HSPA and LTE – Future-proof Mobile Broadband Solutions

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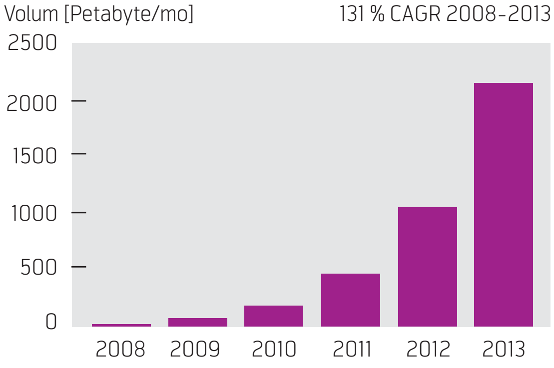
In this paper we take a deep dive into the two major mobile broadband radio standards developed by the 3rd Generation Partnership Project, namely *High Speed Packet Access* (HSPA) and *Long Term Evolution* (LTE). An overview of the two systems is given, and we identify the main differences, ie. the multiple access technique, the architecture and the size of the operation bandwidth. The performance is also investigated, and it is shown that the newer LTE system has an evolutionary performance gain over HSPA. Looking at deployment possibilities, the 2.1 GHz band is the main capacity band for HSPA, while the 900 MHz band will probably be the main coverage band. For LTE, it seems that the corresponding bands will be 2.6 GHz for capacity and the digital dividend (ie. 800 MHz in Europe) for coverage. It should be noted that utilizing the same band for several technologies, as will be the case for 900 MHz in a transition period, introduces some co-existence challenges that must be dealt with.

1 Introduction

The main cellular technology delivering mobile broadband today is *3rd Generation Partnership Project's* (3GPP) HSPA; an enhancement of the 3G technology *Universal Mobile Telecommunications System* (UMTS). Since the first HSPA network was launched in 2006, the number of commercial networks has surpassed 300 worldwide. At the end of 2009 the Global Supplier Association (GSA) reported of 200 million HSPA subscriptions and the number is increasing rapidly [GSA2].

The demand for mobile broadband capacity will increase drastically in the years to come. This is verified by a number of sources, for example Cisco's broadband traffic growth forecast shown in Figure 1. Cisco estimates a *Compound Annual Growth Rate* (CAGR) of 131 per cent in the period 2008-2013, and that the traffic demand in 2013 will be 66 times larger than the demand in 2008.

To address these future needs, 3GPP is now working on further developments of the HSPA standard, often referred to as HSPA+ or HSPA evolution. In addition, the new mobile broadband standard LTE was released by 3GPP in March 2009, based on a new efficient radio protocol and flat all-IP architecture. Both technology paths promise higher capacity, better user experience, and are based on advanced technologies like *Multiple Input Multiple Output* (MIMO) and opportunistic scheduling of users in the time and frequency domain. The first deployments of HSPA+ and LTE were launched in 2009, and many are expected to follow in 2010.



Source: Cisco Visual Networking Index - Forecast, 2008-2013

Figure 1 Global mobile data traffic growth forecast [Cisco09]

The rest of this paper is organized as follows; in Section 2 we give a brief description of the transmission schemes, link adaptation, opportunistic scheduling and multiple antenna techniques, which are all vital ingredients to reach the high capacities required by new mobile broadband systems. We continue by describing the HSPA and LTE systems more in detail in Section 3. In Section 4 the performance of the two systems is investigated, both with respect to capacity and user experience. Section 5 discusses drivers for mobile broadband technology transition and deployment characteristics. The special case of refarming of the 900 MHz band for HSPA is treated in detail. We conclude the paper in Section 6.

2 Advanced Dynamic Radio Schemes

For mobile broadband systems to be able to reach the high requirements to efficiency and capacity, the wireless transmission between the base station and the user terminal must be designed in an optimal manner. Several advanced techniques have been added to the toolbox the last decades. Below we will discuss three techniques focusing on exploiting the time variation and the spatial dimension of the wireless channel. It should be noted that this is not meant as a comprehensive presentation but serves as a characterization of some important development trends within wireless communication before we investigate more in detail the technology choices made for HSPA and LTE.

2.1 Link Adaptation

When a signal travels through a wireless channel it is exposed to attenuation, resulting in a decrease in signal power as the covered distance increases. This phenomenon is often referred to as path loss. In addition, due to objects in the transmission environment, the signal will be subject to reflections, diffraction, and scattering. Consequently, when the signal reaches its final destination the signal level may vary quite a lot, even if the transmitter and receiver are fixed. The rate of these variations may be quite high, depending on the velocity of the transmitter, receiver, and objects in the transmission environment.

For a wireless system to operate efficiently under such conditions it is important that the transmission scheme utilized on the link between the terminal and the base station can adapt to changing channel conditions [Goldsmith98]. A prerequisite for this adaption to take place is that the transmitter is informed by the receiver what channel it is experiencing, ie. channel feedback. Consequently, the channel quality is monitored through estimation and/or prediction at the receiver, and made known to the transmitter through a feedback loop. The content of this feedback information depends on the transmission schemes available. The feedback mechanism should be designed with care to avoid taking up disproportionately large amounts of resources.

Two components present in a transmission scheme are coding and modulation. Coding introduces redundancy in the signal, and is used to make the information more robust against errors introduced over the wireless channel. Modulation is the process of mapping information to symbols that are suited for transmission over the wireless channel. The more information we map to each symbol, the more information we can transmit per time unit. On the other hand, if we map more information per symbol the detection becomes more vulnerable to errors. To summarize, a high degree of coding redundancy and low order modulation gives robustness, while little redundancy and high order modulation gives high throughput. In Figure 2 the normalized throughput, ie. throughput normalized with frequency, is plotted as a function of *signal to noise ratio* (SNR) for a typical system with link adaptation. SNR is an important parameter characterizing the channel quality, and it is defined as the received power in the wanted signal divided by the total unwanted power, ie. interference and noise.

