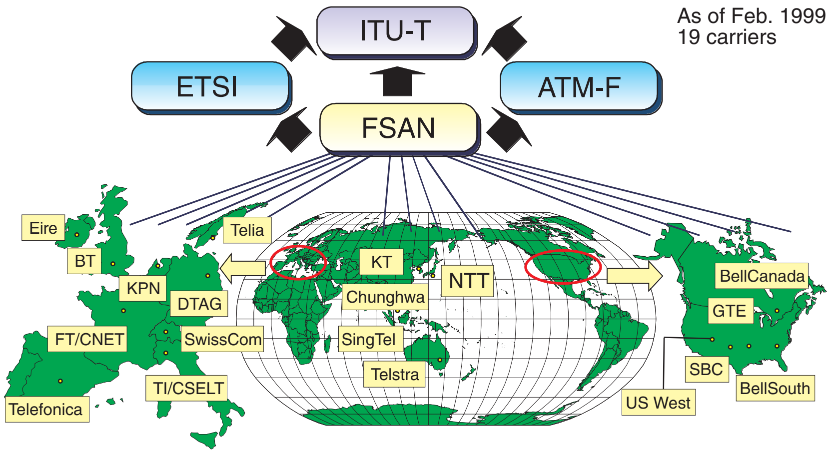


Figure 10 The FSAN structure

8 Commercial plan in NTT

In April 1997 NTT started offering ATM leased line services carried over ATM-PON systems. In Japan, the telecommunication market is very competitive and NTT needs cost-effective access systems and new service provisioning to overcome the severe competition. NTT plans to apply the next version of the ATM-PON system fully compliant to FSAN specifications by June 1999. The FSAN compliant ATM-PON systems are expected to be more economical than the former systems. The interface with the ATM switch, the SNI (Service Node Interface), and the operation interface are also applied in compliance with the ITU-

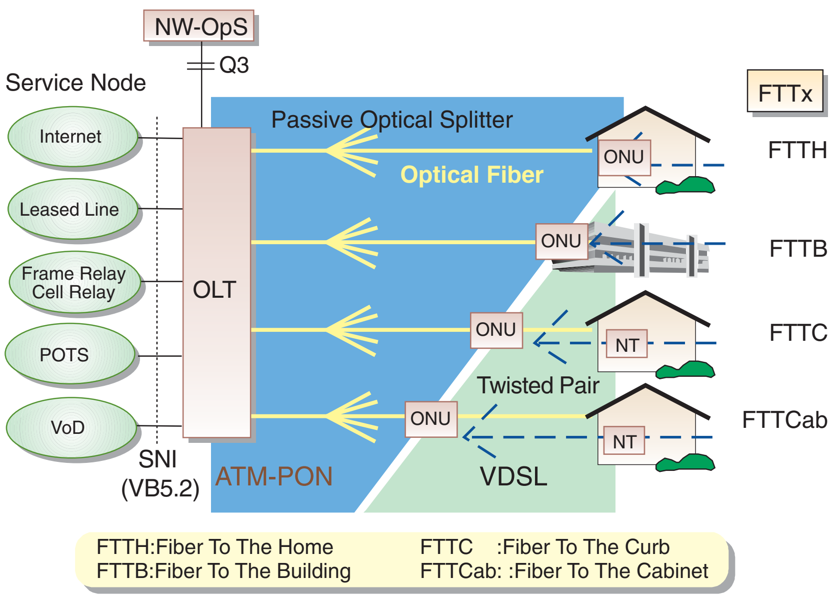


Figure 11 The FSAN architecture

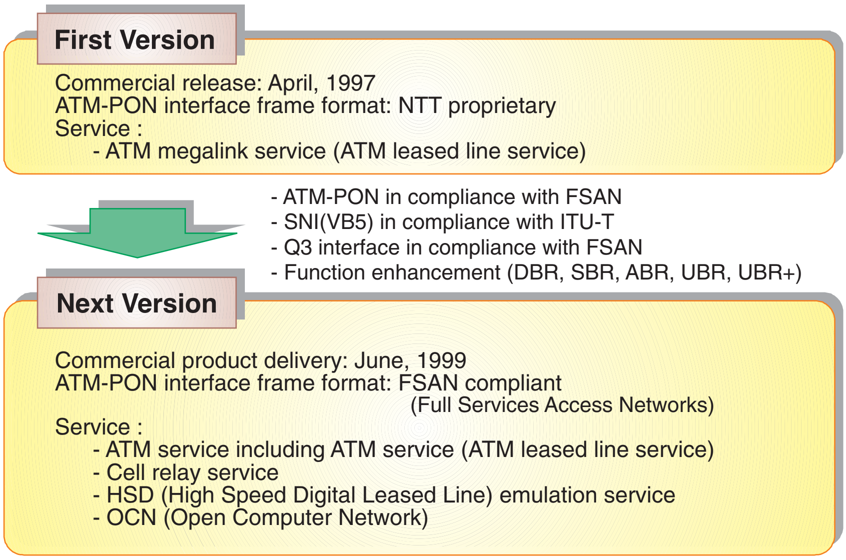


Figure 12 The commercial system of NTT

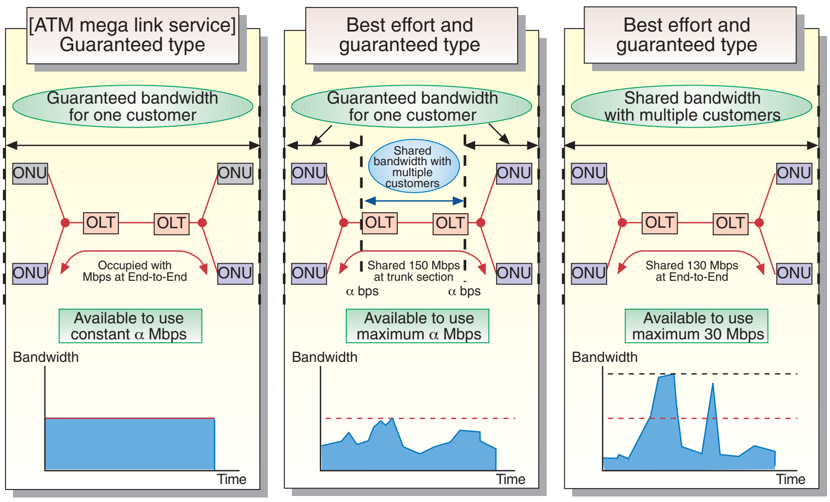


Figure 13 Characteristics of ATM services

T VB5.2 or Q3 FSAN specifications, respectively. The ATM-PON system is expected to cost-effectively provide broadband services over mega-stream, which is the so-called *'Megamedia service'* in NTT. In this sense the ATM-PON system is regarded as the access platform. The system evolution of NTT is illustrated in Figure 12.

At present a guaranteed type of service is available in the 'Megalink service' (see Figure 13).

In this type of service, service speed is guaranteed from end to end (CBR). ATM starts from the CBR type of service like the existing STM-based leased line service. Currently, non-guaranteed cell rates with low price may be acceptable even for a leased line service. There is a possibility of reducing system costs using the UBR+ service (Unspecified Bit Rate with best effort type, GFR). The GFR type of service is realized within core networks first because there are plenty of multiple paths. When broadband services in the future are introduced in the SOHO market, there is a possibility to provide the best effort type of service in the PON section due to the big dispersion of burst data. At that time, additional cost reductions can be expected.

9 Conclusion

The next version of the ATM-PON system targets big to medium businesses. The third step is to accommodate all kinds of services from high-speed services to narrowband services. The cost of ATM-PON systems should be as low as possible to be attractive to all users. The price target for the 'Megamedia service' is around 10,000 yens (80 USD) per month for bi-directional data service of 10 Mbit/s. Considerable effort will be concentrated on this issue.

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Towards broadband access in Norway – the view from Telenor

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This paper presents Telenor's strategy for a market driven development of the access network infrastructure towards an effective production platform serving the future service portfolio. A future flexible and competitive broadband access network will enable Telenor to access the customers with the broadband products to come after ISDN, ADSL, leased lines and GSM. The focus is on the medium to long term development towards flexible access capacities up to 25 Mbit/s for fixed and mobile services (UMTS) in the SME, SOHO and residential market.

1 Introduction

Telenor is the incumbent telecommunications operator in Norway, with a customer base comprising 2.5 million POTS (Plain Old Telephone Service) and ISDN (Integrated Services Digital Network) subscriptions; 1,700,000 cellular subscribers and 225,000 Internet subscribers, in addition to 280,000 cable television subscribers. Telenor operates in one of the world's most advanced telecommunication and information technology markets, and is thus likely to be in the forefront over the next years with regard to network evolution, including access network development. There are several indications that Telenor is now on the threshold of a major development towards broadband access delivery:

- Telenor is currently in the midst of the highest growth in ISDN subscriptions in the world, which among other issues implies the initial step of a future-proof capacity upgrade of the access network.
- In June this year the service *Telenor ADSL* was launched; Telenor being one of the first operators in Europe to offer interactive broadband access on a commercial basis. Initially, the service will be available in central regions of Oslo, Bærum and Tromsø, offering businesses Internet access at speeds up to 2 Mbit/s. The service coverage is likely to be extended to Stavanger, Bergen and Trondheim later this year [1].
- Almost simultaneously, Telenor signed a letter of intent on a comprehensive collaboration with Cisco Systems, with the aim of building a test version of an integrated infrastructure based on the Internet Protocol (IP) for telephony, data and multimedia services from wireline and mobile connections. One possible outcome is that Telenor eventually replaces the variety of networks currently in use with a Full Service Network (FSN) [2]. A key feature of such an FSN is an improved exploitation of the current access network by an increase in the number of local access points compared to the present PSTN (Public Switched Telephone Network) infrastructure. This will enable capacities higher than 2 Mbit/s to be offered to end-users, as well as providing an effective means of meeting the transport capacity requirements of the third generation mobile telephone system, UMTS (Universal Mobile Telephone System).

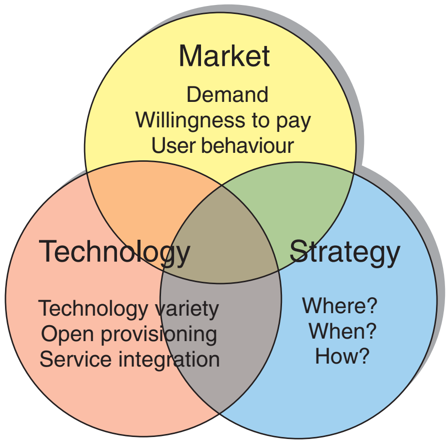

Figure 1 The access network challenge

However, turning the last mile into a long term, first class asset, represents a significant challenge for Telenor and other access operators, well beyond the moves mentioned above. This paper addresses this challenge from a strategic point of view, taking into account the major aspects of market, technology and economics [3, 4, 5, 6, 7]. Figure 1 illustrates the key issues in the development of a future broadband access network. We distinguish between the challenges associated with *market*, *technology* and *strategy*, as discussed next.

1.1 Market challenges

The challenge of broadband services and the last mile is first and foremost connected with the uncertainty in service demand, willingness to pay and usage patterns:

- *Broadband service demand: How large a growth* in demand for transmission capacity can be expected within the next five to ten years? A very significant growth in capacity intensive services is expected, and the transmission capacity is foreseen to be perceived as a commodity.
- *Willingness to pay:* Is there any incremental willingness to pay for new multimedia services? The demand level will to a large extent depend on the price and the pricing schemes, in particular in the very important mass market.
- *Usage pattern:* Which consequences will the development in the industry have on which areas broadband services are applied and how they are used? Very soon the content and distribution are expected to become all-digital. The exponential growth in microprocessor power, memory size and storage capacity will probably continue over the next ten years. This implies that the performance of the end-user systems will continue to increase, possibly to 100 times the performance of the current systems.

1.2 Technology challenges

The future access network architecture will most likely be different from the present one in at least three aspects:

- *Technology variety*. Both fibre solutions, satellite systems, cable-TV networks, radio systems and DSL (Digital Subscriber Line) solutions over the existing copper network can be part of one network. Which solution or combinations should the operator select?
- *Openness:* An open architecture is required in order to operate in a competitive environment with different core network operators.
- *Service integration* refers to an access network in which all kinds of traffic are mixed by means of statistical multiplexing[1)]. This is in contrast to static multiplexing and dedicated connections which are currently being used. The rationale for service integration is

1) *Also called dynamic multiplexing.*

efficient and cost-effective provisioning of broadband access. The challenge is to maintain QoS (Quality of Service) in the mixed traffic stream.

1.3 Strategic challenges

Moreover, a roll-out of a broadband access network implies a set of strategic challenges and imperatives:

- *Where, when, how and to what extent* should the operator invest in access network infrastructure for broadband services?
- *Which deployment strategy* should be chosen in order to balance investment risk and expected market potential?
- *Which access node configuration* should the operator establish, and which technology is best suited?

1.4 Organisation of the paper

The rest of the paper is organised as follows: In chapter 2 the current market situation in Norway is examined, with the emphasis on the competitive situation and the market drivers. Chapter 3 presents Telenor's current network platform, which constitutes the starting point for developing the future infrastructure. In chapter 4 the access technologies are discussed. Migration aspects related to the evolution towards the future access network are treated in chapter 5. Experiences and lessons learned from field trials in Norway are presented in chapter 6. In chapter 7 key findings from economic analyses of broadband access are summarised. Chapter 8 presents Telenor's strategy, based on the discussions in the preceding chapters.

2 The market

Norway has one of the world's most advanced telecommunication and information technology markets, with among the highest market penetration of ISDN, GSM (Global System for Mobile communication) and Internet. The Norwegian market consists of 4.5 million inhabitants, 1.8 million households and 0.2 million companies. In this chapter we will give a summary of the telecommunications market in Norway, including Telenor's current position, the competitive arena, the current market trends and drivers and the emerging broadband service market.

2.1 Telenor's position

At present both fixed network operators, cellular operators, cable operators, power utility companies and new entrant operators are offering telecommunications services in the Norwegian market. Telenor's 1998 annual revenues amounted to 22.2 billion NOK, with a work force of 19,000 employees.

Currently Norway has the second highest penetration of Internet hosts (including dial-up connections) in Europe, totalling approximately 325,000 hosts at the end of 1998. Last year Telenor Nextel, which has 70 % of this market (225,000 subscribers), was among the first Internet Service Providers to start using the H.323 standard.

Norway is one of the two countries in the world with the highest penetration of GSM cellular phones (47.6 %), second only to Finland (58.5 %) at the end of 1998. There are two cellular operators in Norway today, NetCom and Telenor. As of April this year NetCom, which currently only offers GSM, had 570,000 subscribers, whilst Telenor had around 1,450,000 GSM subscribers. GSM 1800 was introduced last year, and already 10 % of the mobile traffic in the larger cities is flowing in the GSM 1800 network. Telenor also offers NMT 450 (Nordic Mobile Telephone) and NMT 900, bringing the total number of cellular subscribers to 1,700,000 for Telenor. Thus in Norway in total, including GSM and NMT, there are around 2.3 million cellular subscribers as of April this year.

The telecommunications network of Telenor was fully digitised in 1997, twelve years after the first digital switches were installed in the network. Telenor is now the world's number one ISDN operator, with around 300,000 ISDN basic access subscriptions by the end of 1998. That corresponds to an ISDN B-channel penetration of 15 %. The growth in ISDN subscriptions in Norway is still very high. In total Telenor has 2.5 million POTS and ISDN subscriptions.

Telenor Satellite is number three of Europe's satellite operators with an infrastructure consisting of satellite capacity and land earth stations. The services offered are:

- Mobile satellite services;
- Satellite network services;
- Satellite distribution services.

From its hotbird satellite position 1° West, Telenor distributes more than 35 analogue and 70 digital TV channels in the Nordic region, Central and Eastern Europe. The five satellite 1° West position has 51 transponders in total. Telenor serves the business markets in Scandinavia, Eastern Europe and the United Kingdom, as well as in Africa. The applications offered include voice and data point-to-multipoint services and satellite Internet backbone services, including satellite intranet.

2.2 Access competition in Norway

Competition in the fixed network in Norway was introduced in 1998, with the main service elements being:

- Establishment of interconnect agreements since the start of 1998;
- Prefix traffic since the start of 1998;
- Carrier preselection from June 1999;
- Introduction of a fixed access product in 1999.

In the access network Telenor is facing competition from four different types of actors:

- Cable operators;
- Mobile operators;
- Power utilities;
- Operators without infrastructure.

The coaxial cable network of the largest cable operator in Norway, Janco Multicom, passes over 500,000 homes, mainly in the larger cities like Oslo. Janco Multicom has 47 % of the cable market in Norway. United Pan-Europe Communications (UPC), the owner of Janco Multicom, plans to invest 1.5 billion NOK (0.2 billion USD) in network upgrades over the next years, preparing the network for interactive and emerging multimedia services. Janco Multicom already offers Internet access, with telephone services expected to be launched during the first half of 1999.

The second mobile operator in Norway, NetCom, has 30 % of the GSM market, and has thus already an alternative access network infrastructure. The owner of NetCom, NetCom Systems, has already tested 42 GHz broadband radio access solutions. Establishing such radio systems by the use of NetCom's existing

GSM sites has the potential of substantial infrastructure cost savings.

The power utility companies and their regional telecommunications subsidiaries have entered the long-distance and city carrier market with significant financial strength and ambitious plans. Currently they are targeting the business customer segment, and have taken significant market shares in some major cities. In addition, power line cable modems are being tested in the field. This technology may enable the power utility companies in Norway to enter the residential market, targeting Internet services.

Tele2 is the major actor of the competitors without access infrastructure, offering prefix traffic and satellite Internet access, with terrestrial twisted pair return. NetCom Systems has a large stake in Tele2, in addition to the ownership in the mobile operator NetCom. Tele2 has seized a significant amount of customers in the business segment, and is attacking the residential market mainly with Internet and prefix traffic. The operator is now the second largest ISP in Norway. However, Tele2 has so far not announced any plans to install their own access network infrastructure.

In summary, Telenor's competitors look capable of competing in the access network, in terms of having the technological means, financial strength and determination.

2.3 Current market trends and drivers

ISDN was commercially introduced in the Norwegian business market in May 1994. Two years later, ISDN-BRA (Basic Rate Access) was introduced in the residential market. At present the ISDN market is growing very fast (see chapter 2.1). The ISDN forecast for the residential market in Norway is shown in Figure 2.

The current telecommunications market is characterised by:

- Data market growth;
- Stagnation and levelling of voice traffic;
- A very strong growth in ISDN 64 kbit/s and Internet traffic.

The main drivers behind the growth in the data market are:

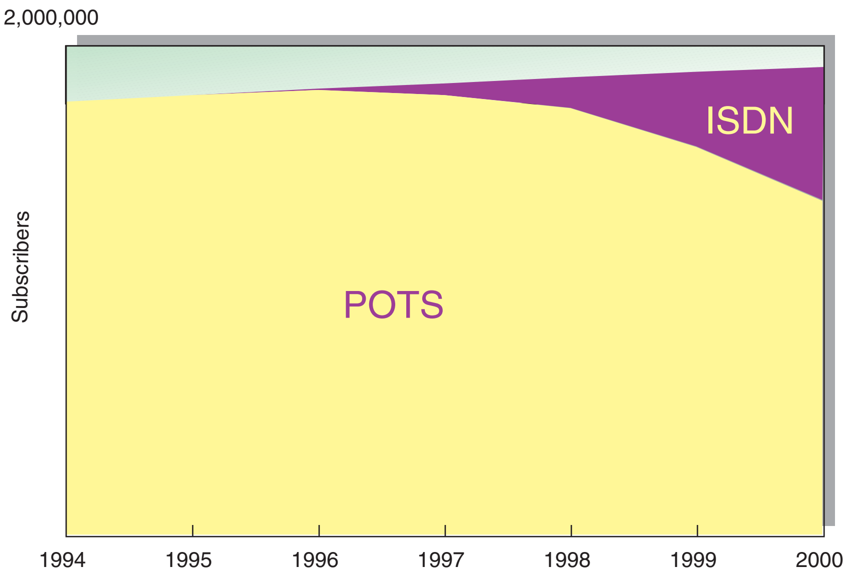

Figure 2 The ISDN-BRA forecast for the residential market in Norway

- Transparent, non-voice ISDN 64 kbit/s traffic;
- Internet;
- Leased lines;
- Frame Relay and ATM (asynchronous transfer mode) services offered on the broadband platform.

The current market trends indicate an evolution towards broadband services, in the SME-market (small and medium enterprise), the SOHO (small office, home office) and residential market. This is also supported by two different Delphi surveys on future broadband service evolution, carried out by Telenor in co-operation with other actors [8, 9]. The experts participating in the Delphi survey used information about market drivers as a basis for their evaluation of the evolution of a future broadband market. The main drivers behind the broadband evolution are identified as:

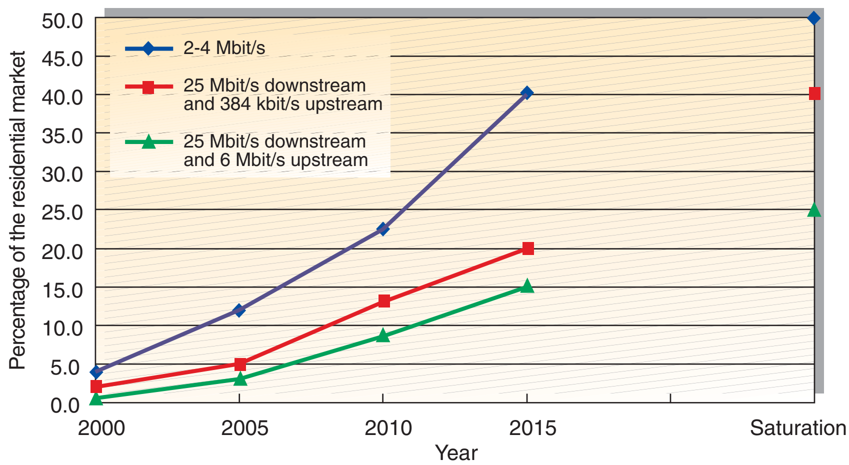

Figure 3 Forecasts of broadband accesses

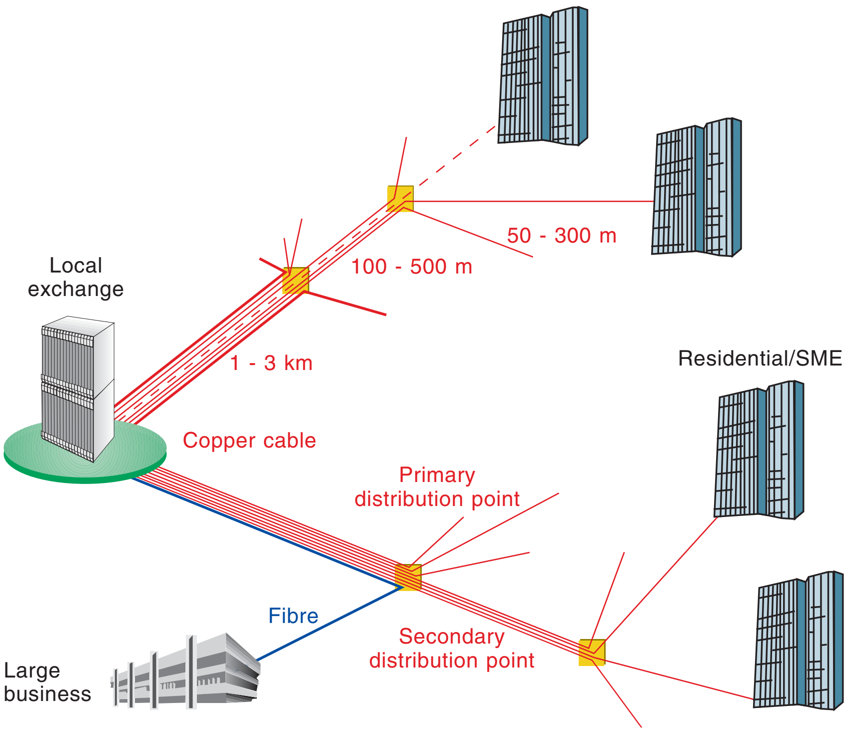

Figure 4 Telenor's existing twisted pair network

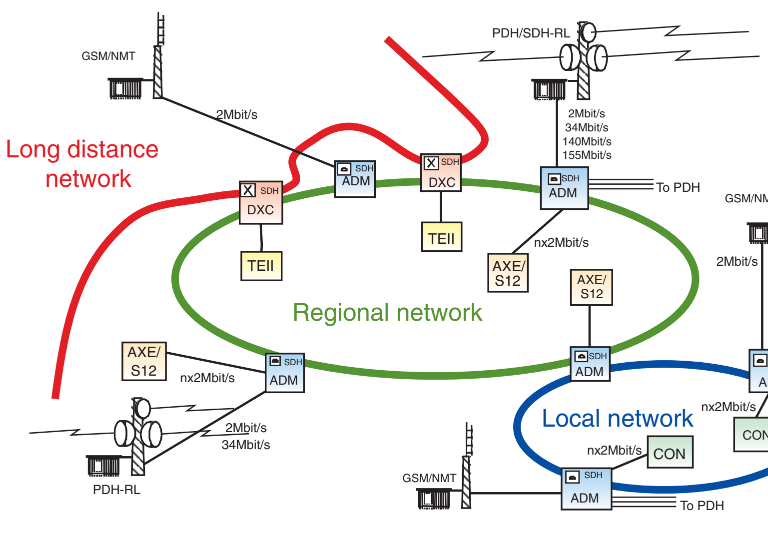

Figure 5 The existing transport network of Telenor

- Development of PC terminals;
- Price evolution of PC processor capacity;
- Price evolution of RAM and disk capacity;
- Internet development;
- Development of applications;
- Development of telecommuting and home office solutions;
- Development of new technology, eg. digital subscriber line (DSL) modems.

Figure 3 depicts the forecast results for broadband accesses from the European Delphi survey [8].

The results from the Delphi survey show that a substantial demand for broadband services can be expected in the residential and SOHO market during the next ten years. The survey shows that the households' incremental willingness to pay for additional broadband applications and additional capacity is limited. Thus, the future interactive broadband arena, and in particular the residential market, is still characterised by a high degree of uncertainty with respect to both service take rates and willingness to pay. This imposes a particular challenge for the access network operators.

3 Existing networks

Telenor has today a versatile access network platform which constitutes the starting point for developing the future infrastructure. The current access networks of Telenor consist of:

- A twisted pair network for PSTN (public switched telephone network), ISDN and leased lines services (< 2 Mbit/s);
- Optical fibre network for leased line services (> 2 Mbit/s);
- Coaxial cable networks for distribution of analogue TV-signals;
- Cellular networks (NMT-450, NMT-900 and GSM 900/1800) for mobile services;
- Satellite network, 1° West for digital and analogue TV-signal distribution and business communications;
- ADSL (Asymmetric Digital Subscriber Line) over existing twisted pair cables.

Figure 4 depicts the existing twisted pair network of Telenor. Today there are around 230 local exchanges in Telenor's network and approximately 3,500 remote subscriber units or systems (RSU/RSS). The number of primary distribution points is about 50,000. Only the business customers with the highest demand are connected by dedicated fibre optic cable to the local exchange.

The local exchanges are connected to the transport network, which comprises local and regional networks as well as the long distance network. The transport network nodes are typically connected by fibre optic transmission systems with capacities in the range 2 Mbit/s to 2,488 Gbit/s. In the transport network both the long distance network, the regional network and parts of the local networks have been upgraded with fibre optic SDH (Synchronous Digital Hierarchy) ring structures. Wavelength division multiplexing systems have already been operational for some time on selected links of the transport network. Figure 5 depicts the existing transport network of Telenor.

Approximately 5,000 business customers are connected to Telenor's ATM platform, either with a Frame Relay connection or with an ATM connection. The access to the ATM network is provided on 64 kbit/s, $n * 2$ Mbit/s, 34 Mbit/s or 155 Mbit/s leased line connections. The network has today approximately 130 nodes, of which 60 are ATM switches. Telenor's IP network consists of around 35 access nodes or POPs (Point of Presence).

4 Access technologies

Telenor has examined a large variety of access network architectures in order to determine the most appropriate ones for the different geographical area types and service demand profiles. The objective is to derive suitable minimum-risk strategies for a migration of existing network infrastructures or for deployment of a completely new access network infrastructure, in view of the underlying fundamentals of where and when to invest in order to create a positive business case for broadband services.

We are facing paradigm shifts along three dimensions, as listed in section 1.2, that change the architectural requirements of the access network. The technology variety is illustrated in Figure 6, in which some of the relevant technologies are sorted by transmission medium.

Within each of the six groups of technologies there are several different options, resulting in a very high number of access network alternatives. This underlines the fact that we are now witnessing the end of a single access infrastructure. The future multiservice access network will most likely be built on a combination of systems and technologies – all supporting the vision of a full service access network.

5 Migration

Given the previously described large number of available access network architecture alternatives, the challenge for an operator such as Telenor is to determine not only the target architecture for future broadband access delivery but also the migration towards this target architecture. Thus, access network migration towards broadband is largely related to the existing network, the target architecture, and the corresponding intermediate infrastructure changes required in order to upgrade the network to the target architecture. For an operator like Telenor it is natural to focus on the evolution of the almost ubiquitous twisted pair copper access and mobile networks. The different alternative migration paths are discussed in more detail in [10]. Figure 7[2)] shows the expected concurrent evolution over the coming years in terms of terminal mobility and capacity. The picture illustrates the fact that as mobile broadband in the range of some 100 kbit/s emerges through the adoption of GPRS (General Packet Radio Service) and UMTS, even capacities higher than 2 Mbit/s will be offered by the use of ADSL and fibre in combination with VDSL or LMDS.

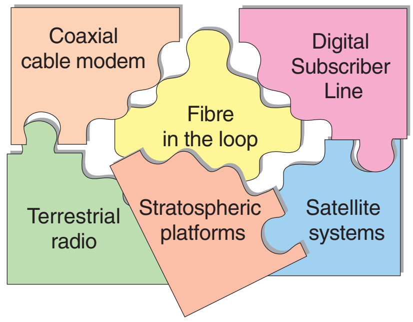

Figure 6 Access network alternatives

2) *FTTN: Fibre to the node.*
FTTC: Fibre to the curb.
LMDS: Local Multipoint Distribution System.

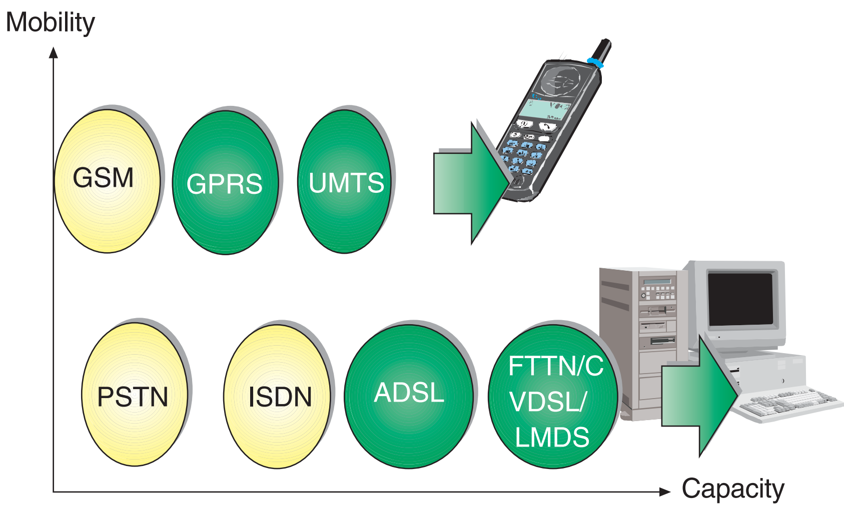

Figure 7 Development of broadband and mobility

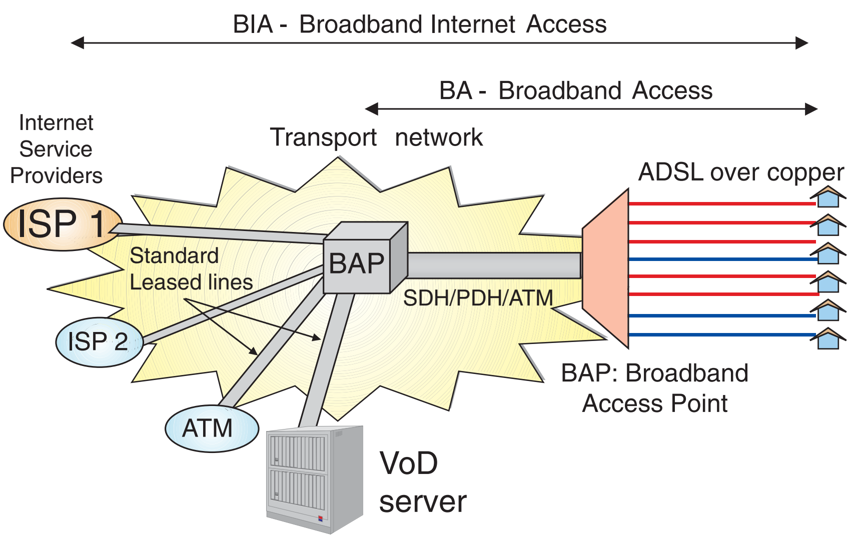

Figure 8 The ADSL field trial configuration

6 Field trials

Telenor has had two broadband service pilots operational since spring 1998, in which broadband Internet access using ADSL technology has been tested. The trial has been run in central Oslo, with approximately 50 SMEs and residential customers connected with capacities of up to 2 Mbit/s downstream and 448 kbit/s upstream. Two different ISP accesses have been tested: IP based access and access based on IP over ATM. The customers have been offered the broadband Internet access service in addition to their existing ISDN or POTS service on the same twisted pair. The main objectives of the trial project have been:

- To test the technical functionality of existing and forthcoming equipment;
- To test the quality and performance of access lines;
- To test the provision of various services through the same cable in terms of crossed lines/interference (ADSL, ISDN, HDSL (high speed digital subscriber line), etc.);
- To measure traffic statistics, including Norwegian traffic patterns, traffic with domestic, international and local providers;
- To measure statistics for the use of various services;
- To test various selections of bandwidth to customers;
- To test supply procedures and the administrative system;
- To test operational requirements and procedures;
- To test support requirements/customer service and procedures.

Figure 8 depicts the ADSL field trial configuration. BIA (Broadband Internet Access) is the product sold to the end-user by the ISP (Internet Service Provider), whilst BA (Broadband Access) is the product sold to the ISP by Telenor Network. The BAP (Broadband Access Point) is described in more detail in section 8.2.

The BAP is a key element in the network architecture, as it is flexible and provides interconnection to both the IP network, ATM networks and other networks.

7 Economics

In devising an access network strategy Telenor has examined the economics of various upgrade alternatives. The techno-economics work performed in the EURESCOM[3] project P614, "Implementation Strategies for Advanced Access Networks" largely reflects the main categories of economic analysis results on which access network strategies may be based [7, 11]. The methodology and tool initially developed by the RACE[4] 2087/TITAN[5] and the ACTS[6] 226 OPTIMUM[7] projects, and now under further development in the ACTS 364 TERA[8] project has been applied in the techno-economic analysis. Upgrade strategies based on a combination of optical fibre systems and Digital Subscriber Line (DSL) technologies are examined for various residential areas with existing twisted pair infrastructure. Figure 9 shows the line cost breakdown at 25 % take rate in the urban area under study. Results are shown for 2 Mbit/s, 8 Mbit/s, 13 Mbit/s and 26 Mbit/s roll-outs, corresponding to different degrees of fibre penetration in the network. A ten year (1998 – 2007) upgrade project with a linear penetration increase is examined.

These overall investment cost analyses confirm several key cost features of the future broadband access networks:

- The cost of bandwidth in the access network is still very significant. The analyses confirm that a broadband upgrade of the access network has costs similar to or higher than the overall costs of establishing the existing access network.
- The node configuration and corresponding degree of fibre penetration is a key strategic decision.
- High capacity upgrades and corresponding high fibre penetration significantly increase the financial risk.

[3] *EURESCOM: European institute for research and strategic studies in telecommunications.*

[4] *RACE: Research in Advanced Communications in Europe.*

[5] *TITAN: Tool for Introduction scenario and Techno-economic evaluation of Access Networks.*

[6] *ACTS: Advanced Communications Technologies and Services.*

[7] *OPTIMUM: Optimised network architectures for multimedia services.*

[8] *TERA: Techno-Economic Results from ACTS.*

The analyses of the economics of broadband access delivery indicate that Telenor as an operator is faced with a set of strategic imperatives which need to be reflected in order to achieve economics of scope and scale when rolling out a broadband access network.

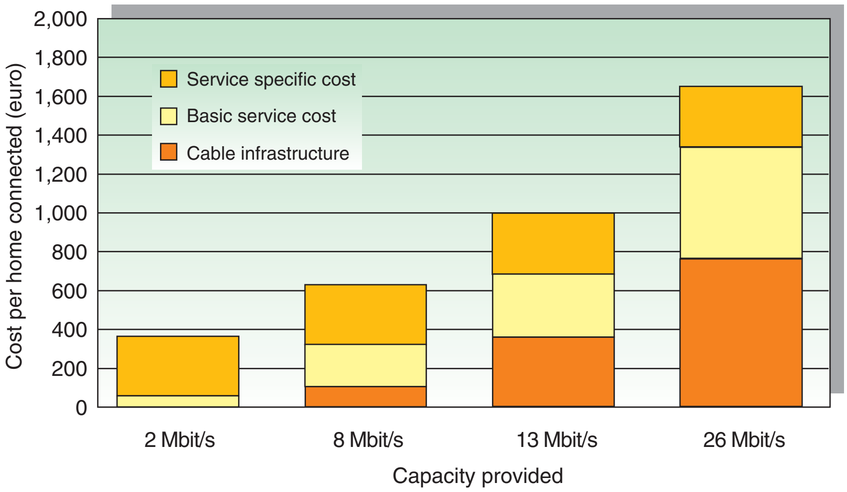

Figure 9 Line cost breakdown @ 25 % take rate

8 Telenor's strategy

In view of the preceding chapters and considerations, Telenor's plans for access network evolution can be formulated, both with respect to access service portfolio, architecture reference model, target network and deployment plan. The target network, described in chapter 8.3 is based on the architecture reference model described initially in chapter 8.2. In the final chapter 8.4, the deployment plan of Telenor is presented.

8.1 Telenor's access service portfolio

One possible evolution of Telenor's access service portfolio, including fixed, mobile and satellite services, is illustrated in Table 1. The table lists different access services, indicating the underlying technology, the access speed offered and the time period during which the service is likely to be available.

Table 1 Telenor's access service portfolio

	Technology	Access speed	Time period
Fixed	PSTN	2.4 kbit/s – 56 kbit/s	1986 – 1997
	ISDN	144 kbit/s, 2 Mbit/s	1994
	Digital (leased line)	64 kbit/s – 155 Mbit/s	1986 – 1997
	Cable modem	512 kbit/s	1998
	ADSL	2 Mbit/s (448 kbit/s)	1999
	Fibre + ADSL/VDSL	25 Mbit/s (asymmetric)	2002
	LMDS	34 Mbit/s (8 Mbit/s)	2000 – 2001
	DTTV	30 – 40 Mbit/s	1999
Mobile	GSM	9.6 kbit/s	1992
	HSCDS	28.3 kbit/s	1999
	GPRS	115 kbit/s	2000
	UTRA (UMTS)	144 kbit/s 384 kbit/s 2 Mbit/s	2002 2002 2002
Satellite	VSAT	2 Mbit/s	1976
	DTH – analogue	---	1987
	DTH – digital	40 Mbit/s	1997
	Turbo – Internet	2 – 8 Mbit/s	1999

8.2 Architecture reference model

The new access network reference model is depicted in Figure 10.

The trend towards open provisioning means that different administrative domains will be involved, as marked by vertical dashed lines. The model distinguishes between access operators, transport providers, service providers and platform operators. As suggested by the figure, cross-domain management is an important issue for the future broadband access network.

The Service Nodes (SN) of the future broadband architecture access network is shown to the left in the figure. The term Local Access Point (LAP) is used for the natural aggregation point covering the customers within a geographical area of moderate size. The Broadband Access Point (BAP) links a number of local areas on one side to one or more service nodes on the other side. A LAP is linked to only one BAP whereas an SN can be connected to several BAPs. Hence, a

BAP defines the termination of a local access network with the corresponding interface to the service nodes denoted SNI. The model facilitates the use of intermediate transport providers on both sides of the BAP.

The physical location of a BAP depends on the customer base in the connected LAP areas, and also the location of the SNs. One extreme case is to co-locate the BAP with one of the connected LAPs. The other extreme is to co-locate a BAP with an SN. In practice, the optimal location will be determined by a trade-off of the transport costs carried by the access operator and the service providers, respectively. The same trade-off will also determine the number of LAPs and BAPs in a nationwide access network.

8.3 Target network

The future access network platform of Telenor will be developed based on a co-ordinated evolution of the fixed access network and the mobile network. The data rate in the mobile network will be increased over the next years by the introduction of GPRS, before UMTS eventually is launched in year 2002.

In the initial phase the fixed network upgrade will mainly consist of a rapid ISDN roll-out. The medium term target network for broadband services is depicted in Figure 11. Basically it consists of ADSL modems installed on the existing copper base, ADSL multiplexers and new broadband access points.

The long term target architecture is illustrated in Figure 12, consisting of fibre optic nodes with fibre optic transmission systems in the primary access network and VDSL modems or LMDS installed between the fibre node and the customer premises (secondary access network). The fibre node structure may also serve the future UMTS base stations with the required transmission capacity. The fibre node size is probably a more important choice than the technology choice itself.

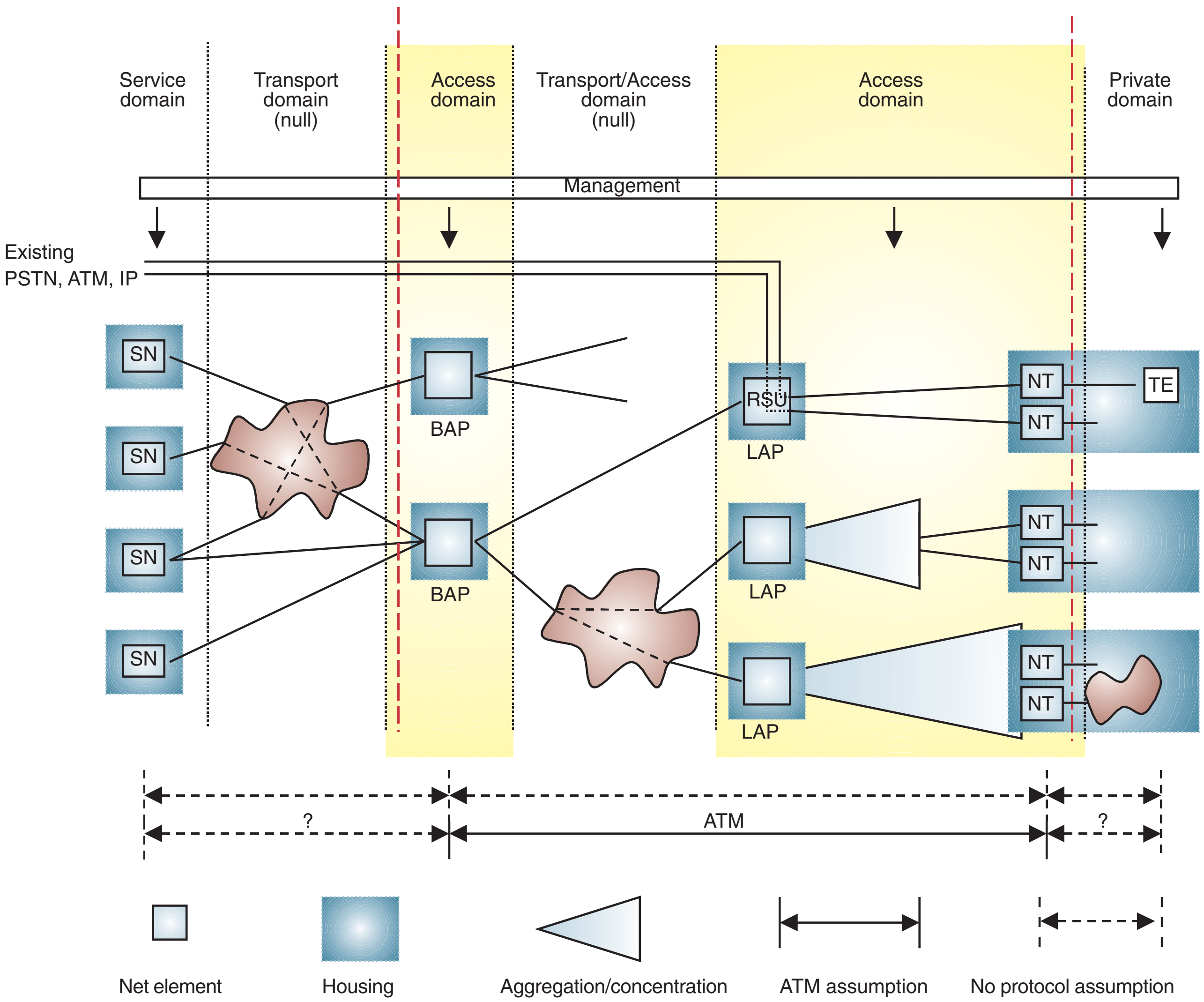

Figure 10 An architectural reference model for the future broadband access network

The fibre node structure will be serving all customer groups, even if initially the SME segment is expected to be the dominating one. In the medium to long term also the SOHO and residential market will be connected by high capacity accesses to the fibre node structure.

The aim is also to establish a service integrating access network, evolving from an ATM based network in the initial phase to an IP based network in the longer term. A likely evolution is that the broadband access network initially will be provision oriented, similar to the current narrowband network. The next step will be to implement free selection of service provider per session. The ultimate step is to let the access network become a true IP subnet interworking closely with arbitrary subnets in the core domain [12].

8.4 Deployment plan

Telenor has established the following deployment plan for the future broadband access network:

1. Telenor will meet the market demand by targeting ISDN to the mass market in the initial phase.
2. In June 1999 a commercial ADSL service was rolled-out, providing 1–2 Mbit/s ADSL to the SME market.
3. Within few years a fibre node structure will be rolled out, aimed at providing capacities up to 26 Mbit/s to SMEs, SOHO and high end users.
4. The high density areas are the natural targets in the initial phase, whilst the mass market is likely to follow when the applications and the price level for broadband access equipment is 'right'.

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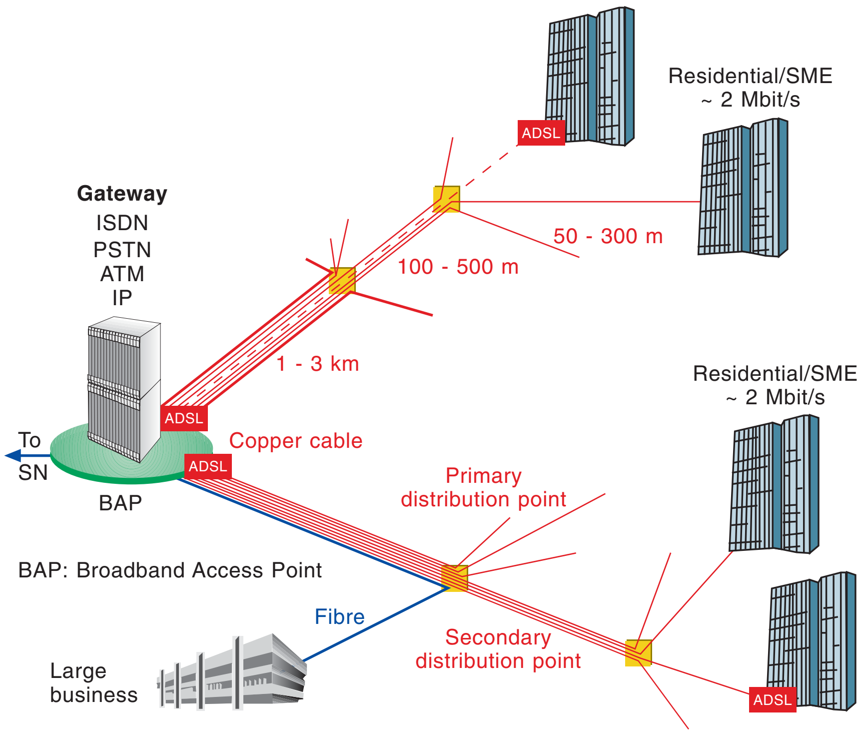

Figure 11 Telenor's medium term target network architecture

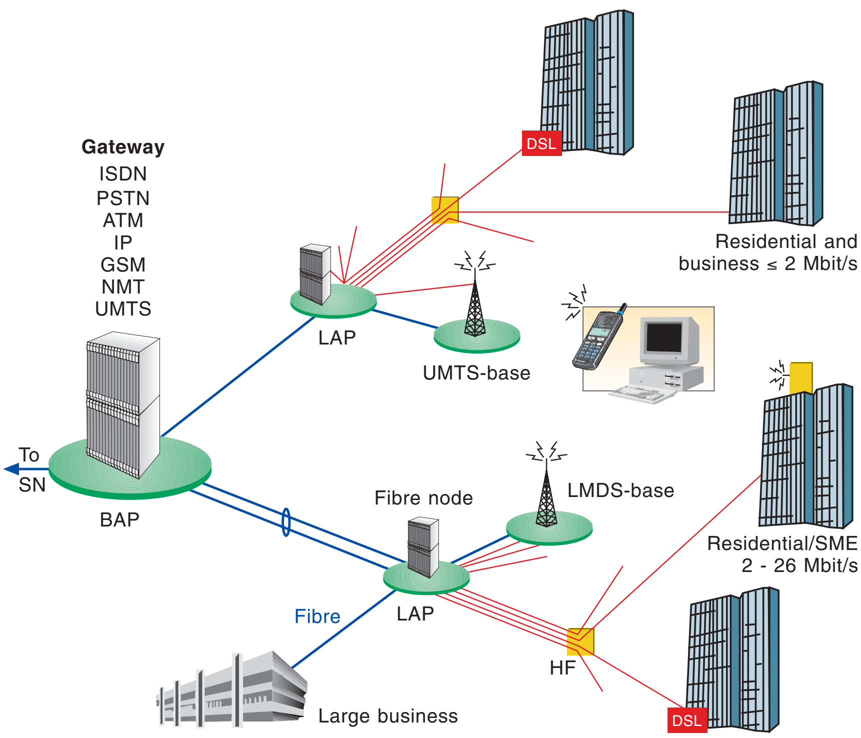

Figure 12 Telenor's long term target network architecture

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The challenge of civil works

GIOVANNI CIOCHETTO

Introduction

Civil works and installation are responsible for more than half of the total cost of the network and have a significant impact on environmental and social activities. The use of new techniques allows a reduction of the global costs related to the deployment of the access network and an improvement of the flexibility of the installation techniques, reducing significantly the environmental and social impact related to civil work and installation.

This paper presents an overview of current practice and emerging techniques.

Improvement in site investigation using Ground Penetrating Radar systems can avoid drawbacks of digging or drilling works for the construction of underground infrastructures.

New construction methods alternative to traditional digging techniques are also presented. The so-called No Dig techniques allow installation of underground ducts performing small tunnels without digging long and deep trenches which, especially in urban environments, cause many inconveniences to cars and pedestrians.

Another interesting alternative to digging is represented by Micro Cabling System, which allows installation of small optical cables in shallow and narrow trenches along roads or pavements.

As far as cable installation is concerned interesting results can be obtained by using air blowing techniques. One of the most interesting points is represented by the new techniques for optical fibres installation. Using appropriate materials and equipment it is possible to install single fibres or fibre bundles directly into small underground ducts by blowing or by pulling.

Ground Penetrating Radar

An exhaustive knowledge on the subsoil right from the first design phases of the construction of underground network infrastructures is essential, both to limit possible damage to existing utilities and to reduce the number of failures especially if new trenchless techniques are used.

The information needed can be obtained partially by consulting existing documentation on any work (eg. laying of utilities, etc.) carried out in the area in question, or through documentation made available by local authorities and other companies (eg. gas, water, power, etc.).

