# Mobile Broadband Evolution – Past, Present and Future

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Mobile and wireless communications technologies have undergone a huge development since the first automatic cellular networks were introduced in the 1980s. The technological development has been exciting, and we see the latest step on this ladder with the introduction of the LTE – Long Term Evolution systems. This article is a walk-through, mostly of the technological development since data services became available also via mobile and wireless systems, but we also present some facts about the explosive market growth and how this growth is forecast to continue the coming years.

## 1 Introduction

In 2001 we wrote in *Telektronikk* about the evolution of mobile communications and had some ideas about the future [1]. This was the year the first 3G networks were launched[1)]. It was a general view that UMTS was the last system to be standardized as a whole and that '4G' would be something else. Generally, the world seemed to be divided into three different views:

- In Europe 4G was about integration and cooperation. A multitude of different devices, heterogeneous and hybrid access, flexible and reconfigurable solutions was thought to bring service and profile personalization.
- In the USA the CDMA2000 standard was the 3G evolution from cdmaOne. The emphasis was then on the evolution of WLAN and WMAN through MBWA (IEEE 802.20), media independent handover (IEEE 802.21) and cognitive radio (IEEE 802.22).
- In Japan the research towards a new mobile broadband standard had already begun.

The introduction of 3G systems had been delayed because of a general economic recession. The so-called 'dot-com' bubble had burst early 2000, which affected the telecommunications sector heavily. In addition, European operators had spent huge amounts of money on spectrum auctions for 3G, more than £22bn [2], and the missing growth in the sector left them with huge deficits. So, all in all, there was very little belief that it would be possible to standardize and deploy any complete new system after 3G. But only a few years later the optimism was back. One also saw that 3G systems had some limitations when it came to growth.

All the above paths have been followed, but in many ways we may say that the Japanese view proved most correct, now that the Long Term Evolution – LTE – standard is ready and being introduced into the market, nine years after the launch of 3G. The 'generation cycle' of approximately ten years is still valid.

In 2001 there were approximately 500 million cellular subscribers worldwide, and we saw an exponential growth. At the World Radio Conference 2000 (WRC-2000) in Istanbul a press release from the ITU projected about 2 billion cellular users in 2010 [3]. We now know better. At the time of writing this article, the global number of GSM and UMTS subscribers has passed *4.2 billion* (more than 62% global penetration), more than twice the number which was anticipated when UMTS was introduced into the market. Of these, 'only' 700 million are mobile broadband users, but the number is rising rapidly.

So, what is 'mobile broadband'? We need to have an understanding and a possible definition. A good start is to check what different authorities define as 'broadband'. The understanding of the term broadband is relative, because it often refers to an improvement from something existing or former performance or experience. Political, financial and technical bodies have all provided definitions of the term 'broadband'.

The *International Telecommunication Union*, Telecommunication Standardization Sector (ITU-T), defines broadband in their recommendation I.113 [4], as "transmission capacity that is faster than primary rate Integrated Services Digital Network (ISDN) at 1.5 or 2.0 Megabits per second (Mbits)". The Radiocommunications Sector (ITU-R) has through its work on IMT-2000 and IMT-Advanced set minimum requirements for standards to be included in the 3G and 4G families which are actually setting the stan-

1) *The first was the FOMA-service from NTT DoCoMo in October 2001. There was a great set-back, partly due to extremely high auction prices for spectrum in Europe together with a general economic recession. In 2003/2004 UMTS was launched in the Nordic countries.*


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dard for mobile broadband. Key features of IMT-2000 are: "high degree of commonality of design worldwide; compatibility of services within IMT-2000 and with the fixed networks; high quality; small terminal for worldwide use; worldwide roaming capability; and capability for multimedia applications, and a wide range of services and terminals." [5] In recommendation M.1645 [6] from 2003 a general discussion on enhancements of the IMT-2000 systems was presented predicting the current available data rates for UMTS/HSDPA from 10 to 30 Mb/s, while systems 'beyond IMT-2000' were expected to reach peak data rates up to 1 Gb/s in 2010. 'Beyond IMT-2000' is now known as IMT-Advanced and is still a couple of years away.

The *Organisation for Economic Co-operation and Development* (OECD) has defined a lower limit on the user bit rate to be 256 kb/s [7]. This is based on the fact that network operators widely advertise DSL and cable modem services to users, starting at 256 kb/s, as being 'broadband'.

From the *United Nations* (UN) the *Partnership on Measuring ICT for Development* has promoted Core ICT Indicators [8], which also define broadband as technologies that provide speeds of at least 256 kb/s, where this speed is the combined upstream and downstream capacity.

In the USA the *Federal Communications Commission* (FCC) does not provide a definition quantified in a specific data rate, but refers to services: "The term 'broadband' refers to advanced communications systems capable of providing high-speed transmission of services such as data, voice, and video over the Internet and other networks. Transmission is provided by a wide range of technologies, including digital subscriber line and fiber optic cable, coaxial cable, wireless technology, and satellite. Broadband platforms make possible the convergence of voice, video, and data services onto a single network."[2)]

The Norwegian *Post and Telecommunications Authority* (PT) has actually defined both 'wireless broadband' and 'mobile broadband' in a memorandum from September 2009[3)]. Mobile broadband is defined as: "... access capacity in which the end user, connected to a public mobile network, has access to data transmission services with a perceived bitrate of at least 640 kbit/s downstream and 128 kbit/s upstream."

A main reason for making such definitions is to collect information about deployments to better understand how and where it is being deployed. It is also used politically to determine goals for nationwide offerings.

All of these technical definitions are based on the fact of transmitting more than one data stream in the same wire by using different frequencies or channels. But for the non-technical user, broadband is strictly tied to 'effective' speed, or, in other words, 'subjective' speed. It can for example be said that if your 1 Mb/s is the slowest in town, it is no longer broadband. *However, in this article we will use the value 1 Mb/s as the current criterion for broadband.*

This article is divided into three major parts: First, we present an overview of the development from mobile data to mobile broadband. Second, we show some facts about the market development for mobile broadband based on open statistics and add some forecasts for this development the coming years. Third and last, we deep dive some more into the specific technological steps which has made this possible up to the latest achievements which have been researched for the last 10-15 years and are now being introduced in the standards and commercial systems.

## 2 From Mobile Data to Mobile Broadband

In Norway 'mobile broadband' was first used in marketing in the spring of 2007 by NetCom when they launched their product based on the new *High Speed Downlink Packet Access* – HSDPA – technology. The first HSDPA version could offer up to 3.6 Mb/s on the physical layer, resulting in 2-2.5 Mb/s aggregated application data rate from one sector or base station. Looking back to our initial discussion on "What is broadband?" we can state clearly that the mobile broadband era started in 2007. Later the same year, Telenor followed with HSDPA and we saw the start of the service 'Ice' based on the competing CDMA2000 technology.

This chapter is a walk-through of the evolution of mobile broadband standards and performance together with other components of the picture. But first, in this evolution story, we will look back on pre-broadband offers and technologies.

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2) *http://www.fcc.gov/broadband/*

3) *http://www.npt.no/ikbViewer/Content/109358/Def_utvalgte_typer_bredband.pdf*

## 2.1 Pre-broadband – Early Mobile Data Services

In principle, NMT – Nordic Mobile Telephone – gave the same possibility for data communications as the ordinary analogue telephone network (PSTN, POTS) but suffered from some disadvantages compared to PSTN due to the varying radio channel conditions and the handover breaks. With excellent quality and stationary NMT telephone, a data rate of 14 400 b/s with no error correction was possible [9].

NMT also supported a simple but robust integrated data transfer mode called DMS (Data and Messaging Service) or NMT-Text, which used the network's signalling channel for data transfer. NMT signalling transfer speeds vary between 600 and 1200 b/s. Signalling between the base station and the mobile station was implemented using the same RF channel that was used for audio with a 1200 b/s fast frequency shift keying (FFSK) modem. This caused periodic short noise bursts, eg. during handover, a unique characteristic to NMT sound.

Using DMS, also text messaging was possible between two NMT handsets before SMS service started in GSM, but this feature was never commercially available except in Russian, Polish and Bulgarian NMT networks. Another data transfer method called NMT Mobidigi provided transfer speeds of 380 b/s.

### 2.1.1 Mobitex Mobile Data

Mobitex is a packet based radio system originally developed by the Swedish 'Televerket Radio' (Now part of TeliaSonera) in the early eighties [10]. From 1988 it was taken over by the company Eritel, a joint venture between Ericsson and Televerket, later a subsidiary of Ericsson. It became operational in Sweden in 1986 and in Norway in 1989. As most systems of the time it comprised not only the access and switching, but also all kinds of services were embedded, like different text-based messages (alarms, telex), data services and even voice.