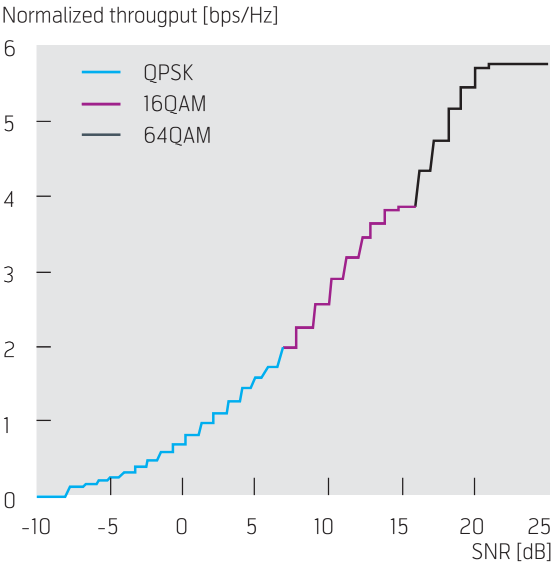


Figure 2 Normalized throughput as a function of SNR [R1-071956]

The figure clearly illustrates how the throughput increases as the channel quality becomes better. We also observe how the increase is done in a step-wise manner, where each step corresponds to a transmission scheme (coding and modulation combination). Furthermore, the low order modulation (QPSK) is utilized when robustness is required, while the modulation order is increasing when the channel quality becomes better (16QAM and further to 64QAM). An example of output from a drive test, ie. received SNR and throughput, is shown in Figure 3.

The figure clearly shows how the channel conditions, ie. SNR, are changing with time, and how the throughput is adapted to these changes.

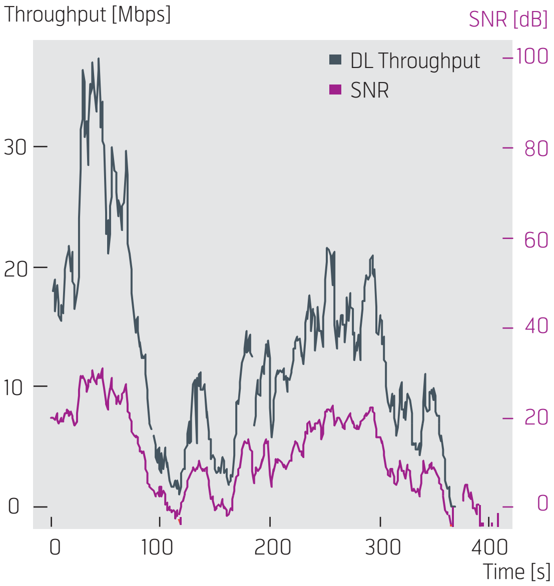


Figure 3 Example output from an LTE drive test; SNR and throughput as a function of time

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2.2 Opportunistic Scheduling

The scheduler is an entity in the base station responsible for distributing the shared system resources between the different users. Depending on the multiple access scheme utilized, resources can be time slots, frequency slots, channelization codes or a combination. The traditional way of doing scheduling is in a round robin manner, which assigns resources to each user in equal portions and in circular order, without any priority.

As discussed in the previous section, the potential throughput on a wireless link between a user and the base station will vary due to the dynamic nature of the wireless channel. In a cellular network with more than one user, it is beneficial, from a system perspective, to give the users priority when they have favourable radio conditions. This is referred to as *opportunistic scheduling* [Hassel07]. The principle is illustrated in Figure 4, where input on the users' channel condition is used to distribute the resources.

By giving priority to the users that have the best channel conditions, the system efficiency can be increased. At the same time, it is usually desirable to provide users who experience less favourable channel conditions over a longer timeframe, eg. cell edge users, with a basic service level. Consequently, a pure 'best channel condition' based scheme is not feasible, and some kind of fairness is needed. The most common opportunistic scheduling scheme today is based on a proportional fair principle, where each user is assigned a scheduling priority that is inversely proportional to its historical data rate. This implies that if a user has been using resources and experienced a high data rate lately, the user may be given lower priority for the next resource allocation, even if he experiences better channel conditions than the one awarded the resources. Such a scheduling scheme offers a trade-off between system efficiency and fairness.

2.3 Multiple Antenna Techniques

Multiple antennas at the transmitter and the receiver can be exploited to increase the wireless system performance. The collective term often used for such schemes is *multiple-input multiple-output* (MIMO) technology [Paulraj03].

The MIMO technique referred to as spatial multiplexing has been given a lot of attention in the research community over the last decade, and now we also see it standardized and implemented in all the major wireless standards. Under ideal conditions, it promises a linear increase in throughput with increasing number of antennas. For example, if we have two antennas at the transmitter and the receiver, the throughput may be doubled compared to a traditional system with one antenna at transmitter and receiver. This can be achieved without increasing the required bandwidth, ie. the spectral efficiency is increased. It should be noted that this gain is heavily dependent on the channel condition, and the linear increase requires optimal conditions. More realistic gains can be found in Section 4.

In addition to spatial multiplexing, other more mature techniques as antenna diversity and beamforming are also playing an important role in the new mobile broadband systems. The multi antenna techniques available can be summarized as follows:

- *Receiver diversity* is used to improve the quality of the received signal by combining different versions of the signal from separate antenna elements. Requires several receive antennas.

- *Transmit diversity* is used to improve the quality of the received signal. The difference from receive diversity is that the combining is performed at the transmitter and not the receiver. Requires several transmit antennas.