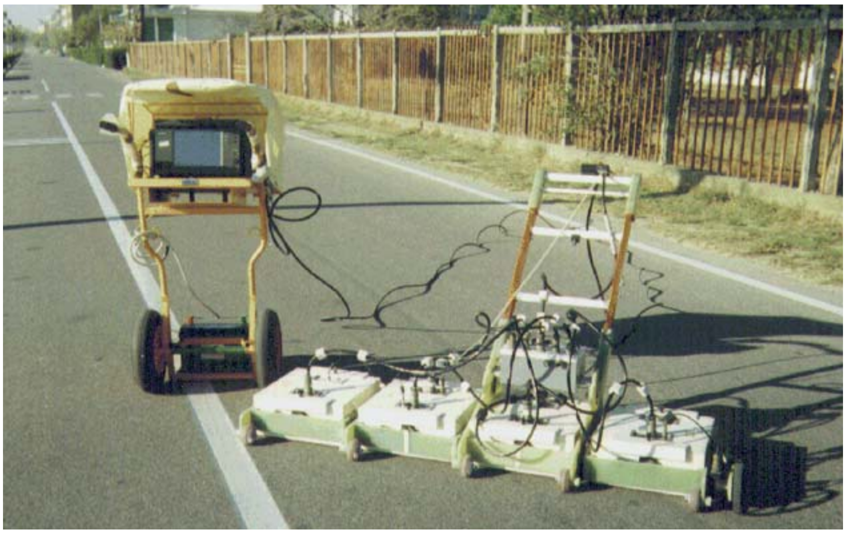

Figure 1 On site acquisition system equipped with a multi-antenna array (Courtesy of IDS Ingegneria dei Sistemi S.p.A., Italy)

Nevertheless, when working with this kind of documentation it is often necessary to distinguish between ‘planning’ and ‘executive’ drawings; the latter may sometimes be reconstructed.

A direct on-site survey is therefore necessary in order to locate the exact position of the existing underground utilities, in particular the most hazardous ones (eg. gas, power, high density TLC cables) and to produce updated maps.

The most popular method for locating underground utilities is definitely Ground Penetrating Radar (GPR), due to its rapidity of execution, good quality results, and capacity to supply 2D images of the subsoil.

An electromagnetic wave is transmitted by a planar antenna into the ground and the returned scattered radiation is received by another antenna and then processed to extract the information relevant to the buried objects. In general any dielectric discontinuity is detected. Targets can be classified according to their geometry: planar interfaces, long and thin objects, localised spherical or cuboidal objects.

The time-domain impulse radar system has become the most widely used commercial system for this scope and is available commercially. Manufacturers usually offer a range of antennas to suit the desired probing range. Depth of less than 3 metres can be investigated using wide-band antennas with a centre frequency of 200–500 MHz. In order to reach greater depths it is necessary to use lower frequency antennas, with the drawback of reducing the resolution and the precision of the probing.

Most antennas have relatively small footprints which means that rapid and wide-area surveying can only be achieved with multichannel radar systems. These systems use more than one antenna mounted in a fixed scheme; it allows the acquisition of a large amount of data in a relatively short time which facilitates the final interpretation of the probing results. These systems are mainly used for identifying utilities and obstacles, although they have also recently been applied for lithological recognition of the subsoil.

More recently, a new conception of radar systems have been developed to improve the detection of underground utility and to automate the production of the final utility map. Multi-antenna and multi-channel arrays, powerful post-processing tools, direct connection with CAD and GIS systems are the main features of these equipment.

The array architecture (see Figure 1) allows performance of a three-dimensional survey of the ground (see Figure 2) acquiring more channels, that is more information, at the same time. The post processing software helps the operator to interpret the radar diagrams by producing groups of parallel radar (vertical) sections (see Figure 3), where targets are represented in a deformed geometry and planimetric radar (horizontal) view of slices of subsoil (see Figure 4), where the real target geometry has been reconstructed.

Finally, the post-processing software may provide a link with a CAD station which allows direct transfer on a digital map of the information relevant to the position and depth of the detected underground utilities, that means considerable time saving and a more functional use of the data.

No dig techniques

The use of no dig techniques in the field of telecommunications was for a long time limited to the execution of railway-, road- and motorway crossings as the only possible solution for the construction of network infrastructures across such obstacles.

Starting in the late 1980s, the use of no dig techniques has grown rapidly and has in some cases become a valid alternative to traditional digging techniques for the construction of longitudinal TLC network infrastructures along roads.

The great advantage compared to digging techniques, is represented by the reduction of social costs, such as traffic delay, hazard for pedestrians, noise, pollution, and road damage, which are normally related to road works.

In fact, in using no dig techniques the ducts are installed underground without digging long and deep trenches, but by performing small tunnels at a fixed depth in which the duct is subsequently pulled. In this way little damage is caused to the road surface, that means less inconvenience to traffic and a considerable cost saving on road repairs.

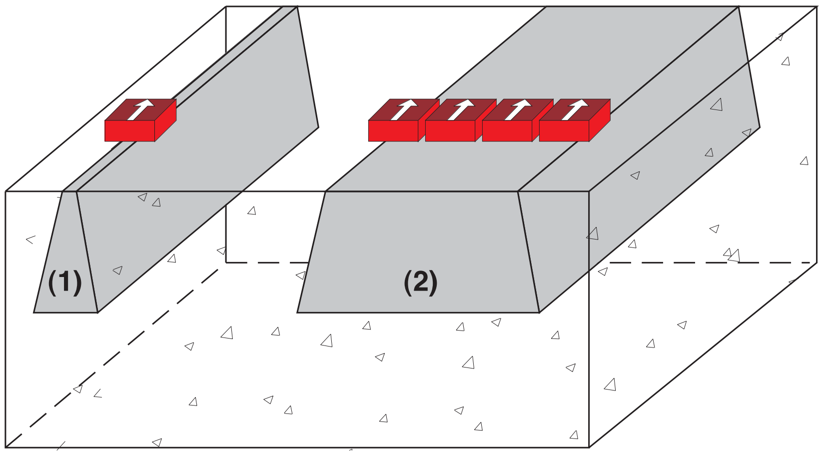

Figure 2 Comparison between:
(1) 2D (single antenna) survey
(2) 3D (array of antennas) survey

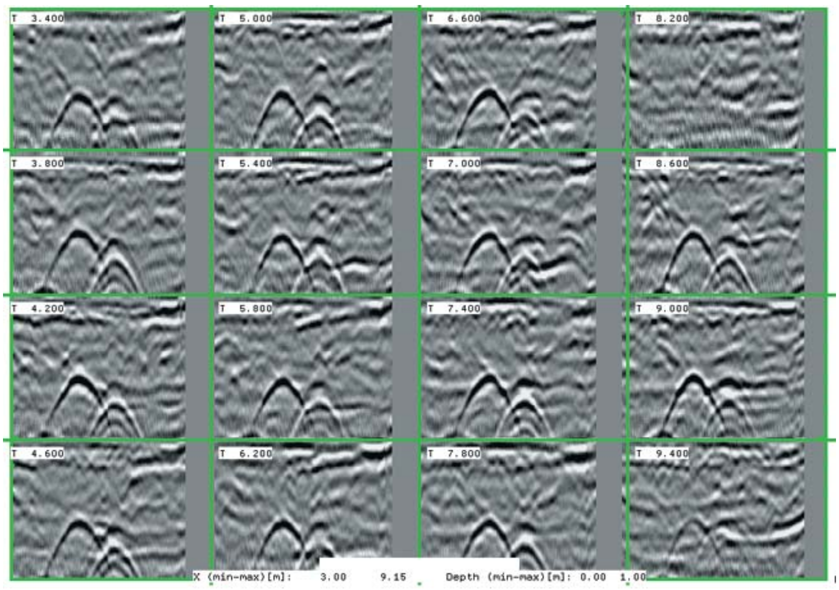

Figure 3 Example of multiple radar section representation

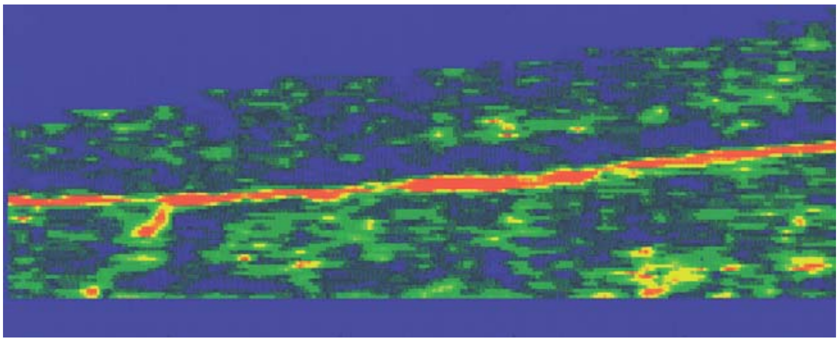

Figure 4 Example of planimetric view of a pipe

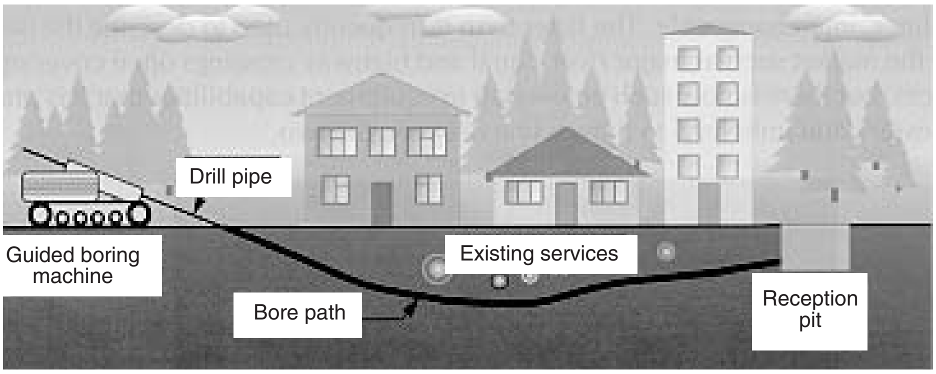

Figure 5 General scheme of the directional drilling technique: drilling the pilot hole

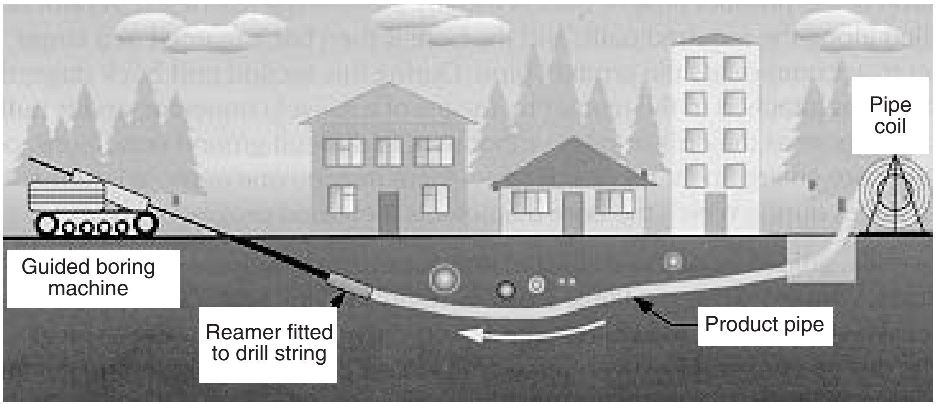

Figure 6 General scheme of the directional drilling technique: backreaming and pulling in the product pipe

On the other hand, no dig techniques are strictly related to the nature of the soil, so that in some circumstances and with some machines it is impossible to perform the drilling successfully. In any case it is necessary to make preventive investigation of the subsoil to know the location of existing utilities or buried obstacles in order to avoid them during the drilling operation.

Different techniques allow installation underground ducts without digging; in the following paragraphs a brief description of these techniques is reported.

Directional drilling

Guided boring and directional drilling techniques are used for the trenchless installation of new pipelines, ducts and cables. The drill path may be straight or gradually curved and the direction of the drilling head can be adjusted at any stage during the bore to steer around obstacles or under highways, rivers or railways. Drilling can be carried out between pre-excavated launch and reception pits, or from the surface by setting the machine to drill into the ground at a narrow angle. The use of new small machines allows the drilling operation to be performed directly between existing chambers or manholes, thus considerably reducing the overall dimension of the working site and the consequent impact on traffic.

Installation of the product pipe or duct is usually a two-stage operation. A pilot hole is first drilled along the required path (see Figure 5) and the bore is then back-reamed to a larger diameter to accommodate the product pipe (see Figure 6).

Most, but not all, guided boring machines use a fluid-assisted drill head which is pushed through the ground at the end of a string of drill pipes. The drill head is usually angled, so that constant rotation of the drill string produces a straight bore, whereas keeping the head in one position causes the line to deviate. A sonde or beacon is usually built into the head or fixed close to it and signals emitted by this are picked up and traced by a receiver on the surface, so allowing the direction, depth, and other parameters to be monitored. Hard-wire guidance systems are also used, with the cable running through the drill string, particularly in cases where the bore path cannot readily be traced on the surface (across rivers, for example) or where the depth of the bore is too great for accurate location by the radio-frequency methods. There are also location systems which use magnetometers.

A bentonite/water mix is often used as the drilling fluid or 'mud', which carries the debris in suspension and may be filtered through a recirculation system. On completion of the pilot bore, the thixotropic mud stabilises the hole ready for back-reaming. The service pipe or duct, generally polyethylene or steel, is drawn in behind the reamer as the original bore is enlarged.

In the case of larger machines, much of the work is done by the rotation of the drill string and the torque of the unit is as vital as the axial thrust and pull-back. As with smaller rigs, it is normal practice to drill a smaller pilot hole and then back-ream to the required diameter while pulling in the conduit behind the reamer, using a drilling fluid to assist the cutting operation and to lubricate and cool the cutting head. The fluid may also power a down-hole 'mud motor' for cutting rock and other hard formations, in which case higher fluid flow rates are necessary.

Some systems are designed for dry operation without the use of water drilling fluids. These are simpler to operate, create less mess and do not require as much on-site equipment, but there may be restrictions on the sizes that can be installed and on the ground conditions that the machines can cope with.

An increasingly common feature is the use of percussive action to complement axial force and rotation. This can be achieved either with a percussive hammer at the bore-head, or by generating the percussion at the machine on the surface and transmitting it along the drill string. Either way, this can significantly improve the ability of guided boring machines to punch through difficult ground or hard inclusions. Dry directional drilling machines, due to the small size of the rig and the absence of drilling fluid, are probably the best solution for 'no digging' in urban environments

A typical mid-range, surface-launched guided boring machine would, depending on ground conditions, generally be capable of installing pipes of approximately 250–500 mm diameter over distances of between 100 and 350 metres.

The largest directional drilling rigs are used primarily for long or large diameter crossings under rivers, estuaries, major highways and long sections. At the other end of the scale compact rigs for use in restricted spaces can install pipes of up to about 160 mm over distances of up to 100 metres. This again depends on ground conditions. Some include the facility to reduce the track spacing for passage through narrow openings.

Dry directional drilling systems using a cone shaped reamer with tungsten-carbide cutting teeth connected directly to the drilling rods can perform the installation of small diameter pipes, ducts or cables (up to about 65 mm diameter).

Dry installation of pipe diameters of up to 250 mm require a pneumatically powered reaming hammer on the drilling head.

Impact moling

Impact moling, or 'earth piercing' as it is commonly known in North America, is defined as the creation of a bore by the use of a tool which comprises a percussive hammer within a suitable cylindrical casing, generally torpedo shaped (see Figure 7). The hammer may be hydraulic or pneumatic. The term is usually associated with non-steered or limited steering devices without rigid attachment to the launch pit, relying for forward movement upon the internal hammer action to overcome the frictional resistance of the ground. During operation the soil is displaced, not removed. An unsupported bore may be formed in suitable ground, or a pipe may be drawn or pushed in immediately behind the impact moling tool. Cables may also be pulled in.

Although hydraulically driven percussive moles are available, most are powered by compressed air. A potential drawback of air-driven moles is contamination of the product pipe by lubricating oil in the exhaust, although there are methods for overcoming this. Hydraulic moles require two hoses (flow and return) and tend to have greater mechanical complexity.

The basic mechanism of impact moling is the reciprocating action of the pneumatically or hydraulically powered hammer within the cylindrical steel body. The piston is driven forward and, on striking the forward end of the unit, imparts its kinetic energy to the body which is driven forward. The energy of the piston for the return stroke is regulated so as to reposition it for the next forward stroke, rather than reversing the unit out of the bore (unless required to do so).

Repeated impacts of the hammer piston advance the whole unit through the ground. As the forward movement takes place, the soil in front of the mole is forced aside and compacted by the conical or stepped nose to form the walls of the bore. The power of the unit is also often used to pull the product pipe, cable or cable duct through the bore at the same time as the impact mole advances.

Impact moling tools are known by several other names including earth piercing tools, soil displacement hammers, impact hammers, percussive moles or pneumatic moles, depending on the term used by the manufacturer and the region of the world where the equipment is being used.

Because impact moling is generally unsteered, the technique is most suitable for short bores (up to 50 metres). A straight bore can often be maintained more easily at large diameters. Diameters range from about 45 to 200 mm depending on the pipe or cable being installed.

Pipejacking and microtunnelling

Pipejacking and microtunnelling are essentially from the same family of pipeline installation techniques, used for installations from about 150 mm diameter upwards. A pipejack is defined as a system of directly installing pipes behind a shield machine by hydraulic jacking from a drive shaft, such that the pipes form a continuous string in the ground (see Figure 8). The pipes, which are specially designed to withstand the jacking forces likely to be encountered during installation, form the final pipeline once the excavation operation is completed.

Within this description, microtunnelling is specifically defined as being a steerable remote-controlled shield for install-

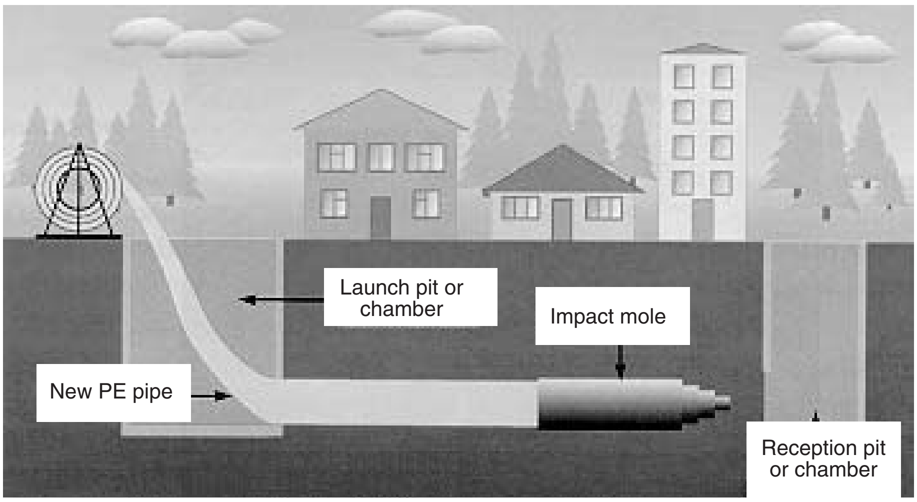

Figure 7 Pipe installation by impact moling

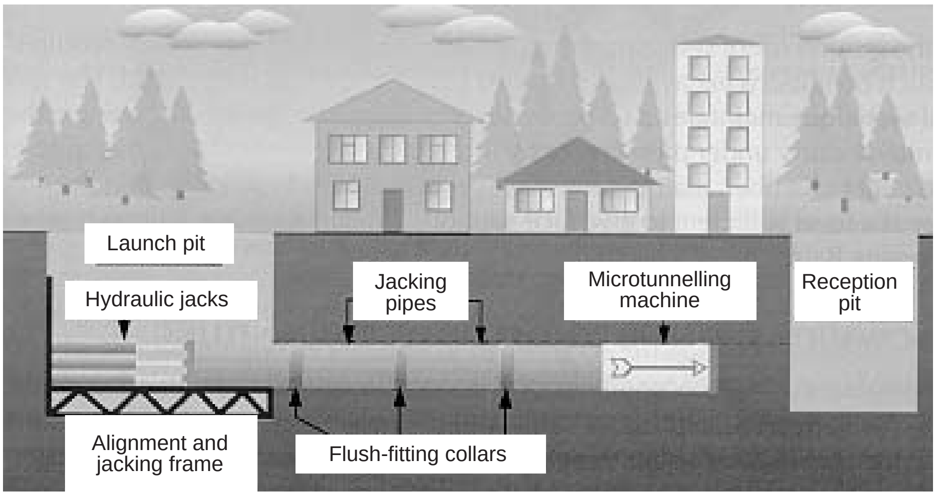

Figure 8 Installing pipes by microtunnelling

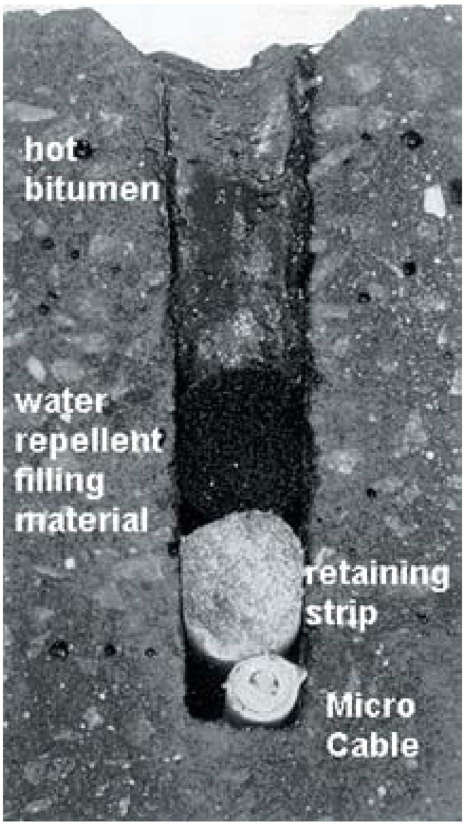

Figure 9 Street cross section

ing a pipejack with internal diameter smaller than that permissible for man-entry. Microtunnellers often use a laser guidance system to maintain the line and level of the installation; though, as with larger pipejacking installations, both laser guidance and normal survey techniques can also be utilised.

Systems are available for the installation of both main pipelines and branch connections.

Both pipejacking and microtunnelling are well suited to situations where a pipeline has to conform to a rigid line and level criterion. The guidance and control systems allow accurate installation within close limits of the target.

Most microtunnelling drives are straight between shafts, although specialised systems are available for curved drives. Where line-of-sight is not possible between the drive shaft and the micro-tunnelling machine because of the curvature of the tunnel, specific alignment systems (eg. gyroscopic devices, combinations of electromagnetic induction and liquid pressure difference) may be used as an alternative to the usual laser equipment.

Micro Cabling System

The purpose of the Micro Cabling System, an installation system developed by Siemens, is to dramatically reduce installation costs and installation time. This is achieved by means of a simple but rugged design of a fibre optic cable which is laid in a groove dug into the asphalt of roads or pavements. As a result the cable is required to meet exacting demands to crush resistance and, in particular, temperature resistance which is needed when sealing the cable in the groove with hot bitumen.

The optical fibres are preferably enclosed in a copper tube filled with a suitable filling compound and surrounded by a PE jacket. There are currently two cable types in use: type 1 with up to 60 optical fibres and an outside diameter (over PE jacket) of about 7 mm, and type 2 with up to 144 fibres and an outside diameter of about 9 mm.

The groove depth is usually 8 to 10 cm, the width about 1 to 1.2 cm. These dimensions are guide values but can easily be adapted to suit other road conditions, eg. with a thin asphalt cover.

The cable itself runs off the reel lightly braked and is laid in the groove previously cleaned with hot air. A retaining strip is then run in to fix the cable in place inside the groove.

The retaining strip is covered by free-running, highly water-repellent filling materials. The groove and groove edges are sprayed with primer (bonding agent) and then sealed with hot bitumen (see Figure 9).

Where the cable makes a sharp change in direction or closures have to be installed, holes are made by core drilling. The holes thus formed are such that they are able to accept the circular closure or can be used to change the direction of the cable without exceeding the smallest permissible bend radius.

For jointing or branching the Micro Cable there are suitable closures available which are able to accommodate up to 60 splices or 144 splices. These accessories are installed level with the surface of the road or pavement and can be provided with a heavy-duty (vehicle-bearing) cover. Other suitable accessories such as eg. underground containers and terminating accessories for the end points are also available.

Fibre installation

Blown Fibre consists of a small fibre bundle or ribbon composed of a number of standard fibres held in a resin matrix and a tube assembly composed of a number of polyethylene tubes within a protective sheath. Compressed air is applied to the Blown Fibre tube and the fibres are fed into the airflow by a special 'blowing head'. The Blown Fibre principle relies on the viscous drag of air over the fibres that produces a distributed installation force on the fibres themselves.

Blowing distances of 1000 m were easily achievable and in certain routes up to 1500 m was possible.

Blown Fibre has several advantages over conventional optical fibre cables. It allows greater installation flexibility and significant cost deferral. Routes can be easily reconfigured using push fit connectors and fibre bundles or ribbons can be recovered and replaced with new specification or higher fibre count versions. Moreover, by installing fibre only as it is needed, the upfront investment can be minimised whilst still enabling the rapid deployment of further fibre capacity.

Mechanical strain on fibres during installation and subsequent use is negligible, and long splice free lengths are possible by using range extending blowing techniques.

The disadvantages are represented by higher stores cost than subducted conventional cables for all but small fibre counts and lower potential fibre density than conventional cables.

Labour costs could be reduced by using higher fibre count bundles or ribbon and by employing simultaneous installation of more than one bundle. Fibre density may also be improved by using higher fibre count bundles and by using a higher tube count.

In summary, it can be seen that Blown Fibre offers the flexibility to only install fibre when it is required (thereby reducing up-front investment) as well as enabling rapid installation of additional fibres. A small premium is incurred, in terms of product cost, for all but small fibre counts.

It is also possible to pull the fibre optic unit through the tube distances up to 1000 m with a pulling force sufficiently low as not to cause any damage to the fibre optics and not impair its long term properties.

In order to use this technique, special tubes are manufactured with pull cords pre-installed. The pull cords were specially developed for the application having very low friction characteristics and a braided construction so that joints between the fibre unit and the cord could be easily achieved.

Also appropriate pulling machines with a continuous speed and tension read out must be used, which are combined pulling and coiling machines capable of pulling surplus fibre through a length of tube and re-coiling it into a pan for onward pulling. By use of this machine it is possible to install long continuous lengths of fibre; however, one disadvantage is that the re-coiling operation substantially increases the time needed to install the fibre unit.

To overcome this problem and speed up the installation of the fibre 'slave' machines have been developed. These can be positioned at an intermediate location so that fibre could exit the duct at this point and re-enter an adjacent length of tube at zero tension. The slave machines will automatically adjust their speed to match the speed of the master machine. This eliminates the need for re-coiling fibre and substantially reduces installation time.

Conclusion

Two focal points must be taken into account for the future deployment of the TLC networks: a growing attention for the environmental impact of civil works and the need for reducing their costs, which now represent more than half of the total cost of the network. The deployment and the use of new techniques for the construction of TLC network infrastructures and for the installation of cables and fibres therefore represent essential actions to take up the challenge for a sustainable development.

Acknowledgement

The author would like to mention the great effort that Telecom Italia is doing for the development of new installation techniques and for the reduction of social and environmental impact of civil works.

Special thanks to Mr. Feliciano Esposto, manager of the outside plant engineering at the Telecom Italia's headquarters in Rome and to his collaborators Mr. Andrea Berardo and Mr. Paolo Trombetti: The work performed together in the last years has been essential for writing this paper.

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Measurements and maintenance of the future access networks

ANGELANTONIO GNAZZO

1 Introduction

In a liberalised telecommunications market, where the customer can choose the service provider, the downtime of networks represents a key aspect for the quality of service for a given operator. To maintain networks with minimal downtime, companies need a variety of tools and practices. By combining a mix of appropriate tools and practices, companies are able to minimise downtime, correct it quickly when it does occur, and obtain cost savings in the process. Tools are represented by monitoring and fault localisation systems.

Moreover the importance of operation and maintenance aspects has been increasing in the last few years: the complexity of the network requires an updating of all infrastructure records in order to keep track of all changes in the infrastructure. This would be possible if the NOs (Network Operators) had a centralised record of all fibre plant with geographic information, technical characteristics and a well defined program of tests. In this way an investment in network maintenance tools and technical solutions could be a real investment, not just an expense.

EURESCOM Project P614 worked on these items giving some ideas to how implement the maintenance/monitoring of the general FTTx networks: this paper reports an analysis of the work performed.

2 Access network and maintenance definition

The access network is commonly defined as *the collection of equipment and infrastructures necessary to perform the connection between the customer equipment and the core network.*

Figure 1 [1] shows a variety of ways to build broadband access networks based on fibre deployment. The basic FTTx architectures under study in most countries are FTTEx, FTTCab, FTTB and FTTH. The most salient feature of the FTTx network architecture is its hybrid nature: different network segments may use a different bearer medium. In a FTTCab or FTTB network, the optic fibre feeder and distribution segments are connected to the customer premises by a drop section based on twisted copper pair or coaxial cable.

ITU-T [2] give the following definition of maintenance: *"Maintenance involves the whole of operations required for setting up and maintaining, within prescribed limits, any element entering into the setting-up of a connection."*

In the FSAN group [3] the definition of Optical Maintenance has been stated as: *"Optical Maintenance (OM) covers all the means to guarantee the performances of the optical carrier (fibres, splices, connectors, passive components), and specifically to detect and locate any fault in the OAN (Optical Access Network)."*

Starting from these two definitions, EURESCOM P614 defines Hardware Maintenance as: *"Hardware Maintenance (HM) covers all the means to guarantee the performances of the physical carrier (fibres, twisted copper pairs, coaxial, splices, connectors, passive components, enclosures), and specifically to detect and locate any fault in the AN (Access Network)."*

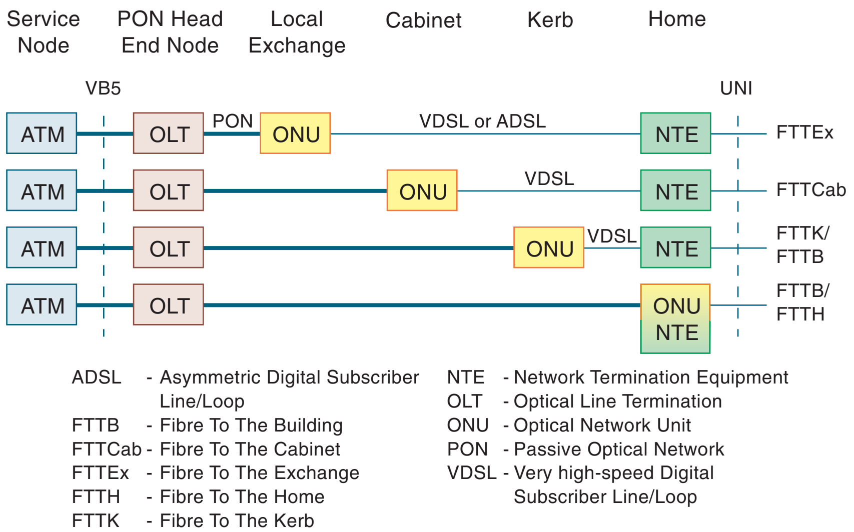

Figure 1 FTTx concept (from FSAN)

3 Preventive maintenance implementation

Today acceptance tests are done in two phases: acceptance of the components (fibre, splitters, filters, etc.) and acceptance of the infrastructure once the components are installed.

The first phase is normally done in the laboratory, on a representative sample of the components. Its objective is to verify if the components' characteristics match the specification presented by the supplier.

This procedure should be seen as a test of supplier control. In order to reduce costs, the responsibility for performance quality can be transferred to the supplier, but for the time being we consider occasional component testing necessary to ensure quality, even if we trust the supplier.

After the acceptance tests for components have been approved, two basic tasks are required to implement an effective preventive maintenance scheme before corrective maintenance:

- Network qualification/acceptance;
- Network monitoring.

Network qualification intends to establish that the actual plant matches the specifications given by the network planner. Absolute value measurements are necessary to check that each of the network elements conforms to specified performances. Qualification of the physical carrier should be performed before any service runs over it and may be even before any actual equipment and systems are installed at its ends.

To proceed with network qualification, tests may be required to ensure that cabling components have been correctly installed and have not been damaged during transport or installation. This phase is valid both for fibre based and copper based media.

A modem connection (GSM or PSTN networks) between the measurement equipment installed in the access points and the centralised data base should be considered. In this way we are able to keep a record of the processes, not on the local level but as a part of the global infrastructure information. The most important aspect is the organisation of this information, in order to keep track of the technology history to support future investment decisions. The decision to record and to organise this information will influence the quality of the infrastructure, and as a consequence the quality of service provided by the operator.

For the optical infrastructure acceptance measurements should include:

- Link attenuation;
- Return loss of splices, connectors and other components.

Other parameters to be determined, for analogue transmission, are chromatic and polarisation dispersion.

Regarding the twisted copper pairs for xDSL lines, the parameters to be determined include:

- Attenuation (the main factor limiting cable length);
- Crosstalk (unwanted coupling between pairs);
- Insulation vs. other conductors and ground (low insulation increases crosstalk);
- Characteristic line impedance.

For coaxial cables loss and return loss (unwanted reflected signal) are of interest.

It is generally accepted nowadays that the infrastructure is stable and reliable. Consequently, preventive maintenance takes on a low priority and most interventions in the optical infrastructure are corrective.

Network monitoring, performed with automatic systems, can be considered as a part of preventive maintenance. It involves periodic measurement of the physical carrier and comparison to a reference measurement established on the basis of the qualified network. If the link is already qualified, no absolute measurement is necessary and only relative ones are required.

4 PON monitoring

Regarding the PON (Passive Optical Network) infrastructure, we focused our attention, as an example, on an architecture with 16 branches, and one or two splitters. The location of the splitters depends on the FTTx solution and on the location of the ONUs.

The most favourable solution, from the viewpoint of maintenance efficiency, is to have all splitters in the central office. In this particular implementation, the PON becomes equivalent to simple point-to-point transmission for maintenance purposes but at the expense of increased network fibre cost.

Optical monitoring should consider processes that identify problems such as:

- Slow and uniform degradation of the attenuation of a fibre;
- Slow increase of attenuation at a discrete point and localisation of new events in a link (events such as attenuation points, reflective points, etc.).

In this way we are able to separate:

- Link fault from equipment fault;
- Link degradation that does not impact on the service;
- Immediate fault localisation if optical monitoring is performed with OTDR.

Another important issue is the creation of an automatic process to record the information. If we do not create this process, we risk losing information. Fibre optic automatic testing systems are available on the market today. These systems are based on a centralised database connected to several test probes (OTDR platforms) which periodically test the fibre links via optical fibre switches.

Automatic testing could guarantee an effective maintenance routine, doing the tests according to programs specified by the operator, producing updated information about the network, measured under the same conditions as the last measurement was done and guaranteeing a proper and automatic record of the information.

These systems could be integrated into the network management system, in order to allow the correlation of the transmission alarms and the fibre tests.

The decision to invest in automatic test systems should be evaluated taking into account the adaptation of the optical infrastructure necessary to install the test system and the required changes in the organisation of the operation and maintenance procedures of the operator. The first one is related to the MDF (Main Distribution Frame) where the changes adopted are a matter of technical and economic consideration. The second relies on the maintenance personnel who should benefit from the new automatic test procedure.

To implement the monitoring of a PON, three methods can be envisaged:

- Use of dedicated branched fibre monitoring (configuration 1);
- ‘Dark fibre’ (configuration 2);
- On-line monitoring (configuration 3).

The dedicated branched fibre monitoring solution shown in Figure 2 can be implemented using one of the splitter ports at each splitting stage for the monitoring function and using dedicated fibres to bring the signals back to the monitoring head. It should be noted that with this method we are able to monitor the sections of the PON but different fibre return paths are required. Data signals can also be used as monitoring signal for path loss measurements, while for fault location an OTDR working at 1625 nm could be used from the fibres connected

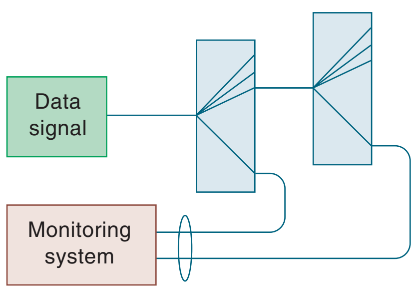

Figure 2 Dedicated branched fibre monitoring: one of the splitter ports at each splitting stage is looped back over a dedicated fibre

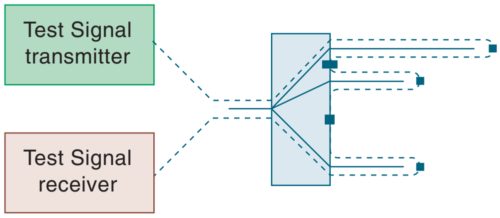

Figure 3 Dark fibre monitoring fibre loop

to the monitoring system. A filter to stop this wavelength must be used in front of the transmitter and receiver equipment. It must be noted that reverse measurement from the far end to the central office is possible.

The dark fibre testing method is a direct application of the following assumptions:

- Most network failures affect not only one fibre but the whole cable, so that most of the time monitoring of one fibre is sufficient;
- Only a small portion of failures is due to passive devices.

One possible dark fibre method is to use two additional fibres for each fibre link (see Figure 3) one upstream, the other downstream and loop them at the user end with splices. The result is one fibre loop passing through all fibre ends with no splitting and the 1550 nm wavelength can be used for monitoring.

Due to the high cost of fibres, this solution could be implemented if the branch lengths are short or if the splitter is located in the cabinet.

On-line techniques refer to the monitoring of every transmission fibre, while the services are running, excluding dark fibres where only a fibre running in the same cable is tested. One of the schemes that could be used is depicted in Figure 4. The monitoring could be done out of band at 1625 nm, using reference reflector (selective or not) to overcome the low dynamic of the OTDR. It will be necessary to install monitoring wavelength filters on each branch even before any real ONU is installed, so that the reference measurement is ONU connection independent. The superimposition of traces is unavoidable, but branch length trimming devices can be used to enable distinction between different branches. To implement this scheme, connectors with embedded filters, WDMs and optical selectors are key components [4].

Figure 5 shows the cost comparison for the various considered PON monitor systems. A 16 branches PON and 10 km length is assumed as a reference for the cost assessment. The following three configurations are used:

1 Dedicated branched fibre monitoring: one of the splitter ports at each splitting stage;

2 Dark fibre monitoring: fibre loop;

3 Generic Optical Maintenance scheme, based on Reference Reflections and/or Optical Selectors.

Assumptions as follows have been considered:

- Configuration 1 uses two splitter stages 1 by 4 (one in central office and the other in the field) so that the total number of ONUs for this configuration is 9. Monitoring is done with data signals and fault location with OTDR at 1625 nm using filters to stop this wavelength.
- Configuration 2 uses only one splitting stage in central office.
- Configuration 3 uses one or two splitting stages.

Considering configuration 1, the cost per ONU using the OTDR is of course higher than using the power meter. The use of the dark fibre is not convenient due to the high cost of the fibre. The cheaper solution is represented by the generic optical maintenance scheme based on reference reflections and/or optical selectors. The most favourable solution, from the viewpoint of maintenance efficiency, is to have all splitters in the central office. In this particular implementation, the PON

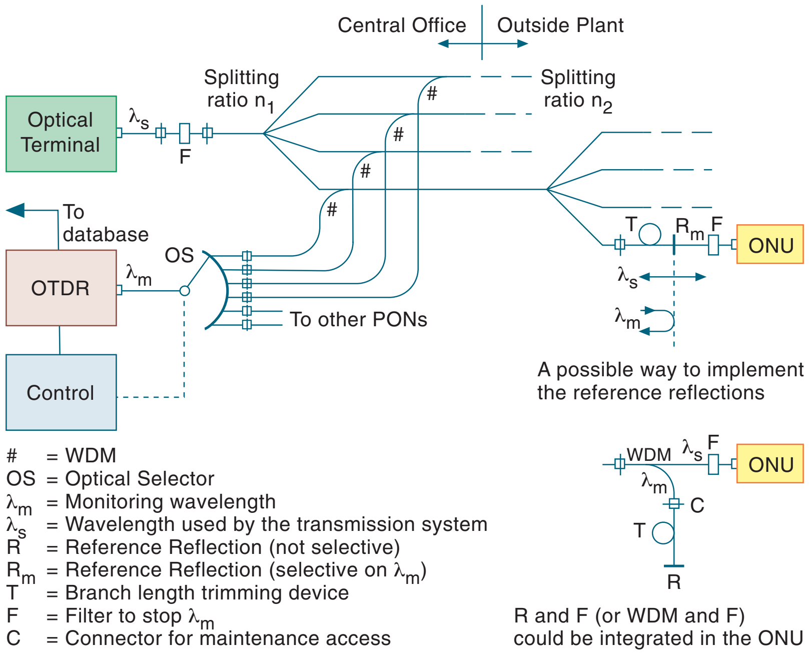

Figure 4 Generic Optical Maintenance scheme, based on Reference Reflections and/or Optical Selectors

becomes equivalent to simple point-to-point transmission for maintenance purposes but at the expense of increased network fibre cost if compared with the splitter in the outside plant.

5 Drop section monitoring

The final section of the access network could be supported by copper pairs (or coaxial cable) or optical fibre. As the ONUs terminate the distribution section and perform a kind of medium adaptation with active interference with the transported signal from one section to the other, it is difficult to implement test mechanisms allowing testing of the transmission medium directly from the exchange. In this case it is necessary to install a test probe in the ONU.

This installation is costly and its impact is related to the number of users connected to one ONU. The decision to install this OAM (Operation Administration and Maintenance) facility can be justified by the reduction in the OAM costs due to the fact that we do not need to send technicians to the field to identify the possible fault. Equipment should have a maintenance channel to allow the communication between the management test system and the test head installed in the ONU.

Future networks will be based on systems that need an active NTE (Network Termination Equipment), so first we should integrate OAM functions in this element. With the OAM functions implemented from the OLT to the NTE we could certify the working conditions of our network and save time.

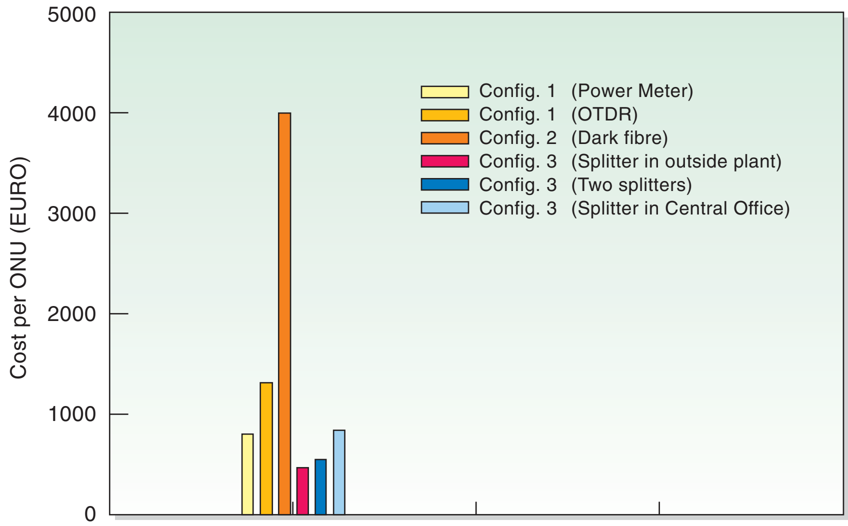

Figure 5 Cost assessment for the considered PON monitor systems

6 Conclusion

The conclusions the group achieved regarding the measurements and maintenance of the future access networks are listed below.

- Acceptance of components, network qualification and network monitoring are the three key phases before corrective maintenance.
- It is very important to have a centralised database that collects the measurements in order to keep a record of the infrastructure. The decision to record the information and the organisation of this information will influence the quality of the infrastructure, and as a consequence, the quality of service provided by the operator.
- Three solutions for optical monitoring are envisaged for ODN: dedicated branched fibre monitoring, monitoring over dark fibres and on line monitoring.
- The first solution uses one of the splitter ports at each splitting stage; continuity testing and monitoring changes in attenuation could be done with the same data signal. Fault location could be performed using reverse OTDR at 1625 nm.
- The use of 1625 nm as test wavelength implies the ODN achromaticity up to this value: we would propose to support the standardisation bodies to extend the present value (1580 nm) up to 1650 nm.
- Measurements using dark fibre with a fibre ring (two fibres each cable) are possible at 1550 nm where the fibre has its attenuation minimum.
- On line monitoring could be the most efficient solution: in this case we are limited to the use of an out of band wavelength (1625–1650 nm), and additional key components are required such as embedded filters in connectors, low cost optical switches with high number of ports and WDMs.
- To monitor PON, it is possible to use information from the equipment systems.
- The most favourable solution, from the viewpoint of maintenance efficiency, is to have all splitters in the central office. In this particular implementation, the PON becomes equivalent to simple point-to-point transmission for maintenance purposes but at the expense of increased network fibre cost.
- Regarding the drop section, as future networks will be based on systems that need an active NTE, we should integrate maintenance functions in this component. With the OAM functions implemented from the OLT to the NTE we could certify the working conditions of our network and save time.

Acknowledgement

This document is based on results achieved in a EURESCOM Project; this does not imply that it reflects the common technical position of all the EURESCOM Shareholders/Parties.
The author gratefully acknowledges the support of EURESCOM for carrying out this work, and wishes to express a special thanks to all Task 4 of P614 participants, since this paper reflects the results of their work.

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Abbreviations

AN	Access Network
EURESCOM	EUropean institute for RESearch and strategic studies in teleCOMmunications
FSAN	Full Services Access Networks
FTTB	Fibre To The Building
FTTCab	Fibre To The Cabinet
FTTEx	Fibre To The Exchange
FTTH	Fibre To The Home
GSM	Global System for Mobile Communication
HM	Hardware Maintenance
ITU-T	International Telecommunications Union – Telecommunications
MDF	Main Distribution Frame
NO	Network Operator
NTE	Network Termination Equipment
OAM	Operation Administration and Maintenance
OAN	Optical Access Network
ODN	Optical Distribution Network
OLT	Optical Line Termination
OM	Optical Maintenance
ONU	Optical Network Unit
OTDR	Optical Time Domain Reflectometer
PON	Passive Optical Network
PSTN	Public Switched Telephone Network
WDM	Wavelength Division Multiplexer
xDSL	(Family of) Digital Subscriber Line

Angelantonio Gnazzo (36) received his degree in physics from the Università degli studi di Torino. In 1988 he joined CSELT and became involved in the design and realisation by MCVD of special optical fibres, such as dispersion shifted, dispersion flattened, polarisation maintained and rare earth doped fibres. From 1994 to 1996 he moved his activity into the fields of integrated optics and Bragg grating devices. Since 1996 he has been working in the plant topology and maintenance department of CSELT.

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Towards a practical implementation of DSL – preparing for new technology and new regimes

PER KLEPSLAND

1 Introduction

Telenor has maintained and developed the access network for the support of telephone and data services. The present situation calls for new solutions: new transmission technologies promise enhanced feasibility and set new conditions for service providers' and other network operators' request for copper access.

In this article the old and new regimes of the access network are discussed. To a great extent the new regimes will set the conditions for the practical implementation of design rules of how to develop the access network.

This article also describes transmission measurements set up in Telenor's access network to characterise the quality and performance of installed cables. An automatic measuring system was designed to perform autonomous transmission measurements in the access network. Parameters like far end crosstalk loss, near end crosstalk loss, insertion loss, impedance and dc measurements were collected from approximately 500 sites. Such measurements are essential in order to establish planning rules for the provision of different transmission systems on copper cables in the access network, both existing HDSL- and IDSL-systems and future systems like ADSL and VDSL.

2 Typical structure of Telenor's access network

Figure 1 depicts some characteristic layout of Telenor's local loop plant. In villages and towns the topology of the copper cable network is a typical star structure. From the switching centre (local exchange or remote concentrator) the size of the main cables ((a) in Figure 1) are usually in the range of 100 to 2000 twisted pairs. The greater cables are spliced into cables (b) with fewer twisted pairs before they are terminated in main cross connect frames. The main cross connect frames serve several end cross connect frames by direct cables (c). In some cases cables from two or more end cross connect frames may be spliced into one cable (d) on their way to the main cross connect frame. Cable joints are more frequent in old installations. Intermediate cross connect frames are normally not installed today. In old environments there may be one –- or even two – intermediate cross connect frames in cascade, and occasionally there may be a connection from one intermediate cross connect frame to another (e). Such optional cables (e) should not be used to carry ADSL systems. In Oslo a bridged tap may – in some cases – be present close to the customer.

In large parts of Norway there are areas with a very low population density. In some valleys or narrow coastlines there may be in the order of ten subscribers per kilometre. This will result in a structure with many cable splices and end cross connect frames along the route (f). Cables with a lead diameter of 0.9 mm are used where the distance between customers and the telephone switching equipment exceeds 5 – 7 km.

3 Typical cables in Telenor's access network

The present cables in Telenor's access network are a result of the investments of several decades, and some of the cables may be dated to the period just after – or even before – World War II. During this period of time the construction and layout of cables have changed significantly. The first period is characterised by paper insulated star quad cables constructed in layers and encapsulated in a lead mantel. The mantel was later made from aluminium.

The normal lead diameters in the access network are 0.4 mm and 0.6 mm. In the trunk network and for long stretches in the access network the lead diameter is usually 0.9 mm. Old cables may also have a lead diameter of 0.5 or 0.8 mm in the access network, some sea cables had 0.7 mm leads and in the trunk network 1.2 mm was used.

In the fifties and sixties the plastic insulated cables were introduced. The first cables had massive polyethylene insulated star quad wires in a layer structure. In the late sixties the polyethylene was foamed and the cable kernel was filled with vaseline.

3.1 Kernel structure of modern cables

The modern cable design was established in the very late seventies. The basic design is a ten-pair group where all twisted pairs have different lay lengths and a random position within the ten-pair group. Larger cables are composed of one or more fifty-pair groups, alternatively one or more hundred-pair groups. The cable kernel is filled with vaseline to minimise the effects of intruded water. The lead diameters are 0.4, 0.6 and 0.9 mm. The overall sheath usually consists of a foil screen and massive polyethylene.

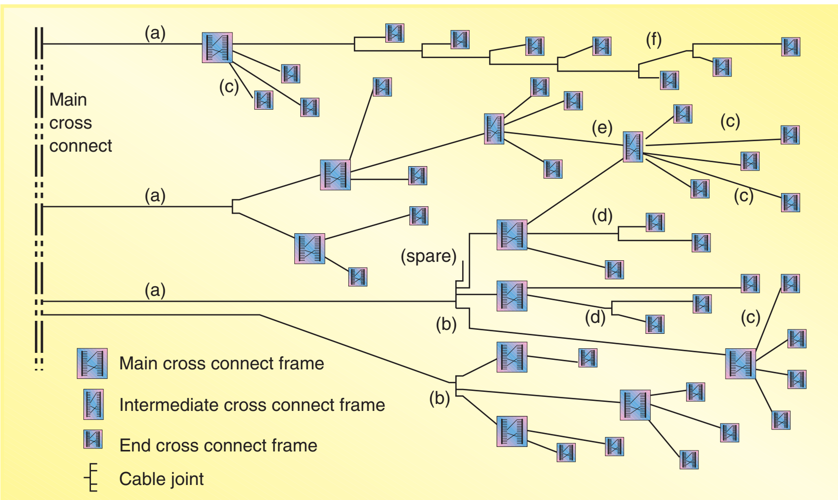


Figure 1 Typical topology of the local loop plant

3.2 Rigid cables for harsh electrical environment

In Norway the soil is in large areas characterised by a high resistivity. In one cable design – developed in the seventies – the outer cable construction is made by helical wrapped solid aluminium wires enclosed by semiconductive polyethylene sheath. This type of cable is mainly installed in the proximity to power plants, power lines and electrified railways.

3.3 Typical design rules of copper plant

The lead diameter is related to the number of pairs in the cable. 0.4 mm pairs are only present in cables of at least 100 pairs. 0.5 mm pairs are only present in cables of 1000 pairs, and for a lead diameter of at least 0.9 mm the cables rarely exceed 100 pairs.

The incitement to use 0.4 mm cables was primarily the investment cost associated with 0.6 mm cables. When cables with 0.4 mm (and 0.5 mm) pairs allowed for the transport of analogue telephone, these cables were normally used close to the exchange. The residual installation was usually made using cables with a 0.6 mm lead diameter.

In sparsely populated areas where the distance to the telephone exchange may be far beyond 5 km, cables with a lead diameter of 0.9 or more are used. For sea cables the lead diameter is often 0.9 mm.

3.4 Cable types in the present access network

The most typical types of cables installed in the access network are listed in Table 2.

The actual cable type installed depends on preferences made at the time of installation (availability, cost, mechanical and electrical properties). The route from the main cross connect up to some end cross connect frame may as well be installed over a long time period, for instance some decades. And also in the time to follow some part of the distance may have been refurbished due to damage or conflicting constructional work. As a result the present route may consist of a large number of cable types, and this complexity makes the planning in the access network difficult and time consuming.