Mobitex is a narrowband, packet switched technology. The initial version supported 1200 b/s using FFSK, the same technique as used in the NMT signalling channel. The second generation supports 8 kb/s bit rates using GMSK modulation. It operated in the VHF band in Norway (160 MHz), while in Sweden it used the 80 MHz (68-87.5 MHz) band [10].

In the mid-1990s Mobitex gained consumer popularity by providing two-way paging network and wireless push email. It was used by the first model of Research in Motion's *BlackBerry*. During 9/11 and the 2005 hurricane rescue and clean-up operations,

*Figure 1 A wireless e-mail solution based on Mobitex. The Ericsson 'Viking express' from 1992 consisting of the Ericsson Mobidem together with an HP-95 palmtop and bundled with Research in Motion's (RIM) MobiLib-Plus application programming interface (API) to work with major e-mail systems. (Source: http://blackberryplanetbook.com/index.php/Image:Mobidemhp.jpg)*

Mobitex proved itself to be a very reliable and useful system for first responders. 30 networks are still operational worldwide [11]. Today, Mobitex is an open standard marketed worldwide by Mobitex Technology [12].

In the Nordic region, there are two Mobitex operators in Sweden, mostly delivering services for public transport, telemetry, taxi dispatch and public safety. In Europe services are provided in the UK, the Netherlands, and a few private networks exist in France, Austria and Italy [11]. In Europe it runs in the 400-450 MHz band, while in North America it uses the 900 MHz band.


*Figure 2 Research-in-Motion's (RIM) Blackberry 950, a Mobitex 900 based text and internet terminal (2001)*


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| Technology | Standardized/ introduced | Domain | Maximum DL data rate | Maximum UL data rate |
|---|---|---|---|---|
| CSD – Circuit Switched Data | 1990/1991 | CS | 9.6 kb/s | 9.6 kb/s |
| HSCSD – High Speed CSD | 1999/2001 | CS | 38.4 kb/s | 14.4 kb/s |
| GPRS – General Packet Radio Service | 1999/2001 | PS | 56 – 114 kb/s | 20 – 40 kb/s |
| EDGE – Enhanced Data Rates for GSM Evolution | 2001/2004 | PS | 250 kb/s | 100 kb/s |
| EDGE Evolution[4)] | 2008/2009 | PS | 1.2 Mb/s | 450 kb/s |

*Table 1 Data services of the GSM family*

### 2.1.2 Cellular Data – GSM

With the introduction of the 2nd generation systems in the early 1990s, mobile data services became more designed and integrated into the cellular systems, like GSM, D-AMPS and IS-136 (Qualcomm CDMA). We do not consider these to be broadband, but according to eg. the OECD definition above, some are close.

GSM – *Global System for Mobile communication* – was originally developed to accommodate voice services and to be the mobile counterpart to ISDN, which in the 1980s was believed to be the future, digital technology for the fixed network.

The GSM family is the most widespread technology and has undergone an evolution in data service capabilities as listed in Table 1.

GSM was originally standardized to operate in the 900 MHz band where 124 channels are defined. Because the capacity soon was filled, a newer version of GSM, initially denoted DCS1800 was standardised, able to utilize the 1800 MHz band.

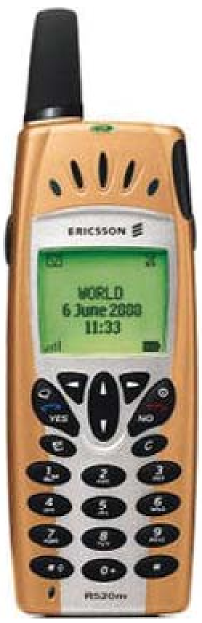


*Figure 3 Ericsson's first GPRS enabled phone, the R520m (2000)*

## 2.2 Broadband Becomes Mobile

In the 1990s Internet access became common, first via telephone modem and ISDN, later fixed broadband using ADSL or cable networks became common in households. Quite soon, wireless access based on Wi-Fi technology became popular. The term 'mobile internet' emerged around 2000, when the GPRS technology was deployed in the GSM networks.

The habits from using Wi-Fi domestically or in public hot-spots eventually also led to a pull for providing broadband access in a real mobile setting. The standardization work on the first system to be able to deliver such services started already in 1995 under the term UMTS – *Universal Mobile Telecommunications System*. This work started in ETSI, however the task became global and was transferred to the 3rd Generation Partnership Project – 3GPP[5)] – from 1999.

### 2.2.1 3rd Generation Systems – the Workhorse for Mobile Broadband

Real mobile broadband became a reality with the introduction of the 3G systems, however the first UMTS release, Release 99, barely deserves the term with its practical limitation of 384 kb/s downlink and 64 kb/s uplink. UMTS can operate as both frequency division duplex (FDD) and time division duplex (TDD) modes. The FDD mode is dominating the world market; in Europe because most spectrum is set aside for FDD operation and the operators preferred to apply for license using UMTS FDD [2]. Therefore the discussion here will concentrate on the FDD mode.

It is only with the introduction of the HSDPA technology in 2006 that real broadband speeds became a reality. The first implementations provided 3.6 Mb/s downlink peak data rate, effectively up to 2 Mb/s user data rate. Table 2 shows the different evolutionary steps of the HSxPA technology. The HSPA technology is described in more detail by Bøhagen and Biningsbø in this issue [13].

4) *Numbers for EDGE evolution assume dual carrier (2x200kHz) operation.*

5) *Group of the standards bodies ARIB and TTC (Japan), CCSA (People's Republic of China), ETSI (Europe), T1 (USA) and TTA (Korea). The 3GPP itself is not a standardization organization and all produced standards must be ratified by a standards body.*


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A new frequency band was allocated globally for 3G by ITU in the 2.1 GHz band (1920-1980 MHz / 2110-2170 MHz). At the latest world congress in Barcelona, 112 Mb/s was demonstrated by Nokia Siemens Networks as a HSPA DL multi carrier system.

### 2.2.2 Mobile Broadband for the Future – LTE

The next step in the Mobile Broadband technology evolution standardized by 3GPP is called LTE – *Long Term Evolution*. LTE is expected to deliver even higher data rates for lower price than the HSPA technology. The standardization began with a study in 2005 and the first release was finished March 2009 (Release 8). Currently a few commercial offers have been launched, but it is more fair to call these offers user pilots. Several tests have been conducted showing peak rates beyond 150 Mb/s using multiple-antenna techniques.

3GPP based standards are used world-wide and are undoubtedly the most successful bundle of mobile technologies. The following numbers illustrate this [14]:

- 3GPP technologies currently serve more than 4.2 billion users, of which more than 500 million are mobile broadband users.

- As of January 2010, there are 293 commercial operations in 119 countries offering mobile broadband using HSPA technology, and the number is growing.

- In January 2010 there were 59 network commitments in 28 countries on LTE. TeliaSonera in Sweden and NetCom in Norway launched the first commercial networks based on LTE in December 2009.

## 2.3 Radio Spectrum – a Critical Resource for Efficient Mobile Broadband

Spectrum is one key resource to efficient and profitable business in mobile broadband, and a change in spectrum management has gradually taken place the last 20-25 years. The monopoly in the telecommunication industry was gradually replaced by competition in the late 1980s and early 1990s. In the mobile industry this basically happened by rewarding parallel spectrum licenses when GSM was introduced. Still, this was part of what is commonly called the 'command-and-control' regime by national regulators, because the license clauses demanded both the use of a specific technology (GSM) and there were detailed requirements on coverage and deployment time scales. Trosby, Johannessen and Rabstad [2] have written a comprehensive overview and analysis of this evolution in another article in this issue.

| 3GPP Release | Maximum DL data rates (HSDPA) | Maximum UL data rate (HSUPA) |
|---|---|---|
| Release 6 'Basic HSPA' | 1.2-14.4 Mb/s | 5.7 Mb/s |
| Release 7 'HSPA+' | 21 Mb/s<br>28 Mb/s | 11 Mb/s |
| Release 8 'HSPA+' | 42 Mb/s | 11 Mb/s |
| Release 9 'HSPA+' | 84 Mb/s | 23 Mb/s |

*Table 2 Evolution of Mobile Broadband data rates based on 3GPP HSPA*

The common trend in spectrum regulation is towards a more liberal regime. This means first of all a so-called technology neutral policy, ie. there is no demand to use a specific technology. Second, there are few requirements on coverage and deployment. Still, the key to success and economy of scale lies in the global regulations imposed by the International Telecommunication Union (ITU) through the triennial World Radio Conferences (WRC) and Radio Assemblies (RA). This usually leads to a de-facto distribution of the different frequency bands on the different technologies (2G, 3G, LTE, WiMAX etc.), a fact that is also underlined in [2].