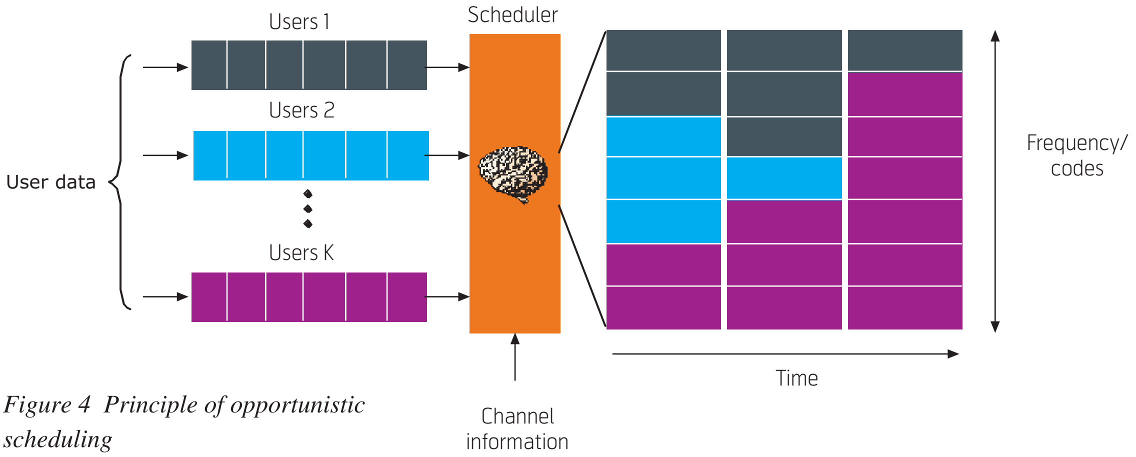

Figure 4 Principle of opportunistic scheduling

- *Beamforming* is used to improve link quality by 'focusing' the power of the transmitted signal towards the user. This may also reduce system interference. Requires several transmit antennas.

- *Spatial multiplexing* improves the data rate of a single user by simultaneously sending different data streams from different antennas destined for the same user. In 3GPP this is often referred to as *Single user* MIMO (SU-MIMO). Requires several transmit and receive antennas.

- *Spatial Division Multiple Access* (SDMA) increases capacity by sending or receiving different data streams to or from different users at the same time. In 3GPP this is often referred to as *Multi User MIMO* (MU-MIMO). Requires several antennas at the base station; however individual users may have one antenna. An example with two users is shown in Figure 5.

A practical system will typically have more than one of the schemes above implemented. The transmission can then change between the schemes depending on the channel conditions and user needs.

3 Radio Access Networks

In this section we will study in more detail the radio aspects of the mobile broadband technologies standardised by 3GPP. We will treat some selected topics; for a more thorough presentation the interested reader is encouraged to pursue books like [Holma09], [Dahlmann08], [Sesia09]. We will divide our analysis between the *air interface*, meaning the wireless link between the terminal and the base station, and the *radio access network* (RAN), meaning the base station and associated interfaces and components that sit between the terminal and the core network. The core network itself is treated elsewhere in this issue of *Telektronikk* [Kjuus10].

The 3GPP consist of groups of telecommunications associations originally formed to make a globally applicable third generation mobile phone system specification within the scope of the IMT-2000 project of the ITU. After the establishment in December

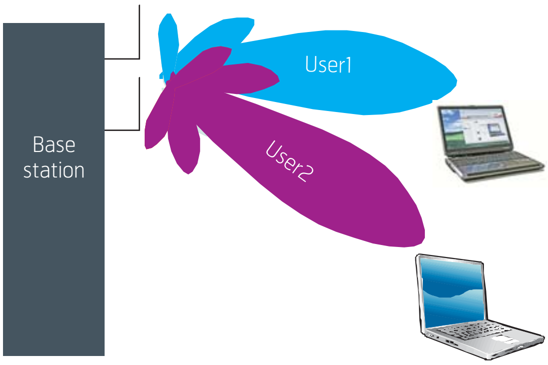

Figure 5 Example of MU-MIMO transmission with two users

1998, the scope has been amended to include GSM, and lately 3GPP has submitted LTE-Advanced as a 'true' 4G candidate technology complying with the IMT-Advanced project in ITU.

The 3GPP standards are structured into *releases* with each release offering new features and improvements over previous releases. Releases are synchronized between GSM, UMTS and LTE. The initial release of 3G UMTS was called Release 99, issued in the year 2000. The next release followed in 2001 and was called Release 4. From then onwards, release numbering is successively increasing. At the time of writing (January 2010), 3GPP has just finalized the Release 9 in December 2009 and is currently working on Release 10. Figure 6 shows the release cycle with the main radio features introduced by each release. Note that the first version of LTE was part of Release 8. The features will be detailed in subsequent sections.

3.1 High Speed Packet Access (HSPA)

HSPA is an addition to the 3G/UMTS technology providing efficient delivery of mobile broadband services. To offer an attractive user experience a mobile broadband technology should deliver high bitrates with low latency. Although the initial release of the 3G/UMTS technology was marketed as a mobile broadband technology, its efficiency and user experience were not matching users' expectations. Thus, it is first with the introduction of HSPA that we can say the 3G is now a true mobile broadband technology.

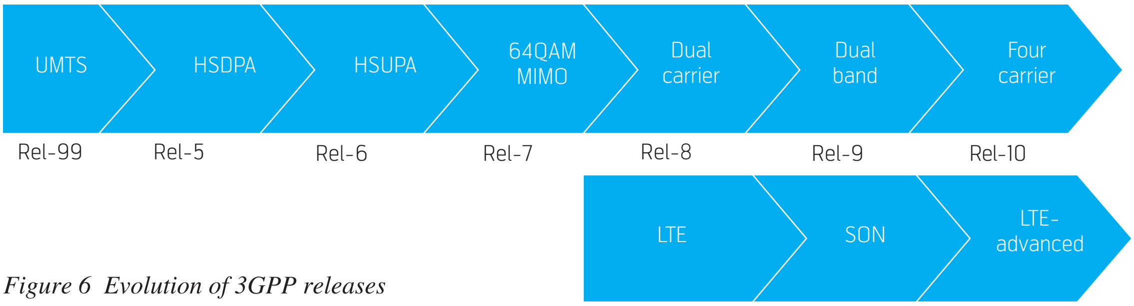

Figure 6 Evolution of 3GPP releases

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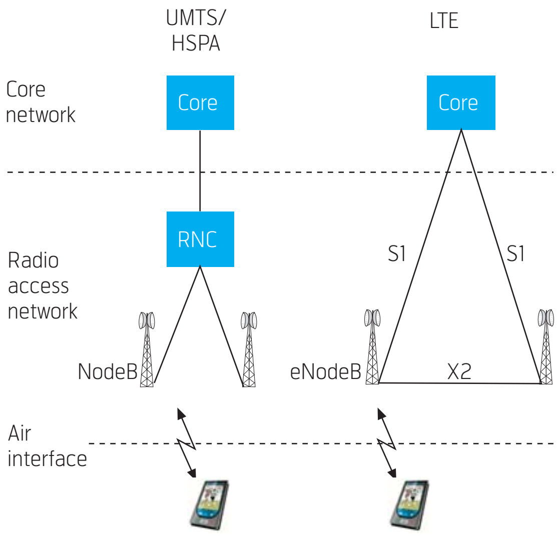