Some convenient simplifications may result in a list of practical cable types as shown in Table 1.

Table 1 Simplified cable types for practical planning

Cables with 0.4 mm leads
Paper insulated cables with 0.4 mm leads (twisted pairs)
Plastic insulated cables with 0.4 mm leads
Paper insulated cables with 0.5 mm leads (twisted pairs)
Cables where maximum 40 % of the length is with 0.4 mm leads
Cables where maximum 20 % of the length is with 0.4 mm leads
Cables with 0.6 mm leads
Paper insulated cables with 0.6 mm leads (star quads)
Plastic insulated cables (non-filled) with 0.6 mm leads
Plastic insulated cables with 0.6 mm leads
Paper insulated cables with 0.8 mm leads (star quads)
Paper insulated cables with 0.9 mm leads (star quads)
Plastic insulated cables with 0.9 mm leads

4 New technologies

The present access network was developed from the requirements for support of the plain old telephone service. This resulted in exchanges with associated access networks with a radius of 4 to 7 km. New technologies, often denoted digital subscriber line and abbreviated 'DSL' [1], with the potential of greater capacity will be introduced in the access network. However, the practical digital transmission systems will often set stricter limits for the obtainable line range than that for the analogue network.

4.1 ISDN

Telenor experiences a great demand for ISDN services in Norway. The actual penetration for the ISDN basic access is about 20 per cent, and within a few years it may become the leading carrier service.

The capacity of ISDN basic access is two B-channels of 64 kbit/s and one D-channel of 16 kbit/s. Several transmission options exist for ISDN basic access, but the normal system [2] makes use of the line code 2B1Q*1)* and echo cancellation technique. This results in a modulation speed of 80 kbaud with a baseband of up to approximately 40 kHz.

The ISDN primary rate consists of 31 B-channels (plus one channel for framing) of 64 kbit/s making up a total of 2048 kbit/s. This is a common bit capacity in both the PDH*2)* and the SDH*3)* hierarchy. The transport may be done in the access network by traditional and proprietary digital line systems (HDB3 line systems) or standardised HDSL systems. The modulation speed for HDB3*4)* systems [3] is 2048 kbaud and the resulting frequency range extends to approximately 1 MHz.

1) 2B1Q (two binary one quarternary) Line code comprising four levels.

2) Plesiosynchronous digital hierarchy.

3) Synchronous digital hierarchy.

4) HDB3 (high density binary, 3) Three-level line code with granted synchronization.

Table 2 Technical properties of cables installed in Telenor's access network (For explanatory notes – see page 216)

	Dia-meter (mm)	Lead insu-lation	Capaci-tance nF/km	Numb. of units	Units	Individ. twist lengths	Position in sub-group	Numb. of sub-groups	Numb. of groups	Type of cable	Overall shield	Overall sheath	Number of pairs	Installa-tion period
1	0.6	FPE + vaseline	45	10	pair	Yes	random	5 / 10	≤ 10	buried, ducted 1)	foil + leader, Al wires *) 1)	PE	2, 5, 10, 20, 30, 50, 70, 100, 150, 200, 300, 500, 700, 1000	1979– ...
2	0.6	FPE + vaseline	45	10	pair	Yes	random	≤ 10	(1)	aerial 6)	foil + leader	PE	2, 5, 10, 20, 30, 50, 70, 100	1979– ...
3	0.4	FPE + vaseline	45	10	pair	Yes	random	5 / 10	≤ 20	buried, ducted 2)	foil + leader, Al wires *) 2)	PE	100, 150, 200, 300, 500, 700, 1000, 1500, 2000	1979– ...
4	0.6	FPE + vaseline	45	5	quad	Yes	fixed	5 / 10	≤ 10	buried, ducted 1)	foil + leader, Al wires *) 1)	PE	2, 6, 10, 20, 30, 50, 70, 100, 150, 200, 300, 500, 700, 1000	1968–79
5	0.4	FPE + vaseline	45	5	quad	Yes	fixed	5 / 10	≤ 20	buried, ducted 2)	foil + leader, Al wires *) 2)	PE	100, 150, 200, 300, 500, 700, 1000, 1500, 2000	1968–79
6	0.6	PE	45	5	quad	Yes	fixed	≤ 10	(1)	aerial 6)	foil + leader	PVC	2, 6, 10, 20, 30, 50, 70, 100	1965–79
7	0.6	Paper	37/ 45	250	quad	max 8	layer	(1)		buried, ducted	Pb or Al, steel *) 3) 4)	jute or PVC 5)	10, 20, 30, (40), 50, (60), 70, (80), 100, (140), 150, 200, 300, 400, 500	... –80
8	0.4	Paper	37/ 45	50/ 100	pair	max 8	layer	≤ 18	(1)	buried, ducted	Pb or Al, steel *) 3)	jute or PVC 5)	100, 150, 200, 300, 500, 700, 1000, 1500, 1800	1957–80
9	0.5	Paper	50	100	pair	max 8	layer	10	(1)	buried, ducted	Pb, steel *) 3)	jute or PVC 5)	1000	1950–68
10	0.6	PE + vaseline	45	10	pair	Yes	random	5 / 10	5	sea	Steel wires	PE	10, 30, 50, 100, 200, 500	1979– ...
11	0.9	PE + vaseline	45	10	pair	Yes	random	5 / 10	(4)	sea	Steel wires	PE	10, 30, 50 (, 100, 200)	1984–
12	0.9	FPE+ vaseline	45	10	pair	Yes	random	5	(1)	aerial 6)	foil + leader	PE	2, 5, 10, 20, 30, 50	1979– ...
13	0.6	PE	37	20	quad	max 8	layer	(1)		aerial 6)	foil + leader	PVC	2, 6, 10, 20, 30, 40	1959–67
14	0.6	PE + vaseline	45	250	quad	max 8	layer	(1)		sea	Steel wires	jute	10, 30, 50, 100, 150, 200, 300, 500	1972–84
15	0.9	PE + vaseline	37	37	quad	max 8	layer	(1)		sea	Steel wires	jute	8, 14, 24, 38, 54, 74	1969–84
16	0.9	PE	37	19	quad	max 8	layer	(1)		aerial 6)	foil + leader	PVC	2, 8, 14, 24, 38	1966–75
17	0.8	Paper	37/ 45	200	quad	max 8	layer	(1)		buried, ducted	Pb or Al, steel *) 3)	jute or PVC 5)	10, 20, 30, (40), 50, (60), 70, (80), 100, (140), 150, 200, 300, 400	1955–75
18	0.9	FPE+ vaseline	45	10	pair	Yes	random	10	(1)	buried, ducted	foil + leader	PE	2, 5, 10, 20, 30, 50, 70, 100	1984–
19	0.7	PE	33/ 60	50	quad	max 8	layer	(1)		sea	Steel wires	PE	6, 10, 20, 30, 50, 100	1966–75

Notes to Table 2

*) Optional, depending on installation.

1) The option of helically wrapped aluminium wires and conductive PE-jacket may also support aerial and simple sea cable applications. (Good EMC performance.)

2) The option of helically wrapped aluminium wires and conductive PE-jacket may also support simple sea cable applications. (Good EMC performance.)

3) The shield consists of 2 (optionally 4) helically wrapped steel tapes.

4) For simple sea cable application helically wrapped steel wires are added. Note 3) applies.

5) Cables with a PVC sheath do not have steel tapes.

6) The overall sheath has been extruded onto the supporting steel rope and the cable core making the characteristic shape of an '8'.

Early appearance in the table implies that a large volume of the actual cable type is installed.

Cables with pair numbers of 40, 60, 80 or 140 were installed before 1970.

Abbreviations:
PE = polyethylene or polypropylene, FPE = foamed PE, PVC = polyvinylchloride, Cu = copper, Al = aluminium-sheathed, Pb = lead-sheathed

Comments to 'Individual twist lengths': Where stated 'max 8', there will be a maximum of four different twist lengths within one layer. The next layer will have a new set of four individual twist lengths.

4.2 HDSL

Principles for HDSL systems have been recommended [4, 5] – for instance by ETSI. Several options exist, but the normal technique is echo cancellation using the 2B1Q line code. There are solutions for three pairs, two pairs and even for one pair. This results in a base band signal with a frequency domain with an upper limit in the 200 to 600 kHz range, depending on the number of pairs used.

4.3 ADSL

ADSL [6, 7] is characterised by unbalanced information transfer in the two directions. The capacity from network to customers is normally in the range up to 6144 kbit/s. In addition there is some duplex capacity up to 640 kbit/s. For some applications the bit capacity may be limited to lower values set by the network operator.

The ADSL systems are not so easy to handle in the planning process. Solutions often utilise the DMT[5)] technique. The actual frequency domain from almost dc to approximately 1 MHz is divided into small portions, and the ADSL system tries to get the best performance possible by allocating the information to be transferred into the most prosperous frequency slots.

Although the DMT technique will add performance to the ADSL modem itself, the existence of such ADSL modems makes the overall planning of the access network more difficult. The noise from an ADSL modem is not quite deterministic but depends to some degree upon the noise environment surrounding the actual twisted pair in the cable.

The line range of the transmission systems described previously (ISDN, HDSL and HDB3 systems) are all limited by NEXT (near end crosstalk). For ADSL modems the effect of NEXT may be avoided by an unbalanced use of available frequency range in the two directions. The dominant and upper part of the frequency band is only used in the direction requiring the highest capacity.

If one should add an ADSL modem connection to an already existing one to make up a composite transfer with equal capacity in the two directions, this will most probably vanish; because the two ADSL modems will now be limited by NEXT. For short distances this arrangement of the two ADSL modems may work, but the line range is dramatically reduced.

4.4 VDSL

VDSL modems [8] will support symmetric or asymmetric information transfer with high capacity. It should be possible with duplex capacity in the range up to 50 Mbit/s. However, the line range will decrease to some hundred metres for the higher capacities. Although some modems have been demonstrated, the market demand belongs to the future.

5 Old and new regimes in the access network

The technology for broadband access to be deployed in the access network develops rapidly and the relevant regimes are changing a lot. The history related to the access network is complex. As telegraphy and later telephone were introduced there were local telephone companies developing the local loop plant. Even as late as the fifties and sixties there were still private telephone companies in some of the big cities in Norway. This multicompany situation also had an impact on the installation procedures and the types of cable being installed. In the late sixties Telenor (previously 'Telegrafverket', later 'Televerket') gained control of the access network in Norway and was in fact in a monopoly situation.

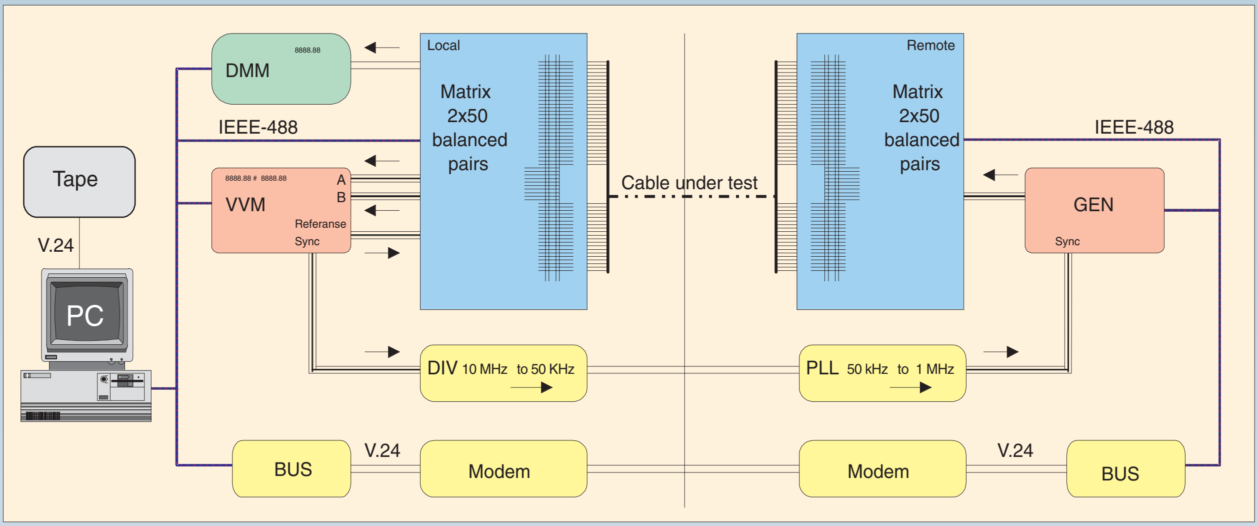
During the last fifteen years the regulation has again relaxed the monopoly situation, first by giving companies other than Televerket permission to install and maintain PBXs, later by allowing network operators for mobile services and providers of value-added services in general. The latest issue is related to the access of the access network. To what extent should other network operators have access to the copper pairs running from Telenor's exchanges up to private and business customers?

5) *Discrete multi-tone is a technique utilising up to 256 discrete carriers for digital modulation.*

Set-up designed for transmission measurements

This set-up was used by Telenor for autonomous transmission measurements in the period from 1984 to 1992. The measuring equipment was transported and installed in a car as the measurements were performed at different sites in the access network.

Before measurements the twisted pairs to be measured were taken out of service and connected to the measuring equipment. The autonomous program, written in Basic, ran for some hours. When the program stopped, the measuring equipment was disconnected and the twisted pairs were put into service again. All measurements were stored on tape. Measurements were performed at 15 (or 19) frequencies scattered over the frequency range from 800 Hz to 8 MHz. The result from one site could be as much as 40,000 single measurements. The measurements were usually done without interactions from an operator. The equipment used will support measurements in the frequency domain up to 13 MHz.



	Equipment		Equipment
PC	Hewlett Packard HP 85A, with IEEE-488 and V.24 interfaces	modem	Modem, Alcatel DCB 19200 MK2
VVM	LF impedance analyser, Hewlett Packard LF 4192A	DIV	Frequency divider, 10 MHz to 50 kHz (custom design)
DMM	Digital multimeter, Hewlett Packard HP-3438A	PLL	AGC amplifier and PLL frequency synthesis, 50 kHz to 1 MHz (custom design)
GEN	Function generator, Hewlett Packard HP-3325A	tape	Tape cartridge recorder, Tandberg Data a/s TDC 3000/3025
BUS	IEEE-488 extender, Hewlett Packard HP-37201A	matrix	Balanced matrix, Creative Engineering a/s (Oslo) CE-1006-1

The two balanced matrices are set by commands over the IEEE-488 bus. Each matrix can provide two independent balanced connections from any of the 50 balanced ports to one or more of the ten instrument ports. Some instrument ports have integrated balancing transformers.

The local IEEE-488 instrument bus is extended to the remote end by modems connected to two spare balanced pairs in the cable under test. The internal frequency reference in the LF impedance analyser (VVM) is divided down to 50 kHz and transmitted to the remote end. Here the 50 kHz signal is amplified and used in a frequency synthesis to restore a 1 MHz reference signal for the signal generator. This is necessary when the remote signal generator is used as a source for the LF impedance analyser.

A substantial demand [9, 10] for access to copper pairs in the access network is anticipated. However, this is dependent on the benefits and drawbacks related to copper access compared to other technical solutions providing transmission capacity [10, 11, 12]. And it is indeed a matter of economics. The Norwegian government is also engaged in the legal and practical aspects of local loop unbundling [13].

This article focuses on the technical aspects assuming that the fee for copper access should be based on cost. The critical point is to what extent the impairments in the copper cables will increase the maintenance cost when new companies introduce new transmission systems into the subscriber cables, and who should be responsible for the compatibility between the different transmission systems provided? Obviously the network operator should guarantee for the compatibility, but in that case the network operator must provide strict technical limits in order to guarantee the necessary quality of service.

6 Systematic registration of installed infrastructure

When serving new regimes it will be even more important to have a good knowledge of the cable infrastructure already installed in order to enable a proper engineering of the development and maintenance of the local loop plant and to support broadband services.

It is important to keep records of the cable capabilities; not only the registration of a pair from one distinct point to another, but also records giving the characteristics about the transmission parameters throughout the route. All cable types along the route should be recorded at the time of installation, at the time of refurbishment and whenever a cable has been damaged and repaired. Polite records should keep trace of and relevant information on all pairs, over-voltage protectors, cables, splices, branches, distributors, connecting material and electronic equipment. A pair with substantial impairments should be clearly marked in the records to avoid this pair being provided for some service requiring better performance. A cable without any record has no substantial value.

Table 3 Measuring methods and conditions for the relevant parameters

Measurement	Near end method / condition	Far end condition	Derived parameters
Loop resistance	between leads	short circuit	$\frac{\text{loop resistance}}{\text{km}}$
Leakage resistance	each lead to ground	open circuit	
Short circuit	each lead to any lead	open circuit	
Insertion loss	12 dB pad	12 dB pad	attenuation constant
Insertion loss in loop	12 dB pad 12 dB pad	looping	attenuation constant phase constant phase velocity
Impedance measurement	Differential insertion loss with the terminated line connected in serial or as shunt	short circuit / open circuit	attenuation constant phase constant phase velocity characteristic impedance
NEXT	120 ohm	120 ohm	NEXT
ELFEXT[6]	120 ohm	120 ohm	FEXT, ELFEXT (normalized to 1 km)

6) *Equivalent level far end crosstalk*

7 Transmission measurements on subscriber cables

In 1993–1994 the Eurescom project P306 [14] focused on the transmission quality and performance of the access network. Most measurements reported were previously collected by Telenor [15, 16, 17]. Unfortunately the NEXT performance presented in 1985 was approximately 20 dB too poor due to an error in the measuring procedure. The set-up was later re-calibrated and the old NEXT results proved to be still valid, but improved by approximately 20 dB.

The first automatic transmission measurements in Telenor's access network took place in February 1984 in the city of Drammen. The main part of the set-up was installed in a car and consisted of a calculator, a voltage vector meter, custom design matrix, modem equipment and a digital multimeter. See brief details of the equipment in separate frame or search more comprehensive information [14, 18].

In total, measurements were collected from more than 500 sites in Telenor's access network. A brief summary of the transmission measuring methods and the derived parameters are given in Table 3, and some of the measurements are presented in the following.

7.1 Attenuation constant

The cable attenuation constant may be obtained from three different kinds of measurements. The results in Figure 2 come from impedance measurements (remote end terminated with short circuit and open end respectively) for frequencies below 1 MHz. At higher frequencies the attenuation constant is calculated from measurement of insertion loss from one end to the other.

For each set-up the mean value of the attenuation constant of the twisted pairs has been calculated. The mean value of the attenuation constant from set-ups with cables of 0.4 mm leads only, is recorded in the solid red line. The lead resistance has been carefully checked to eliminate the set-ups with faulty information about the lead diameter or the length of cable. The other two red and dashed lines give the upper and lower limit defined by the standard deviation. At frequencies below 40 kHz there are 59 set-ups included for 0.4 mm cables. At higher frequencies some of the set-ups with long lengths drop out as the high insertion loss ruins the accuracy.

Similar calculations for 0.6 mm cables are also included in Figure 2. At frequencies below 80 kHz there are 166 set-ups represented by the solid blue line. The other two blue and dashed lines give the upper and lower limit defined by the standard deviation.

The results in Figure 2 gives some indications of the present state of attenuation constant in an access network where the cables have been installed over a long time period.

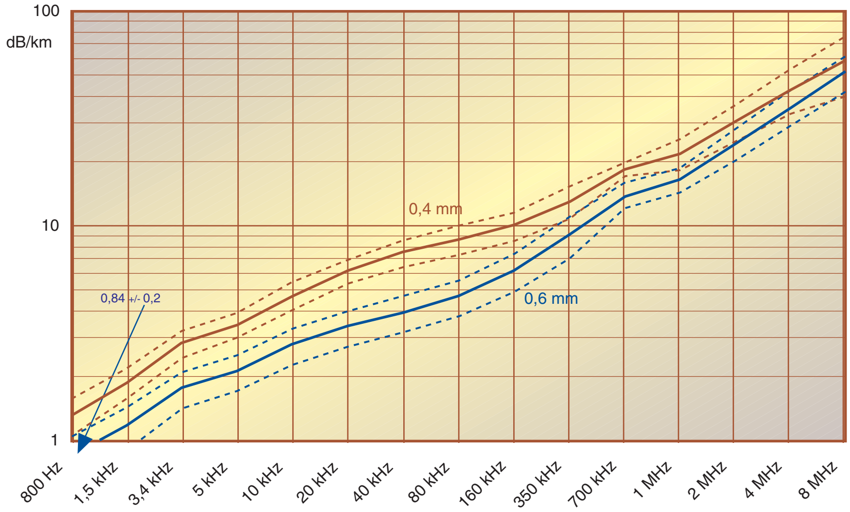


Figure 2 Attenuation constant for cables with 0.4 mm and 0.6 mm leads

7.2 Phase velocity

In Figure 3 the phase velocity is calculated from impedance measurements. For each set-up the mean value of the phase velocity is calculated. Based on these mean values the mean value and the standard deviation of the phase velocity have been achieved for cables with 0.4 mm leads and 0.6 mm leads respectively. The mean value of phase velocity is represented in red for 0.4 mm leads and in blue for 0.6 mm leads. The two solid lines represent the mean value as the dotted lines represent the upper and lower limit defined by the standard deviation. For frequencies below 40 kHz the curves for 0.4 mm and 0.6 mm leads result from 58 and 167 set-ups respectively.

7.3 Near end crosstalk attenuation (NEXT)

Measurements of NEXT have been collected from almost 500 set-ups. For some of the set-ups there may be less than 50 measurements for each frequency while more comprehensive set-ups may contain more than 1000. If, for instance, one pair was transmitting and the crosstalk was measured on the other, measurements were not done with these two pairs interchanging as these two measurements are supposed to be quite equal.

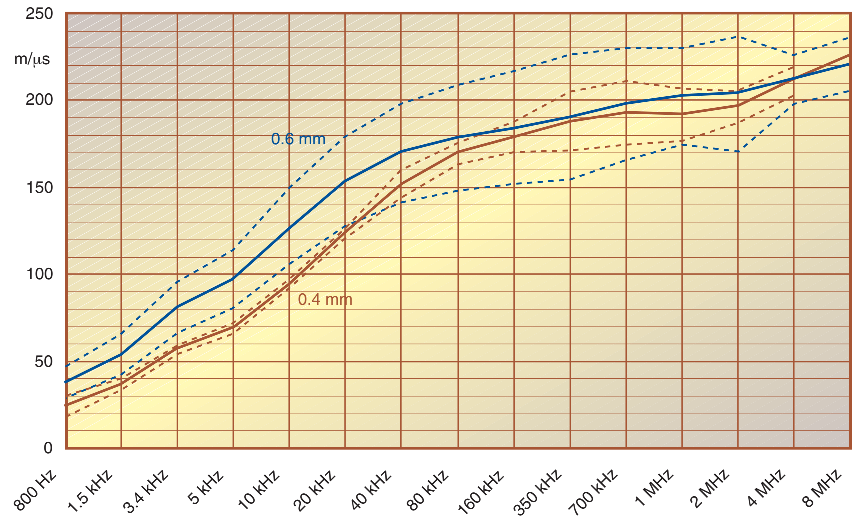


Figure 3 Phase velocity for cables with 0.4 mm and 0.6 mm leads

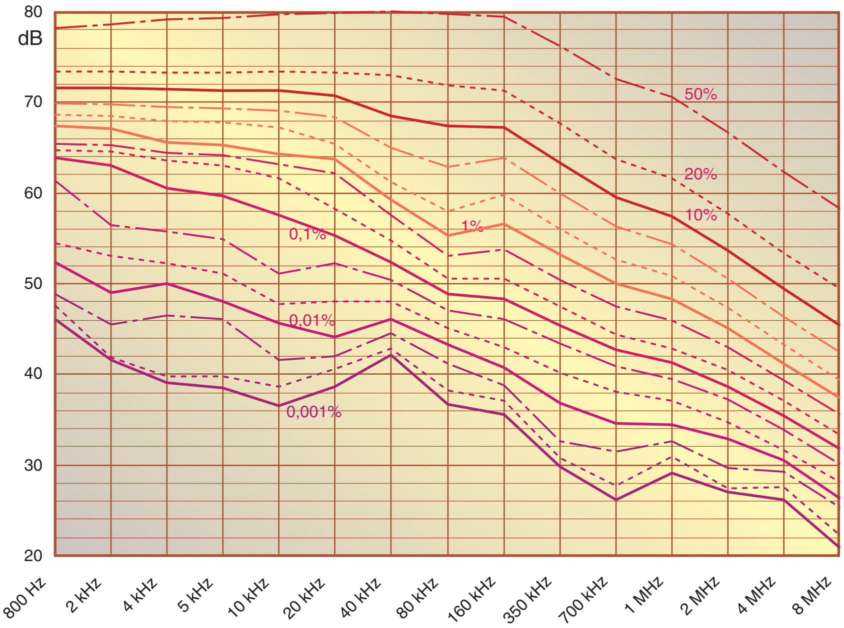


Figure 4 NEXT for all cables measured

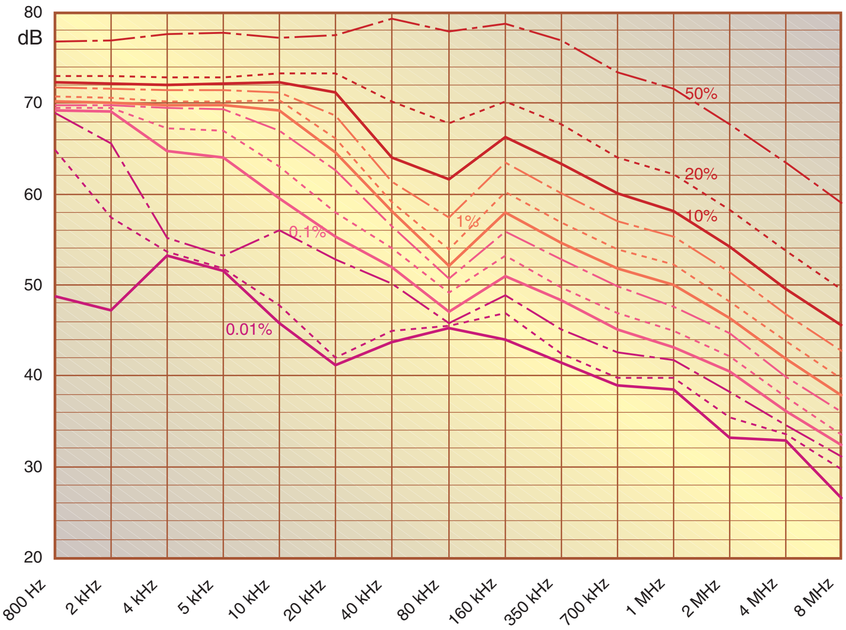


Figure 5 NEXT for plastic insulated cables with 0.6 mm leads

All measurements have been collected and presented in plots showing the frequency dependence of selected percentiles, see Figure 4. For instance, the 5 % percentile separates the better 95 % of measurement from the worse 5 %. As there are more than 220,000 measurements for each frequency, the percentiles range from 50 % down to 0.001 % – the last one separating only four measurements from the others.

Some interesting details can be observed from Figure 4. The first observation is the slope of the different percentiles at frequencies above 160 kHz. The slope seems to be 12 – 13 dB/decade rather than the traditional 15 dB/decade.

At frequencies below 80 kHz the percentiles tend to be more or less independent of frequency. This may originate from reduced balance performance against earth in the measuring set-up at the lower frequencies and insufficient grounding.

Another observation is that all percentiles in the 0.5 % to 5 % range have greater near end crosstalk attenuation at 160 kHz than at 80 kHz. These percentiles are the most interesting ones for network performance dimensioning. Figure 4 indicates that the cables have statistical better crosstalk performance at 160 kHz than at 80 kHz!

Figure 5 shows the same phenomenon even better. The NEXT values are here representative for plastic insulated cables with lead diameters of 0.6 mm. The most interesting percentiles are as much as 4 to 6 dB better at 160 kHz than for 80 kHz. For other frequencies the trend in Figure 5 is quite similar to that of Figure 4.

Paper insulated cables with lead diameters of 0.6 mm show some tendency to have a few percentiles at approximately the same value for these two frequencies, and cables with 0.4 mm all have monotonous percentiles in this frequency range, so this phenomenon is closely related to plastic insulated cables with lead diameters of 0.6 mm.

7.4 NEXT related to quads

The different set-ups have been carefully categorised depending on certain parameters. For instance, set-ups containing a dominant part of cables with quads form such a category, and in this category there are 5,619 pair combinations within the quads and 218,002 pair combinations where the two pairs will not fit into a quad.

Figures 6 and 7 illustrate the crosstalk performance related to quads. The first figure shows percentiles of NEXT within quads and the second figure shows NEXT for the remaining pair combinations. For frequencies above 40 kHz the crosstalk performance is 10 to 15 dB better outside the quad than within.

In Figure 7 it is also observed that the percentiles are sloping merely at 10 dB/decade instead of the traditional 15 dB/decade.

7.5 NEXT for nearby pairs

For most of the set-ups it has been possible to evaluate if a pair combination incorporates two pairs that are located quite close to each other[7)] or not. NEXT values for pair combinations residing in the same area are shown in Figure 8, and in Figure 9 the complementary measurements (NEXT between pairs residing in different areas) are shown. By comparing Figures 8 and 9 the NEXT values between different areas exhibit a performance that is approximately 8 to 10 dB better than within the same area – at least for frequencies above 80 kHz. This is a typical trend recognised for each type of cable.

7.6 NEXT for paper insulated cable

NEXT for paper insulated cables with leads of 0.4 mm is depicted in Figure 10. These cables are characterised by twisted pairs organised in layers. It can be seen that the performance for frequencies above 80 kHz is comparable to the general trend in Figure 4. At lower frequencies the performance seems to be better; however, the number of measurements is limited.

7) Close relation or same area: Pair combination characterised by either

- *two pairs belonging to the same ten-pair group;*
- *one pair in one quad and one pair in the same quad or one of the following/preceding two quads in the same layer;*
- *two pairs separated by no more than three pairs in the same layer.*

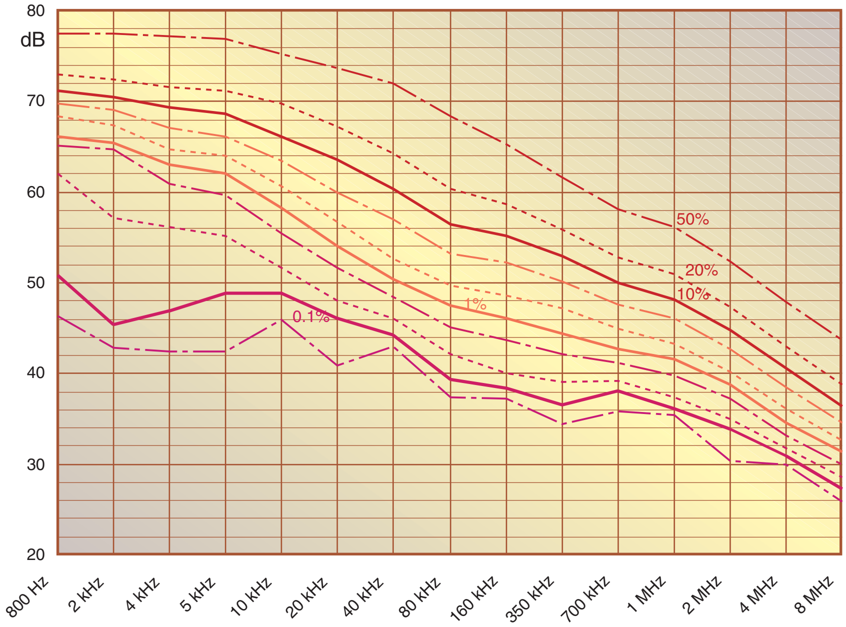


Figure 6 NEXT within quads for cables with quad structure

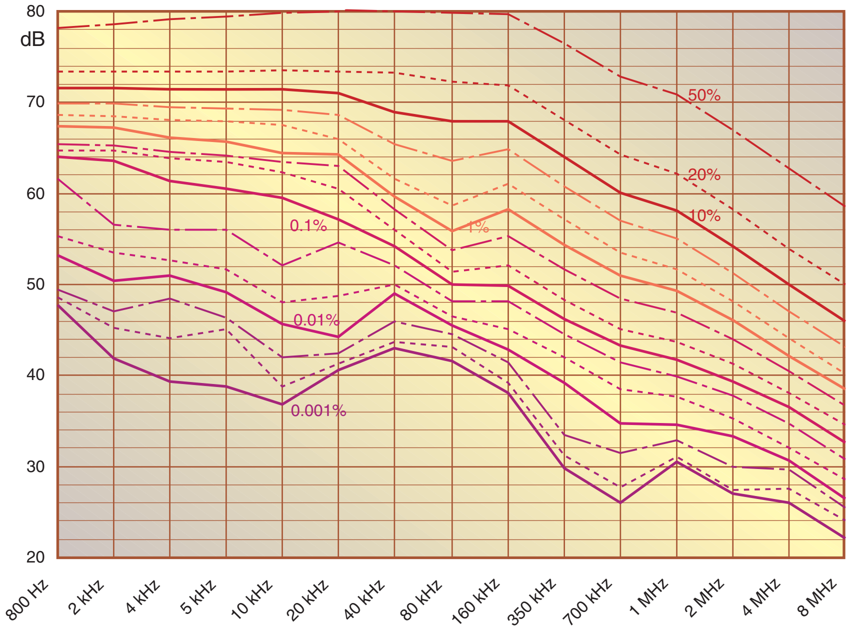


Figure 7 NEXT between pairs residing in different quads

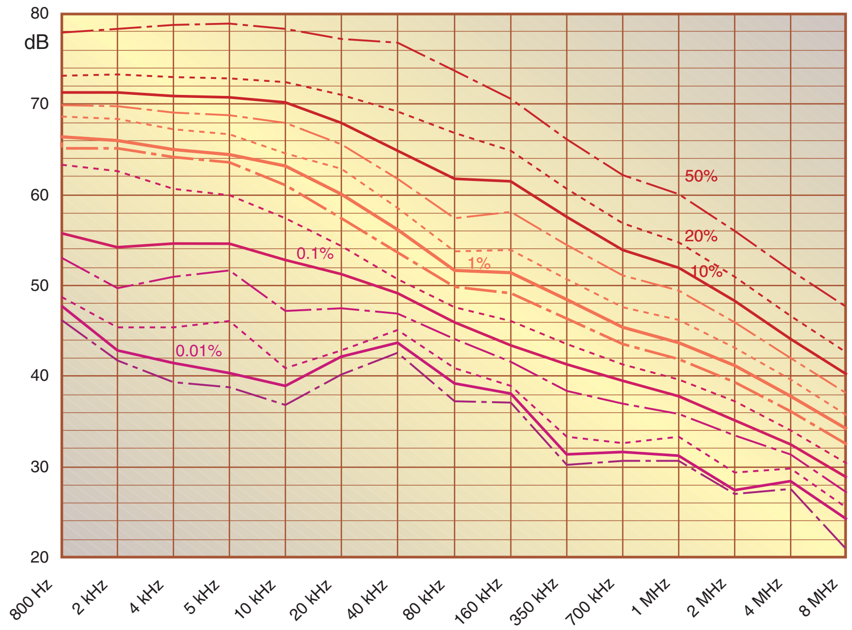


Figure 8 NEXT between neighbouring pairs

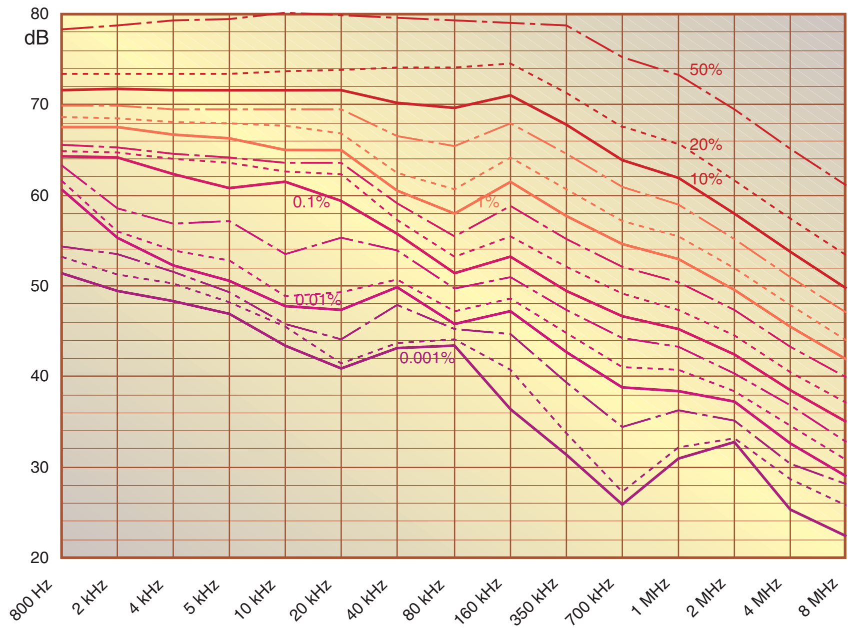


Figure 9 NEXT between pairs other than neighbouring pairs

Table 4 Digital transmission systems on copper cables

2B1Q:	IDSL, ISDN basic access 160 kbit/s
2B1Q:	modem, with 320 kbit/s and 576 kbit/s
2B1Q:	HDSL with (one,) two or three pairs
BiPh:	modems with 128 kbit/s to 320 kbit/s
HDB3:	systems with 704 kbit/s and 2 048 kbit/s

NEXT for paper insulated cables with 0.6 mm leads is shown in Figure 11. These cables are constructed with quads organised in layers. Comparing with Figure 4 the paper insulated quad cables tend to have 1 to 3 dB worse NEXT for most frequencies. Similarly the NEXT within quads for paper insulated cables (no figure given) tends to be 2 to 5 dB worse than the NEXT within quads for all quad cables as given in Figure 6.

7.7 Equivalent level far end crosstalk (ELFEXT)

The equivalent level far end crosstalk has been measured and presented in Figure 12. At lower frequencies there are more than 230,000 measurements at each frequency. Some of the smaller percentiles disappear at high frequencies as the insertion loss of some of the measured cables becomes too large and ruins the value of these particular measurements.

8 Planning rules

Design rules should be established for all transmission systems to be transferred in the copper cables. Examples of actual digital transmission systems are shown in Table 4. The list should be expanded to accommodate for ADSL and other DSL-systems as soon as practical transmission equipment is ready for deployment.

As the analogue telephone service still has the highest demand, the provision for it should also be granted at an acceptable quality of service. In Telenor's access network all analogue telephone lines are immediately terminated in an analogue-to-digital converter. As long as the ISDN basic access may be supported at acceptable quality, the analogue service will most probably also be provided with an acceptable level of quality. This may not necessarily be the case if the trunk network is composed of analogue lines (trunks).

Some analogue one-plus-one carrier systems still exist in Telenor's access network, and there may be some interference problems for lines exceeding 3 km. However, these carrier systems may be succeeded by digital IDSL-systems or avoided by upgrading the infrastructure of the copper cable network.

8.1 Principles for establishing design rules

Telenor's design rules for allowable line ranges are based on some millions of crosstalk measurements in Telenor's access network. The measurements are (almost) evenly distributed in the frequency range from 800 Hz to 8 MHz. The measurements are sorted out and interpolated to support calculations of allowable line ranges for the different transmission systems in Table 4 within each of the cable categories defined in Table 1. The estimated line ranges are calculated based on various numbers of disturbers from the same type of transmission system. Telenor established the first planning rules [19] for digital transmission systems on balanced copper cables in 1989 based on the collected transmission measurements.

8.2 Line range formula

The formula to calculate the line range is as follow:

$$a_{next}(f, P_{conf}, \nu, n) - 10 \cdot \log_{10}(n)$$
$$- a_d(f, l) \cdot l \cdot \kappa - s_{/N} - \text{margin} > 0$$

The estimated NEXT value (a_{next}) is determined by a gamma distribution characterised by the frequency, the confidence level, the parameter ν (calculated from the quotient between the mean value and the standard deviation) and the number of disturbers (n).

The term 10 $\log_{10}(n)$ relates to the equivalent number of disturbers.

The term related to attenuation, $a_d(f, l) \cdot l \cdot \kappa$, is calculated from the sum of the mean value and twice the standard deviation of the attenuation at the relevant frequency. The value of κ is close to 1.0 in most cases.

The signal-to-noise ratio and the margin are specific for the actual transmission system.

8.3 The number of disturbers

For a particular transmission system the presence of other types of equipment may effect the allowable line ranges. A rough estimate of the equivalent number of disturbers should be established.

For each transmission system equivalent values for the impact of the other types of transmission systems are presented.

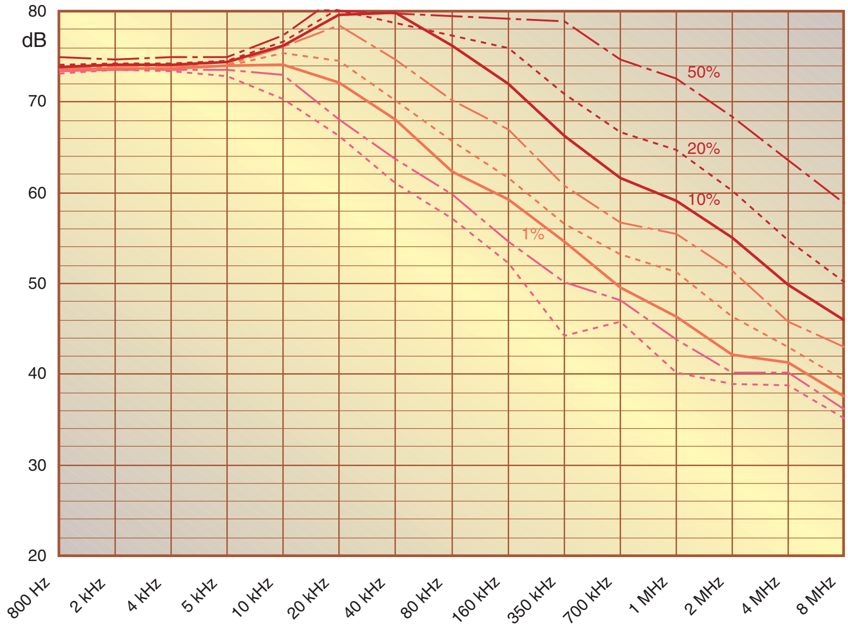


Figure 10 NEXT for paper insulated cables with 0.4 mm leads

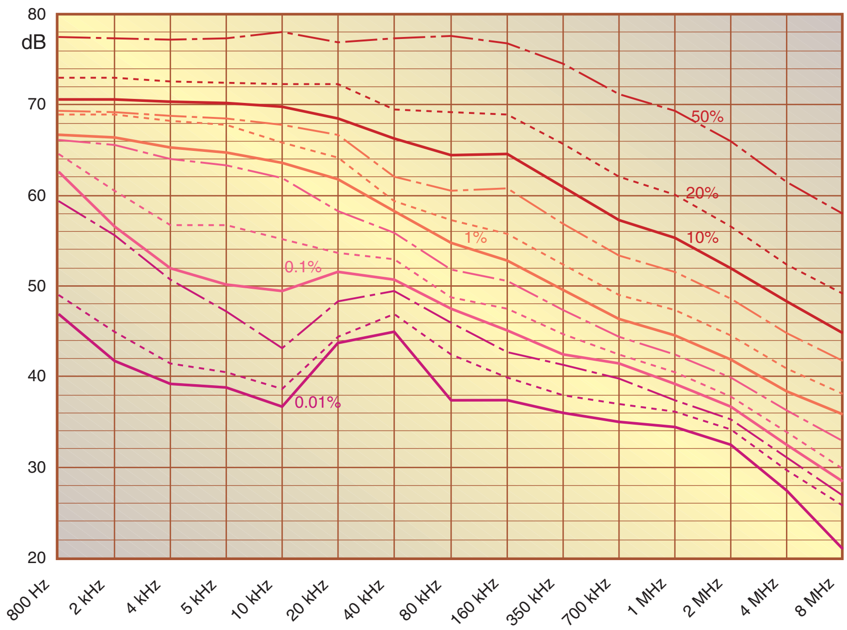


Figure 11 NEXT for paper insulated cables with 0.6 mm leads and quad structure

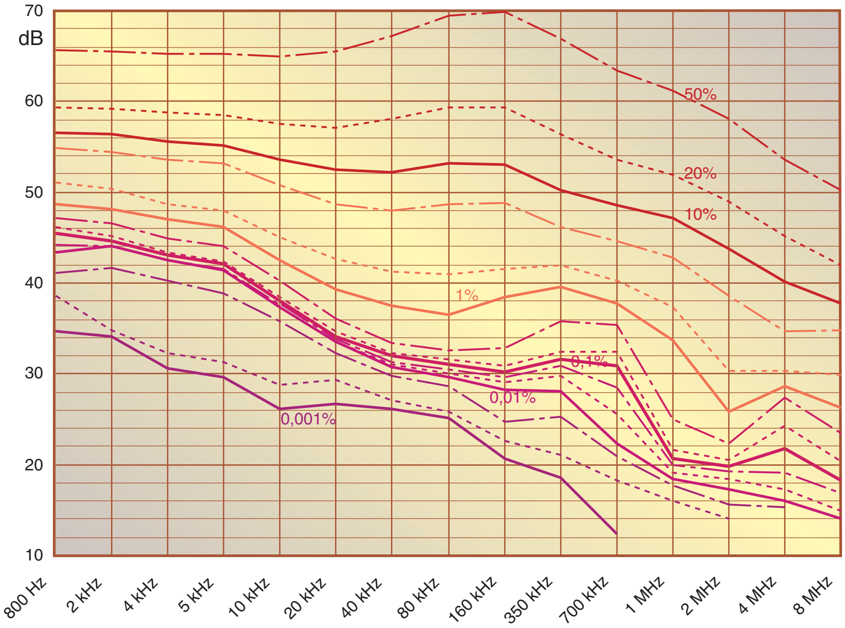


Figure 12 ELFEXT, equivalent far end crosstalk for all cables

For each type of disturbing system the amount should be multiplied with the impact value and added to give one single equivalent number of all disturbers. If the number of equivalent disturbers exceeds ten, the actual number has little impact on the line ranges. The estimated number of disturbers should accommodate for the future situations.

In practical situations the number of neighbouring pairs that contribute with crosstalk noise is also limited. The crosstalk coupling is usually greatest for adjacent pairs. As the distance between pairs increases, the crosstalk coupling tends to decrease and the incremental impact becomes quite moderate, compare Figures 8 and 9.

8.4 Practical results obtained from the formula

The formula may be used to calculate practical line ranges for the actual transmission system. The allowable line ranges are given as a function of the equivalent number of disturbers. The line ranges are primarily limited by near end crosstalk.

One example illustrates this effect. The cable attenuation decreases as the lead diameter is increased. However, for some transmission systems the calculated line ranges may even be less on 0.6 mm cable than on 0.4 mm cable. The main reason for this effect is that the 0.6 mm cables may be severely affected by near end crosstalk, particularly between the two pairs in a star quad of a paper insulated cable.

For this reason the presented line ranges also have optional values where NEXT values within the star quads have been excluded. These results may be useful if a strategy to use only one of the two pairs in the star quads may be established for this particular service.

These examples clearly illustrate the value of keeping polite records; not only of each pair, but also of the cable types used throughout the cabling route.

8.5 Practical aspects related to local loop unbundling

The provision of open access to copper cables is often described as local loop unbundling. The effects of local loop unbundling may have a great impact on the design rules for provision of compatible transmission systems in the access network.

One example may well illustrate this. One network operator provides an HDSL transport to his customers and also provides for local loop unbundling. A competitive service provider terminates his leased lines with HDSL systems with a different line code and with an output level that is at least 10 dB higher than that of the network operator. How will this impact the maintenance cost for the network operator? – and what about compatibility between different transport services?

Even if the line system on the leased line should be defined by standards given by ETSI or any other standardisation body, the situation is still different to that of the network operator not supporting local loop unbundling. As the network operator provides a transmission system for his own network he will also have the possibility to make special agreements with his equipment supplier to adjust the supported equipment, for instance to request for more strict filtering or more exact output level of the transmitting circuits. However, the network operator will normally not be in a position to influence the equipment provided for the competitive service provider as long as the agreed standards are followed. The impact of this situation is not a lot of decibels or kilometres but may well result in an estimated line range being reduced by a few hundred metres.

9 Concluding remarks

The nature of the cable measurements presented in this article shows that there is a need for complex, but simplified, planning rules to aid network planners in how to deploy the access network for existing systems and for new DSL-technology.

The nature of the copper cables will also impact the evolution of new regimes in the access network and define to what an extent local loop unbundling will be practical or not.

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Calculation of cable parameters

PER KLEPSLAND

1 Introduction

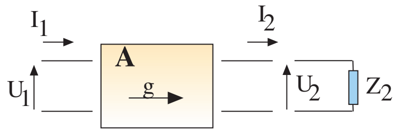
During the 1980s Telenor developed a measuring set-up and relevant methods to measure important transmission parameters of balanced copper cables within the access network. Most measuring equipment lacks the necessary balance against earth to perform cable measurements in the field.

The calculation methods described were elaborated to assist the cable measurements in the field. Impedance measurements may well be done by measuring the difference in insertion loss when the impedance to be measured is connected as a shunt or as a serial impedance. The two methods are analysed. Moreover the article shows some fundamentals of a two-port network and how the attenuation constant can de derived from the measured insertion loss.

The methods and calculations described in this article are relevant for the planning for provision of both low capacity modems and DSL-systems operating in the high mega-Hertz range. Practical results of this type of calculation are contained in the previous article, "Towards a practical implementation of DSL – preparing for new technology and regimes", by the same author.

2 Properties of a two-port network

A two-port network may be characterised by a matrix representation. In Figure 1 the currents and voltages are depicted. The two-port network may not necessarily be reciprocal or symmetrical. The two-port network is characterised by the matrix **A**, represented with the elements a_{11}, a_{12}, a_{21} and a_{22}, the image impedance, Z_1, on port one, the image impedance, Z_2, on port two and the image propagation functions, g and $\dot{g}$, for the two directions.



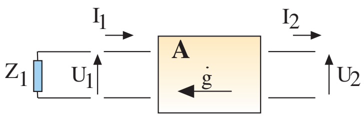
$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \mathbf{A} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{1}$$

Figure 1 A two-port network terminated with its image impedance on port two

If the two-port network is terminated with its image impedance on port two, the input impedance on port one should be equal to the image impedance on port one. Then we have $U_2 = I_2 \cdot Z_2$ and $U_1 = I_1 \cdot Z_1$, and combined with the two equations contained in (1), this gives:

$$Z_1 \cdot (Z_2 \cdot a_{21} + a_{22}) = Z_2 \cdot a_{11} + a_{12} \tag{2}$$

Figure 2 shows the same two-port network. Port one is now terminated with its image impedance. At port two we can estimate the input impedance in the same manner and this should be equal to the image impedance of port two.



$$\begin{bmatrix} U_2 \\ -I_2 \end{bmatrix} = \mathbf{A}^{-1} \begin{bmatrix} U_1 \\ -I_1 \end{bmatrix} = \begin{bmatrix} \dfrac{a_{22}}{D} & \dfrac{-a_{12}}{D} \\ \dfrac{-a_{21}}{D} & \dfrac{a_{11}}{D} \end{bmatrix} \begin{bmatrix} U_1 \\ -I_1 \end{bmatrix} \tag{3}$$

Figure 2 A two-port network terminated with its image impedance on port one

In the matrix representation $D = a_{11} \cdot a_{22} - a_{12} \cdot a_{21}$, we assume that $D \neq 0$. Again we use the relations between voltage, current and impedance on the respective ports. Combined with the equations contained in (3), the result is:

$$Z_2 \cdot (Z_1 \cdot a_{21} + a_{11}) = Z_1 \cdot a_{22} + a_{12} \tag{4}$$

From (2) and (4) the two simple relations follow:

$$Z_1 \cdot Z_2 = \frac{a_{12}}{a_{21}} \text{ and } \frac{Z_1}{Z_2} = \frac{a_{11}}{a_{22}} \tag{5}$$

... and the two image impedances may be expressed by the elements in the matrix **A**:

$$Z_1 = \sqrt{\frac{a_{11} \cdot a_{12}}{a_{21} \cdot a_{22}}} \tag{6}$$

$$Z_2 = \sqrt{\frac{a_{22} \cdot a_{12}}{a_{21} \cdot a_{11}}} \tag{7}$$

The next step is to include (7) in (1) and apply the relation $U_2 = I_2 \cdot Z_2$:

$$U_1 = (\sqrt{a_{11} \cdot a_{22}} + \sqrt{a_{12} \cdot a_{21}}) \cdot \sqrt{\frac{a_{12}}{a_{21}}} \cdot I_2$$

$$I_1 = (\sqrt{a_{11} \cdot a_{22}} + \sqrt{a_{12} \cdot a_{21}}) \cdot \sqrt{\frac{a_{21}}{a_{12}}} \cdot U_2 \tag{8}$$

The quotient between the power on port one and port two respectively may now be established:

$$\frac{U_1 \cdot I_1}{U_2 \cdot I_2} = (\sqrt{a_{11} \cdot a_{22}} + \sqrt{a_{12} \cdot a_{21}})^2 = e^{2 \cdot g} \tag{9}$$

The last equality follows from the definition of the image propagation function. This is related to the quotient between the power supplied on port one and the power extracted on port two when the two-port network is terminated with its image impedance. (α is the attenuation constant, β is the phase constant, γ is the propagation constant and l is the length of the cable.)

$$g = \gamma \cdot l = (\alpha + j\beta) \cdot l = \frac{1}{2} \cdot \ln \frac{U_1 \cdot I_1}{U_2 \cdot I_2} \tag{10}$$

From Figure 2 and the equations contained in (3) we can estimate the similar relation between the power on the two ports. Here the image propagation function is $\dot{g}$,which need not necessarily be the same as for the first direction. The quotient becomes:

$$\frac{U_2 \cdot I_2}{U_1 \cdot I_1} = \frac{I}{D^2} (\sqrt{a_{11} \cdot a_{22}} + \sqrt{a_{12} \cdot a_{21}})^2 = \left(\frac{1}{\sqrt{a_{11} \cdot a_{22}} - \sqrt{a_{12} \cdot a_{21}}} \right)^2 = e^{2 \cdot \dot{g}} \tag{11}$$

From (9) and (11) we get the relation between the elements of the matrix **A** and the image propagation constants.

$$\frac{e^g + e^{-\dot{g}}}{2} = \sqrt{a_{11} \cdot a_{22}} \tag{12}$$

$$\frac{e^g - e^{-\dot{g}}}{2} = \sqrt{a_{12} \cdot a_{21}} \tag{13}$$

The equations (6), (7), (12) and (13) may now be used to establish the matrix **A** expressed by the image impedances and the image propagation functions.