## 2.4 Security Evolution

Parallel to the general increase on security threats on the Internet, the security techniques in the mobile systems have undergone a development towards gradually more secure solutions. Security in telecom can be divided into two main parts:

- *Authentication* is the mechanism used to ensure the true identity of the parts involved in a communication transaction. In GSM it was considered sufficient with a one-way authentication procedure to verify the subscriber identity, while later, in UMTS and LTE, two-way authentication was introduced. Authentication is usually performed by a so-called *challenge-response* technique in which the use of keys is essential.

- *Data protection* is about ensuring that data transmitted through the networks are protected against eavesdropping (data confidentiality) and also against changes (data integrity). Data protection is usually performed by cryptographic methods called *ciphering*. A 'secret' code is overlaid the data, and the two parts share keys to unlock the code.

Both these parts have been strengthened due to the increased threat encountered. In current mobile data and broadband systems, none of these techniques are end-to-end, but the network termination points have moved further into the network. Table 3 summarizes


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| System | Authentication | Ciphering strength | Network termination point |
|---|---|---|---|
| GSM | GSM AKA,<br>One-way challenge-response | 64 bits<br>Key change entering new location area (VLR) | BTS for GSM<br>SGSN for GPRS |
| UMTS | UMTS AKA,<br>Mutual entity authentication | 128 bits<br>Key change entering new location area (VLR) | RNC |
| LTE | EPS-AKA,<br>Mutual entity authentication | 256 bit master key<br>Separation of user and control planes<br>Key change on handover | MME (control plane)<br>eNodeB (user plane) |

*Table 3 Evolution of access security for GSM, UMTS and LTE (simplified)*

the evolution through GSM, UMTS and LTE. A comprehensive description of the access security mechanisms in the 3GPP standards GSM, UMTS and LTE is given by Køien in another article in this issue [15].

### 2.5 Other Technologies for Mobile Broadband

The 3GPP based standards (GSM, UMTS/HSPA and LTE) are the most widespread technology for mobile data and broadband, not counting Wi-Fi based WLAN. Wi-Fi delivers wireless broadband with much higher data rates than current implementations of HSPA, but it is fair to say that it does not deliver mobile broadband. Nevertheless, we will also walk through some other standards than the 3GPP-family.

WiMAX – *Wordwide Interoperability for Microwave Access* – is the most obvious alternative to UMTS and LTE. It is based on the IEEE 802.16 WMAN standard, which was first released in 2001 for fixed wireless broadband. In 2005 mobility was added as an amendment ('Mobile WiMAX'). In 2009 all previous amendments were merged into one common standard (IEEE 802.16-2009). WiMAX is the term used commercially and is a defined and agreed subset of the standard's features which shall be implemented. The WiMAX Forum[6)] defines the so-called WiMAX profiles and certifies equipment to ensure interoperability. As for UMTS and LTE, IEEE 802.16 can operate in both FDD and TDD modes, however TDD mode has been the only one to be defined as a WiMAX profile.

Similar to LTE, WiMAX uses OFDMA (see section 4.2.3) as its multiple access technique both for downlink and uplink. Flexible bandwidth allocation is possible and multiple antenna techniques are possible.

The WiMAX standard is comprehensively described by Grøndalen in another article in this issue [16].

As of January 2010, there are more than 555 WiMAX deployments in 147 countries [17][7)] including both fixed and mobile systems. Still, less than 100 million customers use the WiMAX technology.

Wi-Fi – *Wireless Fidelity* – has become a synonym for wireless local area network technologies (WLAN). Similar to WiMAX, Wi-Fi is an industry initiative to ensure interworking between equipment compliant with the IEEE 802.11 family of standards. WLANs both for consumer and business use have become a success due to their simplicity and low cost. Wi-Fi is not really mobile, but can support certain nomadicity. Physical layer bit rates up to 200 Mb/s are supported with the latest extensions of the standard, the 802.11n version using larger channel bandwidths (40 MHz) and MIMO-technology. Different attempts have been made to introduce true mobility (ie. handover functionality) in public and private WLANs (see eg. [18]), but it mainly remains the workhorse for in-house distribution of fixed broadband in both private homes and enterprises.

We shall also briefly mention *digital broadcast technologies* like DVB and DMB. They encompass two important characteristics: high bandwidth and data rate, and potential large coverage. Both qualities are suitable for mobile broadband systems. However, there are main drawbacks due to the inherent nature of broadcast systems. Attempts have been made to use DxB as fixed wireless broadband carriers in areas with no cable or DSL coverage. It is in the nature of broadcast to be uni-directional, and this has led to some standardization efforts to provide suitable return channels via other networks (GSM, UMTS,

6) *WiMAX Forum: http://www.wimaxforum.org*

7) *This is the number of deployments which WiMAX Forum actually tracks. There may in fact be more deployments.*


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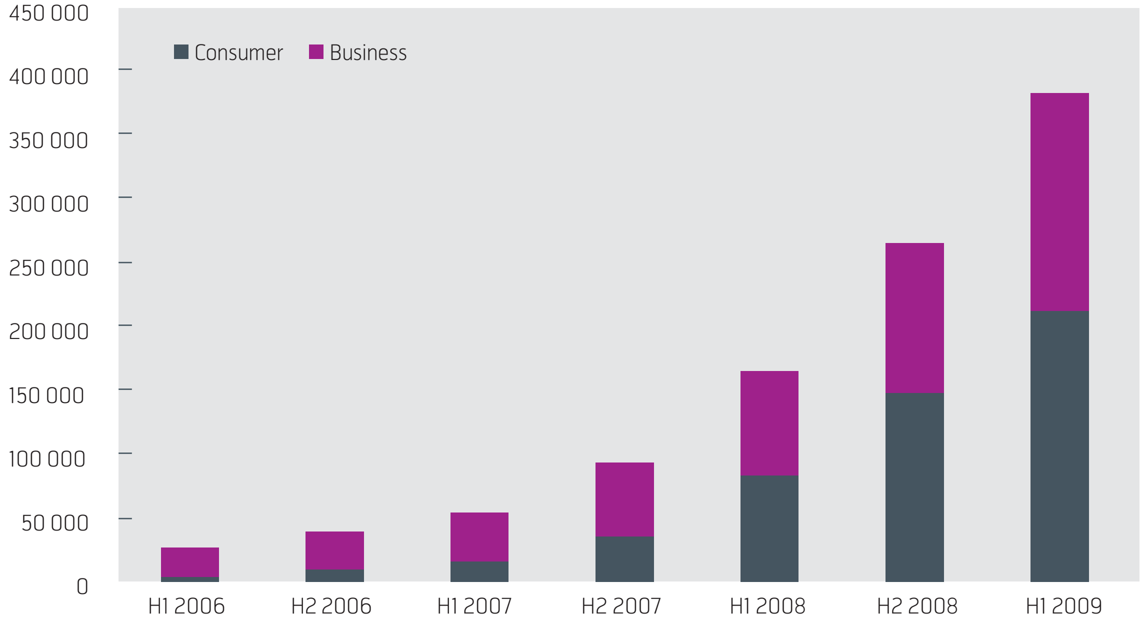


*Figure 4 Number of subscriptions of mobile broadband customers in Norway from 2006 to 2009 [22]*

ISDN), and also via satellite (DVB-RCS [19]). These solutions must however be regarded to be of marginal interest, due to their suboptimal performance.

## 3 Mobile Broadband Market Evolution and Forecast

We have seen the enormous traffic growth in the mobile networks when 'true' broadband was introduced with the HSPA technology. When even more efficient technology is introduced it is expected that traffic will grow further. This chapter presents some forecasts for the mobile broadband market. Some of the forecasts presented are made for a 'fictitious' Western European country with 10 million inhabitants. It has a workforce of 4.5 million, between 15 and 74 years of age. More data about this country, which we shall call 'Europania', is to be found in [20].

### 3.1 Subscriptions and Penetration

According to the ITU, the global penetration of mobile broadband reached 9.5% in 2009 [21], more than the fixed broadband penetration.

In Norway the number of mobile broadband subscriptions reached 382,000 at the end of the first half of 2009 [22]. The consumer market has had the largest growth and constitutes 56% of the total market, a penetration of 4.6%. The growth in the period 2006 up to first half of 2009 is shown in Figure 4.

This trend is expected to continue. In [23][24] forecasts for the consumer and business markets for the period 2008 to 2015 are made for the aforementioned 'Europania', see Figure 5. These forecasts were based on a broadband access evolution in the period 2006 to 2008. The estimated saturation level for the consumer market is 34% (3.4 million). A lower saturation level (30%, 1.35 million) is estimated for the business market.