Figure 7 Comparing the architecture for UMTS/HSPA (left) and LTE (right)

HSPA consists of several parts which have been gradually introduced into the 3GPP standard, each new version improves the peak throughput and system capacity. *High Speed Download Packet Access* (HSDPA) was introduced in 3GPP Release 5, while the uplink counterpart HSUPA was added in 3GPP Release 6. The HSPA system is further improved in subsequent releases with what is commonly referred to as HSPA+, or HSPA evolution, a collective term for individual features like 64QAM modulation, MIMO support and numerous protocol enhancements.

3.1.1 Architecture

To support the improved user experience, some architecture changes to the UMTS system were required. To offer lower latency and better adaptation to a continuously rapid changing radio environment, most of the functionality of the *Radio Network Controller* (RNC) is collapsed into the NodeB. In regular UMTS, the RNC is responsible for Mobility Management control (handover) and Radio Resource Management functions like admission control and packet scheduling. Packets that are wrongly received over the wireless channel must be retransmitted, and the delay in sending such retransmissions all the way from the terminal to the RNC was considered too high. By letting the NodeB handle retransmissions, the radio packet length could be reduced to 2 ms, from up to 80 ms in 3G. Thus the latency is significantly reduced, and in addition the NodeB can react more quickly to rapid variations in the channel quality. The UMTS/HSPA architecture is shown in Figure 7 (left).

3.1.2 Air Interface

This section will describe the air interface of HSPA, and study some selected features in more detail.

The UMTS and HSPA air interface is based on *Wideband Code Division Multiple Access* (WCDMA), which is a variant of so-called ‘spread spectrum’ technology. WCDMA is used both for uplink and downlink transmission. Each user signal to be transmitted is scrambled with a user-specific channelization code, spreading the signal out to occupy the whole 5 MHz bandwidth available. This spreading makes the signal robust against narrowband interference and frequency selectivity in the channel. The channelization codes are based on *orthogonal variable spreading factor* (OVSF), forming a hierarchical ‘code tree’ where the level in the tree

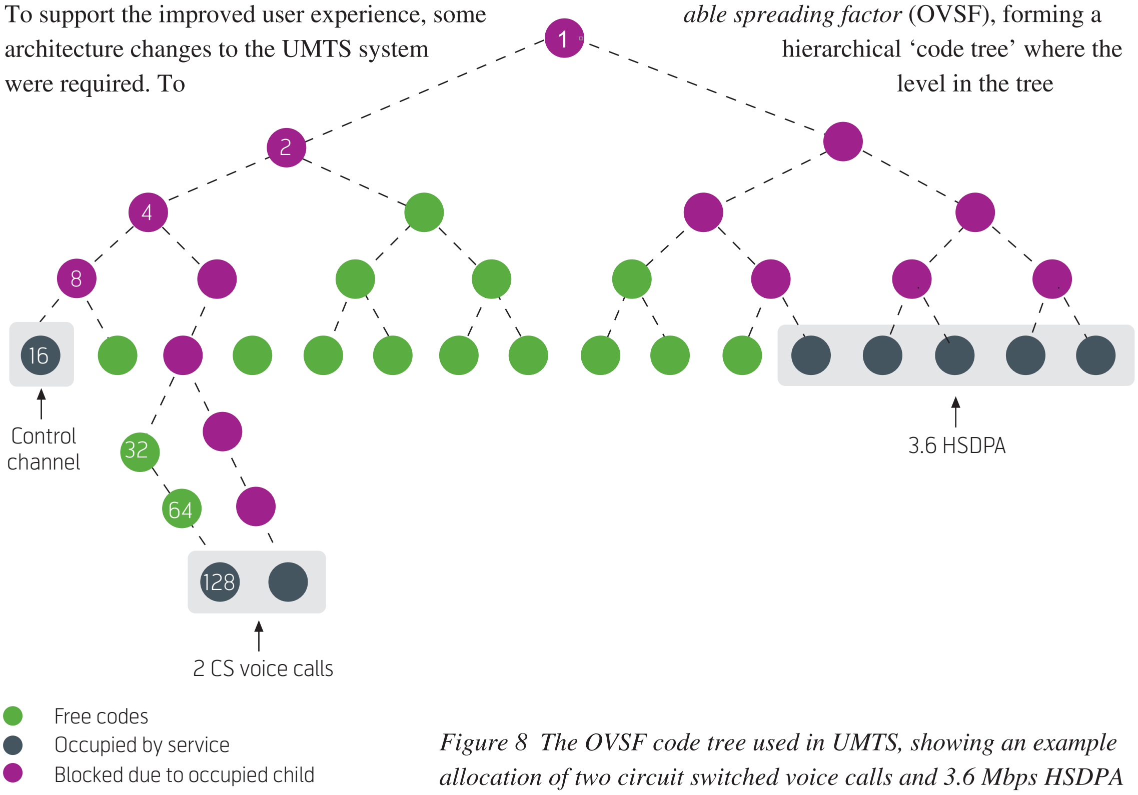

Figure 8 The OVSF code tree used in UMTS, showing an example allocation of two circuit switched voice calls and 3.6 Mbps HSDPA

depends on the spreading factor of the code. A service will be assigned a code, and the level in the code tree will be dependent on the bit rate required by the service. An occupied code effectively blocks all parent and child nodes in the code tree. An example is given in Figure 8.