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} \begin{bmatrix} \sqrt{\frac{Z_1}{Z_2}} \cdot \frac{e^g + e^{-\dot{g}}}{2} & \sqrt{Z_1 \cdot Z_2} \cdot \frac{e^g - e^{-\dot{g}}}{2} \\ \frac{1}{\sqrt{Z_1 \cdot Z_2}} \cdot \frac{e^g - e^{-\dot{g}}}{2} & \sqrt{\frac{Z_2}{Z_1}} \cdot \frac{e^g + e^{-\dot{g}}}{2} \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{14}$$

3 The cable as a two-port network

A cable is characterised as a reciprocal two-port network. This implies that the two image propagation functions are the same. The elements of matrix **A** may now be expressed by the hyperbolic functions instead of the exponential functions in (14).

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{Z_1}{Z_2}} \cdot \cosh g & \sqrt{Z_1 \cdot Z_2} \cdot \sinh g \\ \frac{\sinh g}{\sqrt{Z_1 \cdot Z_2}} & \sqrt{\frac{Z_2}{Z_1}} \cdot \cosh g \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{15}$$

If the cable is terminated at port two with an impedance of Z_L, the input impedance of port one may be calculated from (15)

$$Z_{\text{in}} = \frac{U_1}{I_1} = \frac{Z_L \cdot \sqrt{\frac{Z_1}{Z_2}} \cdot \cosh g + \sqrt{Z_1 \cdot Z_2} \cdot \sinh g}{\frac{Z_L}{\sqrt{Z_1 \cdot Z_2}} \cdot \sinh g + \sqrt{\frac{Z_2}{Z_1}} \cdot \cosh g} = \frac{Z_L \cdot \sqrt{\frac{Z_1}{Z_2}} + \sqrt{Z_1 \cdot Z_2} \cdot \text{tgh } g}{\frac{Z_L}{\sqrt{Z_1 \cdot Z_2}} \cdot \text{tgh } g + \sqrt{\frac{Z_2}{Z_1}}} \tag{16}$$

For representation of cables it is more common to use the propagation constant than the image propagation function. In this way the length of the cable, l, is introduced: $g = \gamma \cdot l$. For a homogeneous cable the two image impedances are equal to the characteristic impedance of the cable, $Z_0 = Z_1 = Z_2$.

A closer look at (16) results in two interesting observations. If the load impedance is removed (open circuit), the input impedance is simply $Z_0 / \text{tgh } \gamma \cdot l$, and with a short-circuit termination at the remote end of the cable, the input impedance becomes $Z_0 \cdot \text{tgh } \gamma \cdot l$.

The electrical equivalent of a balanced cable is depicted in Figure 3. R, L, C and G are the primary constants of the cable, and f is the frequency. The propagation constant and the characteristic impedance can be expressed by the primary constants, see (17) and (18). The four primary constants, though being constants, do show some minor variation depending on actual frequency and environmental temperature.

$$\gamma = \alpha + j\beta = \sqrt{(R + j2 \cdot \pi \cdot f \cdot L) \cdot (G + j2 \cdot \pi \cdot f \cdot C)} \tag{17}$$

$$Z = \sqrt{\frac{R + j2 \cdot \pi \cdot f \cdot L}{G + j2 \cdot \pi \cdot f \cdot C}} \tag{18}$$

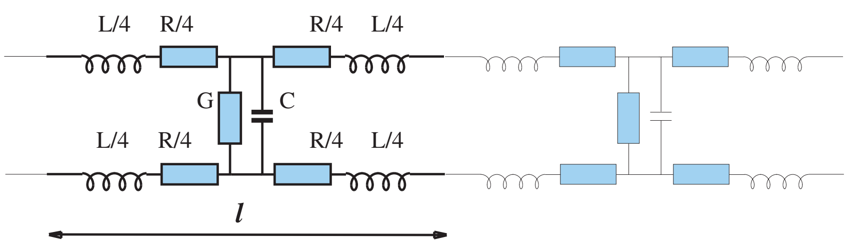


Figure 3 Electrical equivalent of a slice of a balanced cable

4 Measuring open and short-circuit impedances of a cable

According to (16) the input impedance can be measured when the terminating impedance is known. We have the two cases when the load impedance, Z_L, is represented by a short circuit or an open circuit respectively:

Short circuit: $Z_{short} = Z_0 \cdot \text{tgh}\ \gamma \cdot l$ (19)

Open end: $Z_{open} = \dfrac{Z_0}{\text{tgh}\ \gamma \cdot l}$ (20)

This leads to the explicit equation for the characteristic impedance, Z_0, and the transmission constant γ:

$$Z_0 = \sqrt{Z_{short} \cdot Z_{open}} \qquad (21)$$

$$\gamma = \frac{1}{l} \cdot \text{arctgh} \sqrt{\frac{Z_{short}}{Z_{open}}} = \frac{1}{2 \cdot l} \cdot \ln \frac{1 + \sqrt{\frac{Z_{short}}{Z_{open}}}}{1 - \sqrt{\frac{Z_{short}}{Z_{open}}}} \qquad (22)$$

The accuracy in formula (21) and (22) can be estimated by allowing for a fault δZ in the two measurements. According to (23) the accuracy in estimating the characteristic impedance is directly related to the accuracy in the measurements.

$$Z_0 = \sqrt{Z_{short} \cdot (1 \pm \delta Z) \cdot Z_{open} \cdot (1 \pm \delta Z)} = (1 \pm \delta Z) \cdot \sqrt{Z_{short} \cdot Z_{open}} \qquad (23)$$

The relation between the accuracy for γ and the two measurements is more complex.

$$\gamma \cdot l = \frac{1}{2} \cdot \ln \frac{1 + \sqrt{\frac{Z_{short} \cdot (1 \pm \delta Z)}{Z_{open} \cdot (1 \mp \delta Z)}}}{1 - \sqrt{\frac{Z_{short} \cdot (1 \pm \delta Z)}{Z_{open} \cdot (1 \mp \delta Z)}}} \approx \frac{1}{2} \cdot \ln \frac{1 + (1 \pm \delta Z) \cdot \sqrt{\frac{Z_{short}}{Z_{open}}}}{1 - (1 \pm \delta Z) \cdot \sqrt{\frac{Z_{short}}{Z_{open}}}} \qquad (24)$$

In Table 1 the resulting accuracy is estimated on the basis of the insertion loss in dB and the relative measuring accuracy in %. For low values of insertion loss the accuracy is somewhat worse than the measuring accuracy. However, as the insertion loss approach is 20 dB, the relative fault in the calculated attenuation is five times worse.

Table 1 Accuracy of calculated insertion loss based on impedance measurements of a given accuracy

Cable attenuation, dB	Accuracy in impedance measurements (%)	
	0.5 %	5 %
1.0	0.5	5.0
5.0	0.6	5.8
10.0	0.9	8.5
15.0	1.6	14.
20.0	3.2	22.

This method of estimating the cable attenuation from the measured open and short impedances is limited to cable lengths up to 15 – 20 dB. As the cable attenuation increases with frequency this measuring method is most valuable for low frequencies or reasonably short cables. At 1 MHz there is a practical line range of approximately 1 km.

5 Cascading two-port networks

If we have two-port networks in cascade, the effective **A** matrix of all the two-port networks together, can be established by the product of the **A** matrices for each two-port network. Note the direction of currents and voltages and also that the order of matrices can not be permuted.

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \mathbf{A}_{12\ldots n} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} = \mathbf{A}_1 \cdot \mathbf{A}_2 \cdot \ldots \cdot \mathbf{A}_n \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{25}$$

In Figure 4 there are three two-port networks in cascade. From the left there is a cable section of length l_1. At this location there is a spur (bridged tap) of length l_2 connected. As we have already seen from (20) that the input impedance of the spur is Z_{02} / tgh $\gamma_2 \cdot l_2$, the last two-port network is a cable section of length l_3.

A two-port network consisting of a single shunt:
$a_{11} = a_{22} = 1$, $a_{12} = 0$, $a_{21} = 1 / Z_{shunt}$ (26)

A two-port network with a single serial impedance:
$a_{11} = a_{22} = 1$, $a_{12} = Z_{serial}$, $a_{21} = 0$ (27)

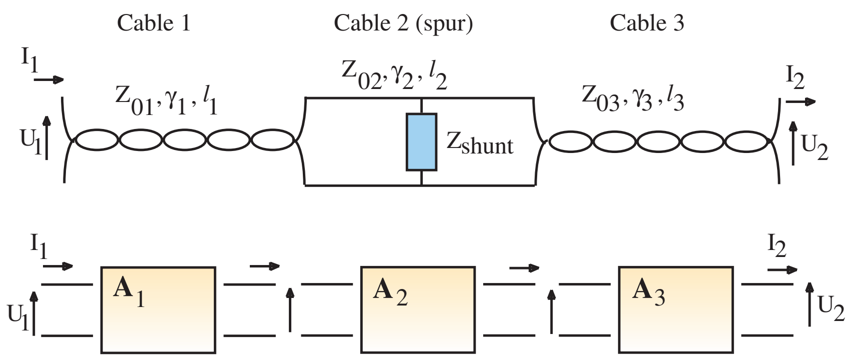


Figure 4 Cascading three two-port networks: Two cable sections with a spur connected in the middle

The $\mathbf{A}_1$, $\mathbf{A}_2$ and $\mathbf{A}_3$ matrices can now be established and the resulting matrix can be calculated from the following equation. (Left for exercise.)

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} \begin{bmatrix} \cosh\gamma_1 \cdot l_1 & Z_{01} \cdot \sinh\gamma_1 \cdot l_1 \\ \frac{\sinh\gamma_1 \cdot l_1}{Z_{01}} & \cosh\gamma_1 \cdot l_1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{\mathrm{tgh}\ \gamma_2 \cdot l_2}{Z_{02}} & 1 \end{bmatrix} \begin{bmatrix} \cosh\gamma_3 \cdot l_3 & Z_{03} \cdot \sinh\gamma_3 \cdot l_3 \\ \frac{\sinh\gamma_3 \cdot l_3}{Z_{03}} & \cosh\gamma_3 \cdot l_3 \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{28}$$

6 Estimation of cable attenuation from measurements of insertion loss

In normal cases it is not easy to measure the cable attenuation by direct measurements. The most practical way is to measure the insertion loss and calculate the cable attenuation. The terminating impedances, Z_g and Z_L, will hardly match the characteristic impedance of the cable at all frequencies, so there will most probably be one reflecting point near to the generator and one reflecting point near to the load. In the general case the image impedances of the cable may be different at the two terminations as shown in Figure 5.

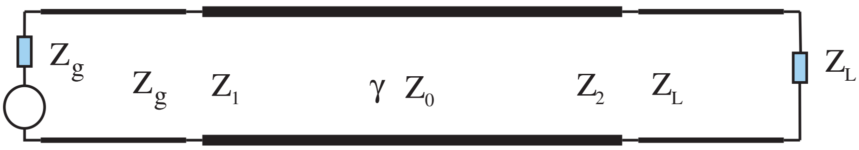


Figure 5 Transmission over a homogeneous cable with reflecting points at the generator and at the load

Cable attenuation:

$$a = \text{real}\,|g| = \alpha \cdot l \tag{29}$$

Loss due to the reflecting point at the generator:

$$g_g = \ln \frac{Z_g + Z_1}{2 \cdot \sqrt{Z_g \cdot Z_1}} = \ln \sqrt{\frac{1}{1-\rho_g^2}} \tag{30}$$

Loss due to the reflecting point at the load:

$$g_L = \ln \frac{Z_L + Z_2}{2 \cdot \sqrt{Z_L \cdot Z_2}} = \ln \sqrt{\frac{1}{1-\rho_L^2}} \tag{31}$$

Interaction loss due to the mutual influence of the two reflecting points:

$$g_m = \ln\left(1 - \frac{(Z_g - Z_1)}{(Z_g + Z_1)} \cdot e^{-g} \cdot \frac{(Z_L - Z_2)}{(Z_L + Z_2)} \cdot e^{-g}\right) = \ln\left(1 - \rho_g \cdot \rho_L \cdot e^{-2 \cdot g}\right) \tag{32}$$

The insertion loss can now be estimated. It is more practical to use the reflection coefficients ρ_1 and ρ_2 in the evaluation. The insertion loss should be the sum of the cable attenuation and the additional loss according to (29) to (31):

$$g_{in} = g + g_g + g_L + g_m = g + \ln\sqrt{\frac{1}{1-\rho_g^2}} + \ln\sqrt{\frac{1}{1-\rho_L^2}} + \ln\left(1 - \rho_g \cdot \rho_L \cdot e^{-2 \cdot g}\right) \tag{33}$$

... or expressed by the different impedances:

$$g_{in} = g + \ln \frac{Z_g + Z_1}{2 \cdot \sqrt{Z_g \cdot Z_1}} + \ln \frac{Z_L + Z_2}{2 \cdot \sqrt{Z_L \cdot Z_2}} + \ln\left(1 - \frac{(Z_g - Z_1)\cdot(Z_L - Z_2)}{(Z_g + Z_1)\cdot(Z_L + Z_2)} \cdot e^{-2 \cdot g}\right) \tag{34}$$

Using (33) and assuming that the load and the generator impedances are equal and that the cable is homogeneous, the two reflection constants will now be equal ($Z_g = Z_L = Z$, $Z_1 = Z_2 = Z_0$, $\rho_g = \rho_L = \rho$).

$$g_{in} = g + \ln\sqrt{\frac{1}{1-\rho^2}} + \ln\sqrt{\frac{1}{1-\rho^2}} + \ln\left(1 - \rho^2 \cdot e^{-2\cdot g}\right) \tag{35}$$

By introducing the exponential function on both sides in the equation (35), this may be written:

$$e^{g_{in}} = e^g \cdot \frac{1}{1-\rho^2} \cdot \left(1 - \rho^2 \cdot e^{-2\cdot g}\right) \tag{36}$$

... and rearranged:

$$e^{2\cdot g} - (1-\rho^2) \cdot e^{g_{in}} \cdot e^g - \rho^2 = 0 \tag{37}$$

This is an equation of order two with respect to e^g. We can now solve the expression and introduce the logarithm:

$$g = \ln\left(\frac{1}{2} \cdot (1-\rho^2) \cdot e^{g_{in}} \pm \sqrt{\frac{1}{4} \cdot (1-\rho^2)^2 \cdot e^{2\cdot g_{in}} - \rho^2}\right) \tag{38}$$

In general there are two solutions, but only the positive sign is valid. This is obvious for the case when the cable is matched at both ends making the reflection coefficients zero.

$$g = \ln\left(\frac{1}{2} \cdot (1-\rho^2) \cdot e^{g_{in}} + \sqrt{\frac{1}{4} \cdot (1-\rho^2)^2 \cdot e^{2\cdot g_{in}} - \rho^2}\right) \tag{39}$$

The characteristic impedance of the cable can be calculated from impedance measurements with open- and short-circuit remote end respectively. As the generator and load impedances should be known, the reflection coefficient, ρ, may be calculated. Together with the measured insertion loss (eg. the real part of the transmission function), the cable attenuation may now be calculated from the formula (39).

7 Balanced measurement of impedance

A method of measuring the value of a balanced impedance (such as a balanced cable) is depicted in Figure 6. The two terminals of the impedance *Z* will meet the same impedance against earth. The resistors are added to ensure that the transformers will work under well-defined load conditions with a minimum of influence from the impedance *Z*. Note that the two resistive two-port networks are balanced but need not necessarily be symmetrical.

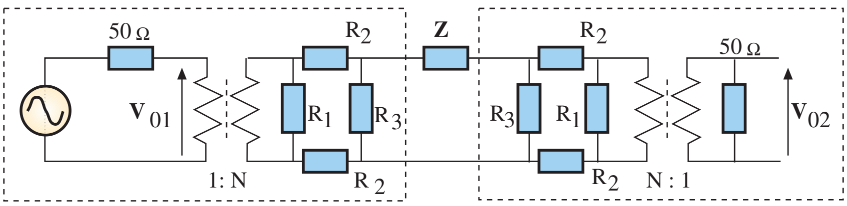


Figure 6 Balanced measurement of impedance

To simplify the problem we establish the Thevenin equivalent of the circuit shown, see Figure 7. The first step is to calibrate the set-up with a short circuit in place of the impedance to be measured. The quotient between the two voltages (in module and phase) during calibration becomes:

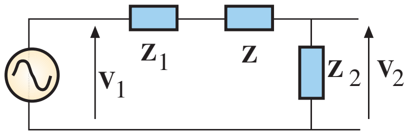


Figure 7 Thevenin equivalent of impedance measurement, serial method

$$\frac{V_2}{V_1} = \frac{Z_2}{Z_1 + Z_2} \tag{40}$$

The measurement is now repeated with the impedance present. The quotient between the two voltages now becomes:

$$\frac{V_2^*}{V_1} = \frac{Z_2}{Z_1 + Z_2 + Z} \tag{41}$$

By combining (40) and (41) the impedance Z can be calculated in module and phase:

$$Z = \left(\frac{V_2}{V_1} \cdot \frac{V_1}{V_2^*} - 1 \right) \cdot (Z_1 + Z_2) \tag{42}$$

The accuracy of the formula can be estimated. If the impedance Z is increased by δZ, this will result in a decrease of the measured voltage V_2^*. Inserted in (42) we get the following.

$$Z + \delta Z = \left(\frac{V_2}{V_2^* - \delta V_2^*} - 1 \right) \cdot (Z_1 + Z_2) \tag{43}$$

By applying (42) and rearranging the variables, the result is:

$$\frac{\delta Z}{Z} = \frac{1}{\left(1 - \frac{V_2^*}{V_2}\right) \cdot \left(1 - \frac{\delta V_2^*}{V_2^*}\right)} \cdot \frac{\delta V_2^*}{V_2^*} \tag{44}$$

If we look once more at Figure 6, we observe that the impedance may as well be connected as a shunt instead of a serial element. The Thevenin equivalent of this circuit is depicted in Figure 8. The calibration is performed when the impedance is disconnected, and the situation is quite similar to the serial method. The quotient between the two voltages is as given in (40). (Note that the values of source and load impedances may be different from those used for the serial method.)

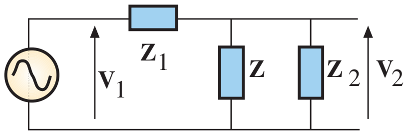


Figure 8 Thevenin equivalent of impedance measurement, parallel method

As the impedance is connected, the relation between the voltages and the impedances becomes:

$$\frac{V_2^*}{V_1} = \frac{Z \cdot Z_2}{Z + Z_2} \cdot \frac{1}{Z_1 + \frac{Z \cdot Z_2}{Z + Z_2}} \tag{45}$$

The impedance can now be calculated in module and phase from the equation (40) and (45):

$$Z = \left(\frac{V_2}{V_1} \cdot \frac{V_1}{V_2^*} - 1 \right)^{-1} \cdot \left(\frac{Z_1 \cdot Z_2}{Z_1 + Z_2} \right) \tag{46}$$

The accuracy of the parallel method can as well be established. If the measured impedance should increase, the result will be an increase in the measured voltage.

$$Z + \delta Z = \left(\frac{V_2}{V_2^* + \delta V_2^*} - 1 \right)^{-1} \cdot \frac{Z_1 \cdot Z_2}{Z_1 + Z_2} \tag{47}$$

By applying (46) and rearranging the variables the following relation is established:

$$\frac{\delta Z}{Z} = \frac{1}{1 - \frac{V_2}{V_2^*} \cdot \left(1 - \frac{\delta V_2^*}{V_2^*} \right)} \cdot \frac{\delta V_2^*}{V_2^*} \tag{48}$$

The two methods for measuring balanced impedance is characterised in Table 2. The column in the centre of Table 2 gives the voltage quotient used in both methods. In the first column the resulting impedance is calculated when the impedance $(Z_1 + Z_2)$ is normalised to 1.0. The next two columns give the overall accuracy for a given accuracy in voltage measurements.

Table 2 Comparison of the two methods for measuring impedance of a balanced cable

Serial method			**Voltage quotient**	**Parallel method**		
Calculated impedance[1)]	Accuracy of measurement[3)]			Accuracy of measurement[3)]		Calculated impedance[2)]
	0.5 %	3 %	dB	0.5 %	3 %	
.12	4.6	28.	1.0	4.4	22.	8.2
.59	1.4	8.4	4.0	1.3	7.7	1.7
.995	1.0	6.2	6.0	1.0	5.8	1.005
1.51	.86	5.1	8.0	.83	4.9	.6614
2.16	.74	4.5	10.0	.73	4.3	.4625
9.00	.56	3.4	20.0	.56	3.3	.1111
99.00	.51	3.1	40.0	.51	3.0	.01010

1) The impedance $(Z_1 + Z_2)$ in (42) is normalised to 1.0.

2) The impedance $(Z_1 \cdot Z_2) / (Z_1 + Z_2)$ in (47) is normalised to 1.0.

3) Estimated accuracy of calculated impedance using (43) and (48) respectively.

The last three columns of Table 2 deal with the parallel method of measuring balanced impedance. The last column gives the calculated impedance based on the voltage quotient measured as the impedance $(Z_1 \cdot Z_2) / (Z_1 + Z_2)$ is normalised to 1.0. The two preceding columns give the overall accuracy for a given accuracy in voltage measurements. In Table 2 only real values are present to illustrate the characteristics and accuracy of the two methods. In the general case the phase relation is joined together with the voltage quotient and the impedance becomes complex.

Some observations may be obtained from Table 2.

1. For a voltage quotient of less than 6 dB, the overall accuracy gets significantly reduced. This can be avoided by using the serial method for high impedances and the parallel method for low impedances.
2. The serial method can be improved by decreasing the value of the impedance $(Z_1 + Z_2)$.
3. The parallel method can be improved by increasing the value of the impedance $(Z_1 \cdot Z_2) / (Z_1 + Z_2)$.

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Techno-economic guidelines for telecommunication networks and services

MARKKU TAHKOKORPI AND MARKKU LÄHTEENOJA

This paper discusses the nature of techno-economic guidelines for telecommunications networks. The strengths and weaknesses of techno-economic guidelines and how they should be derived from techno-economic analysis results are described. The paper also discusses the value of techno-economic guidelines to different players in telecommunications business.

1 Introduction

The current international telecommunications marketplace is increasingly competitive and the regulatory regime is changing for many reasons. New technologies are introduced in the networks and new services are offered. The speed of change has also increased remarkably, which means that important decisions have to be made fast without a too long analysis period.

Thus, techno-economic evaluations of telecommunication network projects are required in order to enable a sound basis for decisions in the midst of a competitive marketplace with inherent high risks and uncertainties. The techno-economic calculation results usually form the basis from which guidelines for network evolution are drawn. In this paper the nature of techno-economic guidelines for telecommunications networks are discussed, and the strengths and weaknesses of such guidelines are outlined.

2 What is a techno-economic guideline?

Techno-economic guidelines in telecommunications can be defined as a set of statements about the generic techno-economic behavior of telecommunications network technologies and services. They are based on results of a comprehensive techno-economic analysis of the subjects in question. This means analysis of selected network technologies and services in relevant socio-economic and geographic environments.

The process of techno-economic guidelines consolidation is illustrated in Figure 1, which depicts such a process within ACTS (Advanced Communication Technologies and Services) [1, 2]. The business cases on which the guideline consolidation mainly is based are defined following a comprehensive information gathering, both from related ACTS projects and other sources. The techno-economic calculations and corresponding results are then condensed and rationalized to consolidated deployment guidelines in co-operation with selected field trials and projects within ACTS and other actors.

3 Motivation for techno-economic guidelines

The Telecom Regulators of today need economic background for their decisions, because they often have strong economic impact on the market players. Decisions like interconnection pricing, national roaming in some mobile services and copper loop unbundling require a strong understanding of their economic implications to operators and their customers.

Established operators selecting network technologies and timing of introduction of new services need strategic level information about economics of these new technologies and services. New operators, as well as established operators entering new markets need to have understanding of the business dynamics in new market situations.

Bankers financing network construction of various operators also need to understand the economics of the businesses their customers are entering, to be able to do proper financing decisions. The same problems can also be seen on a higher level when international establishments like the World Bank make decisions on funding for infrastructure investments in various developing countries.

Equipment manufacturers also need to understand the business of their customers and the impact of their future products to the general business situation.

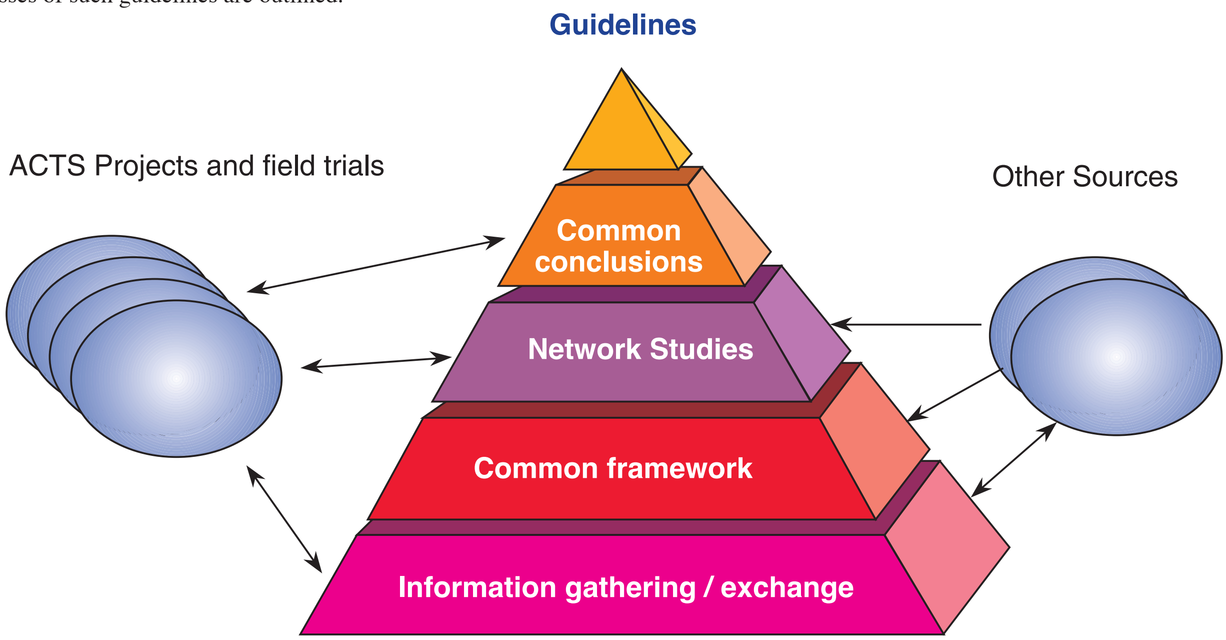

Figure 1 Rationalizing to consolidated techno-economic guidelines

Hence, all of the major actors in the industry are in need of techno-economic guidelines extracted from comprehensive technical and economic assessment of the issues in question.

4 Guidelines for regulators

Regulators of today's telecommunications services are generally aiming at liberalizing the telecommunications marketplace. To do this, they try to make the regulation such that competition can emerge despite the generally very strong market position of the incumbent operators. Because incumbents usually have control of the majority of the infrastructure and initially also the customers, the regulators have to take care of the fact that emerging operators can get access to these resources at fair terms. This often means making regulatory decisions on interconnect pricing, cost of copper line rental, etc. In this respect generic techno-economic guidelines have high value, especially if they are based on analysis independent of the players in the market.

5 Guidelines for operators

Established operators are not as interested in generic guidelines as regulators, but they too are interested in analysis of emerging technologies and services. The most interesting thing for established operators is the timing of introduction of new products for their customers. The new products can be based on new network technologies like WDM transmission or broadband access networks or they can emerge on a service level like Internet access or various IN based services. Generic guidelines are not very useful for operators, but they can give hints on which technologies or services should be analyzed in detail. Operators need to do the analysis themselves or use consultants with their own input data for more accurate results because the local restrictions and assumptions are usually important for the total profitability of a business case.

6 Guidelines for financiers

Financial institutions are usually looking at techno-economic issues at very high level, which means that they can readily utilize generic techno-economic guidelines. They are usually interested in 'Rule of thumb' type of information. The economic output is important for them. They are interested in general cost levels of typical socio-economic and/or geographic areas like Western Europe, Eastern Europe, Urban areas, Rural areas, etc.

Financial institutions will combine these guidelines with general market trends to make their own profitability analysis for the service or network providers they are financing.

7 Guidelines for manufacturers

Manufacturers of telecommunications equipment are naturally interested in areas where their customers can make profitable business, and they will focus their R&D efforts to products where they can increase value added from their customers networks. Manufacturers are more interested in generic guidelines than operators, because they have to sell their products to different types of operators in various markets. Manufacturers will analyze the value added from the product or concept to Operators using generic guidelines as starting point or input for analysis. The interesting question for the manufacturer is "what is the potential market size for a certain product?".

8 Key restrictions

A general representation of a techno-economic evaluation process is shown in Figure 2. The (business) case definition includes specifications of service parameters, network architecture dimensioning and the relevant cost information. The techno-economic modelling takes these three aspects into account and the model run produces results which in turn are analysed. It is these analysis results which form the basis for the techno-economic guidelines.

However, the possible incorrect assumptions in doing the analysis behind guidelines may impose some key restrictions for generic guidelines. Because techno-economic analysis is a complicated issue having multiplicity of inputs, even very generic guidelines have assumptions as inputs. These assumptions may be grouped into four main groups, namely area, regulatory, market and technology assumptions:

Area assumptions: These assumptions have to reflect some kind of average over a certain area, which does not always coincide with the area the guideline reader is interested in. This means that when giving techno-economic guidelines the assumptions behind the results should also be given.

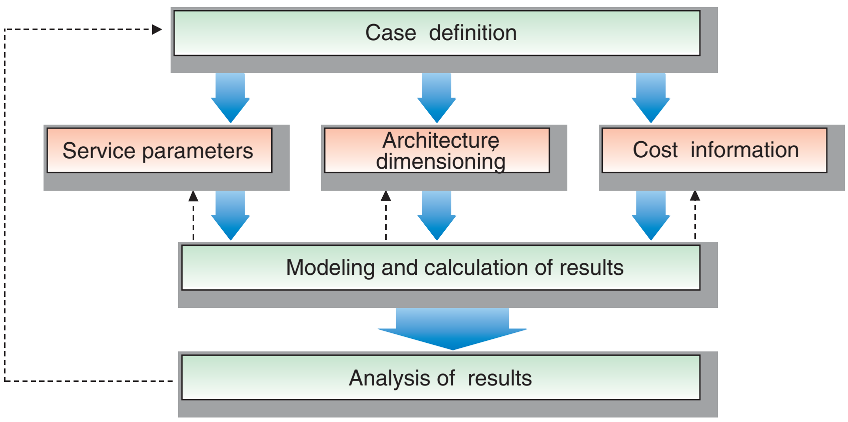

Figure 2 The techno-economic evaluation process

Regulatory assumptions: Another restriction for the guidelines is the regulation of telecommunications business, since the market is nowhere totally free, and the regulatory decisions, varying from market to market, can have strong impact on the economics.

Market assumptions: The market development is likely to have the most significant impact on the overall results of the calculations, and are usually also the most dubious assumptions.

Technology assumptions: Some guidelines are based on analysis of future technologies and there lies a risk in expectations for the future technology capabilities and costs.

The problems of uncertainty in the assumptions can to some extent be tackled by utilizing risk analysis. Guidelines should always be based on analysis with a comprehensive sensitivity and risk analysis. Even if a thorough risk analysis is carried out, the challenge of defining the correct correlation between different parameters and input uncertainty distributions remain, and may restrict the results.

9 Benefits of guidelines

Techno-economic guidelines based on sound analysis work can give valuable information about the behavior of the telecommunications marketplace. Typical of this information are the general cost levels and trends of network functions implemented with different technologies, relative profitability of various services in a typical market, etc.

Guidelines will help different market players to make better decisions either directly based on guidelines or after further more specific analysis. Any case guidelines can speed up the analysis and decision making process notably. They will also inform about the critical issues related to economics.

10 Conclusions

As discussed in this paper techno-economic guidelines can give valuable information on economic aspects of new services and technologies within telecommunications. They can assist regulators, operators and financiers in decision making either directly or as pointing to the issues to be studied in detail.

The evaluation process itself is even more valuable if done efficiently. It gives deeper knowledge on the issues than the guidelines can give because all results cannot be condensed into a short document.

The actual business decisions usually have to be based on each actor's own data, but the guidelines can help in focusing one's own analysis into critical issues.

A good methodology for making the basic techno-economic analysis for deriving the guidelines is the OPTIMUM methodology and tool developed within the EU-funded research projects TITAN (R2087) and OPTIMUM (AC220), and further enhanced in the ongoing TERA project (AC364) (3, 4). The methodology and the tool define a framework for the analysis consisting of a geometric model for mapping of various geographic situations, a European cost database for a large set of equipment and specified methodology for making the economic analysis including the sensitivity and risk analyses. Application of a common methodology like OPTIMUM will help gain comparable results (Benchmarks) from different analyses and widen the scope of validity of the guidelines. The same methodology can also be utilized for specific analyses for each other's own business cases.

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OPTIMUM – a techno-economic tool

BORGAR TØRRE OLSEN

1 Introduction

This paper presents the methodology and tool for techno-economic assessment developed by the projects AC226/OPTIMUM[1)] and R2087/TITAN[2)] within telecommunications research ACTS[3)] and RACE[4)] in the European Union (EU). The tool and methodology are presently supported in the AC364/TERA[5)]. The most important property of the OPTIMUM/TITAN methodology and tool is the ability to combine low level, detailed network parameters of significant strategic relevance (eg. variations in civil works costs, network termination cards, splitting ratio of passive optical networks), with high level, overall strategic parameters such as density of subscribers, tariff elasticity and broadband take rate [1, 2, 3]. The TITAN project developed a model for predicting the cost evolution for the network components which is based on a combination of the learning curves and the logistic model [1, 2, 4, 5]. The TITAN methodology and the tool have been enhanced within OPTIMUM to be able to cope with complex multimedia service and network structures. The methodology has been improved in particular in the definition of services [6, 7, 8, 9] and in the assessment of operations, administration and maintenance costs [10, 11]. Risk assessment is carried out with the OPTIMUM tool by the use of an add-on simulation program called Cristal Ball [12–16]. The OPTIMUM methodology and tool is widely accepted within the ACTS community and among other telecommunications actors as the state-of-the-art approach for techno-economic evaluations of multimedia communication services and networks. The tool has been adopted and extensively used by the relevant EURESCOM projects P306, P413 and P614 for deriving scenarios and guidelines for the European PNOs [3, 18–24].

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1) *OPTImised network architectures for MUltiMedia services.*

2) *Tool for Introduction strategies and Techno-economic evaluation of Access Network.*

3) *Advanced Communications Technologies and Services.*

4) *Research for Advanced Communications in Europe.*

5) *Techno-Economic Results from ACTS.*

2 Background

The Optimum methodology relates back to concepts developed under the first framework programme of the EU for telecommunications research, RACE I. The evolution prospects and frameworks (EPF) group of the RACE project R1044 "Integrated broadband communications development and implementation strategies" developed a first techno-economic approach and the SYNTHESYS tool. This study was based on a simple geometric model for quantifying the duct and cable lengths. The basis was a series of assumptions regarding eg. the flexibility point locations and the distribution of users. The cost database included component costs for the starting year only. The SYNTHESYS tool enabled calculations of the installed first cost as well as sensitivity analyses with respect to the subscriber density, hub size and splitting ratio. At that stage, the cost of innovating optical networks appeared to be prohibitive, since the calculations were based on the initial component costs, which at that time were very high due to low production volume.

The work continued in 1992 through the RACE II framework programme. The project R2087/TITAN focused in more detail on the likely steps which must be taken by operators to develop broadband networks and services from the basis of the existing public switched telephone network (PSTN). The project developed a methodology for the assessment of optical access networks for the residential and small business user. The objective of TITAN was the calculation of the overall financial budget of any kind of access system, and hence the estimation of the economic viability of different kinds of access network evolutions. The TITAN methodology was developed to include:

- all kinds of network architectures;
- any kind of transmission media: fibre, copper or radio;
- various feeder lengths;
- cost data over a study period, calculated from the initial component cost, learning curves and volume demand parameters;
- civil works differentiating the various transmission media and based on different technologies yielding quite different unit prices;
- operation, administration and maintenance costs;
- life cycle costs;
- demand assessment for a wide range of services, using an extensive European Delphi survey [6, 7, 8, 9];
- cash balance based on the above demand assessment and on a first approach of the tariff and revenue aspects;
- a risk assessment regarding the investment in the access network in different environments with a variable degree of regulation, existing infrastructure or competition;
- introduction scenarios for selected case studies, themselves inspired by the European diversity.

This enables the comparison of various optical or hybrid architectures through a global system assessment and contributes to the identification of minimum-risk introduction strategies. The methodology and the tool developed within this project have been validated by comparisons with operating European networks and field trials. The TITAN project developed a model for predicting the cost evolution for the network components, which is based on a combination of the learning curves and the logistic model [1, 2, 4, 5]. During the OPTIMUM project studies, the new version of the tool was extended to model, dimension, and calculate costs of both the transport and switching part of the network in addition to the access network models used with previous versions of the TITAN tool. This was done by extending the number of network levels available in the geometric model and by studying the required resource sharing and traffic dimensioning problems. The methodology has been further improved, in particular in the definition of services and in the assessment of operations, administration and maintenance costs. The OA&M approach in the earlier TITAN methodology was based on the simple assumption that OA&M costs are directly related to the cumulative investments in the network. The OPTIMUM tool automatically calculates the maintenance costs which are split into costs of repair parts which is proportional to the investment costs and repair labour costs which depend on the equipment replacement rate [10, 11]. In addition, the operation and administration costs must be manually modelled in each case. Risk assessment is carried out by combining an add-on simulation program with the OPTIMUM tool [12–16].

3 Framework and methodology

Figure 1 shows the principles of the OPTIMUM tool. OPTIMUM calculates the economic value of network projects based on given tele and data communications needs. OPTIMUM calculates, among other things, costs for network components and installations, civil work costs, operation, administrations and maintenance costs, service revenues, total investment costs, cash flows, net present values, and pay back periods. The lengths of cables and ducts with associated civil works costs are derived within the tool with the aid of different built-in geometrical models. The component costs are extracted from the project's cost database. The cost figures for the network components are collected in an integrated cost database with inputs from many different European sources. The database contains cost elements of varying technological maturity and with different degrees of commercial availability. The cost evolution of the different components are derived from the cost in a given reference year and a set of parameters which characterise the components. Operation, administration and maintenance costs are added to provide the life-cycle costs. The final budget values of the different projects are calculated by integration of the service take rates and tariffs with the life-cycle costs.

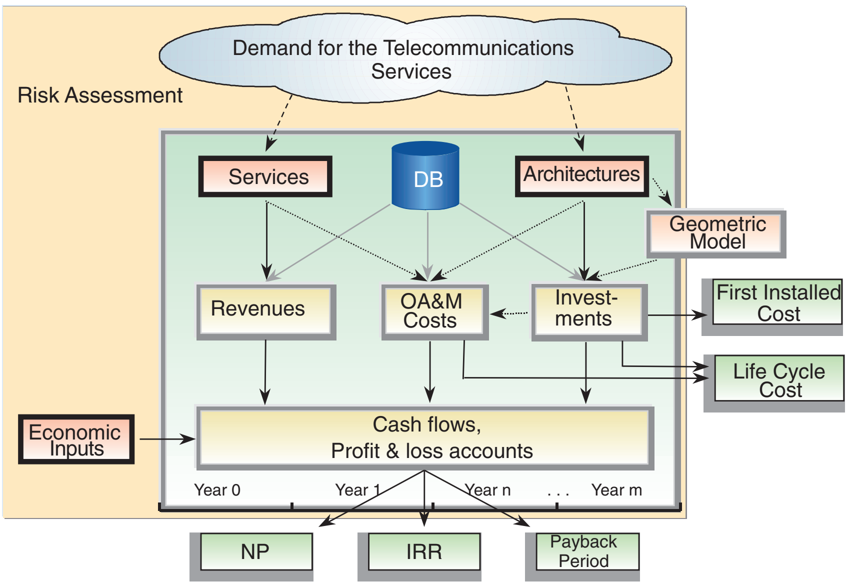

Figure 1 OPTIMUM tool

3.1 Steps in the OPTIMUM calculation

The following steps are needed in the techno-economic evaluations of the network solutions:

1 *Services specification:* The services to be provided must be specified. The market penetration of these services over the study period must be defined. The services have associated tariffs, ie. the part of the tariff that is attributed to the network under study. From the combination of yearly market penetration and yearly tariff information OPTIMUM calculates the revenues for each year for the selected service set.

2 *Revenues:* In most of the evaluations the calculation includes the revenue from the services. The OPTIMUM methodology handles the revenue simply by using a service connection tariff and estimating a certain annual tariff for each service per connected customer. In general, both connection tariffs and usage tariffs are time series over the study period. It must be noted that revenue in OPTIMUM refers to the part going to the network operator, not the service provider. This is not a limitation of the methodology.

3 *Architecture definition:* The network architectures to provide the selected service set must be defined. This needs network planning expertise and is mostly outside the framework of the OPTIMUM methodology. However, OPTIMUM includes several geometric models that will facilitate the network planning by automatically calculating lengths of cables and ducting. These geometric models are optional parts of the methodology and OPTIMUM can be used without them. The result of an architecture scenario definition is a so-called shopping list. This list indicates the volumes of all network cost elements (equipment, cables, cabinets, ducting, installation, etc.) for each year of the study period and the location of these network components in different flexibility points and link levels.

4 *Investments costs:* The costs of the network components are calculated using an integrated cost database developed within the OPTIMUM project, containing data gathered from many European sources. Network architectures together with the cost database give investments for each year. Since the OPTIMUM methodology studies scenarios, investments are usually spread over the study period. To get a single figure of merit for the total investment, the future investments are discounted to the start of the study period using the conventional discounting formula. The total discounted investment cost is usually called First Installed Cost. In the OPTIMUM methodology the network is subdivided into a hierarchy of flexibility points and link levels (see Geometric models, further in this document). Links interconnect flexibility points. All links or flexibility points in the same hierarchical level form a so-called network level. The current implementation of the methodology allows the investments to be analysed based on physical location of the cost components in the network (by hierarchical network level).

5 *OA&M costs:* The OA&M costs are divided into three separate components. Conceptually, the three components are defined as follows:

- M1 – Represents the cost of repair parts. This component is included automatically in the models and is driven by the investments, ie. the same approach as was used in TITAN for all OA&M costs.
- M2 – Represents the cost of repair work. This is also automatically included in the models. Detailed description of the M2 component is given below.

- O&A – This component represents Operation & Administration costs and it has to be included manually when building models. Typically, it would be driven by services, say by number of customers, or by number of critical network elements.

6 *Life-cycle costs:* Investment costs together with the OAM costs give the life-cycle costs (LCC) for the selected architecture scenario.

7 *Project values:* Finally, by combining service revenues, investments, operating costs and general economic inputs (eg. discount rate, tax rate) OPTIMUM gives profits, cash flows and other economic results (NPV, IRR, Pay back period, etc.).

- *Profits:* These time-series are calculated from the revenues, investments, depreciation and taxes.
- *Cash flows:* These time-series are calculated as the difference between life-cycle costs and revenues.
- *Retained cash flows:* These time-series are calculated as the difference between life-cycle costs and revenues minus tax.
- *Cash balance:* The cash balance or cumulative cash flow time-series is a very informative figure for a specific network/service scenario. Especially for a green field case it gives much information in a single picture. A typical cash balance curve for a network scenario goes first deep down to the negative side because of the high initial investments. If the scenario is profitable, the cash flow turns positive fairly soon and the cash balance curve starts to rise. The lowest point in the cash balance curve gives the amount of funding required for the project. The point in time when the cash balance turns positive gives the pay back period for the project. In an investment scenario where most of the expenditure happens at the beginning of the study period, the pay back period gives a good indication of the efficiency of the investment. If the scenario is more complex, that is, if there are for example several technology steps in an upgrade situation, it is sometimes not possible to define a single pay back period. It is still possible to use the cash balance curve as an indicator for the profitability of the scenario. In these cases it is important to study the trend of cash flow at the end of the study period.
- *Pay back period:* The point in time when the cash balance turns positive gives the pay back period for the project. In an investment scenario where most of the expenditure happens at the beginning of the study period, the pay back period gives a good indication of the efficiency of the investment.
- *Net present value:* The net present value (NPV) gives a single figure of merit for a project. Its definition is the sum of discounted retained cash flows plus discounted rest value of the project. It is a good indicator for the profitability of the scenario especially in these cases where the pay back period cannot be used because major investments are spread out in time. The weakest point in this figure of merit is the definition or calculation of the rest value of the network. There are several ways to try to define this value. The usual approach uses the book-keeping value of the network as the rest value because it is the only figure that can be calculated from the inputs already available.
- *Internal rate of return:* The internal rate of return (IRR) is the discount rate at which the NPV is zero. If the IRR is higher than the opportunity cost of money (that is, interest of an average long term investment), the project is viable. If the scenarios to be compared are not similar, for example if the size of these networks is different, these cannot be easily compared using net present values. In these cases internal rate of return gives a good indication on how good 'value for money' these projects have.

3.2 Market input to the model

The service input describes the services and applications provided by the service operators. It identifies the packages of services to be supported by the selected architectures, and provides the description of their penetration over the period under study. In the Delphi surveys carried out by TITAN and the OPTIMUM projects the service penetration was correlated to the level of tariffs and customers' willingness to pay [6, 7, 8, 9]. The elements of the market inputs are:

1. *Service type;*
2. *Penetration of services (initial, forecast);*
3. *Subscription tariffs;*
4. *Market shares;*
5. *Service penetration is the percentage of customers who will subscribe to the service.*

3.3 Technology input to the model

The technology input contains the description of relevant technologies, systems and architectures to provide the services in the form of selected target and intermediate access network architectures. The technology inputs are related to network architectures, network technologies, network equipment and installation and operation, administration and maintenance (OAM) procedures:

1. *Network architectures and technologies;*
2. *Existing network architecture;*
3. *Intermediate network architecture;*
4. *Final network architecture;*
   cost of network equipment and installation;
5. *Cost of operation, administration and maintenance procedures.*

The technology inputs to the model reflect some migration paths from the beginning of the study period to the last year. Selection diagrams as presented in Figure 2 can describe the different potential migration paths.

3.4 OA&M approach

The OA&M approach in the earlier TITAN methodology was based on the simple assumption that OA&M costs are directly related to the cumulative investments in the network. This had to be rethought in OPTIMUM because multimedia networks have different types of equipment and OA&M cost components which means that OA&M costs are not as directly related to the investments as they have been in traditional telecommunications access networks. Figure 3 shows the OPTIMUM OA&M approach.

Calculation of M_2 component

The calculation of M_2 component is based on failure rate and on the time it takes to repair the unit.

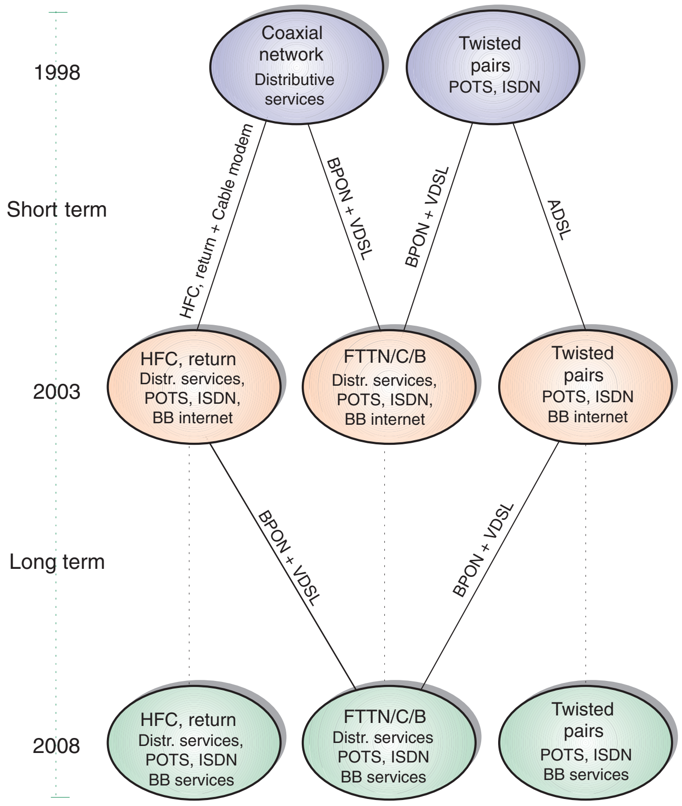

Figure 2 Access Network Migration Example

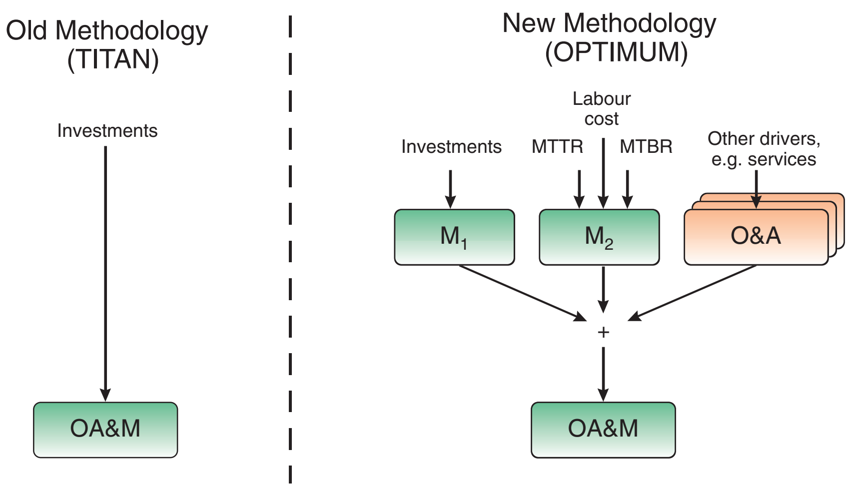

Figure 3 TITAN and OPTIMUM OA&M methodologies compared

Input parameters are:

1 Cost of work hour, P_l [ECU/hour] (defined in time series sheets);

2 Mean Time Between Repairs, MTBR [years] (defined in database for each cost component);

3 Mean Time To Repair, MTTR [hours] (defined in database for each cost component).

The formula for calculating M_2 is

$$M_2 = P_l \cdot \frac{MTTR}{MTBR}$$

In order to implement this, two new classes for MTTR and MTBR must be defined in the database.