This forecast extends the Norwegian development with an increasing growth until 2011-2012 when the growth is expected to slow down. Global forecasts support this trend. In Figure 6, global 3G subscription forecasts indicate a growth from 571 million in 2009 (8.5%) to 3.2 billion in 2014 (46%)[8]. This trend is more exponential than is seen in Figure 5. The development in Western Europe is ahead of the rest of the

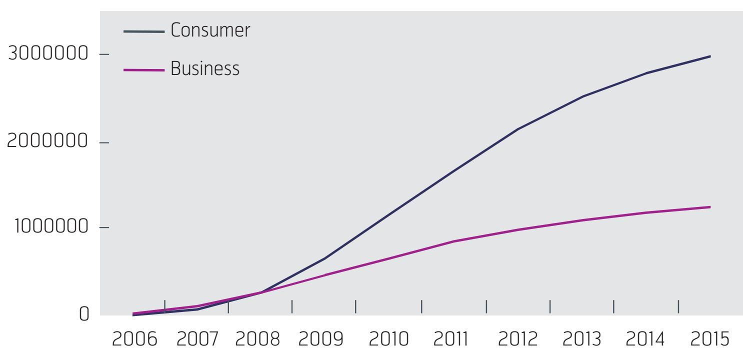


*Figure 5 Mobile broadband subscription forecasts for a medium size Western European country, 2008 – 2015 [23][24]*

8) *Based on an estimated global population of 6.7 billion in 2008, increasing to 7 billion in 2015.*

9) *GB: Gigabyte – 1 billion bytes.*


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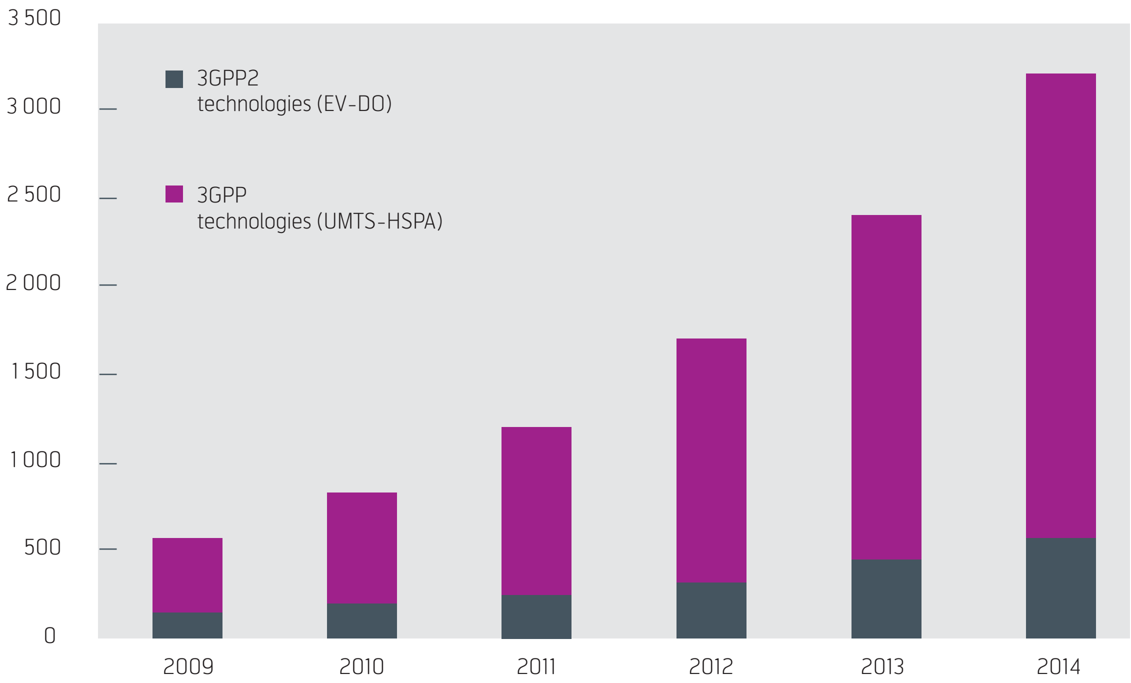


*Figure 6 Global 3G subscription forecasts from 2009 to 2014 [25]*

world, and we should therefore expect an earlier saturation here.

## 3.2 Network Traffic

While penetration forecasts are important in understanding the take-up of new technologies, the traffic forecasts help us plan network dimensioning.

HSPA technology is currently the global workhorse for mobile broadband. Statistics from leading UMTS-HSPA vendors in the period from January 2007 to May 2009 show an 18 times increase in traffic volume for packet data [26].

In the Norwegian market the amount of data transferred in the first half of 2009 was more than 2.6 million GB[9)] in total. By comparison, the volume of data for all of 2008 was about 2.5 million GB. This corresponds to a total mobile broadband traffic increase of 219% from first half of 2008 to first half of 2009, as shown in Figure 7 [22]. This corresponds to 1.1 GB/month per subscriber in the first half of 2009.

The data is split between special mobile broadband subscriptions and Internet access over ordinary mobile telephony subscriptions. The amount of data transferred for own mobile broadband subscriptions has increased considerably. The amount of data transferred for Internet access over ordinary mobile telephony subscriptions is also increasing, but represents only a limited part of the total amount.

We see that residential customers account for more than 80% of the amount of data transferred. This share has increased in the last year.

Forecasts for 'Europania' estimate the monthly traffic per subscriber in the consumer segment to increase

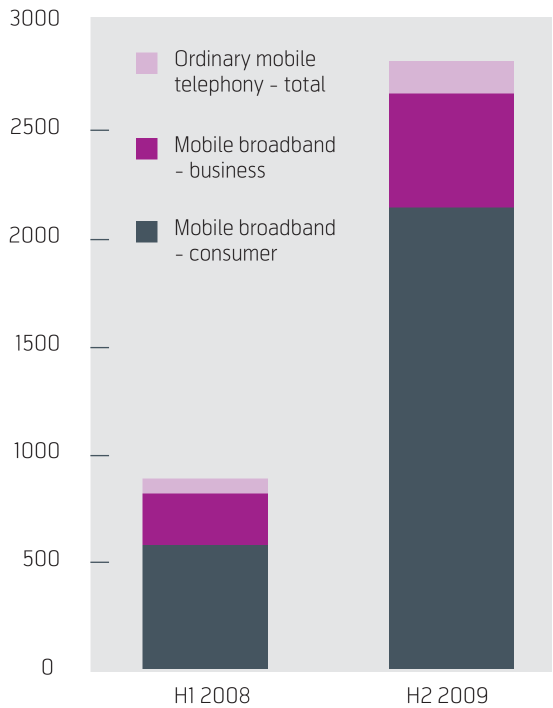


*Figure 7 Volume of amount of data transferred for ordinary mobile telephony and special mobile broadband subscriptions in Norway [22]. Numbers in Terabytes (TB)*


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from 1.3 GB/month in 2010 to 4 GB/month in 2015, more than three times. In the business segment the growth forecast is lower: from 1 to 2.2 GB/month, more than two times [20].

The traffic evolution shows how different types of terminals generate different amounts of traffic. Since 2009, special so-called 'large screen' subscriptions have been available. We can then segment the market for subscriptions and traffic. In this paper we refer to three groups: Mobile broadband traffic generated by 'large screen' subscription contracts, traffic generated by 'small screen' subscription contracts, and mobile broadband generated by users without mobile broadband subscription contracts ('Pay as you go'). Since there is no real connection between eg. 'large screen' subscriptions actually being used only on large screen terminals (PCs etc.), there will be an uncertainty.

According to [23] there is an expected huge growth in the use of large screen terminals as shown in Figure 8. This shows penetration forecasts for large and small screen terminals for the period 2009-2015.

Figure 9 shows the consumer market traffic forecasts for the same period. We see that the difference in traffic between the two screen sizes is expected to increase with a higher rate than for penetration. The conclusion of this observation is that the growth rate for traffic from large screen users is higher than for small screen users. Combined with the subscription growth we should expect a huge growth in total traffic volume.

### 3.3 Revenue Evolution

Important for operators is of course the revenue. According to the Norwegian regulator [22] the revenue of mobile broadband in the Norwegian market is increasing much more than that of mobile telephony, even though there are much more mobile telephony subscriptions than special mobile broadband subscriptions. In general, revenue of data traffic over ordinary subscriptions is for 2009 estimated to be 690 MNOK, while it was 552 MNOK in 2008 [27].

## 4 Technology Evolution

### 4.1 Core Network

Today's core network architecture is an evolution from the initial GSM core, a circuit switched system designed for speech, with added CS data. The introduction of GPRS in 1999 necessitated a redesign of the core. This combined CS+PS (see Figure 11) architecture has since then been the basic core in both GSM and 3G networks.