The channelization codes are orthogonal to each other in the downlink, however in real environments some orthogonality will be lost, leading to self-interference in the cell.

In HSDPA there are 15 channelization codes with spreading factor 16 available for use. Each HSDPA channel occupies one code, and one user might be allocated between one and 15 codes. If five codes are assigned, the well-known theoretical peak throughput of 3.6 Mbps can be achieved. Ten codes will give a throughput of 7.2 Mbps, whereas if all 15 codes are assigned, a theoretical peak throughput of 14.4 Mbps can be reached, assuming 16QAM modulation. Today's networks have mainly deployed 7.2 Mbps HSDPA.

It is worth noting that *circuit switched* (CS) voice calls also use of the same channelization codes, so available capacity must be shared. Normally, CS voice has precedence over mobile broadband traffic.

Hybrid-ARQ

Hybrid Automatic Repeat Request (H-ARQ) is used together with *adaptive modulation and coding* (AMC) to respond quickly to changes in the radio environment. Radio packets are sent over the radio interface every 2 ms. To avoid stopping the transmission stream while waiting for decoding, detection and the retransmission of a wrongly decoded packet, several (up to eight) transmit and receive processes run in parallel, see [Dahlmann08]. Each radio packet can have different modulation and amount of protective coding. The channel quality is estimated by the terminal and reported to the NodeB to aid the NodeB in selecting the optimum coding and modulation.

Higher Order Modulation

Release-5 HSDPA introduced 16QAM (Quadrature Amplitude Modulation) as a downlink modulation scheme in addition to *Quadrature Phase Shift Keying* (QPSK) utilized in regular UMTS. The capabilities were further increased with HSPA+ in Release-7, when 64QAM was added for the downlink, providing a theoretical peak throughput of 21 Mbps for a 5 MHz carrier. It should be noted that a good radio environment (high SNR) is needed to be able to utilize such high modulation schemes. Thus, the highest bitrates can normally be expected to be reached only relatively close to base station.

For the uplink, the highest possible modulation scheme is 16QAM.

MIMO

Multiple input multiple output techniques as described in Section 2.3 can also be used in HSPA. Introducing MIMO into HSPA was not straightforward and a total of 11 different technical solutions were suggested in the several year-long standardization phase. In the end, 3GPP decided to select a solution based on 'Dual-codeword MIMO based on Dual-Stream TxAA' [TR 25.876], introducing spatial multiplexing to HSDPA from 3GPP Release 7. It should be noted that multiple antenna technology was part of UMTS from the initial Release 99, namely the option for the base station to use a transmit diversity technique called *Space Time Transmit Diversity* (STTD), but this technology was not widely deployed in 3G networks.

In Release 8 it further becomes possible to use 64QAM modulation together with MIMO.

Dual Carrier

An UMTS user is constrained by the 5 MHz carrier bandwidth, even if the operator has deployed multiple carriers in order to increase capacity. However, to increase HSPA peak user throughput further, the concept of 'dual carrier' was introduced into HSPA from Release 8. Using 'dual carrier', a single user can receive data from two carriers simultaneously, leading to a doubling of the theoretical peak throughput. The system capacity is also increased, as the NodeB can now utilize opportunistic scheduling over the two 5 MHz blocks. The principle is illustrated in Figure 8.

Most of the above mentioned features can be combined, and the system gain is more or less equal to the sum of individual gain for each feature.

As part of the HSPA improvements, several optimizations have also been done to the radio protocols to improve the user experience and increase battery life.

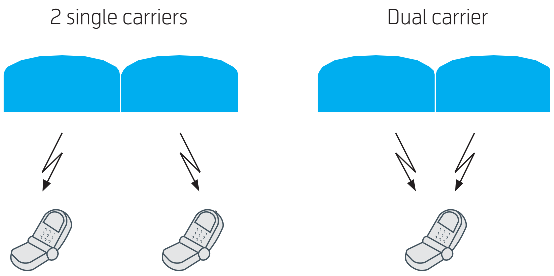

Figure 9 Dual carrier doubles the single user peak throughput

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3.1.3 Radio Bearers

The user traffic is carried over the air interface using radio bearers, occupying one or several channelization codes.

HSPA only offers *packet switched* (PS) data services. PS data was already part of the regular Release 99 UMTS standard, however this was based on dedicated bearers, meaning that one user is assigned a dedicated channelization code corresponding to for example 64, 128 or 384 kbps. The NodeB could upgrade or downgrade the bearer based on variations in usage. With HSPA, there is a conceptual change as all HSPA users share the same physical bearer, and individual resource assignment is based on opportunistic scheduling as presented in Section 2. This leads to a much more efficient usage of the air interface resources.

Voice traffic can be carried in three ways over a 3G network. The first alternative is to use regular CS voice, where each user is assigned a dedicated radio resource for the duration of the call. But as HSPA brings along a more efficient air interface, it is possible to increase the voice capacity per cell by using the shared HSPA bearer instead of dedicated bearers. Two alternatives are then possible; the first is to use the functionality called *CS over HSPA*, in which a regular CS voice packet is encapsulated into a container IP packet and transported using the HSPA bearer between the terminal and the RNC. In the RNC the container is discarded and the CS packet is routed towards the CS core network as a regular CS voice call. The other alternative is to use pure *voice over IP* (VoIP) transported over HSPA. The solution standardized by 3GPP uses the *IP Multimedia Subsystem* (IMS) as call control, although other call control solutions also exist.

Common to the HSPA based alternatives is that to ensure a high voice quality even if congestion occurs, *Quality of Service* (QoS) mechanisms should be employed, so that the NodeB for example can prioritize a low-bitrate voice user over an FTP download from another user.