With this new methodology, the maintenance costs for cables are slightly problematic. In order to produce meaningful results for M_2 in the case of cables, the cable price must be defined as price per kilometre [ECU/km] in the database.

Total maintenance costs

The total maintenance costs caused by any single cost component in year i are

$$M_1 = (M_1 + M_2)_i$$

$$= \frac{V_{i-1} + V_i}{2} \cdot \left(P_i \cdot R_{class} + P_l \cdot \frac{MTTR}{MTBR} \right)$$

where

V_i	is the equipment volume in year i;
P_i	is the price of cost item in year i;
R_{class}	is the maintenance cost percentage (defined by choosing MaintenanceMaterialClass for every cost component);
P_l	is the cost of one working hour;
$MTTR$	is the mean time to repair for the cost item in question;
$MTBR$	is the mean time between failures for the cost item in question.

3.5 Uncertainty in the inputs

The main sources of uncertainties in the model are the competition between operators, the varying costs of network components caused by the unpredictable service market, the lack of knowledge about costs of operating the new architectures and the errors in the prediction of service demand. The uncertainties of the cost elements and market elements have been modelled as functions of time for the risk assessment.

3.6 Evaluation criteria

The identification of a number of evolutionary paths and the selection of scenarios have to be matched with the needs of the operator to select the optimal strategy to achieve his targets. The evaluation criteria listed below can be introduced and qualitatively applied to the selected scenarios and strategies. The OPTIMUM methodology described in this paper illustrates one approach for performing the quantitative evaluations of scenarios and strategies.

- Capability to reuse the existing network and infrastructures;
- Capital and running costs;
- Potential revenues;
- Exploitation of market opportunities or risk of missing them;
- Upgradeability to more advanced solutions;
- Compliance to ONP criteria;
- Need for disposal of installed network;
- Network residual value.

The network residual value is estimated at the end of the study period since it contributes to the total amount of resources available to the operator. The residual value of the capital investments can still be significant after the upgrade period, and may increase the value of the project when it is integrated with the cumulative cash balance estimate to build the Net Present Value (NPV).

4 Geometrical models for cables and ducts

The cost of digging trenches, installing ducts and cables is crucial in the economics of any telecommunications network infrastructure. A geometric model is used to estimate the amount of cable, ducts and civil works (trenches) required in such network. On a conceptual level the geometric model is a function that takes several inputs such as subscriber density, network topology (star, ring, bus), average over-length (adjustment of model outputs), duct availability, etc., and output values like trench length, duct length and cable length. As the geometric model delivers the basis for the quantity calculation of some very important cost components, it is an important and fundamental step towards the broader task of techno-economic modelling of a telecommunications project. Various geometric models were developed and used in the RACE projects SYNTHESYS and TITAN and in the ACTS project OPTIMUM. The model called TITAN/OPTIMUM model, is built upon the most advanced TITAN model.

4.1 The SYNTHESYS model

The SYNTHESYS model is a polygon based geometric model for the access network, as shown in Figure 4.

The first level links consist of A–B, B–C, C–D and C–E links. Second level links are denoted D–F links. Third level links are the links between F and the subscriber premises entrance.

A set of equations has been derived in order to calculate cable length estimates at different network levels. In these equations the following variables are used:

d = number of potential users per km^2;

N = number of potential users per hub;

n = number of fibre cables leaving the hub (n is also the rank of the polygon);

M = Number of potential users per branching box.

The radius of the polygon is:

$$\left|\overline{AV}\right|^2 = R^2 = \frac{2 \cdot N}{d \cdot n \cdot \sin(\alpha)} \qquad (1)$$

where α is the peak angle of the triangular sector:

$$\alpha = 360^\circ / n \qquad (2)$$

Using these variables cable length estimates can be expressed as follows:

$$\left|\overline{AB}\right| = \left|\overline{BC}\right| = \frac{R}{3} \cdot \cos\left(\frac{\alpha}{2}\right) \qquad (3)$$

$$\left|\overline{CD}\right| = \left|\overline{CE}\right| = \frac{R}{6} \cdot \sqrt{1 + 8 \cdot \sin^2(\alpha/2)} \qquad (4)$$

$$\left|\overline{DF}\right| = R \cdot \left(0.132 + \frac{0.336}{n}\right) \qquad (5)$$

Equations (1) – (4) are directly derived from the geometry, whereas (5) is obtained by simulation. The area of surface S corresponding to a branching box is:

$$S = \frac{M}{d} \qquad (6)$$

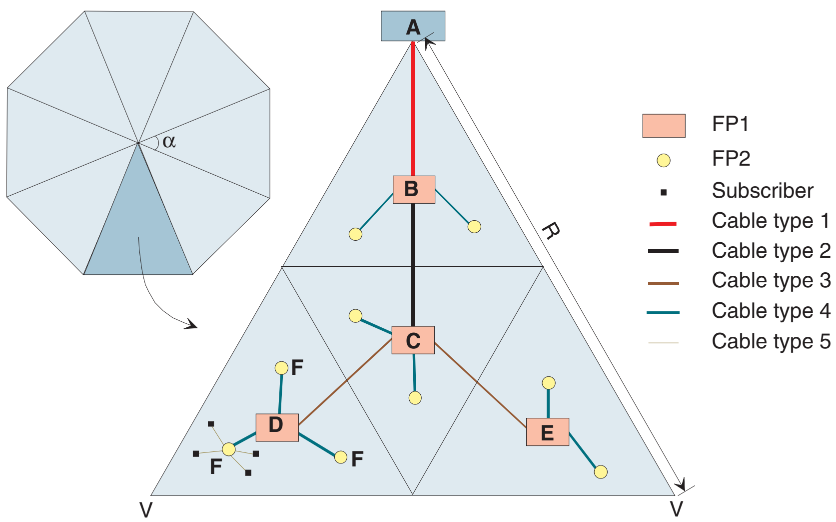

Figure 4 The SYNTHESYS model

By approximating that this surface is equivalent to a circle, ie. $\pi \cdot r^2$, the average distance b between the branching box and building entrance is:

$$b = \frac{2r}{3} = \frac{2}{3} \cdot \sqrt{\frac{M}{\pi \cdot d}} \qquad (7)$$

An average distance of 15 metres is assumed between the building entrance and the subscriber premises. Therefore, the total branching distance L_{branch} is:

$$L_{branch} = b + 15 = 15 + \frac{2}{3} \cdot \sqrt{\frac{M}{\pi \cdot d}} \qquad (8)$$

The additional 15 metres is assumed to be within the building for which no ducting is included. The maximum length of the subscriber line, L_{max}, is:

$$L_{max} = 3 \cdot \left|\overline{AB}\right| + \left|\overline{CD}\right| \qquad (9)$$

Cable lengths are calculated from the geometric model using the same equations as for the duct lengths. To these values further cable overlength due to field constraints is added. Overlength is expressed in percentages, and typically 40 % has been used.

Depending on the situation the estimates for the total cable and duct lengths to be used in economic models are calculated from equations (3), (4), (5) and (8). In some cases it is convenient to form a single equation for the average subscriber loop length by combining the above mentioned equations. However, this equation would not be generally applicable, eg. because some link levels might use different types of cable and hence links could not be combined in modelling.

The SYNTHESYS model as described above has been successfully applied to passive optical network (PON) architectures, among others. However, the large diversity in access network architecture types requires a more flexible model.

4.2 The TITAN/OPTIMUM model

The basic structure of the SYNTHESYS model and its variants is based on a star topology and polygon geometry. In many cases this is a valid assumption, but there are cases where the polygon structure is not ideal. Because of this TITAN and OPTIMUM have developed a completely new geometric model, namely the TITAN/OPTIMUM model, which is more flexible in many senses. This model allows modelling of clustered areas where subscribers are not homogeneously distributed. The topology can be either a star, ring or bus, or a combination of these. In addition, the shape of the model area and location of flexibility points within the model area are taken into consideration.

In Figure 5 the basic structure of the TITAN/OPTIMUM model is shown. The model is based on a layered structure in which each layer uses the same basic geometric model, but with different parameters. A model layer represents a specific type of flexibility point (FP); eg. Head-End (HE), optical nodes or last amplifier in a HFC network, and is characterised by FP area density and distribution ratio. The distribution ratio n at a given layer or network level represents the number of lower-level flexibility points linked to this flexibility point (eg. 50 optical nodes linked to 1 HE). Link levels (LL) interconnect the flexibility points of different levels (eg. LL2 interconnects FP1 and FP2).

Total trench, duct and cable lengths in the model area are achieved by simply adding lengths from different layers. Between the layers there can be a certain amount of empty space. One layer can, for example, represent a village and the next higher layer will be a larger region where there are scattered villages and uninhabited areas in between.

The basic model area in each layer is rectangular as depicted in Figure 6. The area has a length of 'a' units and a width of 'b' units. The unit value relates to the density of flexibility points in the model layer area. For a homogeneous distribution of flexibility points with a density d_f, a unit is $1/SQRT(d_f)$. On the lowest level

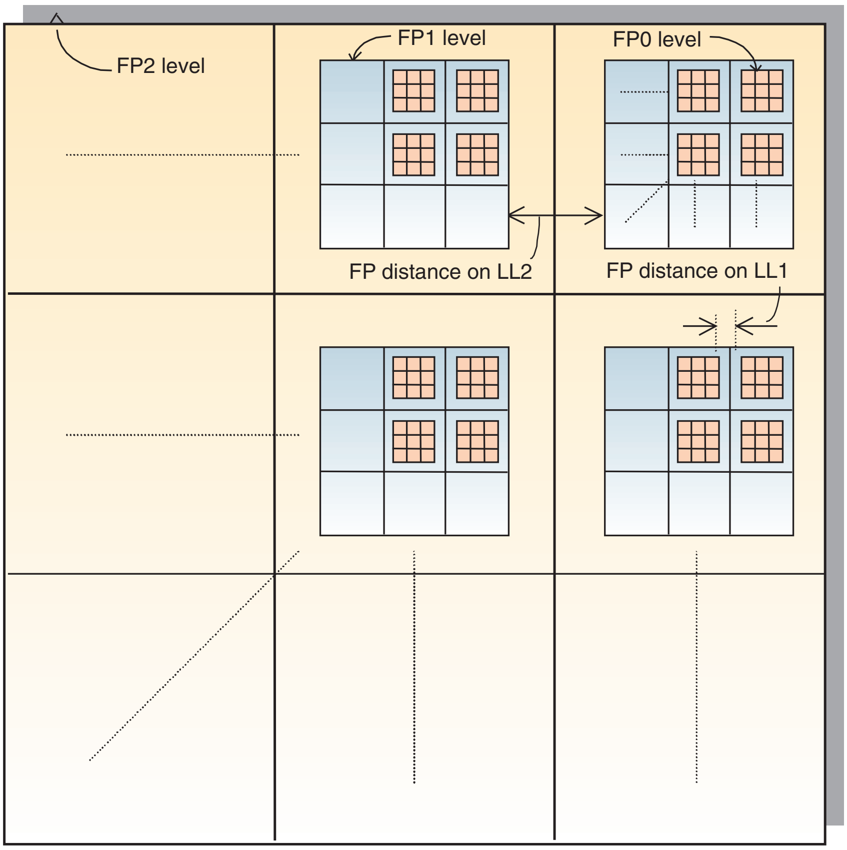

Figure 5 The first three levels of the TITAN/OPTIMUM geometric model

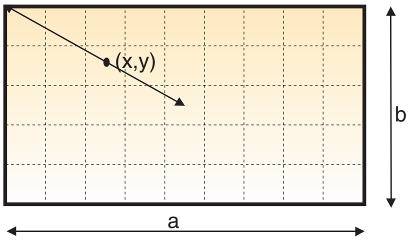

Figure 6 The basic model area for one model layer

of the network model, where the flexibility point (FP0) usually refers to the subscriber location, d_f equals the subscriber density d_s in the considered area. The higher level flexibility point densities are calculated from d_s by considering specific dimensioning rules (eg. maximum optical node size will define the optical node density as a function of the subscriber density). Further in this section we will look at the normalised case with unit value set to 1.

Figure 7 shows how the ducts are located within the basic model area. Also one example cable from flexibility point (x,y) to the user or the lower level flexibility point (i,j) is shown.

The duct length, l_d, is given by

$$l_d = a \cdot b - 1 = n - 1 \qquad (10)$$

where n is the distribution ratio at a given network level. Each square in the model area represents a lower model layer or, at the lowest level, a subscriber. The sublayer or subscriber located at point (i,j) will be connected to distribution point (x,y) with a cable that makes one rectangular turn on its way, as shown in Figure 9. The total cable length in case of a star topology at any given network layer will be:

$$l_c(a,b,x,y) = \sum_{i=0}^{b-1} \sum_{j=0}^{a-1} [|i-y| + |j-x|] \qquad (11)$$

where

- a is the length of the model area;
- b is the width of the model area;
- x is the length co-ordinate of distribution point, $x \in [0, a-1]$;
- y is the width co-ordinate of distribution point, $y \in [0, b-1]$.

After some calculus this yields

$$l_c(a,b,x,y) =$$
$$\frac{a}{2} \cdot \left[(b-y-1)^2 + y^2 + b - 1\right] +$$
$$\frac{b}{2} \cdot \left[(a-x-1)^2 + x^2 + a - 1\right] \qquad (12)$$

The variables used in (12) are not very suitable for use in the final application. It is more intuitive to express the cable length as a function of distribution ratio n, area shape s and position p. The shape factor s indicates the shape of the model area, ie. if the area is a square or a rectangle ($a = s \cdot b$). The position variable $p \in [0,1]$ equals zero when the distribution point is in the middle of the area. As p grows, the distribution point moves along the arrow in Figure 6 towards the corner of the area. When p equals one, the distribution point is in the corner of the area.

Now a, b, x and y can be expressed as functions of n, s and p as follows:

$$a = \sqrt{ns}$$
$$b = \sqrt{\frac{n}{s}}$$
$$x = \frac{\sqrt{ns} - 1}{2} \cdot (1-p)$$
$$y = \frac{\sqrt{n/s} - 1}{2} \cdot (1-p) \qquad (13)$$

Substituting the above expression into (12) gives the cable length as a function of n, s and p.

Previous equations enable the estimation of cable and duct lengths in the case of a star topology. For bus and ring topologies the situation is much simpler. Figure 8 shows the case for a ring topology.

$$l_{duct} = n$$
$$l_{cable} = n \qquad (14)$$

Thus, the cable and duct lengths are the same and equal to the splitting ratio. Figure 9 shows the situation for a bus topology.

$$l_{duct} = n - 1$$
$$l_{cable} = n - 1 \qquad (15)$$

The equations derived here for the TITAN/OPTIMUM model give the estimates for cable and duct lengths in undetermined *units*. Before these estimates can be used in economics modelling, they must be mapped into real length units, eg. metres. This is done by calculating the length of one *unit* at the lowest network level from the subscriber density per square kilometre. After this, the length of a *unit* in the second layer can be calculated from the *unit* length at the first layer and from the known geometry between the layers.

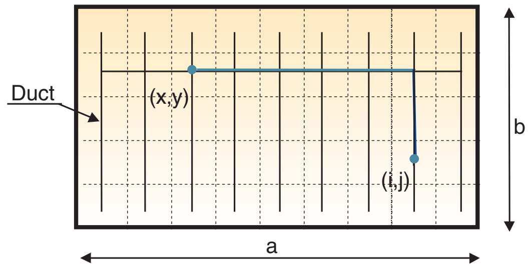

Figure 7 Basic model area for a star topology

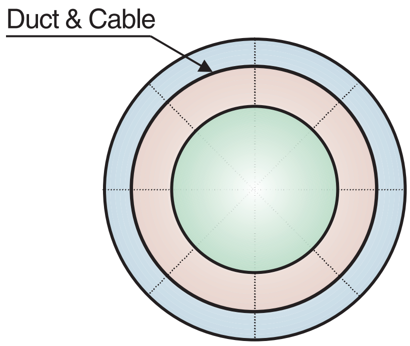

Figure 8 Ring topology (n = 8)

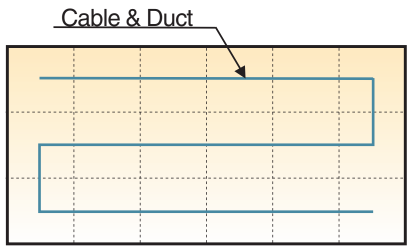

Figure 9 Bus topology (n = 18)

5 Component price versus time

Some of the equipment and components in the TITAN/OPTIMUM cost database have been on the market for some years. In this case traditional forecast methods can be applied to directly estimate the evolution of cost over time. In studying future strategic network projects such as an upgrade of the present narrowband access network towards a broadband access network, new components and equipment with different degrees of maturity are considered. In some cases only target costs can be obtained. The RACE 2087/ TITAN project developed a methodology for estimating the cost evolution of those components which combine information from the production process expressed in the learning curves and an estimating procedure for the volume forecast of the equipment and components [1, 2, 4].

The cost evolution of every component in the TITAN/OPTIMUM cost database is described by the following parameters:

- *Price* (cost) at a given reference year;
- *Reference year*;
- *Learning curve class*, which gives the cost of the component as a function of produced volume with one parameter: K (optimistic or pessimistic);
- *Volume class*, which gives volume as a function of time (forecast volume) with three parameters: Δt, $n(0)$ and γ;
- Δt, which is the time it takes for the accumulated production volume to increase from 10 % to 90 % of the total accumulated production volume;
- $n_r(0)$, which is the accumulated production volume by $t = 0$ (relative to total accumulated volume);
- γ, which describes the asymmetry of the applied logistic curve (set to 1 in the TITAN/OPTIMUM Tool).

In the TITAN/OPTIMUM methodology the description of the growth over time of the accumulated volume of every component in the cost database is a standard demand logistic curve:

$$n(t) = M\left[1 + e^{(a+b\cdot t)}\right]^{-\gamma} \quad (16)$$

By combining this standard demand logistic curve with a learning curve, the cost evolution in time of every component can be easily described [1, 2, 4, 5].

5.1 Learning curve coefficient

T.P. Wright first proposed the concept of learning curves [25]:

$$T_n = n^{-\alpha} \cdot T_0 \quad (17)$$

where T_n is the average production time for n units, given by

$$T_n = \frac{t_1 + t_2 + \cdots + t_n}{n} \quad (18)$$

where t_n is the time to complete the n^{th} unit, T_0 the time to complete the first unit and n is the number of completed units.

J.R. Crawford applied the same formula, but interpreted T_n as the completion time for the n^{th} unit [26]. Wright's law describes the cumulative effect of learning, while Crawford's formula only refers to scale effects. A disadvantage of Wright's law is the appearance of strong autocorrelation, affecting the statistical estimation of its parameters, a problem which always arises when trying to correlate accumulated values.

In the TITAN methodology we have assumed that component cost (price) P_n is proportional to production time T_n for the n^{th} component, which gives:

$$P_n = n^{-\alpha} \cdot P_0 \quad (19)$$

Now we can write

$$P_{2n} = (2n)^{-\alpha} \cdot P_0 \quad (20)$$

which may be expressed as

$$P_{2n} = (2)^{-\alpha} \cdot n^{-\alpha} \cdot P_0 \quad (21)$$

and

$$P_{2n} = (2)^{-\alpha} \cdot P_n \quad (22)$$

and

$$P_{2n} = K \cdot P_n \quad (23)$$

K is the factor by which the price is reduced when the production volume is doubled. K is called the learning curve coefficient and is related to α by

$$K = (2)^{-\alpha} \quad (24)$$

or

$$\alpha = -\log_2 \cdot K \quad (25)$$

$$\alpha = \frac{-\log_x \cdot K}{\log_x \cdot 2} \quad (26)$$

The K factor is a parameter which may be obtained from the production industry.

5.2 Component cost as a function of time

We know that n and P_n are functions of time. Thus

$$P(t) = n(t)^{-\alpha} \cdot P_0 \quad (27)$$

In principle $n(t)$ is the global volume (for the world production of a component) and P_0 is the cost of the very first component. Both of these inputs are sometimes difficult to obtain. To find a more useful expression, one solution is to use relative values, in which case P_0 may be omitted:

$$\frac{P(t)}{P(0)} = \left[\frac{n(t)}{n(0)}\right]^{-\alpha} \quad (28)$$

Furthermore, the global volume $n(t)$ may be removed from the expression, by observing that

$$\frac{P(t)}{P(0)} = \left[\frac{n_r(t)}{n_r(0)}\right]^{-\alpha} \quad (29)$$

(13) holds true since

$$\left[\frac{n(t)}{n(0)}\right]^{-\alpha} = \left[\frac{n_r(t)}{n_r(0)}\right]^{-\alpha} \quad (30)$$

where $n_r(t)$ and $n_r(0)$ are relative values (ie. normalised to 1). Rearranging the expression gives:

$$P(t) = P(0) \cdot \left[\frac{n_r(t)}{n_r(0)}\right]^{-\alpha} \quad (31)$$

or

$$P(t) = P(0) \cdot \left[n_r(0)^{-1} \cdot n_r(t)\right]^{\log_2 \cdot K} \quad (32)$$

$n_r(0)$ is the relative component volume at time $t = 0$. The relative accumulated growth $n_r(t)$ of the component volume in TITAN is described by the logistic curve in formula (1) normalised to 1.

$$n_r(t) = \left[1 + e^{(a+b\cdot t)}\right]^{-\gamma} \quad (33)$$

5.3 The cost evolution in the symmetric case (γ = 1)

In the TITAN cost database the parameter γ is fixed to 1. Let us express a and b with parameters which are more meaningful:

$$n_r(t) = \left[1 + e^{(a+b\cdot t)}\right]^{-1} \quad (34)$$

By setting $t = 0$

$$n_r(0) = (1 + e^a)^{-1} \tag{35}$$

and rearrange

$$a = \ln\left[n_r(0)^{-1} - 1\right] \tag{36}$$

a may be expressed by the relative component volume in year 0.

What about b? Let

$$n_r(t_1) = 0.1 \text{ and } n_r(t_2) = 0.9 \tag{37}$$

Thus

$$\left[1 + e^{(a+b\cdot t_1)}\right]^{-1} = 0.1 \quad \text{and}$$
$$\left[1 + e^{(a+b\cdot t_2)}\right]^{-1} = 0.9 \tag{38}$$

$$1 + e^{(a+b\cdot t_1)} = 10 \quad \text{and}$$
$$1 + e^{(a+b\cdot t_2)} = \frac{10}{9} \tag{39}$$

$$e^{(a+b\cdot t_1)} = 9 \text{ and } e^{(a+b\cdot t_2)} = \frac{1}{9} \tag{40}$$

$$e^a \cdot e^{b\cdot t_1} = 9 \text{ and } e^a \cdot e^{b\cdot t_2} = \frac{1}{9} \tag{41}$$

By dividing the right side by the left side we get

$$e^{b\cdot(t_2 - t_1)} = \frac{1}{9^2} \tag{42}$$

$$b \cdot (t_2 - t_1) = -2 \cdot \ln 9 \tag{43}$$

By definition

$$\Delta T = t_2 - t_1 \tag{44}$$

$$\Delta T = \frac{-2 \cdot \ln 9}{b} \tag{45}$$

$$b = \frac{-2 \cdot \ln 9}{\Delta T} \tag{46}$$

If we substitute the expression for a and b into the logistic curve, we get

$$n_r(t) = \left(1 + e^{\left\{\ln\left[n_r(0)^{-1} - 1\right] - \left[\frac{2\cdot\ln 9}{\Delta T}\right]\cdot t\right\}}\right)^{-1} \tag{47}$$

where the only inputs are $n_r(0)$ and ΔT. Figure 10 illustrates this relation.

The expression for $n_r(t)$ may now be substituted into the learning curve formula (32):

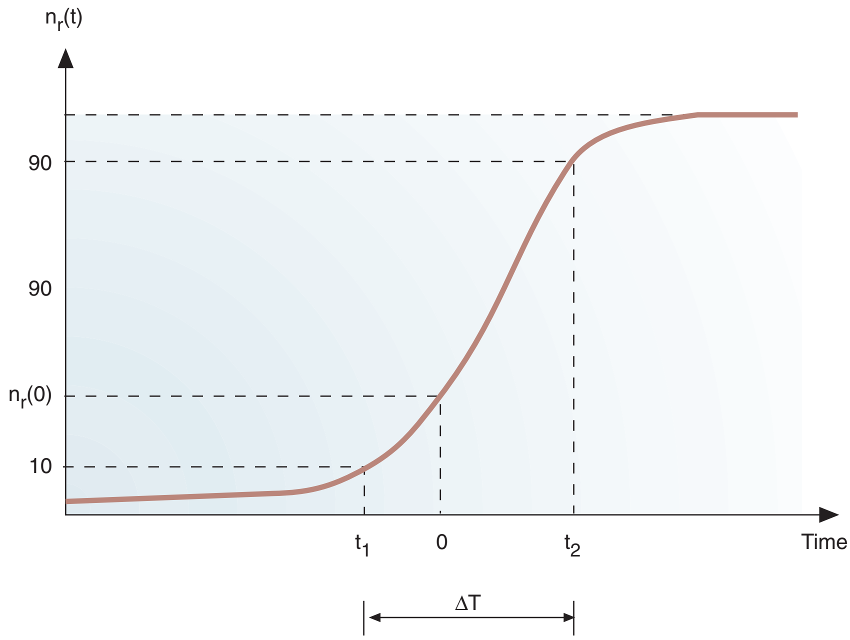

Figure 10 The forecast function for the evolution of the relative accumulated volume $n_r(t)$

$$P(t) = P(0) \cdot \left[n_r(0)^{-1} \cdot n_r(t)\right]^{\log_2 \cdot K} \tag{48}$$

yielding the final expression for price versus time in the TITAN cost database

$$P(t) = P(0) \cdot \left[n_r(0)^{-1} \cdot \left(1 + e^{\left\{\ln\left[n_r(0)^{-1} - 1\right] - \left[\frac{2\cdot\ln 9}{\Delta T}\right]\cdot t\right\}}\right)^{-1}\right]^{\log_2 \cdot K} \tag{49}$$

Only four parameters are input to the formula:

$P(0)$, the price in the reference year 0;

$n_r(0)$, the relative accumulated volume in year 0;

ΔT, the time for the accumulated volume to grow from 10 % to 90 %;

K, the learning curve coefficient.

In order to illustrate this relation, and to get a normalised component price, we put $P(0) = 1$ and $K = 0.95$ (Figure 13). By keeping $n_r(0) = 0.001$ constant and letting the parameter ΔT range from 2 to 20 years, we can illustrate the evolution of the normalised price versus time for different ΔT, as shown in Figure 11. Figure 12 shows the impact of $n(0)$ on the normalised price, keeping $\Delta T = 5$ years as a constant.

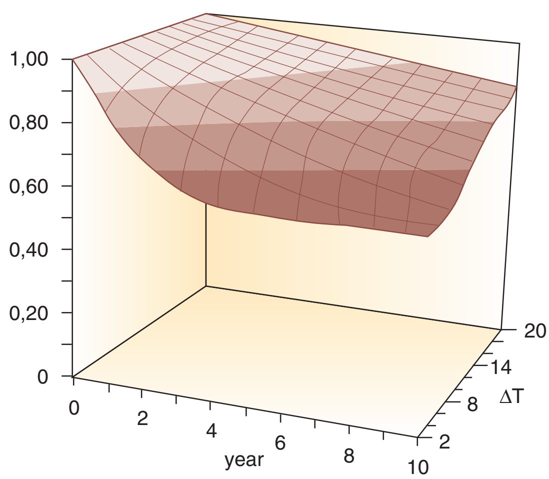

Figure 11 The impact of ΔT on the normalised price, keeping $n_r(0) = 0.001$

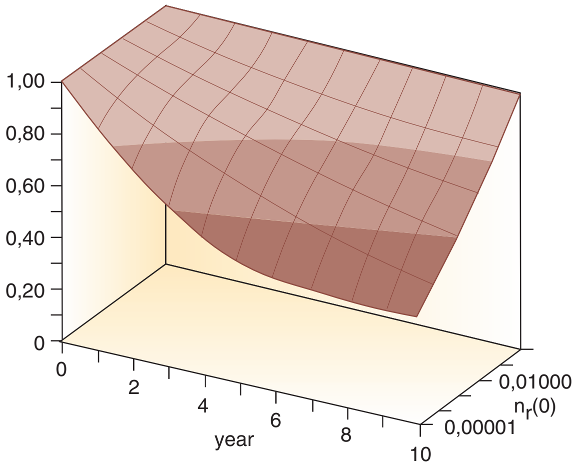

Figure 12 The impact of $n_r(0)$ on the normalised price, keeping ΔT = 5 years as a constant

From the previous expression it is clear that the asymptotic price level when t approaches ∞ does not depend on ΔT, and is given by:

$$P(\infty) = P(0) \cdot \left[\frac{1}{n_r(0)}\right]^{log_2(K)} \qquad (50)$$

In addition, for small t the slope of the price curve is proportional to ΔT^{-1}.

5.4 The cost evolution in the asymmetric case ($\gamma \neq 1$)

The logistic curve for γ different from 0 is illustrated in Figure 13.

Let us express a and b and γ with parameters which are more meaningful:

$$n_r(t) = \left[1 + e^{(a+b \cdot t)}\right]^{-\gamma} \qquad (51)$$

$$n_r(0) = (1 + e^a)^{-\gamma} \qquad (52)$$

$$a = \ln \left[n_r(0)\frac{-1}{\gamma} - 1\right] \qquad (53)$$

Let

$$n_r(t_1) = 0{,}1 \text{ and } n_r(t_2) = 0{,}9 \qquad (54)$$

Thus

$$\left[1 + e^{(a+b \cdot t_1)}\right]^{-\gamma} = 0,1 \text{ and}$$
$$\left[1 + e^{(a+b \cdot t_2)}\right]^{-\gamma} = 0,9 \qquad (55)$$

$$1 + e^{(a+b \cdot t_1)} = 10^{\frac{1}{\gamma}} \text{ and}$$
$$1 + e^{(a+b \cdot t_2)} = \left(\frac{10}{9}\right)^{\frac{1}{\gamma}} \qquad (56)$$

$$e^{(a+b \cdot t_1)} = 10^{\frac{1}{\gamma}} - 1 \text{ and}$$
$$e^{(a+b \cdot t_2)} = \left(\frac{10}{9}\right)^{\frac{1}{\gamma}} - 1 \qquad (57)$$

or

$$e^a \cdot e^{b \cdot t_1} = 10^{\frac{1}{\gamma}} - 1 \text{ and}$$
$$e^a \cdot e^{b \cdot t_2} = \left(\frac{10}{9}\right)^{\frac{1}{\gamma}} - 1 \qquad (58)$$

By dividing the right side by the left side we get

$$e^{b \cdot (t_2 - t_1)} = \frac{\left[\left(\frac{10}{9}\right)^{\frac{1}{\gamma}} - 1\right]}{\left[10^{\frac{1}{\gamma}} - 1\right]} \qquad (59)$$

Defining δ by

$$\delta = \frac{\left[\left(\frac{10}{9}\right)^{\frac{1}{\gamma}} - 1\right]}{\left[10^{\frac{1}{\gamma}} - 1\right]} \qquad (60)$$

yields

$$b = \frac{\ln \delta}{\Delta T} \qquad (61)$$

$$\Delta T = \frac{\left(\ln \left\{\frac{\left[\left(\frac{10}{9}\right)^{\frac{1}{\gamma}} - 1\right]}{\left[10^{\frac{1}{\gamma}} - 1\right]}\right\}\right)}{b} \qquad (62)$$

Hence, the final expression for price versus time in general is:

$$P(t) = P(0) \cdot$$
$$\left[n_r(0)^{-1} \cdot \left(1 + e^{\left\{\ln\left[n_{\ddot{Y}}(0)^{\frac{-1}{y}} - 1\right] + \left[\frac{\ln \delta}{\Delta T}\right] \cdot t\right\}}\right)^{-\gamma}\right]^{\log_2 \cdot K} \qquad (63)$$

Where δ is a function of γ only. Five parameters are input to the formula:

$P(0)$, the price in the reference year 0;

$n_r(0)$, the relative accumulated volume in year 0;

ΔT, the time for the accumulated volume to grow from 10 % to 90 %;

K, the learning curve coefficient;

γ, the asymmetry of the logistic curve.

This relation is demonstrated in Figure 14, in which price versus time is shown for $P(0) = 1$, $n(0) = 0.01$, $\Delta T = 5$, $K = 0.8$ and different γ.

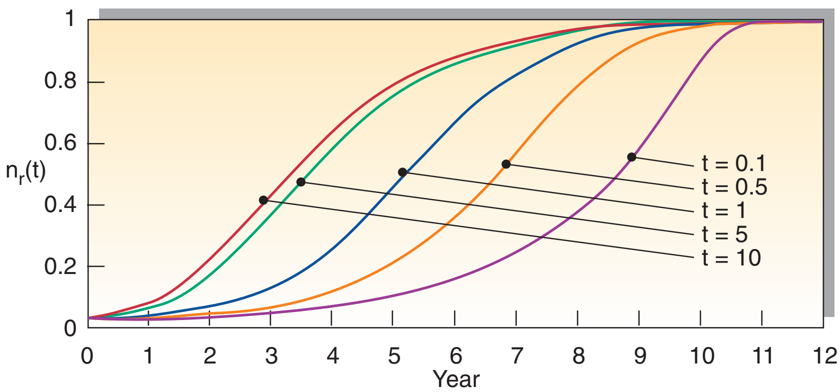

Figure 13 The impact of ΔT on the normalised price, keeping ΔT = 5 years as a constant

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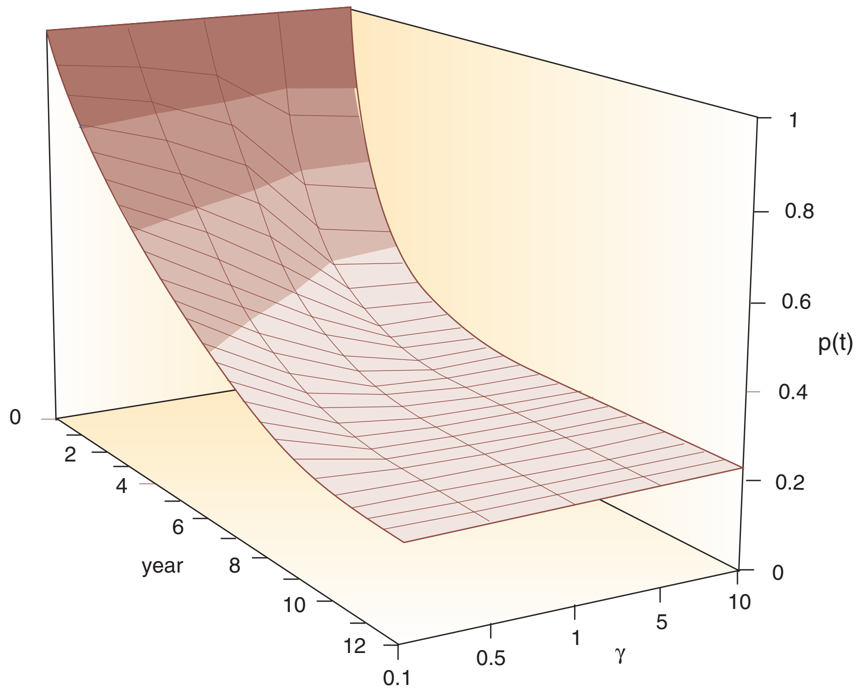

Figure 14 Price versus time for different γ

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Design of access network case studies

LEIF AARTHUN IMS

1 Introduction

This paper provides a brief introduction to how to design a specific techno-economic case study. The design method described is tailored for the OPTIMUM methodology and tool as described in [1, 2], but should also be applicable to similar tools or assessment methods.

A case study in this context is a techno-economic assessment of an access network roll-out or upgrade, given a specific starting situation. Commonly the starting situation is described by a set of geographic, demographic and market parameters. The case study typically includes an examination of a set of service evolutions or scenarios and network architecture migrations, usually by the study of the sensitivity and risk of selected key parameters, key cost elements and critical services and tariffs on the different economic outputs. In order to carry out a case study, specified input requirements are needed in order to ensure

- availability of the information required for techno-economic calculations;
- adaptation of the case studies to the facilities and capabilities of the techno-economic tools;
- consistency in the studies and the results.

The specifications are of course subject to change, depending on the specifics of business cases and technologies under study. However, these input formats and requirements illustrate the level of detail at which the studies are performed, and hence the corresponding level of detail of the inputs. Tables 1 and 2 show the case study inputs and corresponding format required in order to implement a case study in for instance the OPTIMUM tool [1].

2 Study characteristics

The initial specifications naturally consist of seemingly trivial matters such as assigning a name to the study, setting the case study period, defining the number of network architecture evolutionary steps and selecting a greenfield or non-greenfield starting situation. Typically network infrastructure investment projects have a rather long time frame, and thus study periods of between five and fifteen years are commonly used. During this period a change of network technology/architecture may be considered to be an evolutionary step. Thus an ADSL upgrade of

Table 1 Calculation input format and requirements, techno-economic assessment

Case specification	
Name	
Study characteristics	
Study period *Start year – final year*	
Evolutionary steps 0 ... n *Number of steps, point in time*	
Greenfield, non-greenfield	
Service characteristics	
Service 0 ... n *Name*	
Downstream peak bandwidth *bit/s*	
Upstream peak bandwidth *bit/s*	
Concentration *Concentration factor, point of concentration*	
Connection fee *ECU, as a function of time*	Diagram
Annual fee *ECU, as a function of time*	Diagram
Traffic fee *ECU, as a function of time*	Diagram
Usage *Units per year, as a function of time*	Diagram
Average annual revenue per user *ECU, as a function of time*	Diagram
Customer segmentation	
Large Business (LB) customers *% of potential subscribers in area*	
Large business customer services 0 ... n *Service name, penetration of LB subscr. as a function of time*	Diagram
Medium Business (MB) customers *% of potential subscribers in area*	
Medium business customer services 0 ... n *Service name, penetration of MB subscr. as a function of time*	Diagram
Small Business (SB) customers *% of potential subscribers in area*	
Small business customer services 0 ... n *Service name, penetration of SB subscr. as a function of time*	Diagram
Residential (R) customers *% of potential subscribers in area*	
Residential customer services 0 ... n *Service name, penetration of R subscr. as a function of time*	Diagram

Table 2 Calculation input format and requirements, techno-economic assessment

Area characteristics	
Number of potential subscribers in area	
Subscriber density *Number of subscribers per km²*	
Dwelling distribution *% of single house dwellings and blocks*	
Existing network architecture	
Network architecture layout	Diagram
Average copper loop length *Metres*	
Network levels 0 ... n *Name*	
Network type *Ring, star, bus*	
Network level splitting ratio	
Service 0 ... n transmission medium *Coaxial cable, copper pairs, optical fibre, radio*	
Service 0 ... n technology *Carrier, multiplex etc.*	
New network architecture	
Evolutionary step 0 ... n *Time period*	
Network architecture layout	Diagram
Node configuration *FTTN, FTTCab, FTTC,FTTB,FTTH*	
Number of potential customers per optical node	
Network levels 0 ... n *Name*	
Network type *Ring, star, double star, star-bus*	
Network level splitting ratio	
Duct availability *Twisted pair copper, coaxial cable, fibre cable (in %)*	
Civil works type and cost *Ducts, direct burial, aerial cable : cost per metre*	
Service 0 ... n transmission medium *Coaxial cable, twisted pairs, optical fibre, radio*	
Service 0 ... n technology *Carrier, multiplex ,etc.*	
Network components	
Network levels 0 ... n *Name*	
Component type and functionality *Name, diagram of building blocks*	Diagram
Component cost *Fixed and incremental cost elements, as a function of time*	Diagram

an existing copper pair network constitutes one evolutionary step, whereas a study period with an initial ADSL upgrade followed by a later migration towards VDSL contains two evolutionary steps. Greenfield projects are projects for which there is no existing infrastructure, whereas in non-greenfield, or upgrade projects, parts of the existing infrastructure is re-used.

3 Service characteristics

In a case study the description of the services to be provided by the network is crucial. For every service in the service basket characteristics such as downstream peak bandwidth (in bit/s), and upstream peak bandwidth (in bit/s) must be defined. For every service the concentration factor or an indication of the dimensioning bandwidth and the network point of concentration must be indicated. To the extent that any of the parameters are dependent on time, curves must be included which show the evolution of the parameters during time. Typically for the calculation of revenues, the connection fee and its evolution during the study period must be included. Similarly, the annual subscription or rental fee and the traffic fee and corresponding evolutions must be specified. Thus the annual revenue may be calculated from these parameters and the usage of the service. Alternatively, an average annual revenue per user may be defined – if a more simplistic approach is taken.

4 Customer segmentation

The segmentation of the customers demanding the above services is closely related to the service characteristics described above. Typically one service or a basket of services is not taken by all subscribers in the network area under consideration, but taken by one or more segments of subscribers. In our example tables we have segmented the subscribers into a residential market and a business market, of which the latter is segmented into a large business segment, a medium business segment and a small business segment. For each of the customer groups the percentage of potential customers in the area under consideration must be indicated. If this changes during the study period, a time curve is needed to specify the percentage of potential subscribers. Accordingly, for every customer group, the set of services taken must be described, by the use of time curves showing the percentage of subscribers within that particular market segment which is subscribing to the service.

5 Area characteristics

The area characteristics and the existing network architecture specifications often have a significant impact on the overall investment levels, and as such distinguish between area types (Table 2). In a purely residential area the potential number of subscribers in the area may be equal to the total number of households. In developed areas this figure typically stays approximately constant during the period under study, whereas it may increase significantly in areas which are under development. The density of subscribers in the area together with the number of subscribers gives – based on geometric models – crucial network planning distances such as the cable lengths and duct lengths. In non-greenfield copper network areas this subscriber density corresponds to a certain average copper loop length of the existing network. The distribution of dwellings – eg. single houses or apartment blocks – is another parameter which is of relevance both for the calculation of cable lengths and the selection and application of technology and network architecture.

6 Existing network architecture

The existing and new network architectures are usually more complex to describe than the services. The existing network architecture must be documented with a schematic drawing, in which the architecture is described in a hierarchical way. All the components in the network must be located in this hierarchy, so that the quantity of network components may be calculated. Every network level in the hierarchy is assigned a name, and for every network level the types of network (eg. ring, star or bus) are specified. For every network type in a network level the network level splitting ratio is required. This ratio indicates how many network locations in the next lower network level which are connected to one node in the present network level. For every service carried the transmission medium and multiplex type in that particular network type at that network level must be indicated.

7 New network architecture(s)

For every evolutionary step 0 ... *n* selected in the case study, the layout of the new network architecture must be drawn schematically, including a hierarchical description. The node configuration or application mode must be specified and the corresponding number of potential users per (optical) node. Similar to the existing network, every network level in the hierarchy should be given a name. For every network level the types of networks (eg. ring, star or bus) are specified. For every network type in a network level the network level splitting ratio must be given. In addition the availability of ducts for new cable must be defined for every type of cable (fibre, coaxial and copper). Together with the specified type of cable deployment method and type of civil works with associated costs per metre, the duct unavailability enables a calculation of the cable infrastructure costs in the area. As in the case of the existing network, for every service carried, the transmission medium and multiplex type in that particular network type at that network level must be indicated.

8 Network architecture dimensioning

In addition, the dependencies between the capacities of various network elements and the service requirements must be described in order to dimension the network. The equipment dependencies on service penetration and/or usage must also be described. In practical terms the architecture must be described as a ‘shopping list’, in which all the required cost elements are listed

9 Network components

Finally, the type of network components must be specified and input to the cost database. Diagrams are required in order to document the attributes and functionality. In addition, the cost evolution of the component during time must be specified. It is often advantageous to split the cost elements of one component into fixed and incremental cost elements.

10 Calculation procedure

The case study design should also include a calculation plan, which may influence the way the above parameters are specified, and how the study is implemented in the techno-economic tool. Moreover, some calculations, such as risk calculations, will usually require a specification of additional parameters, and at least some distribution of the parameter values.

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Broadband Internet Access – a techno-economic study

ILARI WELLING

1 Introduction

This paper examines the profitability and economic risks of new multimedia services that are provided over wireline and wireless technologies. This study has been carried out jointly by several members of AC226 OPTIMUM project, which is part of the European Union ACTS programme.

This case study concentrates on residential and SOHO customer segments. Two types of services (or actually service categories) are evaluated. The first service, here called the *basic service*, is an interactive information retrieval service, which does not support real time applications. A typical example of this type of service is fast Internet access. The other service category, here called the *enhanced service*, is an interactive information retrieval service with real time application support.

The two services are offered using both telecom operator's and cable TV operator's infrastructure. In both cases we assume an upgrade scenario that makes use of existing cables, fibres, cabinets and buildings. However, in the cable TV operator case some new fibre is included in order to divide the HFC network into small enough segments for bi-directional cable modem services. Network models are implemented in the same model area of 40,000 potential customers. Investments include everything from equipment in the subscriber premises, like the modem or line adapter, up to the server in 40,000 homes passed (h.p.) point.

In the telecom operator scenario both services are offered using rate adaptive ADSL technology in the subscriber line. Fibre is assumed to go down to the Local Exchange (LE) which is in 10,000 h.p. point. From there on ADSL technology is utilised.

In the cable television operator scenario the same services are offered by deploying cable modems. The existing HFC architecture, on which the upgrade is made, is assumed to have fibre down to roughly 4000 h.p. point. At the beginning of the project fibre is taken down to 500 h.p. point. Initially the HFC is assumed to be a one-way system and return channel availability requires upgrades at the amplifiers. This means that we assume conventional cable TV network that requires major upgrades as opposed to modern two-way ready HFC networks that are available in some countries.

The third modelled technology is LMDS (Local Multipoint Distribution System). In the LMDS case the whole LMDS architecture with BS (Base Station) sites and feeders to these sites are included.

As a reference case, a stripped-down basic service is offered in existing telecom networks over ISDN. When interpreting the results, one should remember that this 'reference' case must not be directly compared to other alternatives as the service is not the same over the ISDN.

Finally a risk analysis is carried out on different studied scenarios. The risk analysis has the aim to quantify the associated risks.

2 Services and network models

2.1 Services

Following topics explain the characteristics of modelled services.

The *basic service* is an interactive information retrieval service, which does not guarantee Quality of Service (QoS) for real time applications. Typically this service offers fast connections for traditional delay insensitive applications, but there may be delays or breaks which are unacceptable to applications like video telephony or video on demand systems. In other words, the guaranteed bandwidth is low even if the nominal access speed is high. Typical examples of this type of a service include WWW browsing, ftp and alike.

The enhanced service operates on the same nominal access speed as the basic service, but in this case the guaranteed bandwidth is much higher so that real time applications can be supported. The network includes resource reservation protocol or other means of providing guaranteed QoS. Examples of this service class include video/audio retrieval, video/audio broadcast, video/audio telephony and alike. However, the example networks provide much less return channel capacity than download capacity, which might limit use of some interactive real-time applications like video conferencing.

The model networks for basic- and enhanced services are dimensioned using 20 kbit/s and 600 kbit/s dimensioning bandwidth respectively as described later in chapter 2.2.1.

The basic assumption for penetration of these services goes from 2 % in 1998 up to 20 % in 2007. The penetration is assumed to follow an S-curve shape. Since the assumption for service penetration is inherently uncertain, it has been selected as one of the parameters for risk analysis in chapter 4.

2.1.1 Revenue assumptions

The revenue assumptions used in this study represent the operator's share of the end user tariff, ie. the fee that is paid for the delivery of the information. Possible fees due to information content are beyond the scope of this study.

In the OPTIMUM model revenues are modelled as total annual tariffs, where rental and usage fees are calculated together. This allows sensitivity analysis on a revenue per customer to be carried out easily, without having to speculate whether the rental or usage tariff is changing or perhaps a totally new tariff component is introduced. The most important thing is to see how the overall business profitability is affected by variations in revenues, regardless of what is the source of the variation.

Table 1 shows the assumptions for monthly revenue per customer for different services. In the case of ISDN these estimates come from the existing tariffs in Finland[1)] and for basic service and enhanced service the estimates are averages of figures commonly referred to in telecommunication journals and other publications. The OPTIMUM methodology also assumes time dependency

Table 1 Monthly revenue per customer assumptions

Service	Monthly revenue per customer
ISDN based service	25 ECU
Basic service	32 ECU
Enhanced service	40 ECU

[1)] *Late 1997 situation including the local telephone call charge.*

for the tariffs. The tariffs shown below represent the 1998 level (except ISDN). During the ten year study period the tariffs are assumed to erode by approximately 35 %.

In addition to monthly revenues there is a connection fee which is paid once when a new customer subscribes to the service. The connection fee is 100 ECU for both services (70 ECU for the ISDN case).

2.2 Network architectures

Three different technologies have been used to construct model networks, namely ADSL (Asymmetric Digital Subscriber Line) on top of ordinary telecom networks, cable modems on HFC (Hybrid-Fibre-Coax) networks and LMDS (Local Multipoint Distribution System) which is a wireless access system. In addition to these, ISDN technology is used as a reference case.

2.2.1 Network dimensioning

This topic explains the system used for dimensioning the centralised parts of the network for all different technologies.

In this study we use the concept of dimensioning bandwidth for network dimensioning. The dimensioning bandwidth is defined as the average bandwidth available to all connected subscribers if they were on-line simultaneously. In circuit switched architectures like ISDN or POTS, this is not possible in practice, since there is always concentration in the local exchange. The definition of dimensioning bandwidth is:

dimensioning bandwidth = total_bandwidth_available_in_the_network / number_of_homes_connected

Thus, if a 2 Mbit/s link is shared by 100 customers, then the dimensioning bandwidth equals 20 kbit/s. However, since only some of the customers will be actually using the link simultaneously, the available bandwidth per connection is much higher. Dimensioning bandwidth does ***not*** represent a throughput experienced by a single customer, but it is a useful computational figure.

The dimensioning of the centralised parts of the network is the main factor that separates network models for the basic service and for the enhanced service. The primary difference between the services is that the enhanced service offers a real-time streaming video service, either live or recorded. The bit-rate for the streaming video is assumed to be from 1.5 Mbit/s up to 6 Mbit/s for different material, averaging 3 Mbit/s. This coincides with transport rates used in MPEG-coded broadcast quality material.

Different approaches are used to determine the concentration ratio for each service category. In case of the basic service following two constituent parts define the concentration:

- Simultaneous active connections;
- Traffic multiplexing.

All the dimensioning is based on the busy-hour measurements. Simultaneous active connections can be calculated by assuming a 5-hour busy-hour period per day (17–22), and average 30-minute connections, for a concentration of 1 : 10. This also coincides with the experiences of the ISPs operational today. Traffic multiplexing is a little more vague, since it comprises the statistical multiplexing of ATM, and the fact that the user is not taking up all the capacity even when active. If we assume a nominal access speed of 2 Mbit/s and use a traffic multiplexing of 1 : 10, we have a total concentration ratio of 1 : 100. This results in a dimensioning bandwidth of 20 kbit/s for the basic service. Knowing the number of customers or homes connected in the service area, we can then come up with the total bandwidth needed at different points of the system.

For the enhanced services, the constituents are:

- Simultaneous active connections;
- Average bandwidth of the recording/other stream.

In agreement with the basic service calculations, a 5-hour period is again assumed, this time with an average holding time of 60 minutes, giving a concentration of 1 : 5. Average bandwidth of the stream is taken as 3 Mbit/s. From this we get a dimensioning bandwidth of 600 kbit/s. Total bandwidth is then again calculated by multiplying the dimensioning bandwidth with the number of homes connected.

2.2.2 ISDN reference case

As a reference to new broadband access solutions, one network model is constructed based on the ISDN technology that exists today. The service provided by ISDN is not similar to new access technologies, but it is still interesting to see how the economics of these technologies compare.

The ISDN architecture case requires that the customer is equipped with an ISDN connection: ISDN NT (Network Terminal) at the customer premises and ISDN LT (Line Terminal) at the local exchange. An integrated NT including TA (Terminal Adapter) for analogue telephone is assumed. TA is included for making the ISDN case better comparable to the ADSL case, which maintains the old analogue telephony line. Upgrades in the local exchange capacity and in the SDH transmission capacity between the local exchange and the server site will be needed. The server site includes ISDN WAN Access Switches and a server for basic service (domain name server, authentication server, etc.).

2.2.3 ADSL case

In this model Asymmetric Digital Subscriber Line (ADSL) technology is used for creating fast data connections over ordinary telephone lines.

With ADSL technology no upgrades to the existing access infrastructure are needed. All the ADSL modems regarded operate with existing twisted copper pair wiring, although there will be distance limitations with higher speed modems. For a connection, a pair of ADSL modems is required; an ATU-C in the local exchange, and an ATU-R at the customer premises. In the local exchange the modems are installed into a DSLAM rack, which is connected to an ATM edge switch with an STM-1 link. If the capacity requirements get higher, additional STM-1 links can be used. The edge switches are connected to higher capacity core network ATM switches.