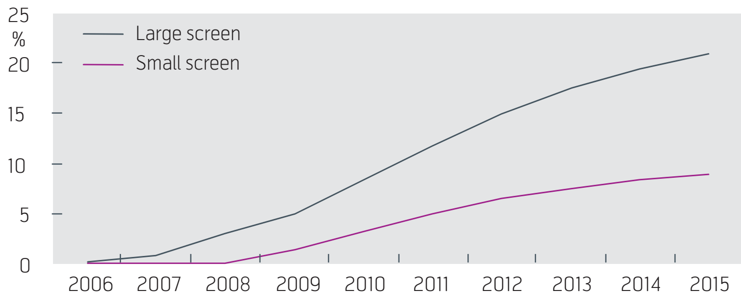


*Figure 8 Mobile broadband penetration forecasts for large and small screen terminals [23][24]*

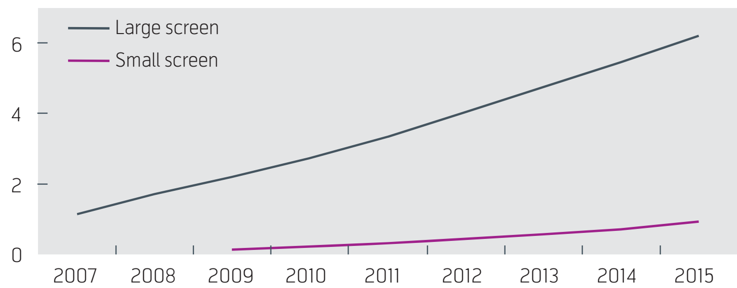


*Figure 9 Traffic forecasts in GB/month for large and small screen subscriptions [23][24]*

The CS domain of the 2G/3G core network handles the voice, CS data (CSD and HSCSD) and SMS traffic. This was the original service portfolio of GSM. The PS domain handles all the packet switched traffic in GPRS/EDGE and 3G/HSPA.

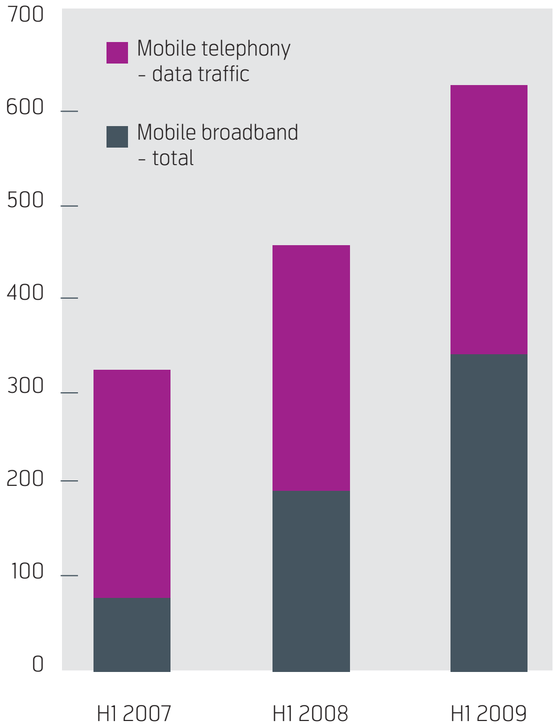


*Figure 10 Revenue of data traffic for ordinary mobile telephone subscriptions and special mobile broadband subscriptions, first half of 2007 to first half of 2009 [27]. Numbers are in MNOK*


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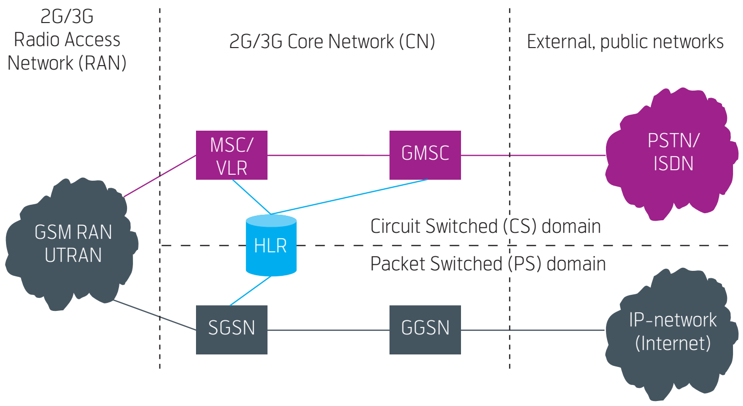



MSC: Mobile Switching Centre. GSM switching node for voice, CS data and SMS

GMSC: Gateway MSC. Central MSC handling traffic between GSM/UMTS and external telephone networks

SGSN: Serving GPRS Support Node. Switching node for PS data

GGSN: Gateway GPRS Support Node. PS Gateway between GPRS/UMTS and external networks

HLR: Home Location Register. Operator's subscriber database

VLR: Visitor Location Register. temporary database of the subscribers who have roamed into a particular area

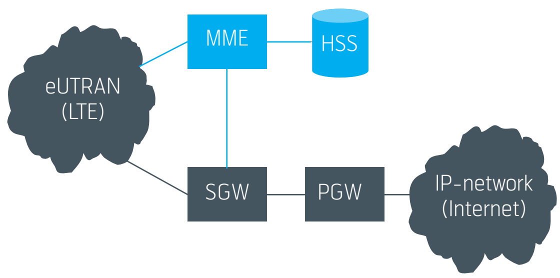
PSTN: Public Switched Telephone Network. The analogue telephone network

ISDN: Integrated Services Digital Network. The digital telephone and data CS network

UTRAN: UMTS Terrestrial Radio Access Network. The 3G radio network

*Figure 11 Simplified core network (CN) architecture for GSM, GPRS and UMTS*

In the standardization work in 3GPP several attempts were made to convert the core network to an IP architecture (see eg. [1]), but it was not until the standardisation of the new *Evolved Packet System* – EPC – that the IP-transition was complete. Service handling in the EPC is closely described by Kjuus and Nordvik in another article in this issue [28]. The EPC also represents a major simplification of the architecture, effectively removing the circuit switched domain (see Figure 12).




MME: Mobile Management Entity. A signalling -only entity managing the terminal

HSS: Home Subscriber Server. The customer database, comparable with the HLR

SGW: Serving Gateway. Local mobility anchor, connected to the eUTRAN

PGW: Packet Gateway. Handles different IP routing functions

eUTRAN: evolved UTRAN. The LTE radio access network

*Figure 12 The Evolved Packet System (EPC) architecture*

## 4.2 Access Technology

The radio access network – RAN – has also developed since GSM. The architecture for UMTS and GSM is fairly similar if we look at the number of nodes. The 3GPP-family consists of three main members: GSM, UMTS including HSPA and LTE. The strength of the 3GPP family is that they are adapted to co-exist and share resources in the network. GSM and UMTS build on the same core network (CN), while using different radio access technologies. The Evolved Packet System (EPC) core network of LTE can also be used together with the UMTS radio access network (UTRAN) PS domain. All three systems use different radio access technologies – developed, tested and optimized for different goals.

### 4.2.1 Narrowband TDMA

GSM uses a radio access technology based on TDMA – time division multiple access. Each user is given a part of the time to communicate. Resource allocation is centrally controlled based on requests from the terminals using a random access signal. In the original CS domain, a user is then reserved one timeslot out of eight in a TDMA frame of 4.615 ms (see Figure 13). The introduction of PS data with GPRS and later EDGE called for a different resource reservation technique where timeslots are allocated more dynamically during the session. GSM is a 'narrowband' system with 200 kHz channel widths and if more than eight simultaneous users are to be accommodated over one base station (BS), more carriers must be installed making GSM actually a combined TDMA/FDMA system. The narrowband property is undoubtedly the most important factor leading to the GSM success also in rural areas where coverage is more important than capacity (see eg. [29]).

### 4.2.2 Wideband CDMA

UMTS was designed to deliver higher capacity both in voice and data. The channel bandwidth was increased to 5 MHz and a new radio access technology was chosen, namely WCDMA – wideband code division multiple access. The different users are allo-