3.1.4 Integrated Mobile Broadcasting

It is also possible to deliver broadcast services (eg. mobile TV) using UMTS networks. In 3GPP Release 8 the *Integrated Mobile Broadcast* (IMB) service has been standardised. This is a broadcasting technology bearing many commonalities with the HSPA air interface, for smooth integration into the mobile networks and terminals. To offer a high capacity in terms of number of TV channels, a broadcasting concept called *Single Frequency Network* (SFN) has been adopted. In an SFN all cells transmit the same signals simultaneously. For the receiving terminal, this means that signals coming from neighbour cells are not seen as interference as in cellular systems, but can instead be effectively and constructively combined in the Rake receiver, thus increasing coverage range and capacity.

IMB is designed to operate in the frequency bands designated for UMTS *Time Division Duplex* (TDD) operation (1900-1920 MHz and 2010-2025 MHz). In Europe, these bands are already awarded to mobile operators, but currently unused as only the *Frequency Division Duplex* (FDD) based technology has been deployed. Thus, introducing IMB into the TDD band does not take away spectrum resources which could otherwise be used for Mobile Broadband.

However, investments are needed as the IMB network must be built as an overlay network over the legacy 3G/HSPA network. Also, the terminal complexity increases as dual radio units are needed, one for IMB and one for voice/data.

3.1.5 Further Evolution of HSPA

Even with the introduction of LTE in 3GPP Release 8, there is still significant standardisation effort going into further improvement of HSPA.

The RAN aspects of 3GPP Release 9 were finalized in December 2009. This release brings along several improvements to the dual-carrier functionality. Dual-carrier can now also be used for uplink traffic, and for the downlink it is possible to have dual carrier between carriers on different frequency bands. It is now also possible to use dual-carrier in conjunction with MIMO operation.

Femtocells (or Home NodeB as they are called by 3GPP) are small base stations designed to be placed inside homes for increased indoor coverage and capacity. Until recently, only proprietary solutions existed, but from Release 9 support for femtocells is added. The standard support ensures that handover between the macro network and the femtocell is possible in both directions, and there are also added mechanisms for interference control between macro and femto, as a very dense femto deployment can lead to severe interference problems.

In Release 10 the dual-carrier concept is planned to be extended to four carriers. This would let a HSPA terminal use a bandwidth of 20 MHz, similar as for LTE. Additionally, 3GPP will study how suitable the HSPA and LTE systems are for mass deployments of machine-to-machine communication devices. Currently there is much focus in the industry on the climate footprint of telecommunication equipment

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and operations, and therefore 3GPP will during the Release 10 timeframe study possible improvements in the standards that can lead to energy savings.

3.2 Long Term Evolution (LTE)

LTE has been developed to support the ever increasing demand for mobile broadband traffic. Although termed as an evolution to the 3G/HSPA standard, from a design point of view LTE is in fact more of a revolution; both the radio interface is completely new and the RAN is significantly simplified. LTE is a PS only network, and the core service offered to the end user is mobile broadband IP access.

3.2.1 Architecture

The architecture of LTE is further simplified compared to HSPA.

The most notable change is that the RNC is completely gone (cf. Figure 7). This is motivated both by a desire to reduce latency and complexity, but also the fact that the CS domain is no longer present. The RAN thus simply consists of one element; namely the base station, or *evolved NodeB* (eNodeB). Between eNodeBs that are located close to each other there will normally exist an interface called X2. Between the eNodeBs and the core network there is a single interface called S1. Both these interfaces are based on IP, and thus the LTE architecture is often referred to as a ‘flat, all-IP architecture’. See Figure 7 for an overview of the LTE RAN architecture.

This architecture also implies that most of the Radio Resource Management functions previously being managed by the RNC, now in fact are distributed between the eNodeBs. The process of handover can be used as an example. When a user moves from one eNodeB to another, the two eNodeBs use the X2 interface to agree among themselves when to execute the handover. The core network is then merely informed after a successful handover has taken place, and must then quickly re-route the user traffic towards the new eNodeB. Any buffered user data in the source eNodeB may be forwarded to the new eNodeB. Similar mechanisms apply for load balancing and interference control between eNodeBs.

3.2.2 Air Interface

In the LTE air interface there is a difference between the downlink and the uplink transmission direction. In the downlink it is based on *orthogonal frequency division multiple access* (OFDMA). Transmitted data are distributed over a number of closely spaced subcarriers, orthogonal to each other in the frequency domain. To provide multiple access among several users, subsets, possibly non-adjacent, of the OFDM symbols are assigned to different users, as illustrated in Figure 10. The smallest possible resource to assign is called a Resource Block, occupying 180 kHz in the frequency domain and 1 ms in the time domain. Individual Resource Blocks, including those belonging to the same user, may have different coding and modulation. This gives LTE the possibility of using frequency selective link adaptation, optimizing the coding and modulation based on the frequency response of the wireless channel.

A different modulation technique is used in the uplink than in the downlink, namely *Single Carrier Frequency Division Multiple Access* (SC-FDMA). Compared to OFDMA, the SC-FDMA signal has a continuous profile in the frequency domain. The reason for selecting a different modulation in the uplink is that SC-FDMA signals have a lower *Peak to Average power Ratio* (PAPR) than OFDMA, and this opens up for more cost-effective amplifier design in the terminals. However, SC-FDMA and OFDMA signal processing have many similarities, so the properties of each signal are harmonized as much as possible.

Scalable Bandwidth

A key property of LTE is the concept of flexible bandwidth. This benefit is more or less inherent from using OFDM, as the system bandwidth can be changed by increasing or reducing the number of subcarriers. Six different bandwidths ranging from 1.4 to 20 MHz are defined, as shown in Table 1. The capacity of the system is also scaled accordingly. This means that the LTE air interface adapts easily to different spectrum allocations in different frequency bands. Further, it also eases the process of refarming, when LTE is gradually introduced into the same frequency band as an existing technology like GSM or UMTS.