A factor which has not been taken into consideration in this study is how an ADSL system in real life scales with increasing number of customers. Issues like cross talk in the access section might increase the OA&M costs noticeably. However, here it is assumed that the capacity can be increased up to the 40 % penetration without cross talk and similar problems.

Assumptions for network design:

- DSLAM contains the access multiplexer and the installation rack.

- One DSLAM supports up to 500 ADSL ATU-C line cards.
- For the maximum 40 % penetration (4,000 homes connected per exchange), 8 racks are needed in an exchange.
- One rack can be configured with from 1 to 10 STM-1 connections.
- For Basic Service, one STM-1 per DSLAM is required.
- For Enhanced Service, two STM-1s per DSLAM are required.

2.2.4 HFC case

In this model new services are offered on top of the cable TV network using cable modems for two-way data connections.

The existing coaxial cable infrastructure between the hub (4000 h.p. point) and the homes is upgraded to a bi-directional network with return path, and 10 Mbit/s cable modems are installed at the customer premises. Apart from new fibres, the infrastructure upgrade is modelled as a cost per home passed (h.p.), which is derived from real HFC installations. At the hub site, the connection is terminated in the cable data router. A total of 120 Mbit/s downstream and 12 Mbit/s upstream shared access capacity is available per router. The subscribers share the upstream and downstream capacity.

The existing HFC architecture is assumed to have fibre down to 4000 h.p. point, before the upgrade is made. The initial cable infrastructure upgrade includes replacing the existing 300 MHz coaxial cable amplifiers with 862 MHz coaxial cable return path amplifiers and taking fibre down to 500 h.p. point from 4000 h.p. point.

For low penetrations one cable router serves the whole 4,000 homes passed area. If more than eight routers per hub are required, the network is segmented at the hub level, now with 125 homes passed per coaxial cable segment.

Since many of the infrastructure upgrades made in the network also benefit the broadcast service, only a certain share of these investments are calculated as investments of the interactive data service. Two thirds of the common investment will be calculated as cost of the interactive data services.

2.2.5 LMDS case

The fourth technology for providing the services is Local Multipoint Distribution System (LMDS). LMDS is a point-to-multipoint type of radio solution which typically operates at frequencies around 28 GHz or 40 GHz. The first commercial installations of LMDS are using the technology primarily for broadcast TV, but the technology also allows fast two-way data connections. LMDS is still an emerging technology and it is evolving rapidly. When compared to other studied technologies, LMDS is different also because it is not really a network upgrade that would make use of existing infrastructure. Because of the nature of the LMDS technology, many assumptions must be made.

The most important assumptions are:

- The system operates at 40 GHz range.
- The infrastructure is built to have broadcast TV capability, but broadcast TV is not included as a revenue generating service. Broadcast TV specific equipment is not included in the investment.
- Many of the infrastructure investments, eg. antennae, customer transceiver and NT, base station sites, fibre optic links, are common between the broadcast TV service and the interactive data service. In order not to burden interactive data service excessively by the common investments, only a certain share of these investments are calculated as investments of the data service. Two thirds of the common investments are calculated as investments of the interactive data service.
- A base station has at least one radio unit, but can be sectorized to provide more capacity. For each sector five 40 MHz channels are reserved for interactive services (200 MHz total). A single 40 MHz channel carries 52 Mbit/s of data traffic, totalling 260 Mbit/s downstream capacity in five channels. For upstream traffic thirty 1.5 MHz channels are reserved, carrying approximately 60 Mbit/s.
- The size of radio cells is defined differently for basic service (dimensioning bandwidth = 20 kbps/user) and for enhanced service (dimensioning bandwidth = 600 kbps/user) cases. For the basic service the maximum cell radius is assumed to be 1.5 kilometre. For the enhanced service the cell size is restricted by the capacity of the BS. With the assumption of 2000 subs/km^2 and 20 % penetration the cell radius can be approximately 0.8 km in order to guarantee 600 kbps for every user.
- Possible loss of customers due to inability to provide the service (line of sight requirement) is not taken explicitly into account. This is comparable to the ADSL case where cross talk or too long subscriber loops might prevent some users from getting the service.
- In order to provide more capacity per square metre sectored antennae is used. The area covered by one base station is divided into 4 sectors. In case of enhanced service each of these sectors is further subdivided into 4 sectors, ie. effectively making the capacity per square metre four fold.

LMDS technology requires that the end user has an antenna, transceiver and NT. Here it is assumed that the antenna is either roof or wall mounted by a specialist and that the specialist also tunes in the equipment. The base station is located at a well established site, possibly having an indoor cabinet for the equipment. Each base station sector has five 40 MHz radio channels available for data services. In addition to this there is a larger number, say 15 channels for broadcast services. Base stations are connected to the Head End by direct AM fibre links. The fibre links are transmitting digital signals and hence the frequency response requirement for O/E converters is lower than in the HFC case. At the HE there is an LMDS modem for each radio channel coming from base stations. The common equipment at the HE site includes multiplexing and de-multiplexing of data signals and an interface towards the central ATM switch. The ATM switch and servers are similar to other cases.

2.2.6 Cost information

Table 2 shows the most important cost components used in this study. This cost information is gathered from public sources. The use of the last fields in the table is explained in chapter 2.3, OA&M cost approach.

For all cost components a certain price evolution is used according to the OPTIMUM methodology. Most of the cost components have been divided into 4 different price evolution classes. The relative price evolution of each class is shown in Figure 1.

Table 2 Main cost elements
(MMC = Maintenance Material Class, MTBR = Mean Time Between Repairs, MTTR = Mean Time To Repair)

Cost Component	Price	Year	MMC	MTBR	MTTR
ADSL Installation	150 ECU	1997	0 %	-	0h
ADSL modem ATU-C	400 ECU	1998	2 %	2 years	1h
ADSL modem ATU-R	400 ECU	1998	2 %	2 years	2h
ATM core switch 5 Gbps	40,000 ECU	1997	2 %	1 years	16h
ATM core switch interface 4*STM1 MM	4,200 ECU	1997	2 %	3 years	1h
ATM edge switch interface STM1 MM	2,000 ECU	1997	2 %	3 years	1h
ATM edge switch 2.4G	10,000 ECU	1997	2 %	1 years	8h
Cable Data Router	39,000 ECU	1998	2 %	1 years	16h
Cable Modem	290 ECU	1998	2 %	2 years	2h
Cable Modem installation	150 ECU	1997	0 %	-	0h
DSLAM equipment and rack 500	100,000 ECU	1997	2 %	1 years	16h
HFC Downstream Capacity Upgrade per h.p.	30 ECU	1997	3 %	-	0h
HFC Return Channel Upgrade per h.p.	30 ECU	1997	3 %	-	0h
ISDN installation	60 ECU	1997	0 %	-	0h
ISDN NT+TA	260 ECU	1997	2 %	3 years	2h
ISDN WAN Access Switch	20,000 ECU	1997	2 %	1 years	16h
LMDS BS installation	1,000 ECU	1997	0 %	-	0h
LMDS BS site	50,000 ECU	1997	1 %	1 years	8h
LMDS HE Common Equipment	10,000 ECU	1997	2 %	2 years	8h
LMDS HE modem for one channel	4,000 ECU	1997	2 %	3 years	4h
LMDS NT and transceiver	1,000 ECU	1998	2 %	3 years	4h
LMDS NT installation	200 ECU	1997	0 %	-	0h
STM-1 link upgrade	10,000 ECU	1997	2 %	2 years	8h

2.3 OA&M cost approach

The Operation, Administration and Maintenance (OA&M) costs are modelled according to the OPTIMUM methodology. Figure 2 shows the basic structure of this methodology.

The costs are divided into two main parts, which are Maintenance (M) and Operation & Administration (O&A). Maintenance costs are in turn further divided into the cost of maintenance material (M_1) and the cost of maintenance labour (M_2). Maintenance material costs are calculated as percentages of the annual investment. All the cost components are assigned to a certain class, which defines this percentage. Table 2 shows these classes for all cost components in this study. For example, if a component is in 2 % Maintenance Material Class (MMC) and the component price is 10,000 ECU, it will follow that every year a 200 ECU maintenance cost is due. This is the M_1 part of the maintenance cost. The M_2 part is calculated also from the class definitions shown in the previously mentioned table. If the Mean Time Between Repairs (MTBR) for a given component is, say 2 years and the Mean Time To Repair (MTTR) is 4 hours, it follows that on average 2 hours of repair work is needed every year for this type of component.

The other part of OA&M represents the Operation and Administration (O&A) costs, which in this study are driven by the number of connected customers. It is assumed that in the beginning there is one O&A employee per 1000 subscribers of the basic service. After 3 years the efficiency of an employee is assumed to increase by 100 customers per year; eg. in year three one employee serves 1100 customers, in year four 1200, etc. Regardless of the number of connected customers the minimum number of employees is set to 3. Running the enhanced service is assumed to need 30 % more personnel. The cost of one employee is 80,000 ECU in 1998 and it increases by 2.5 % every year. The cost of one labour hour is calculated from the annual cost assuming that there are 11 working months per year and 158 working hours per month.

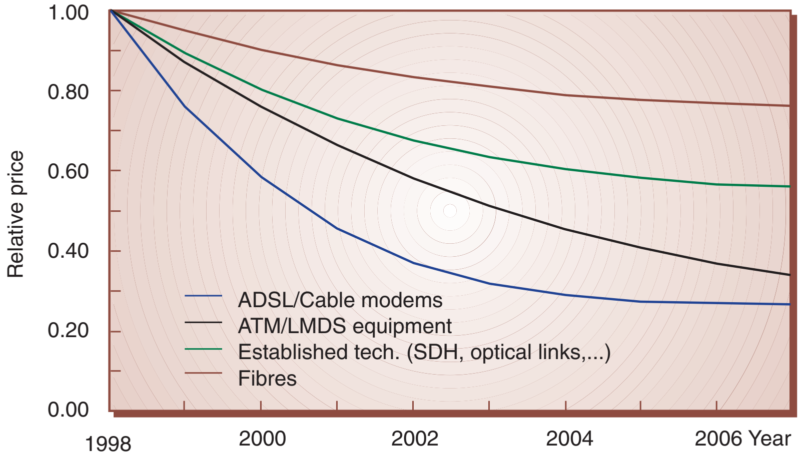

Figure 1 Price evolution trends for network elements

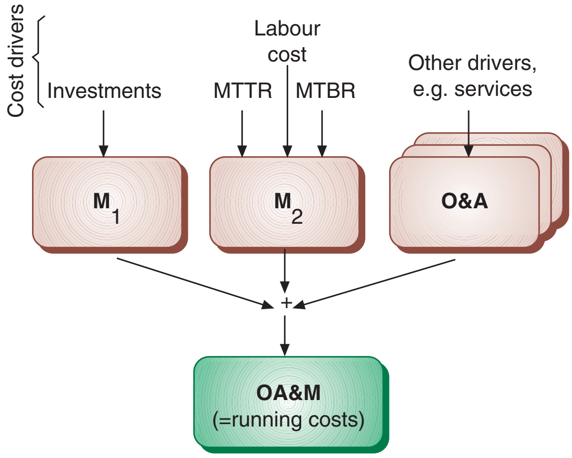

Figure 2 OPTIMUM Operation, Administration & Maintenance cost model

Table 3 NPV (in kECU) and IRR figures under default[2] assumptions

	Basic service		Enhanced service	
	NPV	IRR	NPV	IRR
ISDN *	925	20 %	-	-
ADSL	514	12 %	1106	16 %
HFC	–443	5 %	–302	6 %
LMDS	1402	19 %	1253	15 %

* *ISDN not fully comparable, since the service is not the same.*

[2] *The 'default' assumptions are shown at the beginning of chapter 3.*

One must bear in mind that the operation and administration of the underlying telecom or HFC network is not part of these models even if they utilise the same platform.

3 Results

This chapter presents the economic results for each technology and service combination with the following 'default' assumptions.

- Nominal service penetration assumption, ie. penetration goes from 2 % up 20 %.
- Revenue assumptions are as defined in chapter 2.1.1.
- Basic service dimensioning bandwidth is 20 kbit/s.
- Enhanced service dimensioning bandwidth is 600 kbit/s.

The following tables show characteristic figures of different service & technology combinations.

In Table 3 Net Present Value (NPV) and Internal Rate Return (IRR) figures are given for different scenarios. NPV is calculated at 7 % discount rate.

The basic outcome is that all analysed technologies apart from HFC are profitable. The ISDN reference case gives the best IRR, while both the LMDS cases and the enhanced ADSL case yield better NPV. This indicates that the turnover in the ADSL and LMDS cases is larger, which enables larger net profits. However, the investments are also much larger meaning greater risk in case the sales do not evolve according to the estimates.

The rather poor profitability of the HFC solution is due to the fact that the initial investment for making the HFC network two-way capable is large when compared to other costs. In the ISDN and ADSL cases no comparable upgrades are required to the infrastructure. If the underlying HFC network was a modern one, the results were likely much better in terms of profitability.

The LMDS case gives surprisingly good results bearing in mind that the LMDS case is a greenfield network and other cases are upgrades to an existing network. It has to be noted that in this study we assume that the spectrum used for the service is free. In many countries this is not the case. A remarkable license fee may have to be paid for the utilisation of this part of the radio spectrum. These fees can remarkably deteriorate the business case profitability for LMDS at least for revenue per customer levels assumed in this study. Indeed, for this study 40 ECU per potential customer spectrum license fee paid at the beginning and depreciated over ten years takes the NPV of the enhanced service case to zero. For the basic service the NPV zero level is at 45 ECU spectrum cost/potential customer.

On the other hand LMDS could be a very good candidate for business cases where penetrations are lower and revenue per customer higher. This is supported by the fact that in the enhanced service case LMDS profitability starts to decline at high penetrations because of capacity limitations in air interface.

Table 4 shows the total discounted investment over the ten year study period, divided by the number of connected customers at the end of the project.

An interesting thing to notice is the fact that for ADSL and HFC the investments per user are not so much affected by making the network capable of providing the enhanced service instead of the basic service. Even if the capacity of the centralised parts of the network are increased manifold, the costs per user are not significantly increased. According to these results, it pays off to build transport capacity for ADSL and HFC in order to make full use of the access capacity available. For LMDS the situation is the opposite. The increased capacity requirement means significantly more base stations, which in turn worsen the overall profitability. This is caused by the capacity limitations of the air interface.

Table 5 shows the relation between capital expenditure and operating expenditure, ie. the total running cost over the ten year study period divided by the total investment.

In chapter 2.1 the assumptions for service penetration and also to some extent assumptions for service revenue per customer were made without unarguable justification. Because of this sensitivity analysis is required. Figures 3 – 4 show how different scenarios depend on these assumptions.

Figure 3 shows that the profitability of the ISDN reference case increases faster as a function of the penetration than the profitability of other cases. This does not take into account the fact that after a certain penetration level the local exchange upgrades which are done at the beginning of the project may not be sufficient. Hence the IRR curve of ISDN cannot be extrapolated too much.

In the ISDN case the revenue margin compared to investment per user is higher than in other cases, and hence the changes in tariffs are more clearly reflected in the IRR figure. This is important since if new broadband alternatives to ISDN access are introduced, the ISDN based service tariffs are likely to decrease. This means that the profitability of this service goes down when compared to broadband alternatives.

4 Risk analysis

Many of the input assumptions used in this study are inherently uncertain. There is no way to find any ‘right’ value for certain assumptions. In order to obtain some quantitative measure of the implications these uncertainties have, a risk analysis is carried out. In the OPTIMUM methodology risk analysis means associating probability distributions to uncertain input values and carrying out a few thousand rounds of Monte Carlo simulation. During the simulation the most interesting output values, like NPV, are recorded and as a result we will have probability distribution for the outcome of the business case. This allows us to say something about the likelihood of achieving certain results under the uncertain environment.

Table 4 Total discounted investment divided by the number of connected customers at the end of the project

	Basic service	Enhanced service
	Inv/sub	Inv/sub
ISDN *	294	-
ADSL	497	582
HFC	708	859
LMDS	484	673

* *ISDN not fully comparable, since the service is not the same.*

Table 5 Total discounted running cost to total investment ratios

	Basic service	**Enhanced service**
ISDN case	1.75	N/A
ADSL case	1.29	1.26
HFC case	0.83	0.81
LMDS case	1.09	0.96

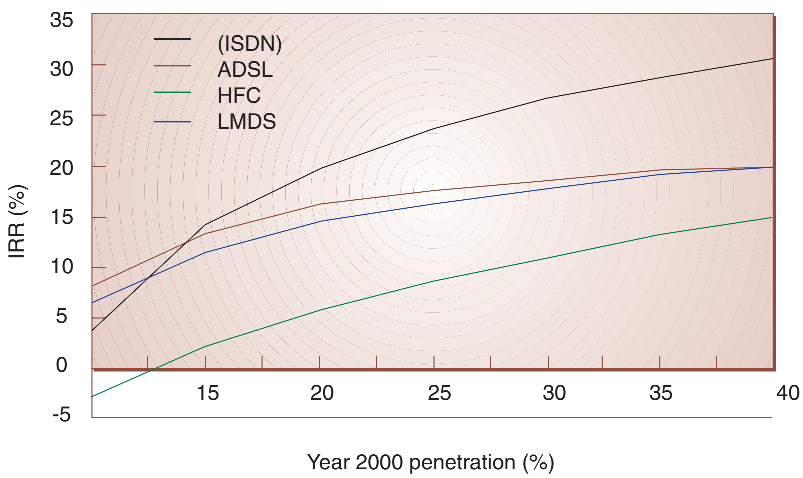

Figure 3 IRR for enhanced service cases as a function of service penetration. The X-axis shows the 2007 saturation value for penetration. (20 % penetration value has been used for results shown at the beginning of chapter 3)

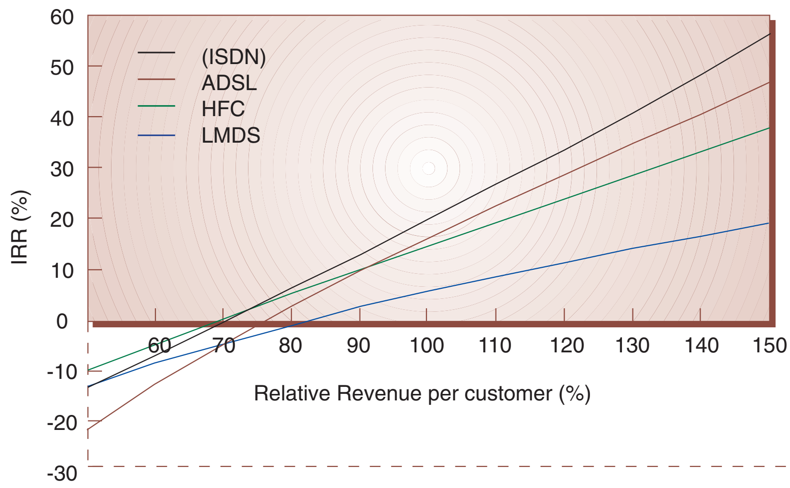

Figure 4 IRR in case of an enhanced service as a function of revenue per customer. The value axis shows the relative revenue compared to nominal revenue presented in chapter 2.1.1

4.1 Parameters for risk analysis

In order to assess the uncertainties in the evaluation of this business case, following parameters have been selected as targets to a risk analysis:

- Service penetration;
- Monthly revenue per customer;
- Price of the access equipment, eg. ADSL/Cable modem and LMDS terminal.

The uncertainty of access equipment price is modelled by assigning probability distributions to the nominal price of the equipment. In addition the K-value in the price evolution equation[3)] is turned into a normal distribution. This effectively makes the prices more uncertain as the years go by. Table 6 lists the parameters and the characteristic values for the normal distributions.

The uncertainty of the market situation is modelled by introducing a random variable *C* that describes the level of competition on the market. This variable has a negative correlation to two other random variables *P* and *R*. *P* indicates the penetration of the service at the end of the study period; eg. if *P* has a value 2, the final service penetration will be 20 %, 3 ⇒ 30 % etc. Random variable *R* indicates relative revenue per customer and is distributed around 1. *R* acts as a multiplier to monthly revenue per customer. Table 7 shows the distributions and their parameters for these random variables.

4.2 Results of risk analysis

After a minimum of ten thousand rounds of Monte Carlo simulation the probability distributions for output variables were well formed. The distribution of NPV for different cases was especially looked at, and Table 8 shows the probability of yielding positive NPV in different cases. Essentially this is the probability that different business cases turn out to be profitable.

However, the results in Table 8 show that there are still significant probabilities that different scenarios may have negative NPV.

The ranking of the variables regarding risk influence is:

1 Monthly revenue;

2 Level of competition;

3 Service penetration;

4 Component price (including nominal price and price trend).

This ranking comes from the contribution that given input probability distribution has on standard deviation of resulting NPV probability distribution. The results from earlier OPTIMUM studies[4)] also support the fact that the market variables generate higher risks than the component prices. One reason for this is that for a set of components, some part of the uncertainty is effectively cancelled since some of the deviations go in opposite directions. The relative influence of different variables varies slightly from case to case, but the ranking order is the same for all technologies and both for the basic service and for the enhanced service.

5 Conclusions

The results of this case study suggest that ADSL and LMDS technologies combined with both service options are profitable under the default assumptions (eg. penetration, revenue). One must remember that models for these technologies imitate the business that is run on top of existing telecom or cable TV networks which have required major investments in the past and which do require significant maintenance efforts all the time. The services analysed here are not being strained by the costs generated in the

Table 6 Characteristics of the normal distributions used for modelling the uncertainty of component prices (0 and K_0 stand for nominal expected value)

	95 % confidence interval for mean price	95 % confidence interval for K value
ISDN NT+TA	$[0.85 \cdot \mu_0, 1.15 \cdot \mu_0]$	$[0.95 \cdot K_0, 1.05 \cdot K_0]$
ADSL modem	$[0.75 \cdot \mu_0, 1.25 \cdot \mu_0]$	$[0.9 \cdot K_0, 1.1 \cdot K_0]$
Cable modem	$[0.75 \cdot \mu_0, 1.25 \cdot \mu_0]$	$[0.9 \cdot K_0, 1.1 \cdot K_0]$
LMDS transceiver + NT	$[0.65 \cdot \mu_0, 1.35 \cdot \mu_0]$	$[0.9 \cdot K_0, 1.1 \cdot K_0]$

[3)] *K-value defines how much the price goes down when cumulative production volume doubles. For more information see [1].*

[4)] *For a list of OPTIMUM reports see web site http://www.fou.telenor.no/optimum/*

underlying network for maintaining the basic functionality of the network, ie. telephony or broadcast TV, even if the same platform is utilised.

Bearing this in mind, the different cases can be compared based on NPV and IRR figures. Following comments are based on IRR figures, which describe the profitability and efficiency regardless of the absolute size of the project. For the basic service LMDS technology promises the best profitability and for the enhanced service ADSL looks like the best candidate. In case of LMDS one must remember that these calculations assume that radio spectrum is free. The HFC based service is the last one out of these technology choices. This is mainly due to the assumption that the cable TV network on which the upgrades are made is originally rather old and two-way services require upgrades both on cabling and on amplifiers. If the underlying HFC network was modern, the profitability would likely be significantly increased.

For the ISDN, ADSL and LMDS based services, the vast majority of the costs lie in the access technology. In some cases only a few percent and in any case less than 25 % of the costs are in the centralised parts of the network. This suggests and the results show that it pays off to make as good use of the available access capacity as possible. Here it is reflected by the fact that networks for an enhanced service give more profitable results.

In addition to calculating economic results under the default assumptions, a risk analysis has been carried out. The results from the risk analysis show that there are significant probabilities that all different cases may yield negative NPV (Table 8).

The most important variable regarding the risk influence is the monthly revenue per customer. A reduction of 30 % or more on the revenue has a dramatic influence on the NPV.

The ranking of the analysed variables regarding risk influence are:

1 Monthly revenue per customer;

2 Level of competition;

3 Service penetration;

4 Component price.

This order is the same for all technologies and for both the basic service and the enhanced service.

Table 7 Random variables X and their probability distributions used in the risk analysis

X	Description	Distr.	Parameters	Correlation
C	Indicates the *level of competition*. This is a latent variable that is connected to the model only through rank correlation with P and R.	Uniform	$C \in [0,1]$	$r = -0.5$ with P and R
P	*Penetration.* Acts as a multiplier to the penetration curve. Final penetration ≈ P · 10 %	Normal	$\mu = 2$ $\sigma = 0.3$ $P \in [0,4]$	$r = -0.5$ with C
R	*Revenue.* Acts as a multiplier to monthly revenue per customer.	Normal	$\mu = 1$ $\sigma = 0.15$ $R \in [0,\infty]$	$r = -0.5$ with C

The market variables in general cause more uncertainty than the component prices. This conclusion is also supported by another OPTIMUM study[5)]. One reason for this is that for a set of components, some part of the uncertainty is cancelled since some of the deviations go in opposite directions.

An important conclusion of this study is that the revenue per customer is by far the most important factor which makes or kills the business case. The cost of technology is of secondary importance. This is even more so, since the uncertainties associated with revenues are much higher than the uncertainty on the cost of technology.

Table 8 Probability of yielding positive NPV for different scenarios

	Basic service	Enhanced service
ISDN case	87 %	N/A
ADSL case	67 %	80 %
HFC case	35 %	39 %
LMDS case	90 %	83 %

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5) *OPTIMUM deliverable 9. For a list of OPTIMUM reports see http://www.fou.telenor.no/optimum/*

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The economics of broadband service introduction

DAGFINN MYHRE

The next generation information services are now being developed worldwide by different actors within the telecommunication arena fighting for larger market shares in an ever increasing competitive environment. Several of these services require a comprehensive network upgrade like for example in the access network. A large variety of access network architectures are available for the operators and must be rigorously examined in order to determine the most appropriate ones for the different area types and service demand profiles. This paper provides a techno-economic analysis of multiservice access network architectures, scenarios and business cases. The paper reports work performed in the EURESCOM[1)] project P614, "Implementation Strategies for Advanced Access Networks". The methodology and tool initially developed by the RACE[2)] 2087/TITAN[3)] project, and further developed in the ACTS[4)] 226 OPTIMUM[5)] project has been applied in the techno-economic analysis. The most important findings of the work, including the main conclusions, are presented.

1 Introduction

Underlying all successful technology developments is a business opportunity framed in terms of demand for products and services. And today's communication marketplace illustrates a robust demand for services that will drive a change in the communications infrastructure. Following the recent dramatic Internet growth interactive broadband[6)] services are now emerging, widely recognised as potentially decisive for the capability of the actors to defend and eventually expand the current revenue base. However, the future interactive broadband arena, and in particular the residential market, is characterised by a high uncertainty both with respect to service rates and willingness to pay. Furthermore, there is no infrastructure in place for the delivery of interactive broadband services to the residential market segment. The main infrastructure bottleneck is found in the cost sensitive access part of the network, which is also the part of the network most closely related to service demand. Accordingly high risks are associated with upgrading this network segment. The future broadband access network infrastructure to a large extent will have to be developed from the existing infrastructure, such as the twisted pair based telephone network, the coaxial cable network and satellite network for television distribution and the cellular network for mobile telephony. In particular the existing twisted pair based local loop represents a significant asset for telecommunication operators, and is regarded as the key enabler for provisioning of new advanced services. A large variety of access network architectures are available for the operators and must be rigorously examined in order to determine the most appropriate ones for the different area types and service demand profiles. In view of the underlying fundamentals of where and when to invest in order to create a positive business case for broadband services [1], the challenge for the operators is to derive suitable minimum-risk strategies for either a migration of existing network infrastructures or for deployment of a completely new access network infrastructure.

The paper presents an in-depth techno-economic analysis of several evolutionary paths for access network providers, including the different options available for traditional telephone operators, cable operators and new entrant operators. Network architectures considered include wireline technologies like hybrid fibre coax (HFC), digital subscriber line (DSL), broadband passive optical network (BPON) and wireless alternatives such as local multipoint distribution system (LMDS) and point-to-multipoint wireless systems. Topologies examined are fibre to the local exchange (FTTLex), fibre to the node (FTTN), fibre to the curb (FTTC) and fibre to the building (FTTB). The aim is to provide techno-economic guidelines for broadband introduction in the access network. The methodology and tool initially developed by the RACE 2087/TITAN project and further developed in the ACTS 226 OPTIMUM project have been applied in the techno-economic analysis [2, 3]. Deliverable 3 was prepared by P614 Task 6. The Participants in Task 6 are:

- Deutsche Telekom
- Telecom Finland
- OTE
- France Telecom
- STET/CSELT
- Swiss Telecom
- Telecom Ireland
- Telefónica
- Telenor.

2 Case study framework

The economy of broadband access network upgrades depends to large extent on the expected future service demand and corresponding revenue streams and variations in existing infrastructure and network area types. For instance, areas with different density of living units have significantly different cost structures. At a strategic level some simplifications with respect to these key parameters are needed. This advocates a segmentation of network areas into suitable network area groups, despite the fact that the definitions of area types are somewhat subjective.

2.1 Area segmentation

The analysis covers non-greenfield upgrades in four network area types within the time period 1998–2007: A downtown area, an urban area, a suburban area, and a rural area [4]. The areas have been segmented and characterised according to the density of living units in the area, availability of existing ducts and surface conditions with corresponding cable deployment type and civil works costs. Representative ranges of the characteristic parameters have been assigned to each network area segment, including average copper loop lengths of 500 – 1,000 m (downtown), 1,000 – 2,000 m (urban), 2,000 – 3,000 m (suburban) and 3,000 – 4,000 m (rural).

The average civil works costs per metre depend on the surface conditions in the area, the cable deployment method and very often the network distribution level. The average civil works costs per metre are based on the assumed deployment of cables in the respective areas, and the

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1) *EURESCOM: European institute for research and strategic studies in telecommunications.*

2) *RACE: Research in advanced communications in Europe.*

3) *TITAN: Tool for introduction scenario and techno-economic evaluation of access networks.*

4) *ACTS: Advanced communications technologies and services.*

5) *OPTIMUM: Optimised network architectures for multimedia services.*

6) *Broadband: Capacity per customer 2 Mbit/s.*

cost ranges for the various deployment options. The ranges of costs are assumed to include the effect of the variation in labour rates in Europe [5].

Area related ranges of duct availability have been assumed. The duct availability as used here refers to the unavailability of ducts for installation of optic fibre cables. The range of effective civil works costs per metre for each area is given by the product of the average civil works costs per metre and the unavailability of ducts for installation of fibre cables.

2.2 Service scenarios

To evaluate the alternative technical options for a broadband access network upgrade, we need to define the services to be provided by the access network operator. This study focuses on broadband bearer services for the mixed residential and small business market only. According to several studies [6, 7, 8], there will be a future demand for asymmetric and symmetric broadband services in the residential and small business market segment.

In the residential market services like Internet, digital broadcast, video on demand (VoD) and distance learning, etc. will be required. The broadband services are typically asymmetric in nature and generically defined in this study as asymmetric switched broadband (ASB) services. We assume that the transmission capacities related to the ASB services will be in the range from 2 Mbit/s to 26 Mbit/s (downstream) and 64 kbit/s to 2 Mbit/s (upstream). In the small business market services like data communication, video-based communication, co-operative working, etc. will be required. The broadband services are typically symmetric in nature and generically defined as symmetric switched broadband (SSB) services. We assume that the bandwidth related to the SSB services will also be in the range from 2 Mbit/s to 26 Mbit/s.

The total broadband penetration level (saturation level) is set equal within all areas. Three representative bandwidths are provided: 2 Mbit/s ASB/SSB, 8 Mbit/s ASB/SSB and 26 Mbit/s ASB/SSB. It is assumed that the bearer services with lower bandwidths will have an early take up and reach higher penetrations in the final year compared to services with higher bandwidths. The access network operator will be faced with a continuous bandwidth 'migration' during time from lower towards higher bandwidths, expected to provide all bearer services in all areas at the same time.

According to results from [6–8] a broadband service penetration level of 20 % to 30 % is forecast in the served areas by 2007. Total broadband saturation level in this study is assumed to be 25 % in the final year (2007). Each of the defined bearer services are described by a certain penetration level with respect to time, as shown in Figure 1. The penetrations are given in percentage of total number of potential customers in the area. Downtown areas are assumed to be dominated by small business customers mixed with a minor group of residential customers. Areas like urban, suburban and rural are dominated by residential customers mixed with a minor group of small business customers. The distribution between ASB and SSB reflects the assumed distribution of customers based on typical figures found from internal studies in some European countries. In the downtown area 80 % of the customers demand a symmetric broadband connection, whilst the remaining 20 % asks for a asymmetric connection. The symmetric service demand decreases with the density of living units, with exact figures as follows: 30 % symmetric demand in urban areas and 20 % symmetric demand in suburban and rural areas.

2.3 Revenue model

A general model for revenue has been used, consisting of the sum of connection, rental, usage and churn revenues. The connection tariff is a one time tariff charged per new connection to a service, the rental tariff is a monthly tariff charged per connection to a service, the usage tariff is the tariff charged per minute (during which traffic is generated) and the churn tariff is a one-off tariff charged per churned connection. In this work tariffs are not specifically considered, but line revenues. It is assumed for the revenue modelling that the churn revenue = 0 for all bearer services and that the usage revenue = 0, ie. a flat rate for all bearer services. The connection revenue includes revenue from any installation fee charged for new connections. Basically, as similar equipment is installed at the customer premises (at least for HFC and XDSL based networks), a unique connection revenue per line of 100 euro is defined for each type (asymmetric and symmetric) of service, based on a European survey.

The rental revenue includes monthly or yearly income per connection. The rental revenue modelling is the most complex part of the revenue modelling. It should reflect the performance of the service in term of service type (ASB or SSB) and the speed (2, 8, or 26 Mbit/s) of the service. The model is based on

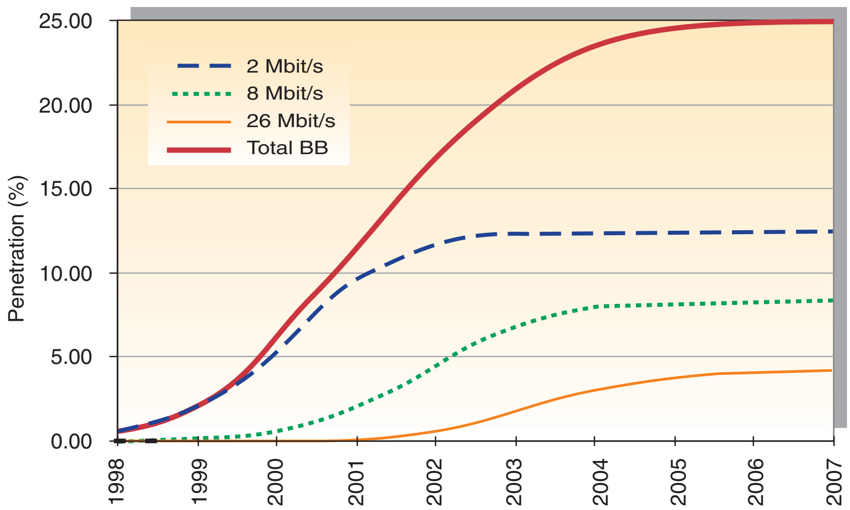

Figure 1 Market penetration for the 2 Mbit/s, 8 Mbit/s and 26 Mbit/s broadband bearer services

revenue per line, and considers that symmetric services are charged 50 % more than the asymmetric services. The 8 Mbit/s services are charged twice the 2 Mbit/s services and the 26 Mbit/s services are charged 3.5 times the 2 Mbit/s services. The factors between services have been chosen considering a survey of current tariffs. The tariffs take into account the high quality of service provided to the customer and used for the network dimensioning (1 % blocking probability at 0.1 user activity factor), which is certainly better than the quality of service assured by current HFC based Internet Service Providers.

2.4 Operation and administration costs model

A simplistic model for operation and administration (OA) costs has been used in this study. It is based on the assumption that the implementation of new broadband architectures involves operation and administrative running costs for the network operator, which may be divided into operations and maintenance costs, and administrative costs. The administrative costs are generated by administrative staff which cover technical resources, economic resources, sales and marketing resources. The operations costs are generated by operational staff which operate and manage the networks and services. The maintenance costs are generated by maintaining networks and services in operation, principally by repairing failed equipment and failed network elements. The maintenance costs are already a part the OPTIMUM methodology. The additional operation and administrative costs are modelled based on information of one European Telecom operator. This work is only concerned with access network bearer services, therefore the relevant information to be extracted is the OA costs per line. The network staff proportion is evaluated by the ratio of the number of employees working in the network division divided by the total number of employees. The network staff proportion excluding logistic and head quarter staff is about *35 %*. The turnover of access network services (which essentially cover the access copper network for POTS and ISDN, but exclude switching and long distance services) divided by the turnover of all network services is about *20 %*. The access network staff size is estimated by the product of the total number of employees and the two above ratio:

*Access network staff size = total number of employee * 35 % * 20 %*

Therefore one access network employee administrates and operates in average a certain number of copper lines, which is given by the "total number of copper access lines" divided by "access network staff size" (about *2,800 lines* per access network employee).

The annual cost of an employee is given by the product of the average of paid hours (1,800 hours/year) multiplied by the cost per hour (50 euro/hour). This gives *90,000 euro/year*. Thus, the OA cost per line per year is 32 euro, which in our analysis is rounded to *30 euro* per connected broadband user per year.

2.5 Techno-economic tool

The methodology and tool initially developed by the RACE 2087/TITAN project and further developed in the ACTS 226 OPTIMUM project have been applied in the techno-economic analysis [2, 3]. The objective of OPTIMUM is the calculation of the overall financial budget of any kind of access system. This includes: the discount system cost; operation, maintenance and powering costs; life cycle costs; and the cash balance of the project. The ability to combine low-level, detailed network parameters of significant strategic relevance with high level, overall strategic parameters is a key feature of the OPTIMUM methodology and tool, as compared to other similar assessment methods and tools recently reported. In OPTIMUM the network costs are calculated taking the evolution of component costs into account. A database including costs at a given reference year for components, installation and civil works costs has been developed within the OPTIMUM project and the EURESCOM P614 project. The cost trends of the various network elements are derived from initial cost. The cable lengths are calculated using geometric models.

3 Architectures and evolutionary paths

Access network migration towards broadband is to a large extent related to the existing network, the target architecture, and the corresponding intermediate infrastructure changes required in order to upgrade the network to the target architecture. In the analysis several evolutionary paths have been defined for traditional telephone operators, cable operators and new entrant operators, ie. competitive new operators who do not have any current access network, but start service offering in areas already covered by incumbents. The evolutionary paths have been grouped according to three different starting situations for the access network provider: Twisted pair based evolutionary paths, coaxial cable based evolutionary paths and "New-Operator" evolutionary paths.

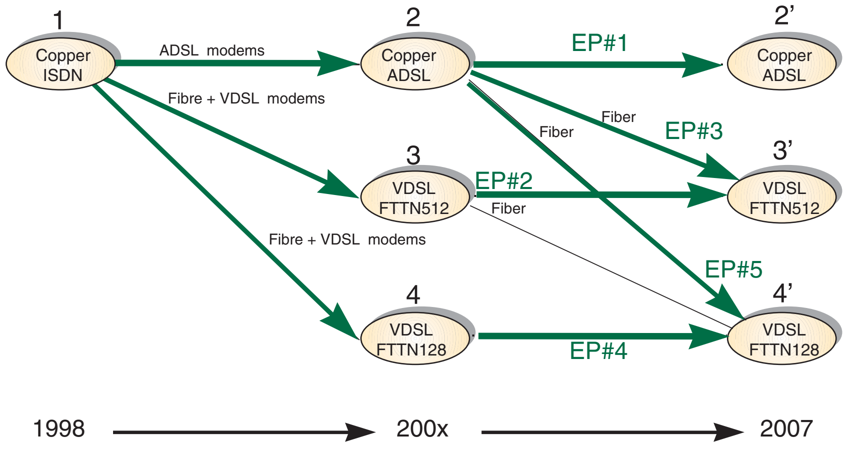

Figure 2 Selected evolutionary paths for telephone operators with an existing twisted pair network

The alternative evolutionary paths towards a future broadband network are depicted in Figures 2, 4 and 6. The circles indicate the network type and configuration at that particular point in time and during the preceding upgrade period. Solid lines between the circles represent network upgrades, whereas dotted lines indicate no infrastructure changes during that particular period. The different proposed migration paths are marked with thick arrowhead lines from the existing architectures to the final ones. The architectures considered have been dimensioned for a quality of service probability of 0.01 and a 10 % activity factor for the users, according to the recursive Kaufman-Roberts formula [9, 10].

3.1 Twisted pair based evolutionary paths

The group of twisted pair based evolutionary paths (EPs) comprises the likely migration alternatives for a telephone operator, which at the initial stage has a twisted copper pair access network. A combination of fibre in the loop and DSL systems are likely to constitute the future broadband access network for operators with an existing twisted pair infrastructure. The deeper the fibre penetrates the access network, the larger is the number of potential customers who can be offered broadband services. Given a migration towards fibre in the access network, how deep should the fibre be deployed? This major question is addressed in the analysis, as seen from the five selected EPs for this starting situation shown in Figure 2.

The proposed EPs include the installation of ADSL (asymmetric digital subscriber line) modems in the local exchange (state 2), as shown in the upper part of Figure 3. Additionally, the selected EPs include the use of BPON (broadband passive optical network) equipment in combination with node or curb located VDSL (very high-speed digital subscriber line) modems (states 3 and 4), illustrated in the lower part of Figure 3.

3.2 Coaxial cable based evolutionary paths

The group of coaxial cable based EPs include the migration alternatives for a cable operator, who initially has a coaxial cable based access network with no return capability, used for distribution of analogue television signals. Thus, the

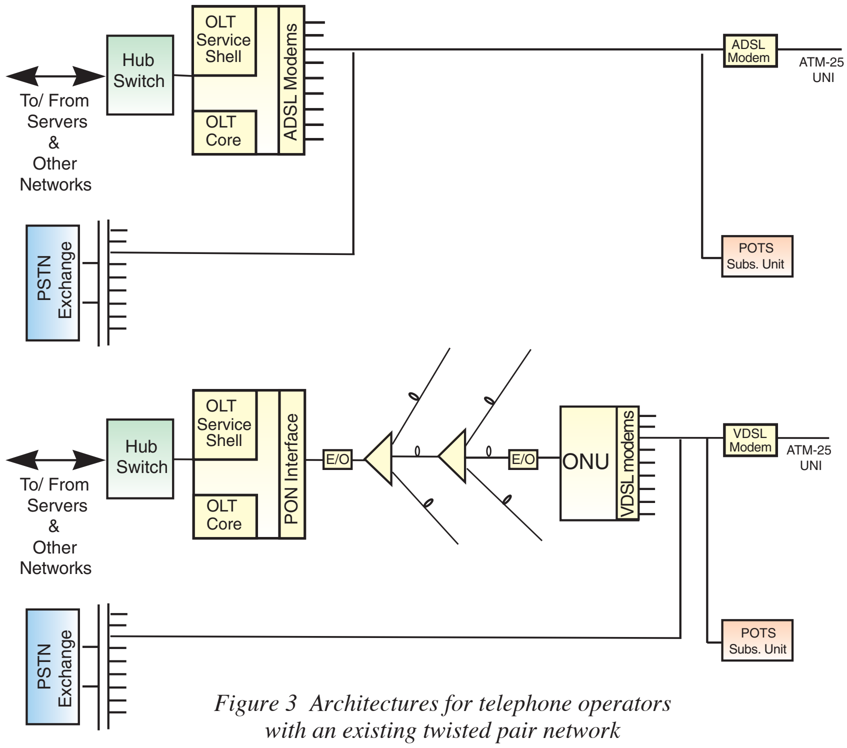

Figure 3 Architectures for telephone operators with an existing twisted pair network

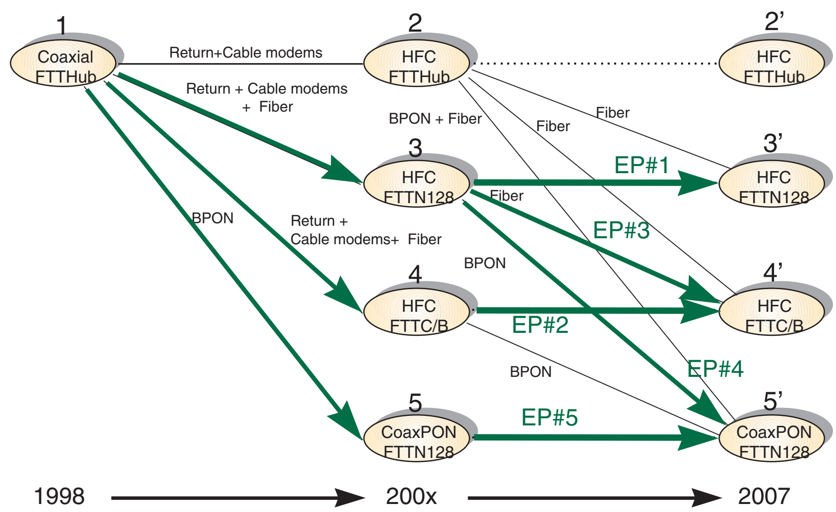

Figure 4 Selected EPs for cable operators

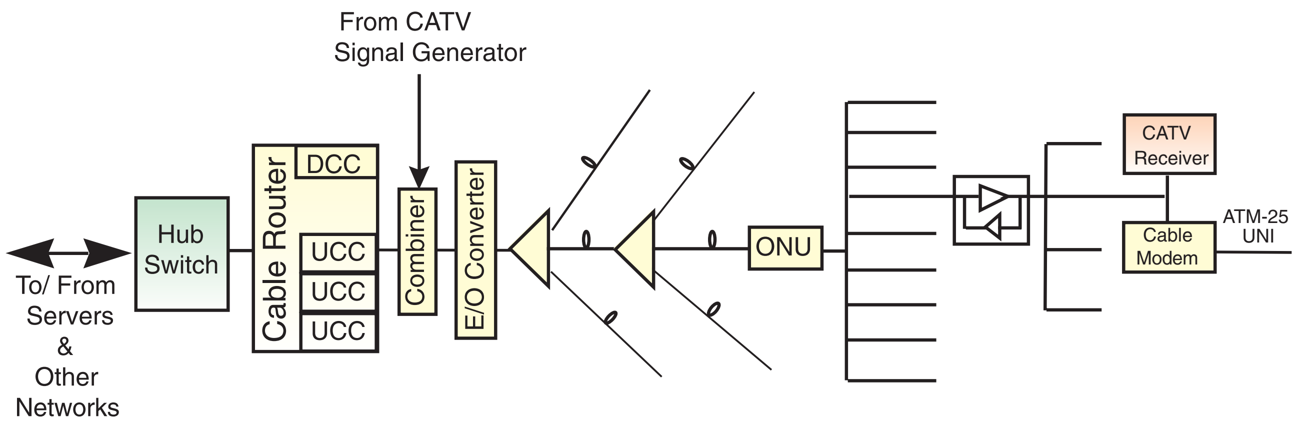

Figure 5 Architecture for cable operators with an existing coaxial cable network

cable operators usually have a starting situation for a migration towards interactive broadband access which is significantly different from the situation of the telephone operator. The twisted pair network of the telephone operator has a point-to-point topology and the coaxial cable network has a distributive topology. Upgrading the coaxial cable network to interactive broadband usually implies the installation of cable modems and return amplifiers. In addition a splitting of the coaxial cable network into smaller segments by the use of fibre optic feeder cables and HFC technology will most likely be required in order to achieve the required return path capacity. The size of the coaxial cable segments in terms of homes passed, and accordingly the fibre penetration is a crucial question related to HFC upgrades. This issue is addressed in the analysis, illustrated in the five selected EPs for this starting situation (Figure 4).

The proposed EPs include the use of cable modems without additional fibre (state 2) or with fibre (eg. state 3). The latter alternative is illustrated in Figure 5. Alternatively, installation of fibre to the node or building (states 3 and 4) and the use of BPON equipment with a coaxial drop (state 5) may be used.

The available cable modem equipment is not able to offer the higher bitrate broadband services defined in the study framework. Hence, an additional reduced bitrate service, with 256 kbit/s downstream and 64 kbit/s upstream capacity, has been defined and examined together with the 2 Mbit/s service described in chapter 2. Very few coaxial cable networks are installed in rural areas today, and hence this area has not been considered in the analysis of the coaxial cable based evolutionary paths.

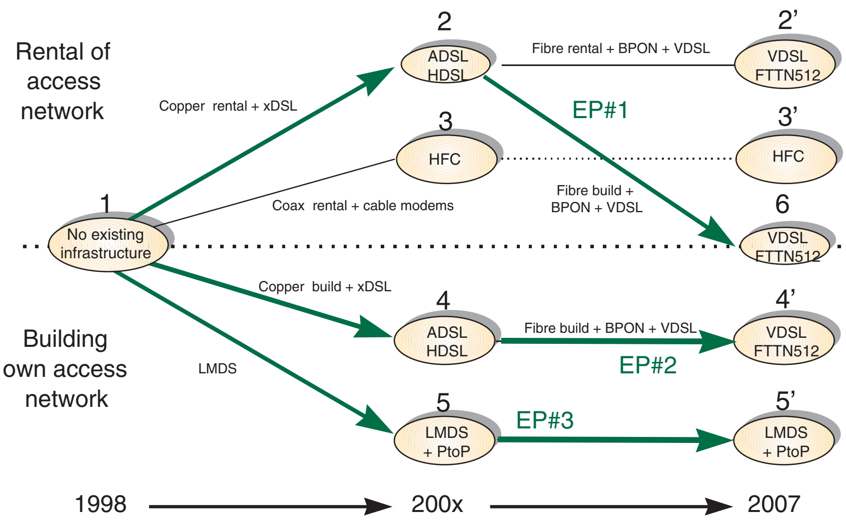

Figure 6 Selected EPs for a ‘new’ operator

3.3 “New-Operator” evolutionary paths

With the new operator the starting situation is always no existing infrastructure, with three different basic alternatives envisaged: Rental of access network, building of own (wireline) access network, or building of own wireless access network.

It is assumed in this study that the new operator wants to rent access network capacity from the existing operator at the lowest possible cost level. That means ‘blank’ copper pairs excluding eg. DSL modems. The new operator will act as a competing network operator with his own equipment in the access network, not as a service provider utilising the access network capacity of the existing operator. This study concentrates only on the downtown and urban areas as defined in chapter 2. Figure 6 shows the selected new operator EPs.

From these EPs for the new operator the three most relevant were selected for the more detailed assessment. The installation of wireless broadband systems is considered as a reasonable alternative for this situation, as illustrated in Figure 7. LMDS and point-to-point radio links are used.

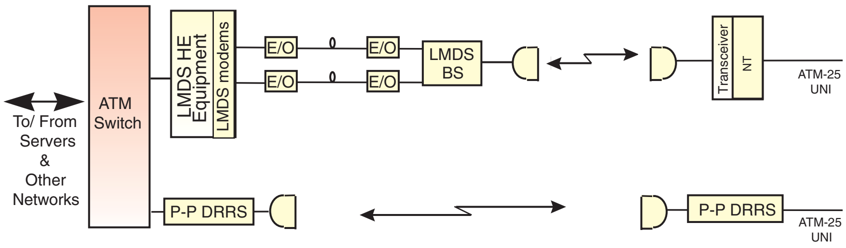

Figure 7 LMDS architecture for a 'new' operator

3.4 Broadband wireless access architectures

A more detailed study on broadband wireless access solutions has been performed. The study includes aspects influencing the dimensioning of radio networks such as the maximum achievable radio range, cellular coverage, structure of coverage and network upgrading strategy. The two main broadband radio network options of LMDS and point-to-multipoint are analysed. The LMDS system analysed supplies 2 Mbit/s ASB and SSB services in addition to 8 Mbit/s ASB and 26 Mbit/s ASB services. The point-to-multipoint architecture is assumed to supply all the previously mentioned services except the 26 Mbit/s ASB service. In both cases point-to-point wireless systems are deployed for the remainder of the service set defined in section 2. The LMDS system is deployed in downtown and urban areas, whereas the point-to-multipoint system is deployed in suburban and rural areas. The bearer service demand profile is equal in the suburban and rural areas, and with a radio cell radius of three km the network dimensioning will be the same in the two areas. Thus, under these assumptions the results given for deployment of point-to-multipoint wireless systems are the same in the two areas. The point-to-multipoint wireless architecture is shown in Figure 8. A radio network upgrade may be performed by increasing the number of transceivers per antenna, introducing a finer sectorisation or by increasing the number of access points. We have examined two different strategies for allocation of radio resources during the ten year study period.