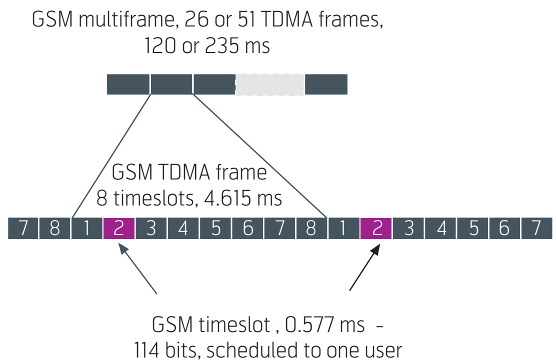



*Figure 13 TDMA frames in GSM*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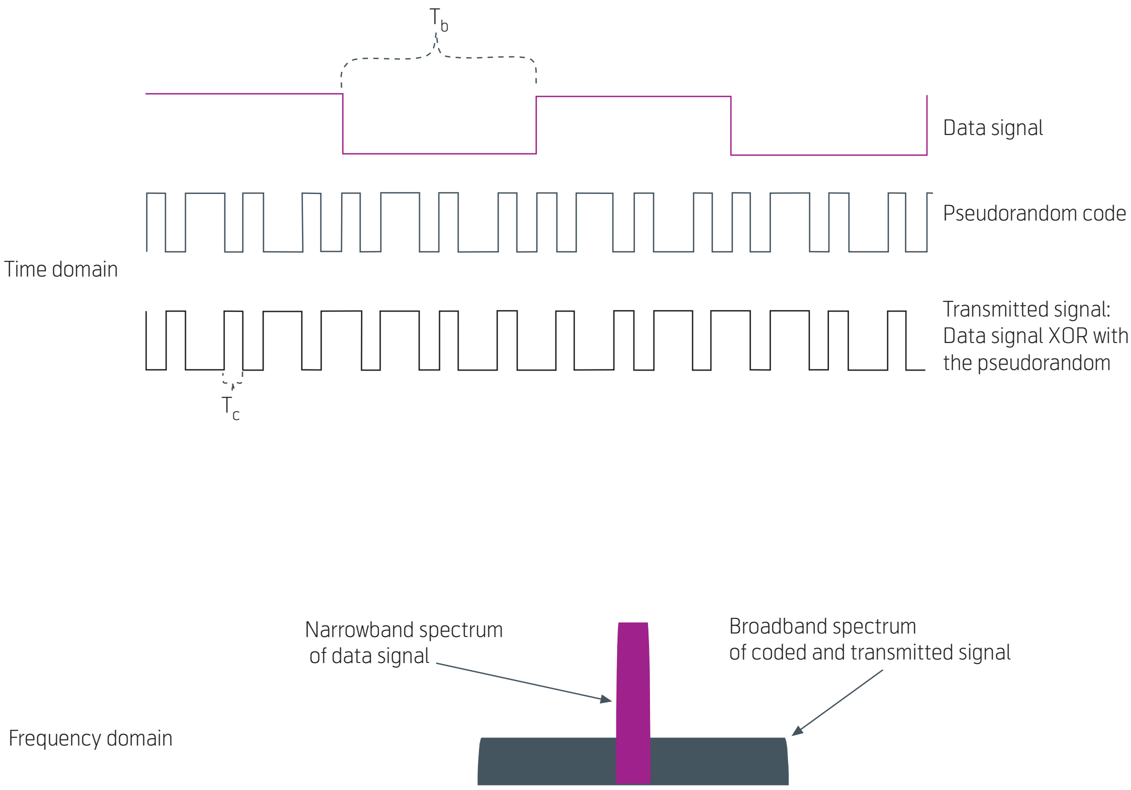


*Figure 14 Spreading of data signal using pseudorandom codes. Each user is allocated a unique code from a set of orthogonal codes*

cated different, orthogonal codes which are used to spread the data across the total bandwidth (see Figure 14). The so-called spreading factor (SF) varies with the information bandwidth of the service. A voice call using the standard codec will use one code with a spreading factor of 128. Theoretically, one could then expect that up to 120 simultaneous voice calls could be possible, however due to power limitations and co-channel interference the limit is closer to 70. A HSDPA 3.6 service however uses five codes with SF = 16 [13].

UMTS is not a frozen standard; the HSPA is being further developed to provide higher data rates using *multiple input – multiple output* (MIMO, see section 4.2.4), carrier aggregation and higher order modulation.

### 4.2.3 Orthogonal Frequency Division Multiple Access – OFDMA

The UMTS/HSPA standard had some limitations that were hard to come by, and a new standard had to represent a break in backward compatibility. This also meant that one could think freely about radio access technology and network architecture. This time, OFDMA – *orthogonal frequency division multiple access* – was chosen for the downlink (DL), a technique which had proven its strength in eg. broadcast systems, Wi-Fi and WiMAX. In many ways OFDMA has more similarities with TDMA/FDMA in GSM than with the CDMA technology of UMTS.

Users are again allocated resources in a time/frequency grid based on resource blocks (RB) of 180 kHz (12 sub carriers – SC) and 0.5 ms (1 Slot) as shown in Figure 15. On the uplink, a slightly different technique called SC-FDMA (single-carrier FDMA) is used, basically a modified OFDMA technique employing a pre-spreading of the signal using a fast Fourier transform (FFT). The use of OFDMA is also believed to be cheaper (more bits per buck) than WCDMA. The OFDMA technology in general and how LTE uses it is explained more comprehensively in eg. [30]. Due to the flexibility of the OFDMA signal LTE can be deployed in different bandwidths ranging from 1.4 MHz to 20 MHz, giving operators good opportunities in different markets with different spectrum offers. It is also easier to trade-off between coverage and capacity within the same frequency band. MIMO is now an integrated part of the physical layer, with the capability of up to four data streams (4x4 antennas) on the downlink.

*LTE-Advanced* is the evolution of LTE in order to provide even higher data rates and more cost-efficiency. Techniques like higher order MIMO up to 8x8 (DL) and carrier aggregation will provide both higher spectral efficiency and higher peak data rates.


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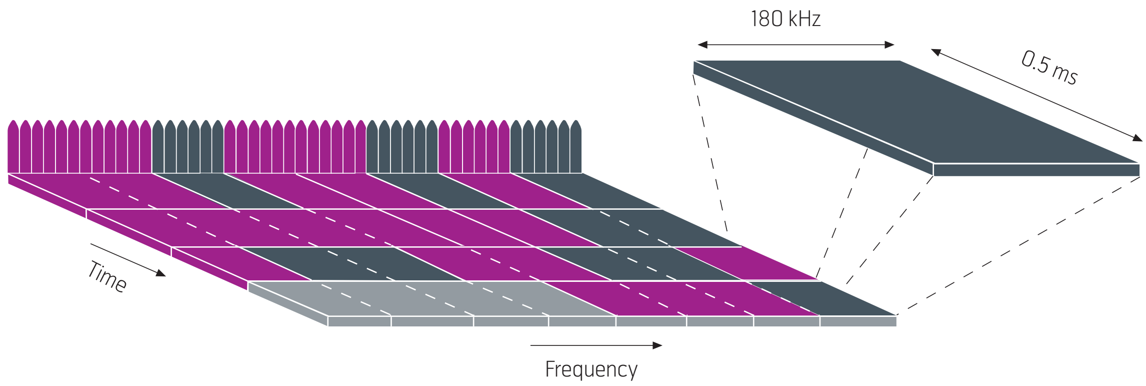


*Figure 15 Orthogonal Frequency Division Multiple Access (OFDMA) technique used on the LTE downlink*

Techniques like SON – self-organizing networks – and CoMP – coordinated multipoint transmission/reception are developed to even further enhance the efficiency with interference control and also reducing the need for manual tuning and optimization of the network.

#### 4.2.4 Multiple Antenna Systems

The rapid increases in data rates and capacity of mobile broadband technologies are due to several enhancements in all parts of the system. On the physical layer, the introduction of multiple antenna technologies is one of the most important techniques.

Multiple antenna techniques are not new. Increasing the gain and range with *antenna arrays* has been used for a long time in broadcast towers, radars etc. The novelty with techniques often termed 'smart' or 'adaptive' antennas is the possibility of a dynamically tuneable array where feedback from the channel is used to optimize the antenna array with respect to eg. signal strength or signal-to-noise ratio.

The latest addition is the *multiple input – multiple output* (MIMO) technique. The first successful tests with this were done by Bell Labs in the 1990s [31]. After this, research efforts have been massive and MIMO is now available in the commercial standards HSPA, LTE, WiMAX and Wi-Fi. Often the term MIMO is used for all multiple antenna systems, however this is not entirely correct; MIMO is just one of them.

We can divide multiple antenna techniques into three main categories:

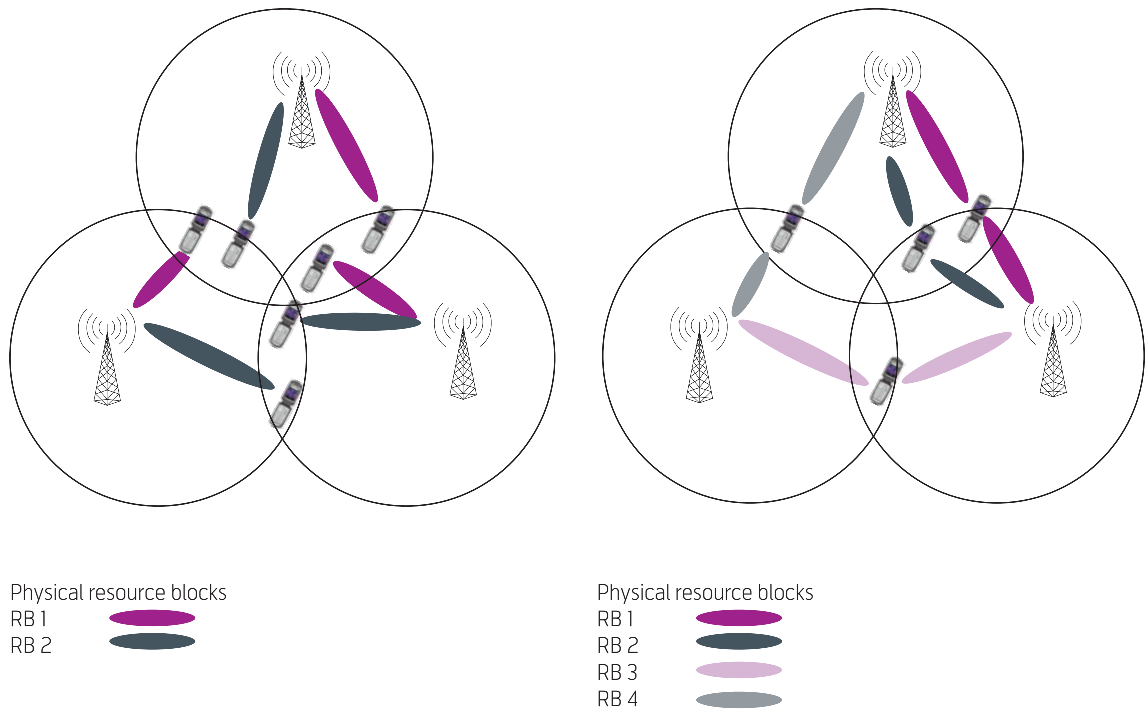


*Figure 16 Coordinated multipoint (CoMP) transmission techniques in LTE-Advanced. Left: Coordinated scheduling/beamforming, right: joint transmission and spatial multiplexing*


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- Beamforming techniques
- Diversity techniques
- MIMO

*Beamforming techniques* are evolutions of the aforementioned array antenna systems, in which the antenna element weights are tuned based on the channel feedback. Several beamforming schemes are possible and may be termed differently; switched beam, phased array and adaptive array [32].

Switched beam, also called switched lobe is the simplest technique and comprises only a basic switching function between separate directive antennas or predefined beams of an array. For dynamically phased arrays (PA) a direction of arrival (DoA) algorithm is included for the signal received from the user. Then, continuous tracking can be achieved and it can be viewed as a generalization of the switched lobe concept. For the adaptive array (AA) a DoA algorithm for determining the direction toward interference sources (eg. other users) is added. The radiation pattern can then be adjusted to null out the interferers. In addition, by using special algorithms and space diversity techniques, the radiation pattern can be adapted to receive multipath signals which can be combined. In practical systems, simplifications are often made.

Tests done by Telenor on 2.1 GHz (UMTS frequency band) for possible gain of different beamforming techniques in urban and suburban environments showed that both switched beam and phased array had similar performances [33]. Using an 8 element linear array, the power increase was 5 dB on average, and the improvement in signal-to-noise ratio was 6 dB, while the adaptive array technique showed as high as 12-16 dB improvements in signal-to-noise ratio. The reference was a standard 65° sector antenna. The performance shows some dependency of the number of interfering signals as shown in Figure 17, where an example from downtown Oslo is shown.

*Diversity techniques* have been used since the first mobile telephone systems on the base station receiver

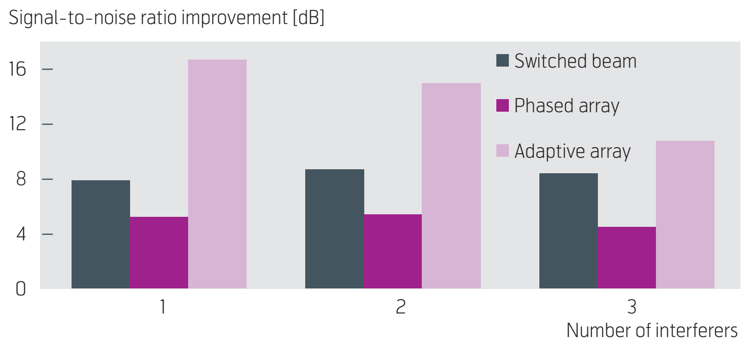


*Figure 17 Experimental improvement at 2.1 GHz in signal-to-noise ratio for different beamforming techniques for an urban area [33]*

to mitigate fading effects. The signals from two or more receiver antennas are combined to enhance the signal strength or signal-to-noise ratio. In UMTS and LTE, also transmit diversity techniques are introduced, where the signal is simultaneously sent from typically two antennas. For receiver diversity, different ways of combining the signals are used: selection combining (SC), maximum-ratio combining (MRC) and equal gain combining (EGC). MRC is the technique with the highest gain. In this case, the signals from the diffent branches are combined with weights proportional to the signal-to-noise ratio of the individual signals. The principle of selection combining is shown in Figure 18. Theoretical gain for the three receiver diversity techniques is shown in Figure 19 [34]. The SC scheme is the simplest to implement, while MRC gives the best performance. EGC is a compromise with less complexity than MRC on the expense of the gain.

The values in Figure 19 assume that the signals from the branches are uncorrelated. This is of course not possible in real systems. To obtain as low correlation as possible different separation techniques must be used. Separation in space is the best known method, but it takes typically up to 10 wavelengths (3 m on 900 MHz) to obtain a sufficiently low correlation. Later, in order to save space, polarization diversity has been introduced. Two antenna branches are separated by having orthogonally polarized antennas, typ-

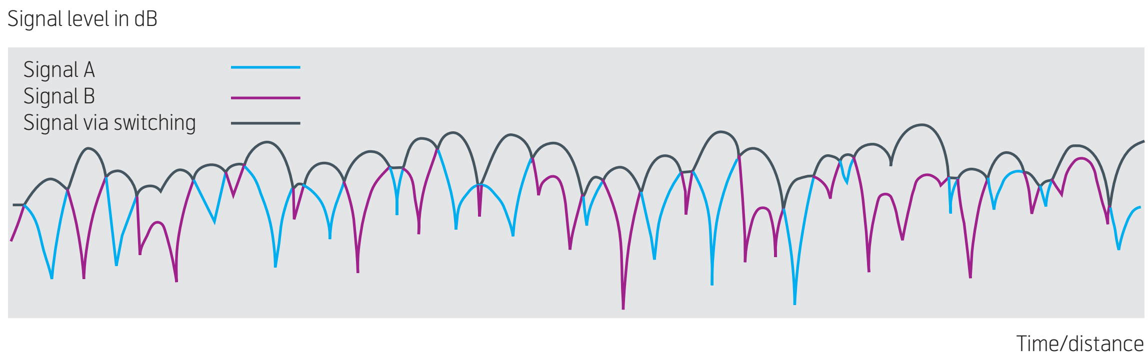


*Figure 18 Principle of receiver diversity using selection combining (SC)*


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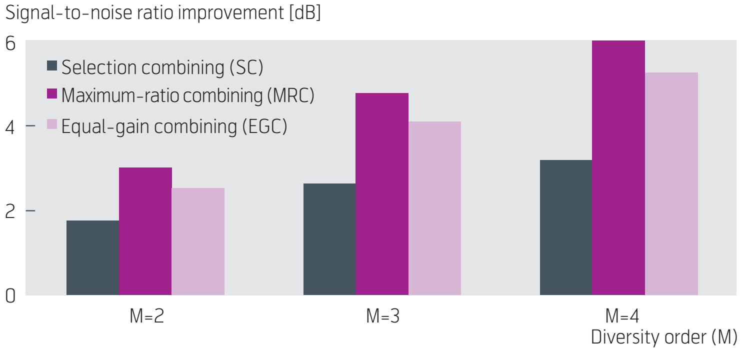


*Figure 19 Theoretical gain for different receiver diversity techniques [34]*

ically +/- 45°. A third separation technique is angular separation by having directive antennas pointing in different directions.

*Multiple input – multiple output* (MIMO) is the most general technique and is based on the possibility of transmitting different signals on different spatial paths in a highly uncorrelated channel. As the name indicates, multiple antenna elements are used both on the transmitter and receiver. One could then imagine that it should be necessary to use a considerable number of antenna elements to spatially separate the different paths between the transmitter and receiver. According to [35] the separation of the signals could be made at the receiver only, where the channel is easily measured, but if available, the transmitter weights could be used in a joint transmit-receive optimisation to maximise the wanted powers. It leads to the normal situation where there is a multitude of rays, and there is no chance with a few elements to put many nulls in the radiation pattern. The key point is that it is not necessary to do so. Physically, as with the adaptive antenna, we can explain the situation as putting the unwanted signal in a deep fade instead of a null in a radiation pattern, and the result is the same. The information must in all cases be spread over the transmit elements, and so-called space-time coding is one common technique used for this.

One of the real breakthroughs came when Foschini [31] and Winters [36] realised that this situation could also be created with closely spaced elements in a scattering environment, where the scatterers would act as angularly widely spread parasitic elements of the array. Thus we have a situation where propagation and antenna aspects are interrelated in a new way.