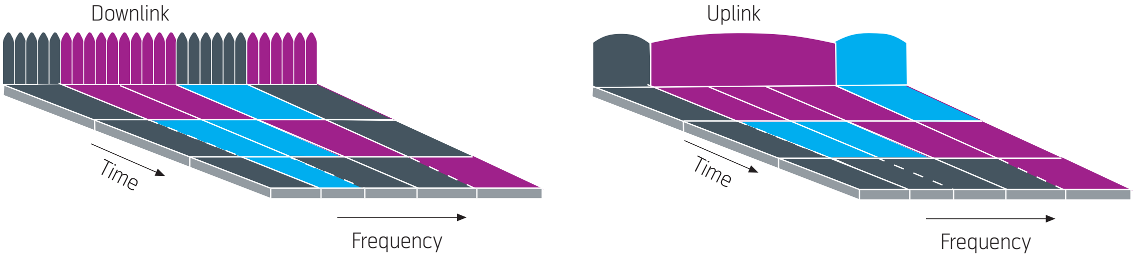

Figure 10 The LTE air interface; using OFDMA in the downlink and SC-FDMA in the uplink

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Bandwidth [MHz]	1.4	3	5	10	15	20
Number of RBs	6	15	25	50	75	100

Table 1 Different LTE bandwidths [TS 36.300]

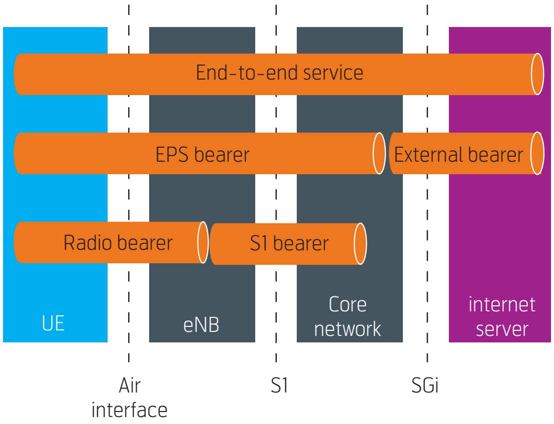

Figure 11 The LTE bearer model [TS 24.401]

MIMO

MIMO is used extensively in LTE, but different from HSPA, MIMO is part of the standard from the first release. This implies that all terminals are aware of the concept of MIMO, even though not all terminals are required to support spatial multiplexing. Compared to HSPA, LTE offers a wider portfolio of multi-antenna techniques, including multi-user MIMO and beamforming. For spatial multiplexing, both open-loop and closed-loop mode of operation is possible. In open-loop mode, the eNodeB lacks detailed channel-state information and a robust transmission scheme is chosen. Closed-loop MIMO utilizes the channel-state information from the terminal to optimize the transmission mode. In general, it can be said that closed loop MIMO has better performance than open loop MIMO in low-speed environments but has worse performance than open loop MIMO in high-speed environments [3GA_MIMO].

Another difference between HSPA and LTE is that the current version of LTE may have up to four antennas at both the receiver and transmitter.

3.2.3 Radio Bearers

The design of LTE radio channels and bearers draws upon the advantages experienced from HSPA, namely using a shared channel combined with opportunistic scheduling. Apart from some channels needed for control signalling, the LTE air interface consists of simply one shared channel for PS data. All dedicated channels for voice and data present in 3G have been removed.

Each user may transmit data over one or several radio bearers (cf. Figure 11) over the air interface. Each radio bearer must have different *Quality of Service* (QoS) profiles, specifying requirements for throughput, delay, packet loss and priority relative to other users, however different sessions from the same user may share a radio bearer if their QoS requirements are identical. There are nine QoS profiles specified for LTE, as can be seen in Table 2. Each profile is identified by the *QoS Class Indicator* (CQI). Four of these profiles have a requirement that the system should ensure a Guaranteed Bit Rate (GBR). It is the responsibility of the scheduler in the eNodeB to assign resources among users so that all QoS requirements are satisfied (cf. Section 2.2). If the QoS requirement for a user cannot be fulfilled, the eNodeB can try to hand the user over to another cell which might have enough resources available. Otherwise the bearer must be dropped.

The QoS profiles apply to bearers inside LTE only, and thus the end-to-end performance of services located on the public internet cannot be guaranteed unless the mobile operator and the 3rd party service provider has made legal agreements and taken technical measures to ensure sufficient end-to-end performance. For services located inside the operator's own network, QoS can be guaranteed provided proper network design and dimensioning.

Without a CS domain at all, it becomes clear that voice traffic must be handled as VoIP. The 3GPP standards proclaim the use of IMS as call control for VoIP. As LTE coverage might be limited during the first years of LTE deployment, a smooth interworking with the legacy 2G and 3G network is important to avoid frequently dropped calls due to the user moving out of LTE coverage. Therefore, a mechanism has been standardized for one-way handover of a VoIP call in LTE to a CS call in 2G/3G. This functionality is called *Single-Radio Voice Call Continuity* (SR-VCC).

However, as all networks may not have deployed IMS at the launch of LTE, another mechanism called *CS Fallback* [TS 23.272] has also been standardized. Here the terminal requesting or receiving a voice call is immediately handed over to 2G or 3G prior to the call setup, so that the call control and the voice call itself is handled solely by the CS domain. This solution is viewed as an interim solution until IMS deployment becomes widespread.

3.2.4 Broadcasting in LTE

In 3GPP Release 9, LTE was extended with broadcasting functionality, termed *evolved Multimedia Broadcast Multicast Service* (eMBMS). Unlike the 3G broadcast technology IMB, which is an overlay

QCI	Resource Type	Priority	Packet Delay Budget	Packet Error Loss Rate	Example Services
1	GBR	2	100 ms	10^{-2}	Conversational Voice
2		4	150 ms	10^{-3}	Conversational Video (Live Streaming)
3		3	50 ms	10^{-3}	Real Time Gaming
4		5	300 ms	10^{-6}	Non-Conversational Video (Buffered Streaming)
5	Non-GBR	1	100 ms	10^{-6}	IMS Signalling
6		6	300 ms	10^{-6}	Video (Buffered Streaming) TCP-based (eg. www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		7	100 ms	10^{-3}	Voice, Video (Live Streaming) Interactive Gaming
8		8	300 ms	10^{-6}	Video (Buffered Streaming) TCP-based (eg. www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
9		9			

Table 2 The Quality of Service (QoS) profiles in LTE [TS 23.203]

network using dedicated hardware, eMBMS uses the regular LTE shared channel described above. Consequently, eMBMS may be deployed without adding new hardware in the RAN.