4 Analysis results

The techno-economic analysis was carried out in two steps, starting with a pure cost-study and then extending the study through a complete business case analysis including revenues from the selected bearer services. Installed first costs (IFC), life cycle costs, project revenues, cash flows, pay back period, internal rate of return (IRR) and net present value (NPV) have been calculated for the EPs and area types considered, including the total network upgrade costs for the whole area under consideration and the discounted costs per connected user. In this section some selected example results from the cost study and the business case study are shown.

4.1 Evolutionary path cost studies

The cost per user is given by the sum of the IFC and maintenance cost divided by the number of connected customers at the end of the study period. The number of connected users differs among some of the EPs examined, and thus a direct comparison must be carried out with care. The total upgrade investments are distributed on *cable infrastructure investments* (civil works, ducts and new cables), *basic service investments* (optical line terminals and optical network units) and *service specific investments* (DSL modem pairs). A higher financial risk is associated with the former two cost components compared to the latter.

4.1.1 Twisted pair based evolutionary paths cost study

The twisted pair based evolutionary paths studied combine the use of fibre based systems and DSL modems, reflecting

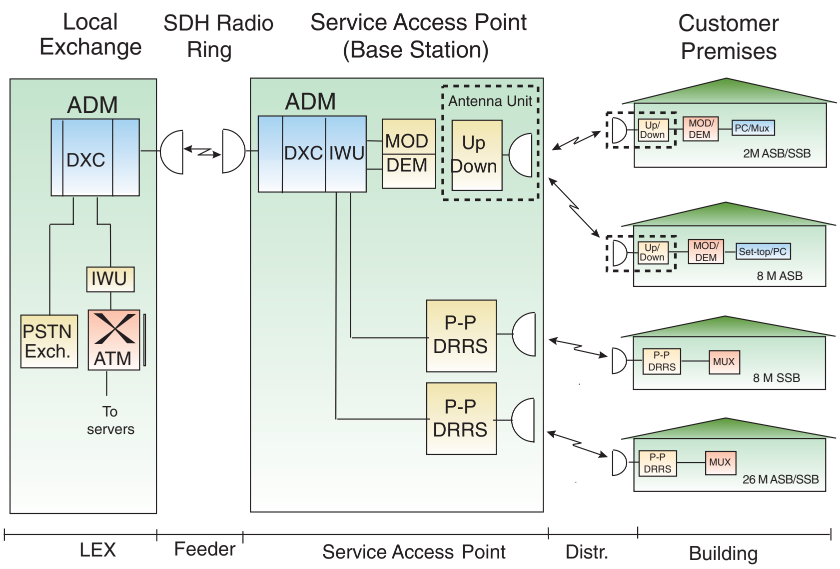

Figure 8 Point-to-multipoint architecture

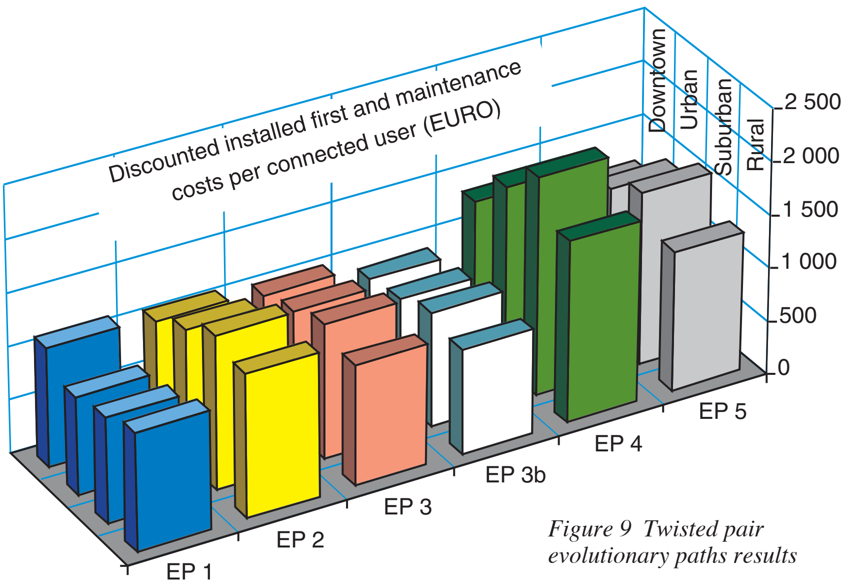

Figure 9 Twisted pair evolutionary paths results

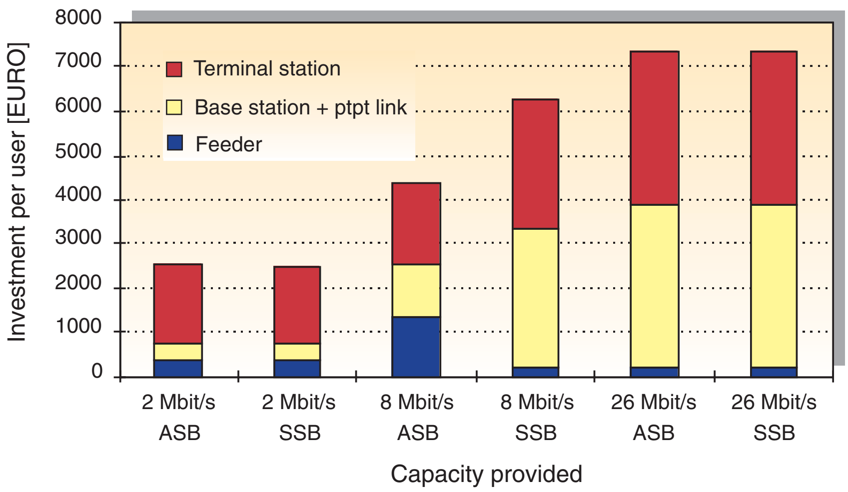

Figure 10 Cost breakdown, point-to-multipoint wireless upgrade

differences in aggressive and cautious strategies for introduction of fibre based systems in the network. For all the four areas and the EPs examined with the given service assumptions the discounted cost per connected customer is in the range from 900 euro[7)] (downtown area) to 2,000 euro (suburban area). This investment level is comparable to the costs associated with the establishment of the present access network infrastructure for telephony services. Figure 9 shows for all areas the discounted installed first costs and maintenance costs per user for the twisted pair based EPs studied.

The cost per connected customer largely depends on the area type and is very sensitive, since it is composed of a variable part due to modems, a basic part due to other equipment, and infrastructure costs divided by the total number of customers. The number of customers is defined as a function of area characteristics and the maximum loop length. Thus, a reduction in maximum DSL transmission distance will lead to very different figures.

The cost difference between different fibre penetration levels has been examined with the calculation of FTTN and FTTC architectures. The results confirm that the node configuration and corresponding degree of fibre penetration greatly impacts the cost level.

The analysis of the twisted pair evolutionary paths shows that the timing of the network upgrade has a significant impact on the costs. An immediate introduction of a VDSL and fibre based FTTC architecture will have a significantly higher cost than a network evolution towards FTTC based on an ADSL based intermediate step.

4.1.2 Broadband wireless access cost study

The in-depth analysis of the point-to-multipoint wireless upgrades shows an average discounted cost per user in suburban and rural areas of 4,500 euro. However, as can be seen from the cost breakdown in Figure 10, the more expensive point-to-point wireless systems deployed to serve the 8 Mbit/s SSB and 26 Mbit/s ASB and SSB service demand increase significantly the average cost per connected user.

An additional study of point-to-multipoint wireless upgrades, in which only 2 Mbit/s ASB/SSB and 8 Mbit/s ASB services were offered, and hence no point-to-point wireless systems are installed, resulted in a reduction of the cost per user by 1,000 euro.

The corresponding analysis of an LMDS upgrade indicates a cost per connected user of 4,900 euro in downtown and 2,800 euro in urban areas. In the LMDS study the corresponding investment levels without point-to-point wireless systems are 1,900 and 1,700 euro respectively. The pure LMDS upgrade in the urban area is cheaper than in the downtown area since the urban area benefits from higher cost sharing of common equipment due to the higher number of customers being served.

The LMDS upgrade has lower costs than the point-to-multipoint upgrade, mainly due to the more expensive terminal station of the point-to-multipoint systems

7) 1 euro ≈ 1.2 USD.

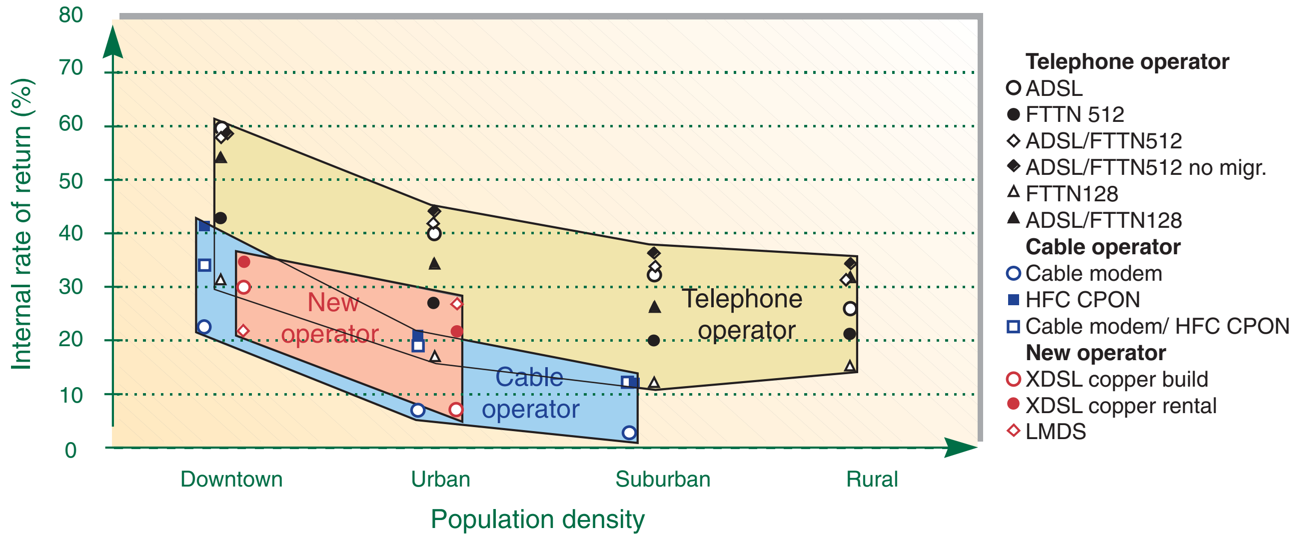

Figure 11 The internal rate of return results (in %) for the operators and their different evolutionary paths applied in various areas

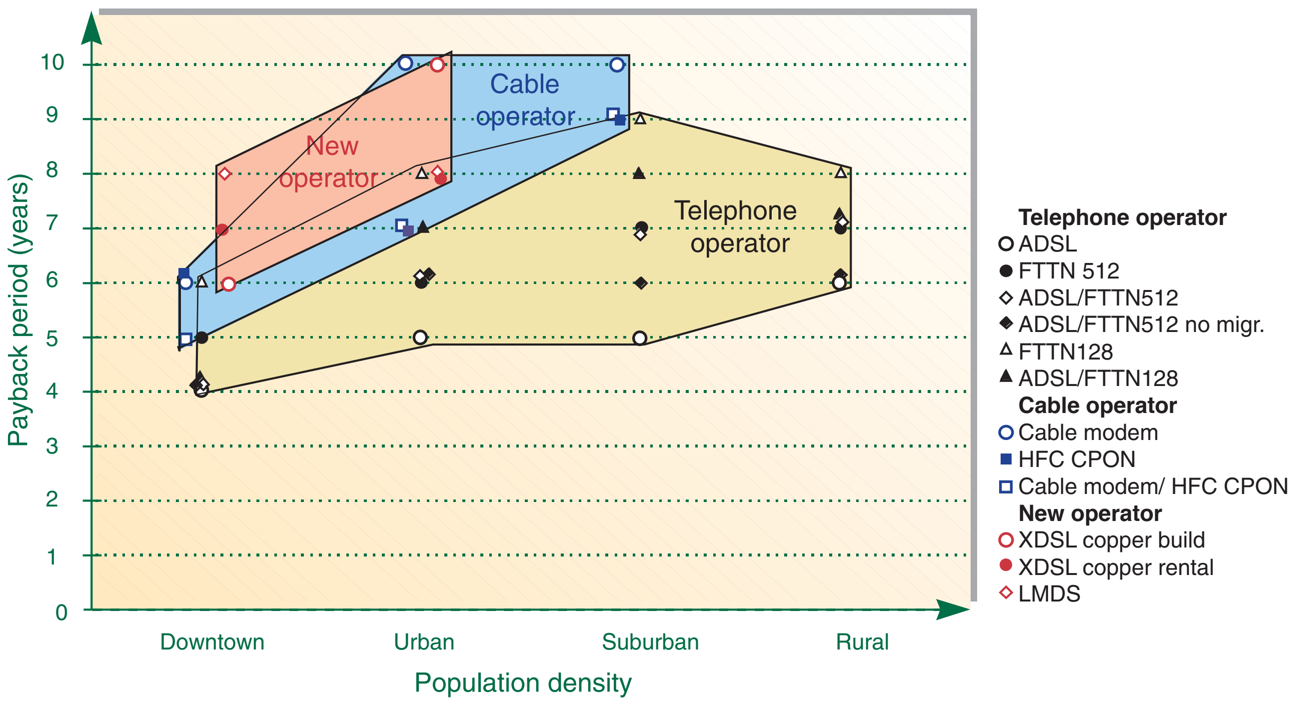

Figure 12 The pay back period results (in years) for the operators and their different evolutionary paths applied in various areas

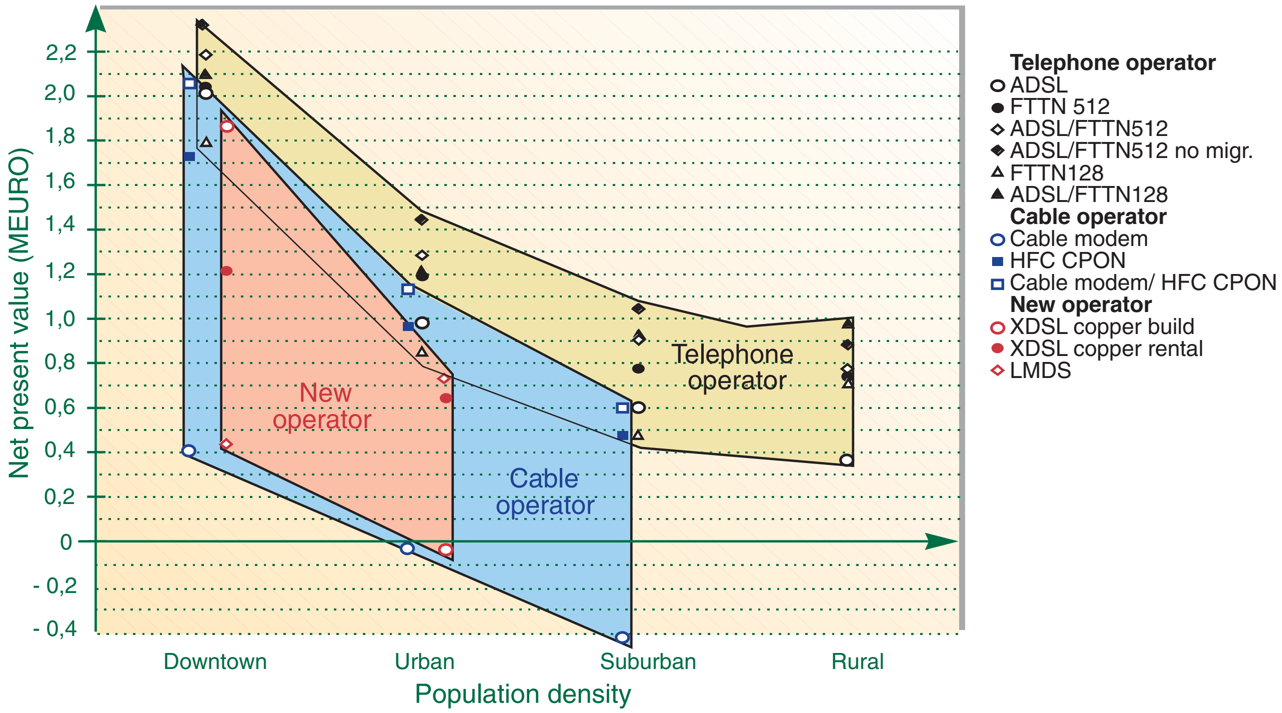

Figure 13 The net present value results (in Meuro) for the operators and their different evolutionary paths applied in various areas

and the expected smaller decrease in price during time for this technology.

In our study we compared an upgrade strategy in which the radio resources are continuously allocated as close as possible to the incremental capacity demand with a second strategy in which the radio resources are more coarsely allocated initially. The results show that the second upgrade strategy is only around 10 % more expensive in total, and that the cost difference mainly arises from the higher investments required in the first year of the study period.

4.2 Service scenario and business case analysis

In EURESCOM P614 a comprehensive techno-economic analysis of the business case for broadband access network upgrades has been performed. The network upgrade options examined are those described earlier in this paper. The investment analysis has been extended to include a service revenue model and operations and administration costs. Based on these enhanced models, financial parameters such as internal rate of return, pay back period and discounted cash flow have been calculated. Additional studies have been performed by sensitivity analyses of relevant network parameters for each EP.

4.2.1 Summary of evolutionary path business case analyses

Figures 11–14 summarise the results from the evolutionary path business case analyses. Figure 11 shows the summary of the internal rate of return results for the different operators and their different evolutionary paths applied in various areas.

All of the evolutionary paths examined have acceptable internal rate of return, above 20 %, in the downtown area. The evolutionary paths of the telephone operator are on average more profitable than the evolutionary paths of both the cable operator and the new operator. The telephone operator projects have an average internal rate of return of 51 % in downtown areas, whereas the cable operator and new operator projects have average internal rates of return of 33 % and 29 % respectively, with the given assumptions. In the urban area, the evolutionary paths examined for the telephone operator have an average internal rate of return of 34 %. Only some of the cable operator and new operator projects have acceptable economic results. For the new operator the XDSL copper rental and the LMDS upgrade with a limited service set have acceptable levels of internal rate of return, above 20 %. In the suburban area, all of the evolutionary paths examined for the telephone operator give acceptable levels of internal rate of return, except the most aggressive 1998 roll-out of a FTTN configuration with 128 homes passed per node. None of the cable operator projects have acceptable levels of internal rate of return. Only telephone operator projects are examined for the rural areas, and they all give acceptable levels of internal rate of return above 20 %, except the above mentioned aggressive 1998 roll-out of an FTTN configuration with 128 homes passed per node.

Figure 12 shows a summary of the pay back period results (in years) for the different operators and their different evolutionary paths applied in various areas.

The average pay back period for all projects in the downtown area is six years. The evolutionary paths of the telephone operator have on average shorter pay back periods than the evolutionary paths of both the cable operator and the new

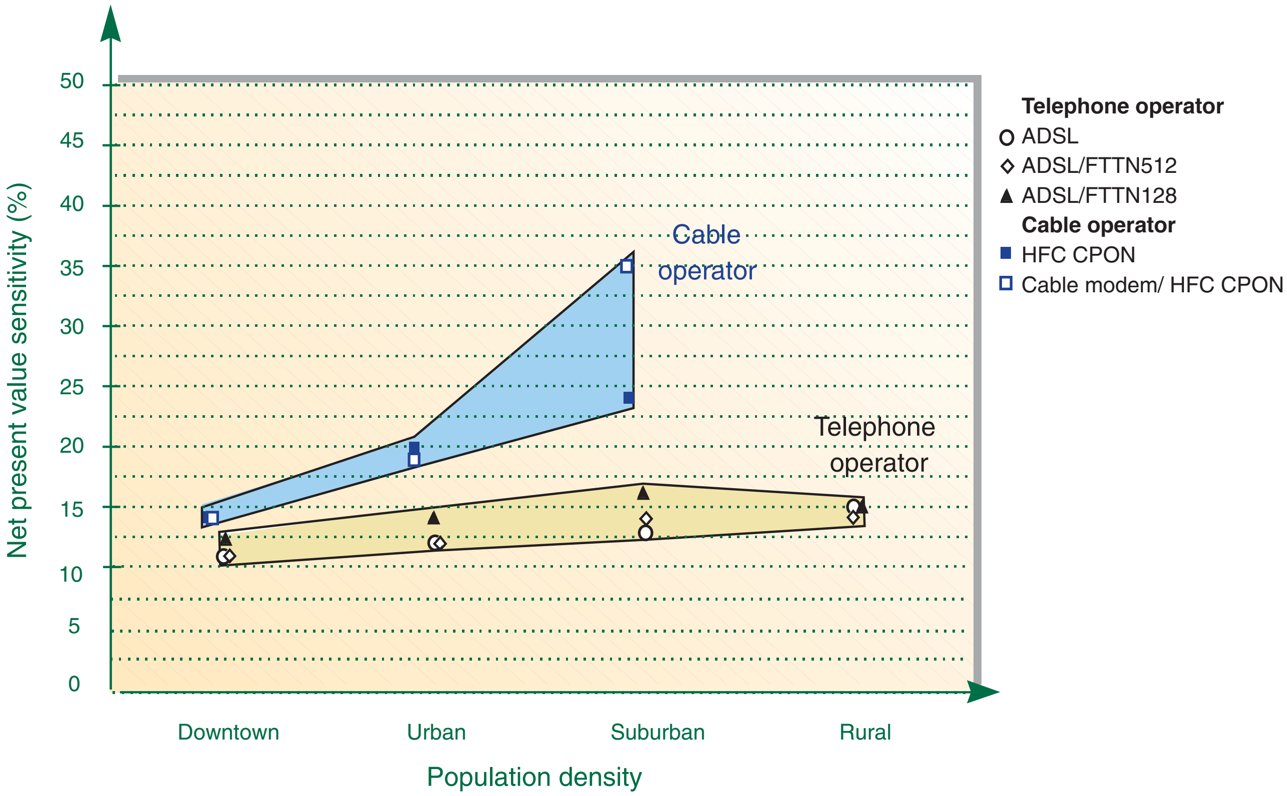

Figure 14 Sensitivity of the net present value to a 10 % variation of the penetration level (25 % – 22.5 %) for the three operators and their different evolutionary paths applied in various areas

operator. On average the pay back periods in the urban and suburban areas are longer than in the downtown area, with eight years average pay back periods for both areas for all upgrade projects examined. Interestingly enough, in the rural areas telephone operator projects have pay back periods similar to the ones of the same operator in suburban areas.

Figure 13 shows a summary of the net present value results (in Meuro) for the three operators and their different evolutionary paths applied in various areas.

On average, the net present values of the downtown area projects are much higher than the ones of the other areas. The average net present value of all projects in the downtown area is 1,680 keuro, which is twice the size of the highest average net present value for the other areas. The net present value of the telephone operator projects is also on average significantly higher than the corresponding values of the cable operator and the new operator, between 50 % and 100 % higher. As illustrated in the figure, there is a certain risk for the cable operator, and also for the new operator, to end up with negative net present values in mid-density customer areas like urban and suburban. The range of net present values is different between the operators. The cable operator and the new operator face variations in net present values for the upgrade projects two, or even three times greater than the telephone operator projects analysed.

Figure 14 shows the sensitivity of the net present value to a 10 % variation of the penetration level (25 % – 22.5 %) for the operators and their different evolutionary paths applied in various areas.

The results show that the net present values vary depending on the penetration level for all projects in all areas, where the telephone operator projects seem to be less sensitive to penetration variations. This is illustrated by higher variation of the average NPV, 14 – 30 %, faced by the cable operator projects compared to the lower variation of the average NPV for the telephone operator projects, 11–15 %.

The telephone operator projects show the same variation in NPV, more or less independent of the area type. The cable operator projects seem to be more sensitive to market size variation in areas with lower customer density compared to areas with higher customer density. This illustrates the higher risk related to cable network investments in for example suburban areas.

5 Conclusions

The EURESCOM P614 project has performed an extensive techno-economic analysis on the evolution of the access network towards broadband in downtown, urban, suburban and rural areas, including the different alternatives available for traditional telephone operators, cable operators and new entrant operators.

In general the analyses confirm that the cost of increased bandwidth in the access network for interactive broadband delivery is high, independent of the operator's existing network situation, area type and broadband technology choice. Both telephone operators, cable operators and new entrant operators are likely to face broadband upgrade investment levels per connected user similar to or higher than the overall costs of establishing the existing access network.

The cost analyses show significant differences among the upgrade costs both with respect to area types and between the operators when full service set is considered. With the given assumptions, downtown areas have the lowest upgrade costs per connected users in most of the cases analysed. In particular suburban areas with relatively low duct availability and high average civil works costs have high upgrade costs. The node configuration and corresponding degree of fibre penetration has a great impact on the cost level. Simultaneously a full service coverage largely depends on a high fibre penetration. Thus, the fibre penetration and the location of the optical nodes in the network is a key strategic decision.

Furthermore, wireless broadband upgrades are significantly more expensive than their wireline counterparts for a full service set including capacities from 2 Mbit/s to 26 Mbit/s. One main reason is that the radio links needed for the 26 Mbit/s high capacity symmetric service provisioning are very costly compared to the LMDS technology used for asymmetric services and lower rate symmetric services. However, for a limited asymmetric service set the LMDS (in downtown and urban areas) and point-to-multipoint broadband wireless access systems (suburban and rural areas) have investment cost levels comparable to the HFC and the BPON upgrades.

The business case studies indicate that the telephone operator achieves the highest average project values for all areas in terms of net present value, internal rate of return and pay back period. His projects also seem to be the ones least affected by market variations. According to the results almost all telephone operator upgrades have acceptable project values with internal rates of return above 20 % in all areas, except immediate aggressive fibre roll-outs in suburban and rural areas. The results show that for a new operator XDSL copper rental and LMDS upgrades are feasible solutions in downtown and urban areas. However, civil works and rental costs heavily influence the economic performance. The calculations indicate that all operators may achieve acceptable project values in downtown areas.

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This document is based on results achieved in a EURESCOM Project. It is not a document approved by EURESCOM, and may not reflect the technical position of all the EURESCOM Shareholders. Further information on EURESCOM P614 is available at http://www/ eurescom.de *and the EURESCOM P614 homepage* http://www.cselt.it/Cselt/ euresc/P614. *The author gratefully acknowledges the support of EURESCOM and the project members in carrying out this work: Leif Aarthun Ims, Markku Lähteenoja, Borgar Tørre Olsen, Kjell Stordahl (Telenor), Antonio Ruiz-Cantera (Telefonica I+D), Benoit Rose, Marie-Christine Combes (France Telecom), Bodo Jacobs (Deutsche Telekom), Jari Mononen (Telecom Finland), Lucien Budry (Swisscom), Valter Benedetto, Umberto Ferrero (CSELT), Dermot Collins (Telecom Ireland), Michael Mavis (EURESCOM).*

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Risk methodology for evaluating broadband access network architectures

KJELL STORDAHL, LEIF AARTHUN IMS AND BORGAR TØRRE OLSEN

The first part of this paper gives an overview of the risks connected to a roll out of a broadband infrastructure. The risk methodology developed in the OPTIMUM and TERA projects is described. The paper shows how risk methodology can be applied for evaluation of various network architectures. The second part of the paper presents risk and techno-economic analyses of broadband access network upgrade strategies for Public Network Operators and Cable Operators in a competitive environment in the residential and small business market. The effect of uncertainties in predictions of critical parameters such as demand forecasts and market shares are analysed. The assessed technology options include broadband twisted pair modems, hybrid fibre coax networks and ATM-based passive optical networks.

Introduction

Over the last 10 years the EU Commission has given high priority to various research programmes to support the development of broadband communications. The RACE programme – and later the ACTS programme – contain a substantial set of projects which promote high capacity technology, multimedia applications and broadband networks. The most advanced 'communication' countries co-operate through the FSAN community to establish broadband industry production and to give inputs to production standards.

So far no administration has started to deploy a large scale broadband network. Still there is too many uncertainties and economic risks involved. However, the evolution of broadband technology has developed important network architectures for transport of broadband communication. The hybrid fibre coax architecture, passive optical networks, digital subscriber technology and high speed radio networks are relevant technologies.

The rapid expansion of the Internet has created a new market for narrowband applications. Further development will create demands for broadband applications. The question is: What is the need for broadband applications and how will the market evolve?

This paper gives an overview of various risks connected to the deployment of a broadband network and also some examples of how the risks can be quantified by use of risk analysis and simulations.

Key risks – an overview

Many complex and interacting factors have an impact on the network evolution. The main factors are: Applications, technology, network platform, service quality, cost evolution, demand, price, environment and strategy/policy. The broadband deployment is influenced by *the risk* of all these elements.

The strategy of the network operator is governed by estimated revenue, expected return on investments and assessed economic risks. The introduction of new technology, new applications, new network platforms, new architectures etc. depends on the long term revenue prospects and also on the related uncertainties and risks. Strategic decisions play an important role in the near term positioning when competition increases. The environment of the telecommunication market is now changing dramatically in Europe and will continue to do so in the coming years.

New applications and services can be implemented by using the same network platform, or by expanding the network platform, or by introducing a new technology. The preferred alternative will depend on the cost of network components and the cost evolution. The price of the given application depends on investment cost, operation and maintenance cost and revenue considerations. The demand depends on the expected competition, the market potential for the applications, expected market shares, substitution effects between applications, penetration as a function of time, price and service quality. In addition there are interactions between the main factors.

Market risks

Substantial risks are linked to the predicted evolution of the broadband market. A basis for the evolution is new and enhanced broadband applications. Uncertain demand forecasts generate significant risks influencing the investments and also other costs. One realisation is an unexpected delay in demand. Overestimation of the demand implies overestimation of investment costs, where parts of the costs are bundled and not utilised for a period. Underestimation of the demand will generate waiting lists, a bad reputation and lost market shares. Also the problems in the roll out, in component and service supply and in service quality will induce bad reputation.

If some customers are lost to a competitor, it is difficult to win these customers back. This risk problem is denoted the churn problem. The customer can be lost from specific market segments, specific user groups or in specific geographic areas.

The risk of lost market shares may also be caused by substituting applications and services.

Competition risks

The main objective for the regulator is to establish a competition regime where the newcomers should have a fair competition, while the incumbent operator should have a significant handicap. The effect will be a reduced market share and power for the incumbent operator and a more balanced market between all operators. The risks and the uncertainty are influenced by unpredicted regulations, the number of new competitors and alliances between the operators and also service providers. The risks are lost market shares.

The geographic deployment strategy for roll out influences the market shares as well as the service mix, service quality, customer support and type of billing systems compared with the other network operators. Another important competitive factor is the tariffs and the tariff strategy. Significant risks of losing market shares are linked to the tariff evolution for the different competitors.

Regulatory risks

Since the public network operators (PNOs) own large parts of the access network, the European regulators have taken some actions to induce competition in the access network. In some countries the PNO has been forced to implement Local Loop UnBundling, LLUB. In other countries specific transmission equipment for permanent access can be hired from the PNO. However, there is a lot of uncertainty connected to the actions of the regulator. The regulator may generate changes in some important parts of the telecommunication law. The regulator controls the number of licenses for the operators. The regulator may prevent the incumbent operator in offering given services. The body influences the interconnect tariffs and may also regulate the ordinary tariffs. The regulator also controls the Universal Service Obligation, the USO regime.

Technology risks

A wide range of technologies is available for transport of broadband communication. In the access network a fibre node structure or a coax structure has to be deployed. The last part of the access network can be covered by ADSL or VDSL modems on copper, or by the radio solution LMDS, or in the future the universal mobile telephone system – UMTS. Other alternatives are satellite communication combined with a wireline return channel or a hybrid fibre coax system – HFC. The technologies may substitute each other or may be deployed as supplements in different parts of the network. In the transport network deployment strategies for substitution between PDH and SDH transmission equipment are carried out. In parallel, the fibre capacity is expended by introduction of wavelength division multiplexing – WDM. Another technical problem not solved is the switching. One possibility is to use ATM, another is to use IP, and a third one is to implement IP over ATM.

There are substantial risks of implementing the wrong technology at the wrong time. Important questions are:

- Selection of optimal technology in different parts of the network;
- Strategies for roll out based on competition in specific areas;
- Strategies for robust upgrading of the upper part of the access network giving possibilities for utilising different technologies;
- Strategies for minimising the upfront costs for the initial period.

In addition specific technology problems may occur. The quality of some components does not satisfy the norms and they have to be replaced by other types of components. The selected manufacturer has significant problems and does not satisfy the production specifications. The effect is bad quality for the customers, delivery problems, waiting lists and a bad reputation. The same risks can be generated if the demand forecasts, planning, dimensioning, projecting or deployment of the network are poor.

To get insight into these problems for understanding the risk, economic evaluations of the different technologies have to be performed by rather comprehensive calculations. One possibility is to use the TERA/OPTIMUM tool. Some examples are shown in this paper.

Operational and investments risks

Investment and operational costs can be divided into:

- Investment costs
- Operational and management costs
- Maintenance costs
- Administrative costs
- Costs for support systems
- Customer support costs
- Marketing costs.

Implementation of a new broadband network including new services and applications will generate uncertain cost estimates. The main input is demand forecasts for the total market and estimates for lost market shares because of competition. If the forecasts turn out to be completely wrong, then the investments will also be out of scale. Since forecasts for new services are uncertain substantial cost risks are generated. Important questions are:

- Time of optimal roll out;
- Which geographic areas should be covered at the start;
- Which market segments should be covered at the start;
- The size of the broadband nodes and the structure are of crucial importance;
- Dimensioning of the network and estimated demand controlled expansion.

The network components and the technology standards induce risks when an operator starts a roll out before the standards have been adapted. Additional investments and replacement of quite new components may be necessary. There is substantial uncertainty related to the prediction of component costs. The learning curve forecasts show that the component costs decrease as a function of large scale production. However, there is significant uncertainty in the predicted component cost evolution.

Economy risks

To be able to evaluate a broadband network upgrading, the discounted sum of revenues, investments, operations and maintenance costs etc. has to be calculated over a 5 – 10 years period. The result can be expressed in net present value, payback period, internal rate of return, installation first costs, life cycle costs, payback each year, etc. The economic risks are the sum of all the above mentioned risks.

Important economic risks are caused by:

- Higher investment costs than expected;
- Higher operational and maintenance costs than expected;
- Higher administrative costs;
- Higher customer support and marketing costs than expected;
- Investment restrictions due to lower profit or new priorities;
- Reduction of service mix;
- Loss of market shares;
- Higher revenue reductions due to substitution effect between other services;
- Lower subscription and traffic demand;
- Slower broadband application evolution;
- Restricted regulations.

Risk methodology and framework

This section describes the methodology for performing risk analysis. The main criteria for evaluating a network deployment or implementation of a new network structure are net present value, payback period or internal rate of return. An assessment of these criteria, however, gives only one value for each. The question is: What is the deviation from the calculated value if some of the assumed conditions change? To be able to make the right decisions, it is of crucial importance to have knowledge of how much the calculated values of net present value, payback period, internal rate of return, etc. change when the assumptions change, and also of the related probability for these events.

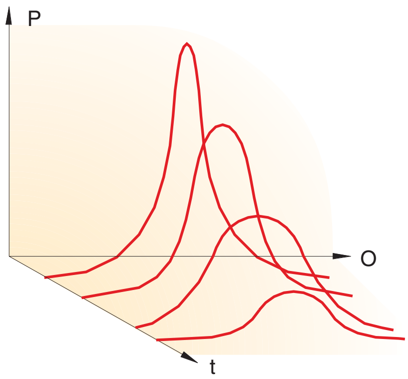

Figure 1 The probability distribution as a function of time

The application of risk methodology answers these questions. The critical variables like penetration forecasts, tariff evolution, market share, evolution of component costs and operations and maintenance costs are described not only by their expected value, but also by a probability density describing the probable deviation from the expected value. The risk analysis is carried out in performing a large number of simulations based on these probability densities.

The risk framework in the TERA project is developed to have an effective uniform methodology to analyse the risk. Important elements are:

- Choice of probability density functions;
- Potential establishment of correlation between important variables;
- Simulation performance;
- Methodology for cost predictions and uncertainties;
- Methodology for demand forecasts and uncertainties;
- Methodology for tariff predictions and uncertainties.

Choice of probability functions

The uncertainty in the assumptions made has to be quantified with respect to probability functions and limits of the uncertain variables when risk analysis is performed. Since it is meaningless to operate with negative costs, tariffs or forecasts, the Beta distribution is introduced to solve the problem. Traditionally the Normal distribution can be used, but in cases where there are significant probabilities for generating negative values, the Beta function is recommended.

An example of probability functions for the tariffs is illustrated in Figure 1. Suppose that we know the exact year 1999 tariff for a broadband connection.

In year 2000 the tariff will decrease, but still our estimate of the expected tariff is rather good. Hence the probability distribution describing the tariff variation has a small standard deviation. *The uncertainty in the tariff estimate will increase as a function of time. At the same time the expected value of the tariff decreases as a function of time.*

Correlation between important variables

In some situations, especially when risk analysis is performed to examine the effect of uncertainty in cost predictions on various components, there is a need to introduce correlation between input variables. The TERA/OPTIMUM tool uses Crystal Ball as a simulation program package. The simulation package contains options for making models with correlated variables. In the input sheet the estimate of the correlation has to be defined between each variable.

Simulation performance

When performing sensitivity and risk analysis, the uncertain parameters are described by suitable probability density functions. The techno-economic scenario is then calculated based on a certain number of times using Monte Carlo or Latin Hypercube simulation; each time a random number is picked from each distribution. In general, it is difficult to give advice on the number of simulations since there is a dependency of the complexity in each case study analysed. The best way to control the problem is to do some test simulation series and calculate the uncertainty in the output distributions. Based on experience so far the sufficient number of simulations could be 500 – 10,000.

Risk simulations

Figure 2 illustrates how the risk assessment is performed. One probability density is defined for each variable studied. Important variables are: Component costs, penetrations for the services studied, market shares for the services, tariffs for the services, etc. The Normal distribution is often used to describe the fluctuations of a variable. The Normal distribution is uniquely defined when the expected value and the standard deviation are known. If there is a significant probability of generating negative values, the Beta function is used instead of the Normal distribution. The Beta function is defined when the expected value and the standard deviation are given together with the realisation interval for the variable.

The expected value for each year is the estimated component cost, penetration, market share, tariff etc. In the following paragraphs a methodology for estimating the standard deviation is described.

Since there is a strong correlation between consecutive observations from one year to the next, it is not possible to perform independent simulations for the whole time series. Independent simulations may cause demand to move up and down instead of having a more smooth increase. One possibility is to introduce correlation between the observations. Another possibility is to make one simulation for the time series; then all observations in the time series will either be larger than the expected trend or smaller. Since the number of simulations is rather high, the described simulation procedure is acceptable.

Methodology for determining cost predictions and related estimates of uncertainties

The extended learning curve model

The extended learning curve for predicting component costs has been developed in the OPTIMUM project. Wright and Crawford's learning curve models [1–3] for cost predictions were examined. The models for cost predictions were extended not only to estimate the costs as a function of number of produced units, but also as a function of time [4]. The cost prediction curve is dependent on a set of parameters: Starting cost at the starting time, type of component, penetration at the starting time and penetration growth. The TERA cost data base contains estimates on these parameters for all components and generates cost

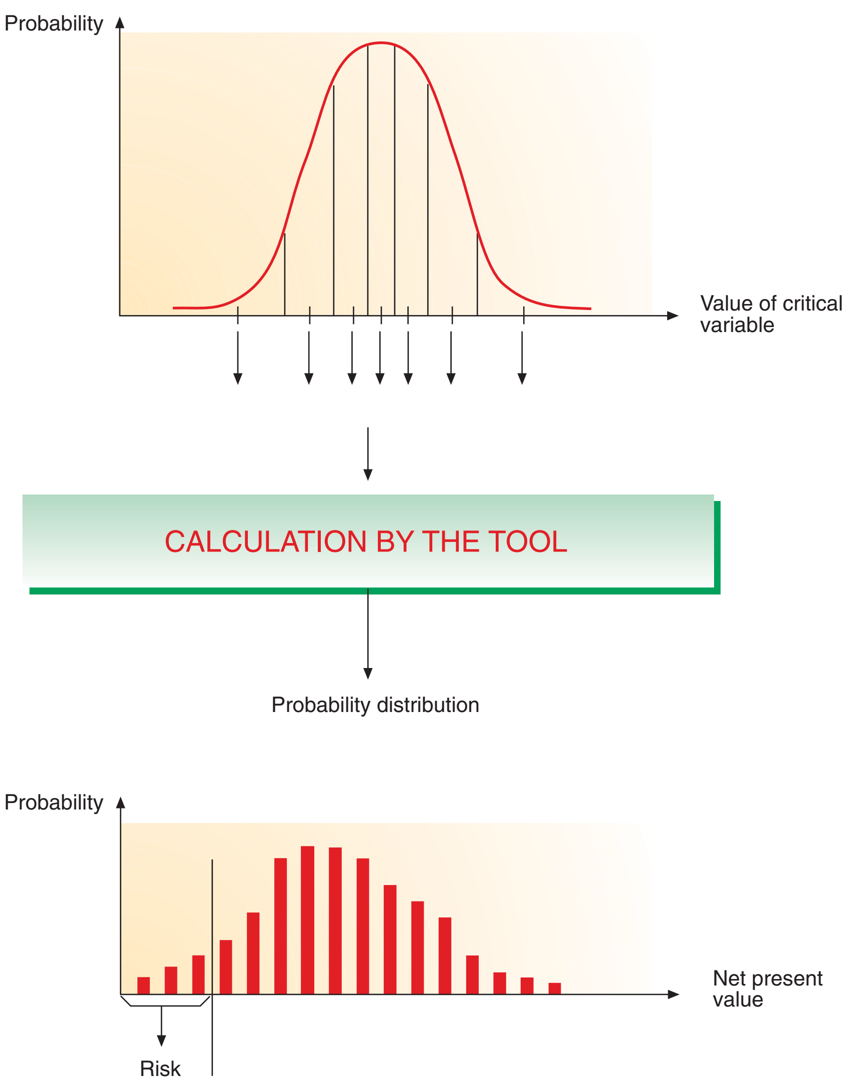

Figure 2 Risk simulations

predictions based on the extended learning curve. The methodology takes into account the variation in uncertainty for different technology. For example, the uncertainty in the cost of civil works is smaller than the uncertainty in the cost of electronics. In addition a time component increasing the relative uncertainty is implemented in the model.

The cost prediction of each network component is described by expansion of the learning curve given as function of the parameters:

- $f(0)$ The predicted costs at time 0
- $n(0)$ The relative proportion of produced components at time 0
- Δt The time interval between 10 % and 90 % penetration
- K The relative decrease in the cost by the double production.

The extended learning curve function is given by:

$$f(t) = f\,(f(0), n(0), \Delta t, K, t) = f(0)\,[n(0)^{-1}\,(1 + \exp[\ln(1/n(0) - 1) - 2\,t\,\ln 9/\Delta t])^{-1}]^{\log_2 K}$$

Uncertainty estimates of cost predictions

The methodology described suggests to estimate the uncertainty proportional to the time and to the cost predictions by the extended learning curve model. The uncertainty estimates are expressed by standard deviations used to describe the probability distributions as input to the risk assessment.

It is reasonable to assume that the uncertainty in the cost predictions is *proportional* to:

- t the time;
- $f(t)$ the cost predictions.

Suppose that the relative uncertainty in the costs increases with a given percentage each year. Then the relative uncertainty can be expressed as a linear function:

$$u(t) = 1 + a\,t$$

where a is the yearly increase.

The relative uncertainty related to the learning curve is given by the expression:

$$f(t)\,/\,f(0).$$

Then the uncertainty of the cost predictions expressed by the standard deviation is given by:

$$s(t) = \text{const}\ u(t)\,f(t)\,/\,f(0).$$

When $t = 0$, we get $s(0) = \text{const}$. Hence we get the following expression for the standard deviation:

$$s(t) = s(0)\,u(t)\,f(t)\,/\,f(0).$$

The standard deviation function is dependent on the standard deviation at time 0 and the parameter a and of course on the relative change in the learning curve. A reasonable estimate for the standard deviation at time 0, $s(0)$, should be proportional to the cost, $f(0)$, at time 0. Hence

$$s(0) = \text{const}\,f(0) = b\,f(0).$$

Now, if $b = 0.15$, then the standard deviation, $s(0)$, is equal to 15 % of the cost estimate at time 0. We decide to estimate the standard deviation by using the last expression. When the risk analysis is carried out, a set of different values of b will be used for each technical solution.

Substituting the last equation into the previous one, gives:

$$s(t) = b\,u(t)\,f(t)$$

Table 1 Relative standard deviations

t			0			5			10	
a	b	0.10	0.15	0.20	0.10	0.15	0.20	0.10	0.15	0.20
0.01		0.10	0.15	0.20	0.11	0.16	0.21	0.11	0.17	0.22
0.05		0.10	0.15	0.20	0.13	0.19	0.25	0.15	0.23	0.30
0.10		0.10	0.15	0.20	0.15	0.23	0.30	0.20	0.30	0.40
0.20		0.10	0.15	0.20	0.20	0.30	0.40	0.30	0.45	0.60

or

$$s(t) = b\,(1 + a\,t)\,f(t).$$

In some situations the concept relative standard deviation is used in statistical analysis. The relative standard deviation is given by s/f. Putting $t = 0$ in the equation, we get:

$$s(0) / f(0) = b.$$

Hence b is the relative standard deviation at time 0. When t is different from 0, we get the following expression for the relative standard deviation:

$$s(t) / f(t) = b(1 + a\,t).$$

Hence the relative standard deviation is a function of the parameters a and b. Table 1 illustrates how the relative uncertainty changes as a function of a and b. The table shows that the relative standard deviation increases as a function of time (because $a > 0$).

Of course it is also possible to use other functions than the suggested linear function suggested. It is also possible to use a set of fixed values representing the standard deviation for each year. The table is so far a guideline for selecting reasonable a and b values for estimating the standard deviation.

Cost prediction by the extended learning curve

The extended learning curve is defined in the first part of the section. The parameters in the learning curve are: $f(0)$, $n(0)$, Δt and K. In the OPTIMUM cost database the values shown in Table 2 are used for the various volume classes:

Table 2 Variation in n(0) and Δt for each volume class

Volume class	$n(0)$	Δt
1	0.5	5
2	0.1	5
3	0.01	5
4	0.5	10
5	0.1	10
6	0.01	10
7	0.001	50

The K values are defined as follows:

- Civil work $K = 1$
- Copper $K = 1$
- Installation $K = 1$
- Sites and enterprises $K = 0.95$
- Fibre $K = 0.9$
- Electronics $K = 0.8$
- Advanced optical comp. $K = 0.7$.

In the cost database all components are listed with a given $n(0)$, Δt and K value in addition to the estimated cost $f(0)$ at time 0. Then the extended learning curve is uniquely defined and the prediction of the costs is determined. Hence combinations of the a, b, $f(0)$, $n(0)$, Δt and K give the variations in the estimated standard deviations. In addition each component is described by a confidence class which can be used as a guideline to determine a and b.

Methodology for estimating demand forecasts

Demand forecast modelling

It was decided to develop analytical forecasting models instead of the usual tables as input to the TERA tool. The analytical functions will be part of the new framework for TERA. It is more convenient to use functions instead of tables as input

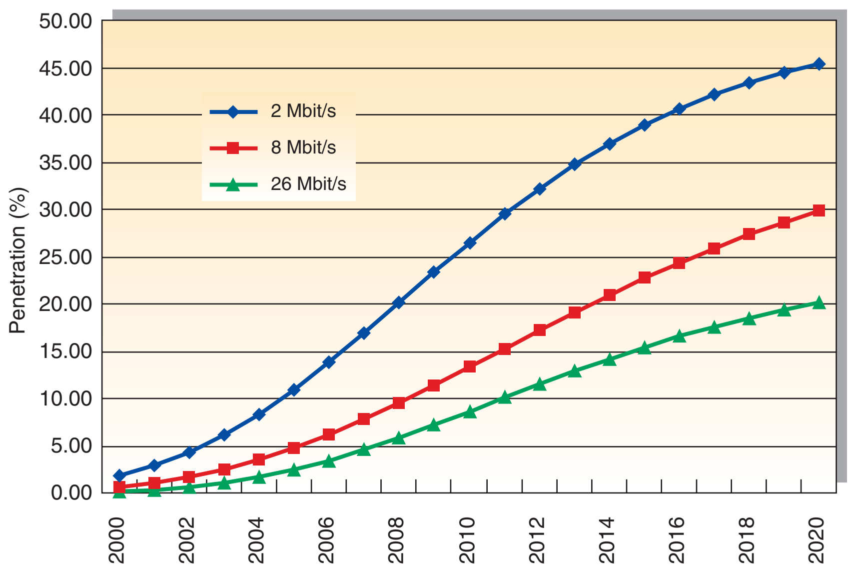

Figure 3 Broadband penetration forecasts

to the tool. In addition the functions give more flexibility for variations when risk analysis is carried out. The models are based on the results from the last Delphi survey performed at the last OPTIMUM workshop in Aveiro in October 1997 [15]. Different analytical forecasting models for fitting the Delphi data are tested. The extended Logistic model with three parameters gave rather good fitting for 2 Mbit/s, 8 Mbit/s and 26 Mbit/s.

The model is defined by the following expression:

$$Y_t = M / (1 + \exp(\alpha + \beta t))^{\gamma}$$

where the variables are defined as follows:

Y_t	Demand forecast at time t
M	Saturation level
t	Time
α, β, γ	Parameters.

The parameters α, β, γ cannot be estimated simultaneously by ordinary least square regression since the model is nonlinear in the parameters. Instead a stepwise estimation procedure is used to find the optimal parameter estimates.

In addition specific forecasting models for symmetric and asymmetric demand penetration are constructed. The models and also the forecasts for symmetric and asymmetric accesses are described in [15].

Uncertainty estimates for the demand forecasts

Demand forecasts are of course rather uncertain. Since we have used a stepwise estimation procedure to estimate the parameters in the model, we cannot use the traditional procedures to find the confidence interval of the forecasts. A relevant alternative is to use the same methodology as for the costs. The relative standard deviation $s(t) / Y_t$ is equal to:

$$s(t) / Y_t = b(1 + a\ t)$$

where

Y_t	is the forecast at time t
$s(t)$	is the standard deviation of the forecasts at time t
b	is the relative standard deviation at time 0
a	is the increase in the linear increase in the relative uncertainty per year.

Table 1 is used to see the changes in the relative uncertainty for different values of a and b. The equation for the estimated standard deviation is given by:

$$s(t) = Y_t\, b\ (1 + a\ t).$$

The function Y_t is the forecast which significantly increases as a function of time.

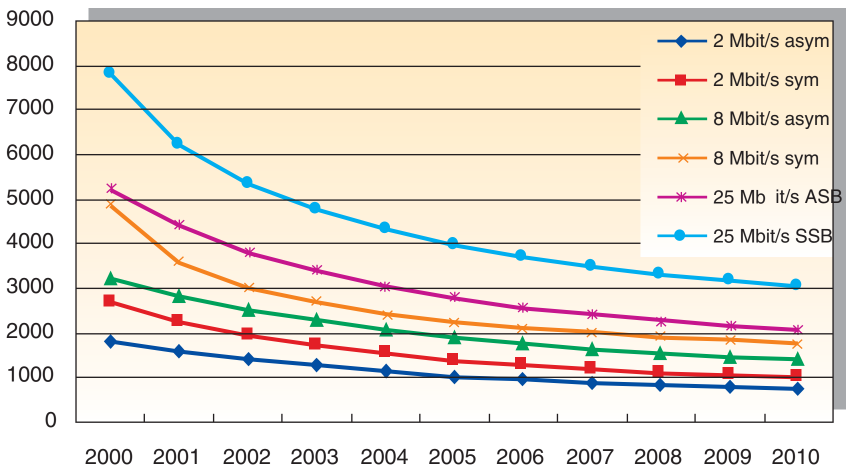

Figure 4 Expected annual tariff evolution (euro) in the residential market for 2 Mbit/s, 8 Mbit/s and 26 Mbit/s asymmetric and symmetric access. The annual tariff consists of subscription and traffic costs

For the component costs this function is strongly decreasing. Hence the estimated standard deviation for the forecasts increases much more than the standard deviation for the cost predictions. The last equation defines the estimated standard deviations for given values of a and b.