The gain of MIMO can be realized in basically two ways, either by increasing redundancy, or by increasing link capacity. The first technique is a joint transmitter-receiver diversity technique which can be seen as a generalization of the aforementioned diversity techniques. To realize this, *space-time coding* is most common, where the same symbols are transmitted twice over different antennas. The most common coding scheme is called Alamouti-coding [37], a space-time block code (STBC) using two transmitter antennas. STBC does not increase the link capacity; however, an improved signal-to-noise ratio is achieved resulting in a better link budget. Combined with adaptive coding and modulation schemes, a certain gain also in link capacity can be achieved, especially on cell-edge. However, the most marketed aspect of MIMO is the prospect of high link capacity and spectral efficiency gain. This can be achieved by utilizing the channel spreading with so-called *spatial multiplexing* (SM). Theory predicts that a gain equal to the number of antenna elements in the array with the fewest elements is possible in a perfectly uncorrelated channel. Thus, if we have a 2x3 array, the capacity can be doubled. In practise, such channels do not occur and we also have a problem of obtaining a perfect, instantaneous channel estimate. Real gains have proved to be much less than the theoretical figures. More comprehensive reading on MIMO can be found in previous issues of *Telektronikk* [35] [38].

Multiple antenna techniques are now finding its way into standardized and commercially available technology for mobile broadband, and Table 4 shows how LTE, HSPA, Wi-Fi and WiMAX is able to utilize them.

| | Receive diversity | Transmit diversity | Beamforming | Spatial Multiplexing | Comments |
|---|---|---|---|---|---|
| HSPA | Uplink and downlink | Downlink | Downlink | 2 streams on downlink | Introduced in Release 7, terminals expected in 2010 |
| LTE | Uplink and downlink | Uplink and downlink | Downlink | 4 streams on downlink | More antennas in LTE-Advanced (8x8) |
| Mobile WiMAX | Uplink and downlink | Downlink | Downlink | 2 streams on downlink | Based on IEEE 802.16 |
| Wi-Fi | Uplink and downlink | Uplink and downlink | None | 4 streams on uplink and downlink | Based on IEEE 802.11n |

*Table 4 Implementation of multiple antenna techniques in current standards*


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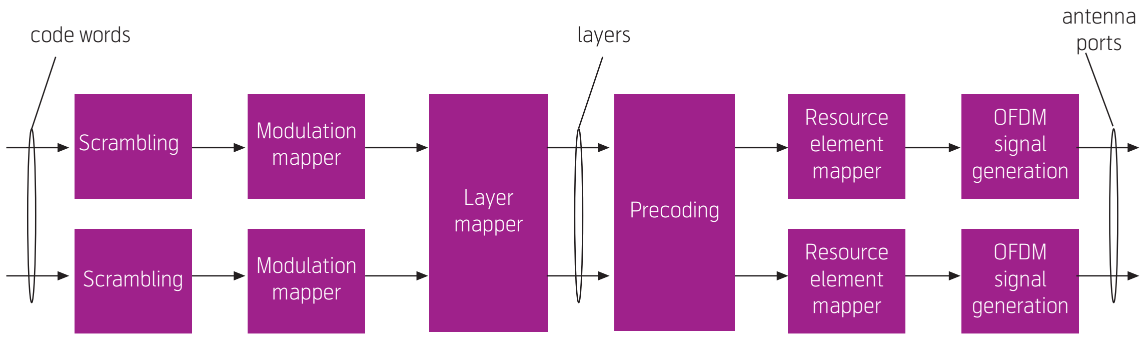


*Figure 20 Downlink physical layer processing in LTE [39]. Two antenna cases are shown*

In LTE all the different multiple antenna techniques have been integrated into one single physical layer architecture as shown in Figure 20 [39]. The combined response of the layer mapper and precoding decides which scheme is used.

On the LTE downlink, three techniques can be used: spatial multiplexing, transmit diversity using space-frequency block coding and beamforming. Up to four antennas can be used on both sides of the link.

### 4.2.5 Cognitive Radio

The term 'Cognitive radio' was first coined by Joseph Mitola III in 1999 [40]. The original definition of the concept comprised features supporting the user communications context, the access network demands and realizing a protocol for real-time spectrum rental. Cognitive radio (CR) can be regarded as one major motivation for the software defined radio (SDR) technology. From the early views on intelligent radios, the collaborative aspects have become more in focus by introducing a cognitive resource management framework [41].

Cognitive radio technology is certainly one of the most exciting new directions in wireless access, and the current focus, at least from an operator's point of view, is the spectrum management possibility it opens. Thus, CR is the latest addition to technologies promising improved spectrum utilization by exploiting so-called 'white spaces'. Telenor currently participates in research on CR through the participation in two European Union founded projects in the 7th framework programme ICT. The two projects SENDORA [42] and QoSMOS [43] are further presented from an operator's point of view by Tardy and Grøndalen in another article in this issue [44].

## 4.3 Performance Evolution

Through the technological development, the performance has evolved significantly since GSM. This is covered more in detail by Bøhagen and Binningsbø in another article in this issue [13].

One of the most important metrics is of course the data rate, and selected peak rates for different generations are shown in Figure 21. It is quite easy to understand, that mobile broadband really came with the introduction of the HSPA extension to UMTS.

A data rate increase has been made possible by a number of methods. One is a more efficient modulation and coding technique, but mostly it has come as a result of increased bandwidth and the use of multiple antenna techniques. Therefore, the real test for performance evolution is found in the spectrum efficiency. In [13] it is shown that the average downlink spectral efficiency has increased from 0.15 b/s/Hz for UMTS Rel-99 to 1.5 b/s/Hz for LTE using 2x2 MIMO, a ten-fold increase.

Another performance metric is the latency. Latency is a measure for the response time of the system and is especially important for real-time services like voice and gaming. A measure for latency is the Round Trip

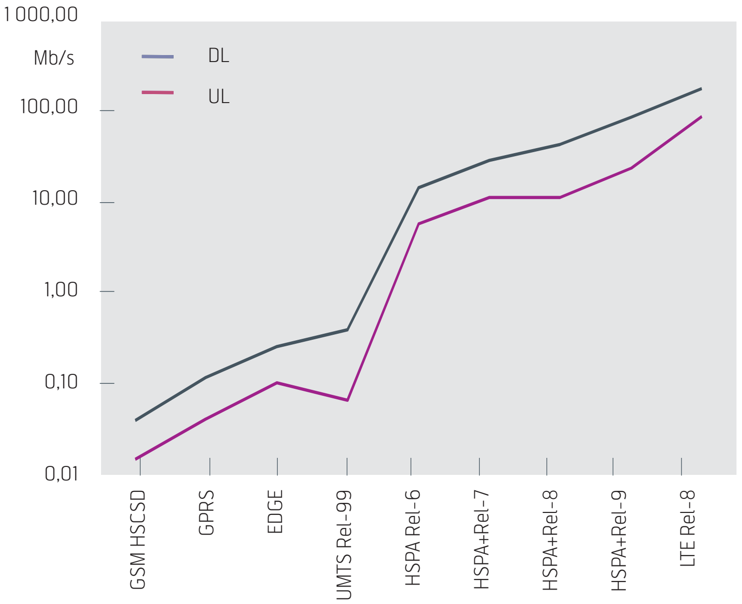


*Figure 21 Data rate evolution for mobile data and mobile broadband. The vertical axis is logarithmic so we can see the (slow) evolution of the pre-broadband data rates*


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Time (RTT) which is the time it takes data to traverse the network and back, ergo the response time. This has decreased from approximately 200 ms for UMTS Rel-99 down to 25 ms for LTE.

## 5 Conclusive Remarks

In this article, we have tried to tell a story about mobile broadband technology, from the roots which were planted in the development of the early wireless data services, via the transition from being voice-centric and circuit-switched to being data-centric and packet-switched. Earlier, data was transferred using voice techniques, now voice is transferred as data. We have tried to explain how different development lines and drivers have converged into what we now see emerging; the all-IP based network providing any services – wired, wireless and mobile.

Seen with an operator's eyes, there are great challenges and opportunities with this transition. The challenges are first and last to keep the costs down. The current trends in business models and price plans make it difficult to charge actual use of the network resources since flat rate subscriptions have become the norm. Thus, it is necessary to make the technology more efficient and 'get more bits for the money'. We have presented new technologies which have been researched over the last 10-15 years and which now are on their way into standards and products such as multiple antennas and cognitive radio. Cognitive radio is not yet mature for the market but gives great opportunities for operators to better utilize the available radio spectrum.

Another challenge is the so-called 'backhaul' transmission. When the base stations in the radio access network in less than ten years shall provide more than ten times the data rate to the users, the bit pipe into the core network becomes the bottleneck. In addition to introducing fibre and high capacity radio links, we probably need a technology leap also here.

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