Methodology for estimating tariff predictions and related uncertainties

Model for tariff predictions

It was decided to develop analytical demand models instead of the usual tables as input to the TERA tool. The analytical functions will be part of the new framework for TERA. It is more convenient to use functions instead of tables as input to the tool. In addition the functions give more flexibility for variations when risk analysis is carried out. The tariffs are given as functions of the penetration according to the demand curves extracted from the OPTIMUM Delphi survey carried out in 1997 [15]. The tariffs are service penetration dependent, which is needed in a reasonable risk model.

The suggested demand model based on three parameters was:

$$y = e^{(\alpha + \beta p)^{\gamma}}$$

y	Demand
p	Price
α, β, γ	Parameters in the model.

The parameter estimates are found by OLS regression on the Delphi demand data for given γ values. The estimation gave a fairly good fitting. A variant of this model is based on the assumption that the demand is 100 % when the price is 0. Evaluating the results showed that the fitting was not satisfactory. Therefore, the demand model is not based on this assumption.

An alternative demand model uses the above three parameter equation together with two restrictions:

- The tariff is fixed in the starting year;
- The tariff is fixed in the long run.

The restrictions are included because it is important to utilise “near future knowledge” into the model. In addition a hypothesis that the long broadband costs will converge against today's telephone costs. The tariff predictions are found by putting the demand forecast into the above equation and then solve the equation with respect to the tariff p_t:

$$p_t = [(\ln y_t)^{1/\gamma} - \alpha] / \beta .$$

When the forecasts y_t are put into the model for different t values, we get tariff prediction as a function of time. A more detailed description of a demand model is given in [15]. Figure 4 illustrates the tariff evolution for 2 Mbit/s, 8 Mbit/s and 26 Mbit/s asymmetric and symmetric access. *The tariff includes both annual subscription costs and annual traffic costs for expected use of the service.*

Uncertainty estimates for tariff predictions

The tariffs are of course rather uncertain. It is suggested to use the same methodology as for the costs to estimate tariff uncertainty. The relative standard deviation $s(t) / p_t$ is equal to:

$$s(t) / p_t = b(1 + a\,t)$$

where

- p_t is the tariff prediction at time t
- $s(t)$ is the standard deviation of the tariff prediction at time t
- b is the relative standard deviation at time 0
- a is the increase in the linear increase in the relative uncertainty per year.

Table 1 is used to see the changes in the relative uncertainty for different values of a and b. The equation for the estimated standard deviation is given by:

$$s(t) = p_t\, b(1 + a\,t).$$

The last equation defines the standard deviation function for given values of a and b.

TERA tool for techno-economic evaluations

Within the European programs RACE and ACTS the projects RACE 2087/TITAN and AC 226/OPTIMUM and TERA have developed a methodology and a tool for calculation of the overall financial budget of any access architecture. The tool handles the discount cost system, operations, maintenance, life cycle costs and the cash balance. This enables a comparison of various optical or hybrid architectures through a global system assessment. The tool has the ability to combine low level, detailed network parameters of significant strategic relevance with high level, overall strategic parameters for performing evaluation of various network architectures [8–11].

A methodology described in the next section has been developed based on an expansion of the Wright and Crawford's learning curve models to predict future costs of the network components [12–14]. Geometric (geographic) models are used to map network structures into the tool. A specific model for operation and maintenance costs has been developed. The tool also has a specific module used for risk assessments. In addition forecasts of the demand for the services offered and the relating tariffs are necessary for the calculations.

Application of risk methodology – an example

This part of the paper addresses some of the challenges and risks faced by a PNO and a Cable Operator in adapting their present fixed network to competition. The analysis of broadband upgrade alternatives focuses on one of the most competitive market segments: an urban apartment block area with short outdoor average loop lengths, in which both the PNO and the Cable Operator have an established infrastructure.

The methodology and tool developed within the EU project RACE 2087/OPTIMUM have been used to evaluate the selected set of network upgrade alternatives and strategies [5–9]. *The methodology is based on the same principles described in the previous part of the paper. However, there are some changes since the services evaluated are CATV, ISDN and 2 Mbit/s accesses and related penetrations and market shares.*

In this paper extensive risk assessments are performed based on forecasts of the residential and small business market, and market shares between PNO and Cable Operators for the services POTS (Plain Old Telephony Service), N-ISDN (Narrowband Integrated Services Digital Network), CATV (Cable Television), 2 Mbit/s Asymmetric Switched Broadband (ASB), and 2 Mbit/s Symmetric Switched Broadband (SSB) [10, 11]. Other important economic variables like network component costs, civil work costs, Operation, Administration and Maintenance (OAM) costs, tariffs etc. are predicted for each year, but are not varied according to a probability distribution.

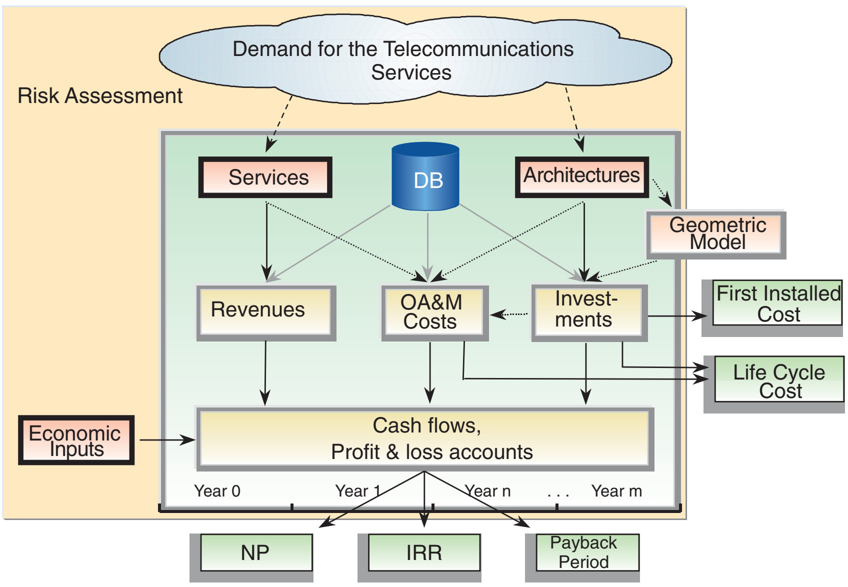

Figure 5 Model for techno-economic evaluations

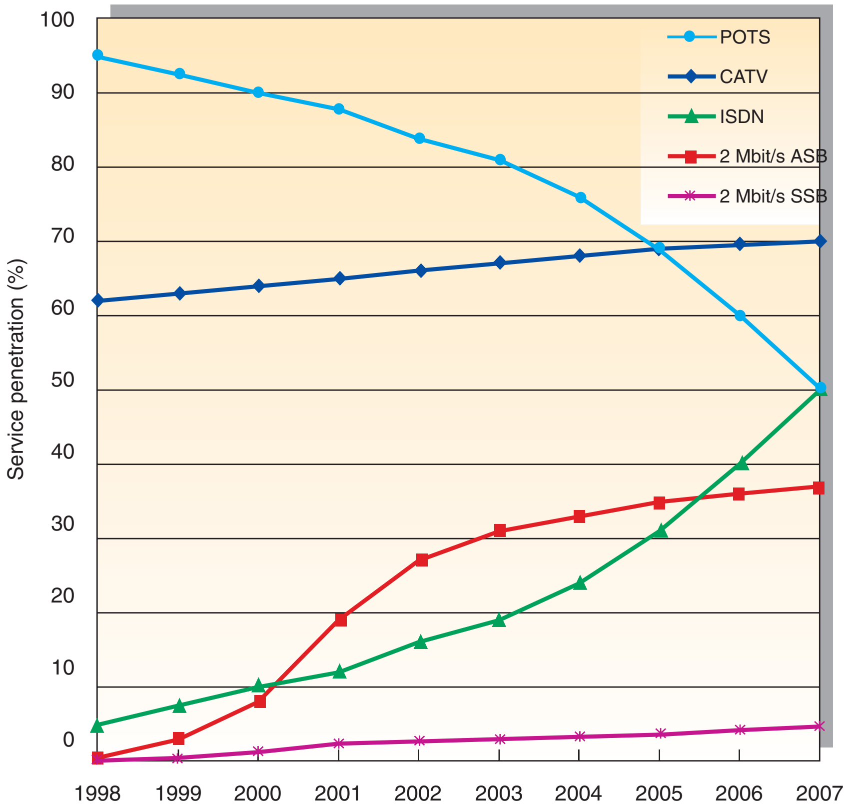

Figure 6 Forecasts for the services POTS, N-ISDN, CATV, 2 Mbit/s ASB, 2 Mbit/s SSB for the years 1998 – 2007 in percentage of the small business and residential market

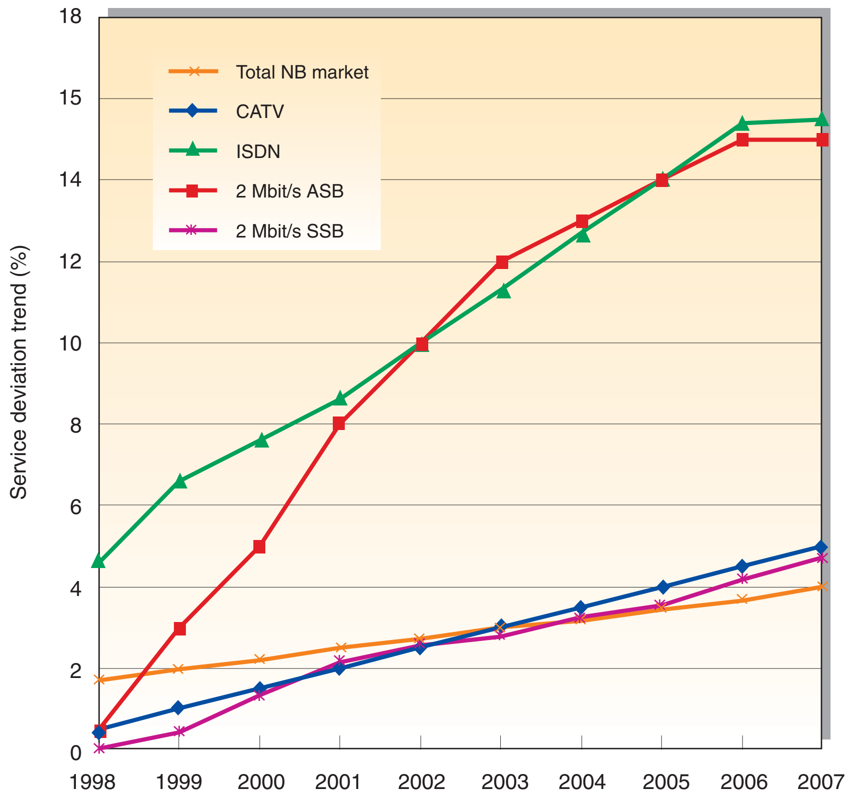

Figure 7 Forecasts of the estimated uncertainty (standard deviations) for the service penetrations and the total NB market in percentage of the small business and residential market

The broadband case study

A network evolution during a 10 year period from 1998 to 2007 has been examined. Upgrade boundary conditions for both the PNO and the CATV operator, like the demographic area, the existing networks, overall service take rate and market shares, are included in the case study.

Network area characteristics

One of the most competitive market segments is analysed: an urban, residential and small business area with customers living in apartment blocks. Network architectures for PNO and Cable Operators have already been established in the area, and the duct availability for new cables is low (20 % for fibre and 10 % for coaxial cable).

The market forecast

The scope of this paper is the study of the broadband upgrade of the above two networks. The evolution scenario is similar to the ones presented by Luck in 1995 [12]. A common set of bearer services is assumed to be provided by both operators: POTS, N-ISDN, CATV, 2 Mbit/s ASB, and 2 Mbit/s SSB. The CATV service penetrations used here are European averages.

Service take rate and market shares

Figure 6 shows forecasts for the service penetration and corresponding standard deviations in percentage of the small business and residential market for each service studied. The forecasts indicate the evolution from 1998 to 2007. In the simulations the sum of the narrowband market (NB) which includes POTS and ISDN is assumed to remain constant at 100 % penetration during the period.

The correlation between the POTS and the ISDN markets has been taken into account. The simulated value for the POTS penetration is obtained by subtracting the simulated value of the ISDN penetration from the simulated value of the total narrowband market. Throughout the period it is assumed that the PNO operator will maintain 75 % of the POTS market and the N-ISDN market, the CATV operator will maintain 75 % of the CATV market, while the two operators equally share the broadband market:

50 % each. Shares are simulated around their trends for each service.

Figure 7 shows the standard deviations. The standard deviation estimates are partly based on results from the Delphi survey. The estimates reflect that the uncertainty in the forecast penetrations increases as a function of time, mainly because of the size of the demand, but also because of the length of the time period. A Normal distribution is used as input to the risk analysis to describe the uncertainties. The substitution effect between POTS and ISDN is taken into account through the total narrowband market.

Tariff elasticity

Only the annual subscription tariffs for bearer services have been considered in the analysis. Traffic income is not accounted for, since this is assumed to be trunk network specific revenue. The tariffs used are based on European averages from the Delphi survey and other sources. The evolution of tariffs is strongly related to competition and penetration. Tariff elasticity for the broadband switched services are derived from the Delphi survey, as described in [13]. The CATV tariff elasticity is modelled by a similar approach. Figure 8 shows the expected evolution of annual tariffs for the various services. The evolution of market shares for PNO is described in Figure 9. For the CATV operator the situation is inverse since the two operators control the whole market (100 %). It is assumed that the PNO loses 25 % of the POTS and ISDN market during the study period, while the CATV operator loses 25 % of the CATV market. Since there is a CATV network in the area in 1998, it is assumed that the CATV operator starts by having 70 % of the 2 Mbit/s ASB and 2 Mbit/s SSB market. The uncertainty given by the standard deviations is estimated at 5 % during most of the study period.

Broadband upgrade alternatives

Two different access network upgrade architectures have been examined for each of the two operators:

1 PNO, alternative 1: FTTN (Fibre To The Node, 1,000 homes passed per node) architecture with enhanced copper.

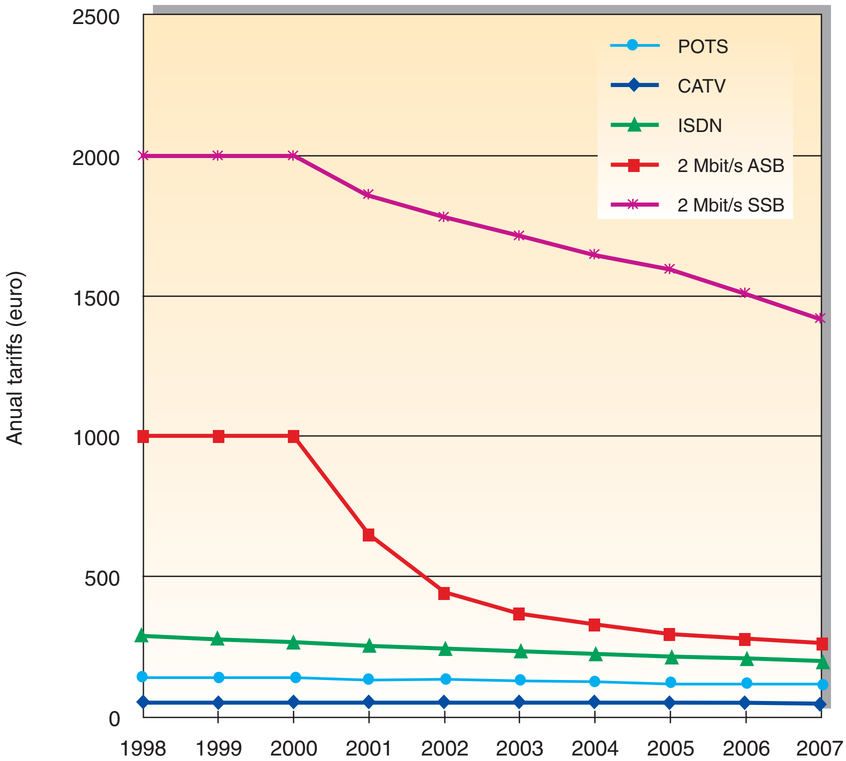

Figure 8 Tariff evolution, nominal penetrations

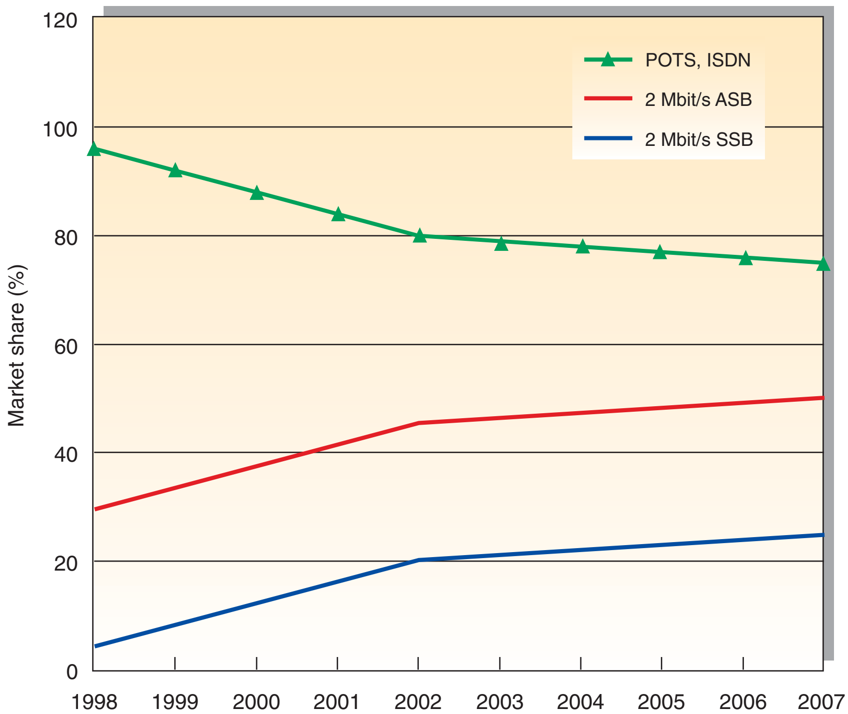

Figure 9 The market share evolution for the PNO

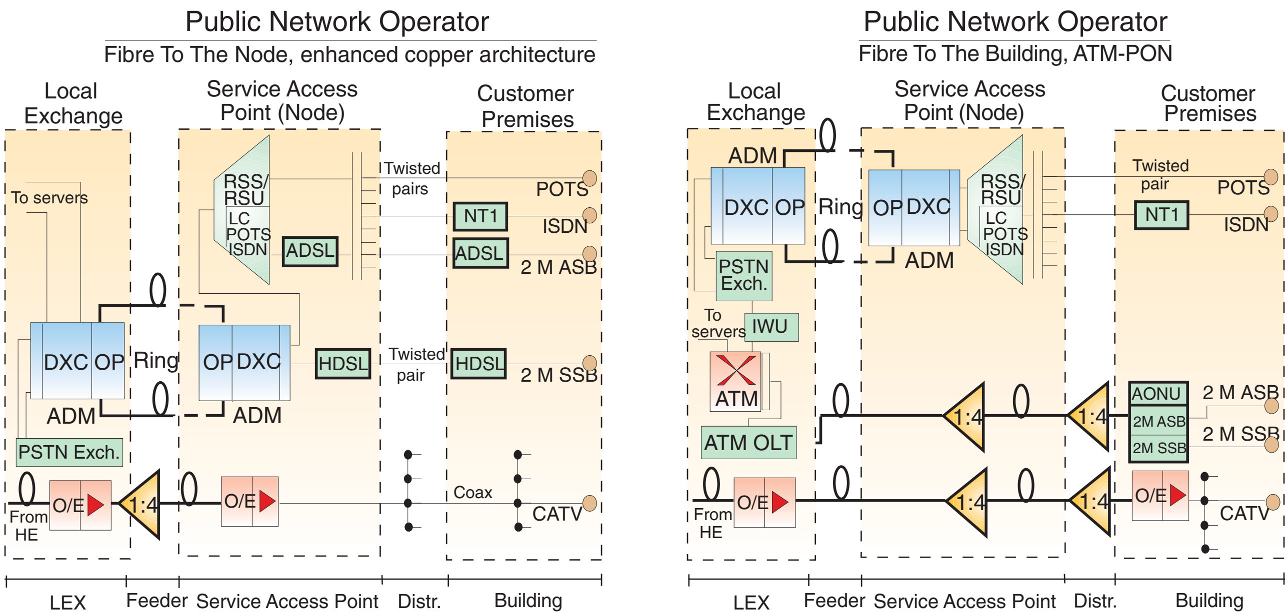

Figure 10 The PNO FTTN upgrade architecture with enhanced copper (to the left) and an FTTB architecture by ATM-PON (to the right) and a parallel distribution network for CATV

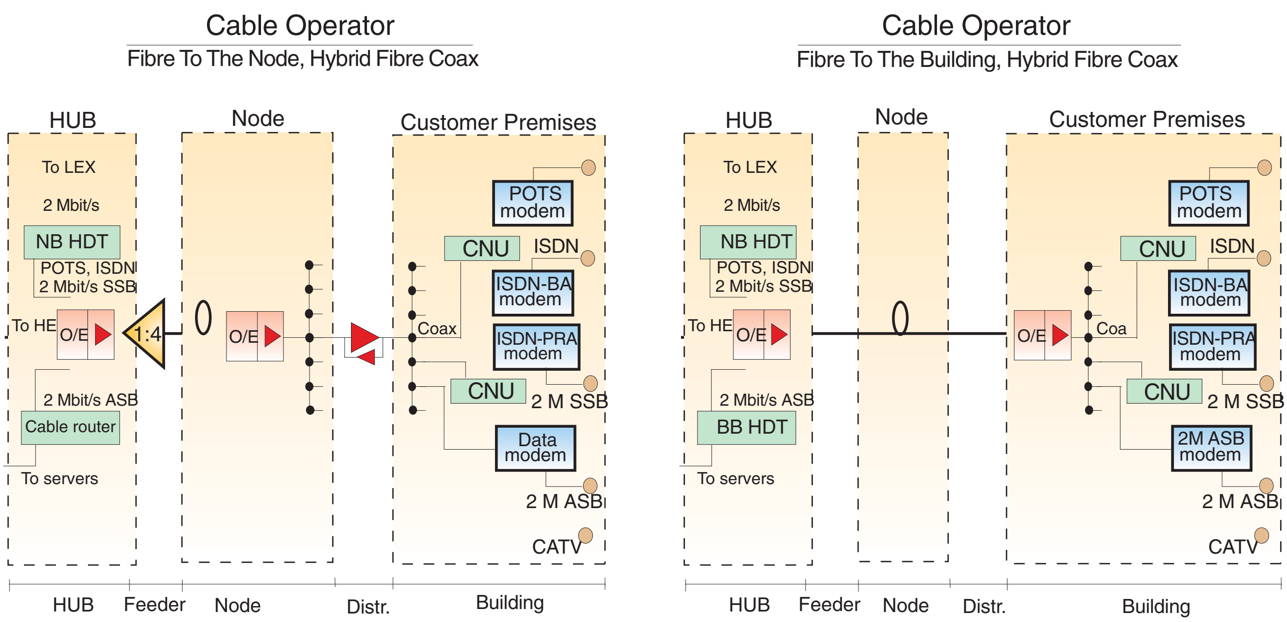

Figure 11 The Cable Operator FTTN upgrade architecture (to the left) and FTTB upgrade architecture (to the right) with a HFC network for all services

2 PNO, alternative 2: FTTB (Fibre To The Building) architecture based on ATM-PON

3 Cable operator, alternative 1: FTTN architecture based on HFC with Cable modems.

4 Cable operator, alternative 2: FTTB architecture based on HFC.

PNO upgrade alternatives

The alternatives considered highlight the economic and technological implications for moderate operators which aim to utilise the existing twisted pair copper cables as the basic transmission medium, and aggressive operators which extensively upgrade the network with broadband fibre technology [14]. The former represents a limited degree of service integration, whilst the aggressive upgrade enables an introduction of a full service fibre network. Detailed sketches of the architectures for the PNO alternatives are shown in Figure 10.

PNO, FTTN: The PDH ring between the Local Exchange (LEX) and the SAP was replaced by an SDH ring in 1998. In the distribution network ADSL and HDSL equipment is installed to provide new services such as 2 Mbit/s ASB, ie. Service on Demand (SoD) or fast Internet Access, and 2 Mbit/s SSB. In addition, a coaxial cable network is installed for CATV distribution.

PNO, FTTB: The PDH ring connecting the SAP to the LEX is replaced by an SDH-based ring structure. The deployment of an ATM-PON in an FTTB configuration started in 1998 in order to provide new services like ASB and 2 Mbit/s SSB. In addition, a combined fibre-coax network for CATV distribution was installed in 1998.

Cable Operator upgrade alternatives

The Cable Operator upgrade alternatives represent moderate operators which only partially integrate their network by sharing duct layout, and aggressive operators which fully integrate the network by providing the service set over the same duct layout, transmission medium and network termination units as well. Detailed sketches of the architectures for the Cable Operator alternatives are shown in Figure 11.

Cable Operator, FTTN: The existing coaxial cable infrastructure between the access node serving 1,000 subscribers and the homes is retained during the upgrade period. In 1998 the CATV network is upgraded to a bi-directional network with return path. All services are then offered on the integrated coaxial cable network. Cable modems are installed at the customer premises.
10 Mbit/s shared access data modems are used for 2 Mbit/s ASB.

Cable Operator, FTTB: Fibre was deployed to the buildings in 1998. This yields a fibre rich network with separate fibres between the HUB (serving approximately 4,000 homes) and the buildings. Cable modems are installed, with 2 Mbit/s dedicated channels access data modems for 2 Mbit/s ASB subscribers.

Risk assessment assumptions

The assumptions used in the risk assessments are shown in Figures 12 and 13. For each service penetration and each market share one expected value and one estimated standard deviation are given. For each variable the values uniquely defines a Normal distribution. The set of Normal distributions is used to simulate all service penetrations and market shares. Since all service penetrations and market shares are simulated simultaneously, it is necessary to perform a great number of repeated runs in order to achieve a representative output of the economic results of the different upgrade alternatives studied.

Results and discussion

The risk assessment has been applied to all four technical upgrade alternatives. The results illustrate the uncertainty in the different techno-economic outputs and the ranking of parameters having the most significant effects on the uncertainty. In general for all four upgrades, the analysis shows that the uncertainty in the total market forecasts for the different services has the most significant influence on the variation of both the NPV, the ratio NPV/IFC and the expected payback period. In particular the total market forecast for ISDN and 2 Mbit/s ASB contributes significantly to the variation of the NPV and the ratio NPV/IFC. The estimated values of the NPV for all

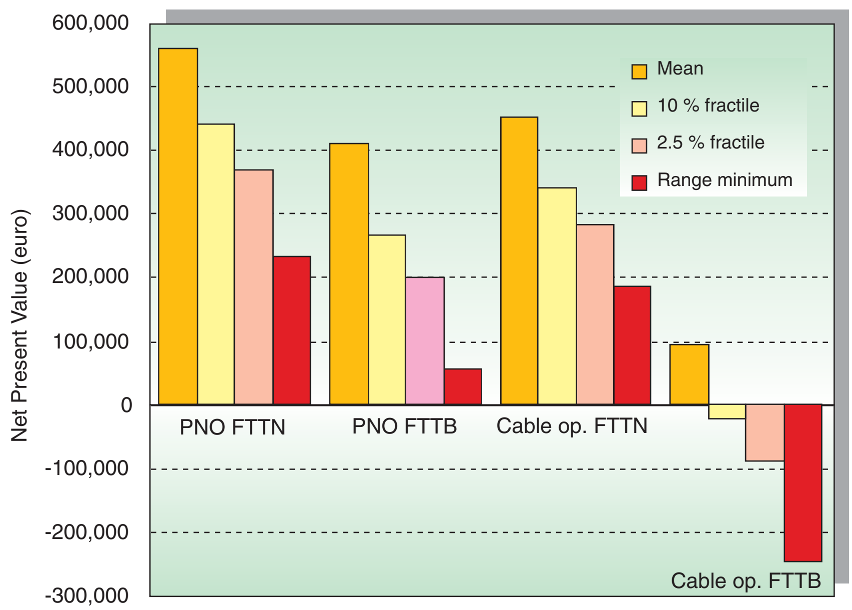

Figure 12 The estimated values of the NPV with mean value, 10 % fractile, 2.5 % fractile and the minimum

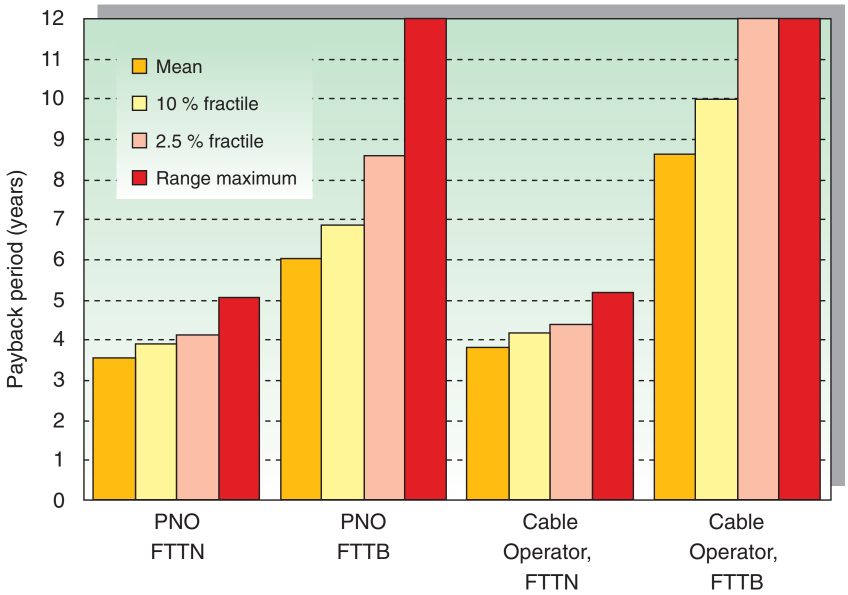

Figure 13 The estimated values of the payback period with mean value, 10 % fractile, 2.5 % fractile and the minimum

upgrade projects are shown in Figure 12. The results in Figure 12 show that the FTTN solutions give a much better net present value than the FTTB solutions. In addition the PNO has the most profitable projects. Comparison of 2.5 % fractile and mean value indicates a significant difference. The relative difference varies between 65 % and 45 %. In the PNO FTTB it is a 2.5 % probability that the net present value will be reduced to 45 % of estimated mean value (408,000 ECU to 192,000 ECU). The variation is caused by the uncertainty in the market evolution. The CATV operator project FTTB is shown to be a more risky project as indicated in the figure.

The results from Figure 13 show that the payback period for the FTTN solutions is acceptable. The expected payback period is about four years and the uncertainty is rather limited. The FTTB solutions are more expensive and have a longer payback period. In addition the projects give significantly higher risk. The range minimum for the PNO and the CATV FTTB solution is cut off in the figure. The PNO and CATV operator have a range maximum of 20 and 73 years respectively.

The total market forecasts of ISDN and 2 Mbit/s ASB together with the market share of 2 Mbit/s ASB and CATV have the most significant influence on the variation of the payback period.

Concluding remarks

The risk assessment and additional analysis show that the FTTN alternative of the PNO is the best economic alternative with the lowest risk. The FTTB project for the Cable Operator is the least economic alternative and also a highly risky project. The service forecasts for the total market contribute more to the variation of the results than the service market shares of the operators when the calculation period is more than five years. The market shares between the operators contribute more to the risk when the calculation period is shorter. The ordinary POTS, ISDN and 2 Mbit/s ASB services generate more uncertainty than the other services, mainly due to the high penetration. Depending on the technical alternative, type of operator and economic output, different sets of market variables explain the main part of the variation.

In this paper only market variables (forecasts of total market penetration and market shares for a set of services) are simulated according to given probability distributions in order to evaluate their effect on the economic results for various upgrade alternatives. These variations are based on a set of assumptions mainly derived from a European Delphi survey. Supplementary analysis including risk assessment of cost elements like civil works, network components and operation and maintenance in addition to the tariffs will be presented in supplementary papers.

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Techno-economic risk assessment of PNO access network evolutionary paths

NILS KRISTIAN ELNEGAARD, LEIF AARTHUN IMS AND KJELL STORDAHL

This paper reports work done in the area of risk analysis of broadband access network upgrade strategies. The risk methodology and implementation is worked out by the ACTS project TERA ("Techno-economic Results from ACTS"). The architecture descriptions and framework for the case study are provided by the project EURESCOM P614 ("Implementation Strategies for Advanced Access Networks"). As a case study we have chosen to focus on likely evolutionary paths for the incumbent operator's twisted pair copper network. Thorough techno-economic risk analyses have been conducted for fifteen different investment projects, namely the combinations of five different evolutionary paths and three different area types. The motivation of this study is to provide a first set of guidelines for risk and profitability of fibre access networks.

1 Introduction

The public network operators of today are faced with a bewildering choice of possible technologies and evolutionary paths. In addition to this, broadband take rate, tariff structures, competition and the regular environment are all highly uncertain in the future market of telecommunication services. It is evident that the operators who incorporate risk analysis into their broadband strategies will gain a competitive advantage. The challenges for the operator are to:

- Identify the parameters which are expected to contribute to the uncertainty and the associated risk in broadband upgrade projects;
- Identify which evaluation criteria ensure a fair comparison, such as the net present value (NPV), the internal rate of return (IRR), payback period, etc.;
- Incorporate risk into a business strategy model by establishing qualitative and quantitative models that are at the same time simple and clear in order to be used at a strategic level;
- Carry out risk analyses which add value to the traditional techno-economic analyses.

This paper presents the techno-economic analyses of upgrade projects associated with a high uncertainty, with respect to the market evolution, the tariff evolution, as well as the technology evolution. The object of the risk analysis is to examine the business risks associated with different broadband access network upgrade strategies in three different types of areas that differ in subscriber density, duct availability, average copper loop length before upgrade as well as surface characteristics and thereby the cost of civil work. The analysis is focused on upgrades of the twisted pair based on the xDSL technology.

Typical questions of relevance in decision making are listed below:

- What is the difference in risk level between different roll-outs with different fibre penetration levels? On the one hand, a higher fibre penetration enables a more flexible and better service offering with the potential of additional revenue streams. On the other hand, the additional revenues needed in the long term to pay back the more aggressive fibre deployment required for the extended service portfolio, will be associated with a higher uncertainty, both due to the inherent increase in uncertainty as a function of time and also due to the uncertainty in the willingness to pay for extended services.
- What has the greatest impact on the risk of the selected projects – the market uncertainty or the uncertainty in the cost evolution?
- What is the difference in terms of probability for a significant reduction in the net present value (NPV) for the different evolutionary paths assessed in the downtown, urban and suburban area types?
- What is the 5 % risk value for the NPV?
- What is the risk that NPV is below a certain amount?
- What is the difference in terms of probability for a negative NPV for the different evolutionary paths applied in different geographic areas?

2 The case study

The risk analysis covers non-greenfield upgrades in three network area types in which there is an existing twisted pair copper network. The area types are downtown, urban and suburban. The case study is based on:

- Evolutionary paths and architectures;
- Housing structure, density of living units and average loop lengths;
- Average and effective civil works costs;
- Service definitions, including penetrations and tariffs;
- The model of operation, administration and maintenance costs.

The main assumptions for the study case are listed below:

- *The study period* in the risk analysis is from year 2000 to year 2009.
- *Total number of potential customers:* 4096 in all projects.
- *Service penetration model:* has been established, based on the OPTIMUM Aveiro Delphi survey results [1]. The models include an asymmetric S-curve. The bearer service capacities offered (downstream) are 2 Mbit/s, 6 Mbit/s and 26 Mbit/s, both symmetric (SSB, symmetric switched broadband) and asymmetric (ASB, asymmetric switched broadband).
- *Market share model:* the market share of switched broadband services is 100 % in 2000 and 76.38 % in 2005. The market share in the final year depends on the upgrade strategy chosen.
- *Tariff model:* has been established, based on the OPTIMUM Aveiro Delphi survey results [1]. For low penetrations, the tariff is kept constant below 2 % service penetration. For high penetrations, the tariff is kept constant above 20–40 % service penetration, depending on the service.
- *Technology cost evolution* is modelled by the extended learning curve model described in [5].

2.1 Selected architectures and evolutionary paths

Five twisted pair based evolutionary paths comprise the likely migration alternatives for a telephone operator, which at the initial stage has a twisted copper pair access network. A combination of fibre in the loop and DSL systems are likely to constitute the future broadband access network for operators with an existing twisted pair infrastructure. The deeper the fibre penetrates the access network, the larger is the number of potential customers who can be offered broadband services. However, an aggressive fibre build-out is inherently risky due to the heavy initial investments in infrastructure combined with the uncertainty in the take rate of broadband services.

The evolutionary techno-economic framework for the study is worked out by the project EURESCOM P614 ("Implementation Strategies for Advanced Access Networks") [2, 3, 4] and the risk framework is worked out by the ACTS project TERA ("Techno-economic results from ACTS") in co-operation with EURESCOM P614.

Figure 1 shows the evolutionary paths considered in this study. The reference architecture is the present twisted pair copper network offering N-ISDN services.

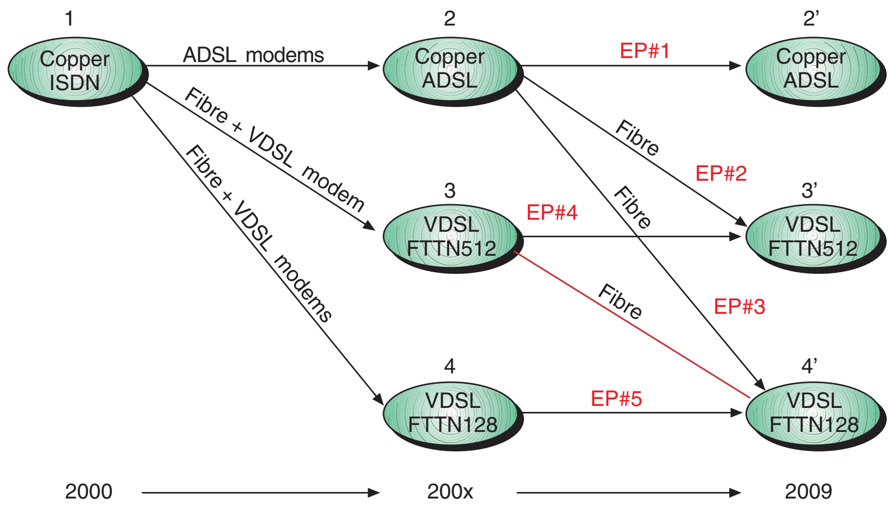

Figure 1 Broadband access network evolutionary paths

- *EP #1: Copper ISDN – Copper ADSL – Copper ADSL: states 1–2–2'*. It is a very cautious attitude from the PNO, unbelieving that broadband services demand will explode, and possible service offer available with ADSL and S(H)DSL technologies will sufficiently cover customers' needs. The roll-out year is 2000 for every area type. The target architecture is also called FTTLex (fibre to the local exchange).
- *EP #2: Copper ISDN – Copper ADSL – FTTN512 VDSL: states 1–2–3'*. It is an evolutionary path through ADSL and S(H)DSL technology. When the demand for higher bitrates takes off, it becomes necessary to use VDSL technology. Fibre penetrates deeper into the access network to the primary distribution point (DP1). 512 customers can be covered by each optical node. At this point, the operator can choose to migrate all ADSL and S(H)DSL modems to the ONUs by replacing them with VDSL modems, or to keep them at their location (Lex), and to set DSL modems for each new demand, whatever the needed bitrate. In this study ADSL and HDSL/SDSL modems are replaced with VDSL modems. The roll-out year is 2005 for every area type.
- *EP #3: Copper ISDN – Copper ADSL – FTTN128 VDSL: states 1–2–4'*. It is similar to EP #2 with ONUs located at DP2 (secondary distribution point). More broadband customers can be reached than in EP #2. 128 customers can be covered by each optical node.
- *EP #4: Copper ISDN – FTTN512 VDSL – FTTN512 VDSL: states 1–3–3'*. It is on the contrary a gamble on exploding demand for broadband services. No intermediate step through ADSL technology is necessary and it is supposed that VDSL technology is mature when optical fibre is deployed up to DP1. The roll-out year is 2000.
- *EP #5: Copper ISDN – FTTN128 VDSL – FTTN128 VDSL: states 1–4–4'*. It is similar to EP #2 except that the ONU is located at DP2.

2.2 Area segmentation

The five evolutionary paths are studied in three different area types: a downtown area, an urban area and a suburban area. Rural areas have not been considered.

Table 1 Characteristics of area types

Network area	Average copper loop length before the upgrade (m)	Average density of customers (sub./km2)	Average civil works costs per metre (euro)	Duct availability	Effective civil works costs per metre (euro)
Downtown	500 – 1,000	9,200	60 – 120	80 % – 95 %	3 – 36
Urban	1,000 – 2,000	1,000	47 – 93	40 % – 80 %	9 – 56
Suburban	2,000 – 3,000	365	29 – 57	10 % – 40 %	17 – 51

The effective civil works cost per metre can be quite low in downtown areas if the duct availability is high.

2.3 Model for broadband penetration demand

The extended Logistic models with three parameters are used to fit demand data from the Delphi survey carried out in October 1997 [1]. The model is defined by the following expression:

$$S(t) = M / (1 + \exp(\alpha + \beta t))^{\gamma} \quad (1)$$

where M, α, β and γ are the necessary parameters to describe the S-curve. M is the saturation, α is found from (1) when M and $S(0)$ are known. β is related to the growth rate of the penetration and γ is the asymmetry parameter of the S-curve.

The following ratios between symmetric switched broadband (SSB) and asymmetric switched broadband (ASB) have been used:

- Downtown area: SSB = 80 %, ASB = 100 % – SSB = 20 %
- Urban area: SSB = 30 %, ASB = 100 % – SSB = 70 %
- Suburban area: SSB = 20 %, ASB = 1000 % – SSB = 80 %.

This gives the penetrations for the six bearer services without including uncertainty:

$$S_{c\ \mathrm{Mb/s\ SSB}}(t) = \mathrm{SSB} \cdot S\,(t, M_{c\ \mathrm{Mb/s}}, \beta_{c\ \mathrm{Mb/s}}, \alpha_{c\ \mathrm{Mb/s}}, \gamma_{c\ \mathrm{Mb/s}}),\ \text{symmetric} \quad (2)$$

$$S_{c\ \mathrm{Mb/s\ ASB}}(t) = \mathrm{ASB} \cdot S\,(t, M_{c\ \mathrm{Mb/s}}, \beta_{c\ \mathrm{Mb/s}}, \alpha_{c\ \mathrm{Mb/s}}, \gamma_{c\ \mathrm{Mb/s}}),\ \text{asymmetric}$$

where the downstream capacity c is either 2 Mbit/s, 8 Mbit/s or 26 Mbit/s.

The uncertainty in the penetration of each service is modelled in the following way for the symmetric and asymmetric case respectively:

$$S^i_{c\ \mathrm{Mb/s\ SSB}}(t) = \mathrm{SSB} \cdot S\,(t, M_{c\ \mathrm{Mb/s}} \cdot X^i_{M,\ c\ \mathrm{Mb/s}}, \beta_{c\ \mathrm{Mb/s}} \cdot X^i_{\beta}, \alpha_{c\ \mathrm{Mb/s}}, \gamma_{c\ \mathrm{Mb/s}}) \quad (3)$$

$$S^i_{c\ \mathrm{Mb/s\ ASB}}(t) = \mathrm{ASB} \cdot S\,(t, M_{c\ \mathrm{Mb/s}} \cdot X^i_{M,\ c\ \mathrm{Mb/s}}, \beta_{c\ \mathrm{Mb/s}} \cdot X^i_{\beta}, \alpha_{c\ \mathrm{Mb/s}}, \gamma_{c\ \mathrm{Mb/s}})$$

$X^i_{M,\ c\ \mathrm{Mb/s}}$ and X^i_{β} are random numbers taken from a distribution with a mean value of 1. As can be seen from (3), three independent random numbers are used to model the saturation of each bearer service capacity, while X^i_{β} is used for all services to describe the general trend in growth of broadband penetration.

2.4 Market share

For the market share a decrease is assumed from 100 % to 77.38 % between 2000 and 2005 (5 % relative decrease per year) due to increased deregulation and competition. In EP #1 the market share drops to 56.65 % (7.5% relative decrease per year from 2005 to 2009) in the final year, whereas for the other EPs the market share stays at 77.38 %. The uncertainty is modelled by using multipliers as for the service penetrations.

2.5 Cost predictions

For the cost predictions of network components, the extended learning curve model defined in [5] is used. The relative uncertainty in the cost prediction of the k^{th} network cost item is described by the time-dependent standard deviation given as

$$\sigma_k(t) = b_k\,(1 + at) \quad (4)$$

where b depends on the class of the cost item as in [5]. b which is the relative uncertainty at time $t = 0$ is higher for advanced optoelectronic components than for example cables and installation costs. When we include uncertainty, the cost of the k^{th} cost element is modified in the i^{th} run of a Monte Carlo simulation:

$$f^i_k(t) = f_k(t)\,(1 + \sigma_k(t)\,X^i_k) \quad (5)$$

where X^i_k is a random number taken from a suitable probability distribution which has zero mean and a standard deviation equal to 1.

2.6 Tariffs

The tariffs are extracted from the penetration and willingness to pay for each service according to the demand curves extracted from the OPTIMUM Delphi survey mentioned earlier. Uncertainty distributions have been defined, including trends. Limits are imposed in the model on low and high penetration tariffs. For low penetrations, the tariff is kept constant below 2 % service penetration. For high penetrations, the tariff is kept constant above 20–40 % service penetration, depending on the service.

Tariffs are expected to be highly uncertain. The uncertainty is modelled by the use of tariff multipliers. One multiplier is used to describe the general trend X_{Trend}. This multiplier is used on the tariffs of all six bearer services. The uncertainty among the various services are modelled by so-called 'tariff noise' multipliers. One multiplier is used for each capacity which means that the same multiplier is used for let us say 2 Mbit/s ASB and 2 Mbit/s SSB because symmetric service is always more expensive than asymmetric service for a given bitrate. These multipliers are named $X_{2\ \mathrm{Mb/s}}$, $X_{8\ \mathrm{Mb/s}}$ and $X_{26\ \mathrm{Mb/s}}$ respectively. In the i^{th} run of the

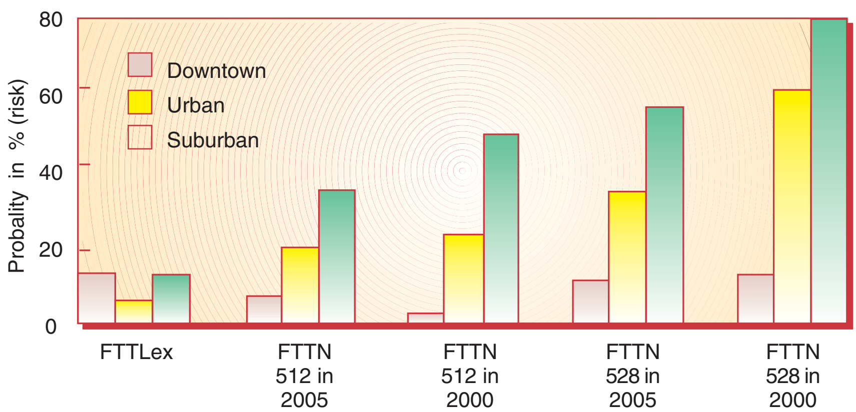

Figure 2 Probability of negative NPV

Table 2 Statistics of service penetrations, market share and tariff multipliers

Forecast	μ	σ
2 Mbit/s penetration in 2009	23.10%	10.86%
8 Mbit/s penetration in 2009	11.51%	6.02%
26 Mbit/s penetration in 2009	7.35%	4.28%
Market share in 2009	77.57%	6.11%
Tariff trend multiplier	100 %	20 %
Tariff noise multipliers	100 %	10 %

Monte Carlo simulation, we get the following tariffs:

$$T^{i}_{c\ \text{Mb/s ASB}}(t) = T_{c\ \text{Mb/s ASB}}(t) \cdot X^{i}_{Trend} \cdot X^{i}_{c\ \text{Mb/s}} \quad (6)$$

$$T^{i}_{c\ \text{Mb/s}}\ \text{SSB}\ (t) = T_{c\ \text{Mb/s SSB}}(t) \cdot X^{i}_{Trend} \cdot X^{i}_{c\ \text{Mb/s}}$$

3 Results

In the calculations the related network components for eg. electronics are correlated. In the same way different installation costs are correlated, and so on. A correlation of 0.5 is chosen. The penetrations of bearer services are negatively correlated with the tariff trend (–0.5). Spearman's method 6 for rank correlation is used.

For the standard deviations chosen in the different assumptions we get the following set of simulated mean values and standard deviations:

The Monte Carlo simulation using 1000 runs has been used as the calculation method. Detailed statistics of various forecasts such as NPV (net present value), IFC (installed first costs) and LCC (life-cycle costs) are generated in a report after each calculation. One risk indicator that can be used to compare the different projects is the probability or risk of a negative NPV. The results are shown in Figure 2.

The upgrades are listed by increasing aggressiveness. As can be seen, fibre build-out is extremely risky in urban and suburban areas. Fibre to the primary distribution point (FTTN 512) is adequate for 100 % coverage of all services in the downtown area. Fibre to the secondary distribution point (FTTN 128) is not the most profitable migration strategy in any area. Due to the high potential revenue base in the downtown area caused by the higher penetration of symmetric services an early investment is recommended. In the other areas however, a more cautious strategy must be chosen, namely FTTLex. The NPVs for the FTTN 512 strategy in urban and suburban areas only weakly depends on the roll-out year. However, the risk is considerably higher for an early investment in fibre build-out and VDSL technology.

It must be stressed that the risk of course heavily depends on the tariff level and on the size of standard deviations in the assumptions. Another set of simulations ('low risk' scenario) were carried out but for standard deviations that were only 50 % of the values given in Table 2. Only EP #2 and EP #4 were considered for the three areas. The probabilities for negative NPV are compared for high and low values of standard deviations:

As can be seen the negative NPV probability decreases in the area of 10 % when the standard deviations in the assumptions are halved. In the suburban area, even for small standard deviations, the risk is significant. The risk is most dramatically reduced for the urban area and for the downtown area the risk is now insignificant (~0 %). The general trend from sensitivity studies shows that the most significant contributors are the tariff trend and the growth rate of broadband demand whereas the uncertainty in the cost evolution of network components, installations and civil work only has a minor impact on the risk.

4 Conclusions

Extensive risk analyses have been carried out for 15 different access broadband upgrade projects, namely the combinations of 5 different evolutionary paths spanning from the cautious FTTLex to the very aggressive strategy of fibre to the secondary distribution point and three

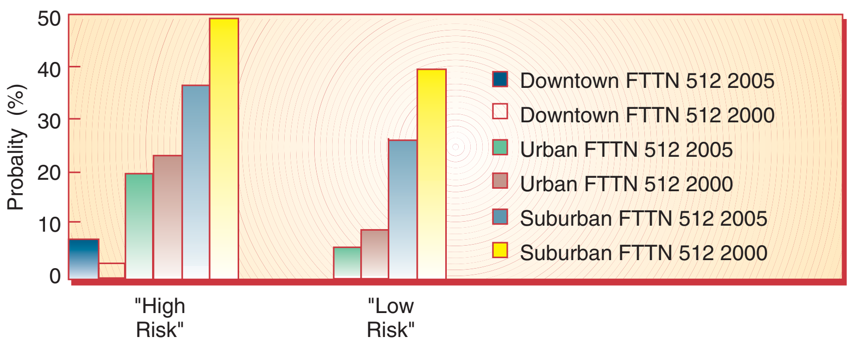

Figure 3 Probability of negative NPV for different sizes of standard deviations in the assumptions

different area types: downtown, urban and suburban. Even for low standard deviations in the assumptions defined, aggressive evolutionary path strategies are extremely risky in urban and especially suburban areas due to the heavy initial investments in infrastructure and uncertainty in broadband demand.

An early investment in a downtown area by upgrading with fibre to the primary distribution point is both the most profitable and least risky of all projects analysed. The risk profiles and thereby the probability of a negative NPV depend heavily on the standard deviations in the assumptions. Even for small standard deviations in the assumptions, there is still a high probability of a negative NPV in a suburban area. Depending on the size of the standard deviations, the downtown area with fibre build-out in the first year (FTTN 512) has a probability of a negative NPV of about 3 % for high values of the standard deviations. In the 'low risk' regime where the standard deviations in penetration, market share and tariffs are halved the probability of a negative NPV is insignificant. EP #3 and EP #4 with fibre reaching the secondary distribution point (FTTN 128) are not the most profitable strategies in any area.

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