As pointed out in Section 3.1.4 on IMB, to gain wide coverage and high capacity, broadcast networks use the SFN concept, whereby all base stations transmit the same signal at the same time to eliminate intercell interference. Each broadcast packet contains scheduling information with the exact timestamp that the packet is to be transmitted over the air interface, which resource blocks to use, and which modulation and coding to apply. Thus, SFN operation is achieved for just those resource blocks while the other resource blocks carry user specific traffic. An eMBMS-capable LTE network then effectively switches between being a cellular network and a broadcast network.

3.2.5 Self Organizing Networks (SON)

One of the design targets for LTE coming from the operator community, was to standardize functions that lead to lower cost of operating the network. A lot of effort currently goes into the configuration and optimization of existing 2G and 3G networks. Operators face the challenge of even more increased complexity when several radio access technologies must be maintained in parallel. To improve that situation, several concepts for *self organising networks* (SON) were derived. The SON concepts aim to relieve the operator of several tasks that have to be performed manually today, but also to let the network dynamically adjust its operating parameters in order to achieve optimum performance.

SON can be divided into *self configuration* and *self optimization*. A self-configuration process is defined as the process where a newly deployed eNodeB is configured by an automatic installation procedure to get the necessary basic configuration for system operation. Self-optimization processes are processes in which operating parameters are continuously autotuned in order to maximize system performance.

It should be noted that 3GPP does not standardize implementation details regarding SON functions, but only necessary terminal measurements and X2 interface behaviour that are deemed necessary to fulfil a certain use case. Examples of use cases are:

- Neighbour cell list optimization
- Interference coordination
- Coverage and capacity optimization
- Mobility robustness optimization

In the following we will briefly describe two selected use cases.

Inter-Cell Interference Coordination (ICIC)

We forsee that LTE will be a 1:1 reuse network, meaning that all cells use the same frequency. Thus in the overlap area where the signal strength from neighbouring cells is more or less equal, there is a high risk of interference. To counter such interference, a SON functionality called *Inter Cell Interfer-*

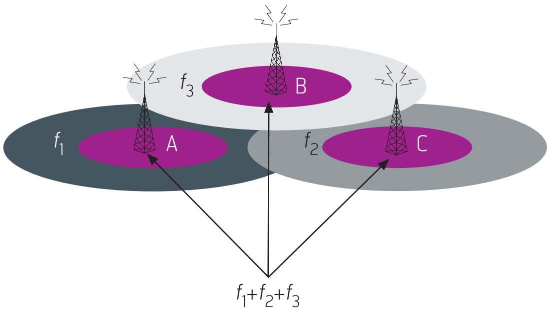

Figure 12 ICIC using Fractional Frequency Reuse

ence Coordination (ICIC) has been devised. ICIC is vaguely specified in the 3GPP standards as “the task to manage radio resources (notably the radio resource blocks) such that inter-cell interference is kept under control” [TS 36.300].

As 3GPP does not specify implementation details, ICIC solutions can differ between different vendors. A commonly referenced implementation is based on fractional frequency reuse, for which a static example is given in Figure 12; here the three cells *A*, *B* and *C* are allowed to use the full available bandwidth ($f_1 + f_2 + f_3$). But this is only allowed in the area close to their cell centre where there is no coverage overlap from neighbouring cells. Then in the outer part of the cell only one third of the bandwidth is allowed to be used (*A* can use f_1, *B* can use f_2 and *C* can use f_3). Thus the frequency reuse factor differs between the cell centre and the cell edge. With SON, this static case is extended to be dynamic; a cell experiencing severe interference may send a *High Interference Indicator* (HII) message to the interfering eNodeB, indicating which resource blocks that should be avoided.

Mobility Robustness Optimization (MRO)

The MRO functionality aims to optimize the parameters used for handover decisions. The functionality shall detect events like:

- *Too late handover;* typically identified by a call drop before the terminal is successfully re-established in the new cell.
- *Too early handover;* typically identified by a call drop immediately after the terminal is successfully re-established in the new cell.
- *Handover to wrong cell;* a scenario similar to a too early handover, but where the terminal ends up camping on a third cell after the call drop.

To better support the MRO use cases, an X2-based framework for the negotiation of handover parameters has been standardised. The operator can set an allowable range for the handover parameters, and then the eNodeBs are free to optimize their settings within this range. Such a range restriction may counter the risk that an optimizing system which is purely distributed starts to oscillate.

3.2.6 Evolution of LTE

LTE was introduced into the 3GPP specifications from Release 8. The subsequent Release 9 was specified during 2009 and can be thought of as a maintenance release. Apart from eMBMS and more SON functions, there is no major new functionality for the radio access part.

However, 3GPP is currently working on Release 10, and this release will bring along many large improvement steps for LTE. The motivation for introducing these changes is for LTE to be compliant with the ITU requirements for IMT-Advanced [ITU-R M.2134], supporting peak throughput of 1 Gbps for the downlink and 500 Mbps for the uplink. Consequently, LTE Release 10 will be termed LTE-Advanced. The following building blocks are introduced in order to reach the ITU requirements:

- Support of wider bandwidth
- Coordinated Multipoint transmission (CoMP)
- Higher order MIMO
- Relaying

Larger bandwidth than the 20 MHz limitation in Release 8 is required to reach the high peak throughput requirements of ITU. *Carrier aggregation* is employed to aggregate several Release 8 compliant carriers, supporting up to a theoretical max bandwidth of 100 MHz. The carriers can be contiguous or non-contiguous, and may also be aggregated from different bands.

Coordinated Multipoint transmission means that several cells coordinate their transmission between themselves. CoMP is targeted mainly towards improving the performance for the cell edge users that suffer from interference. Inference can be combatted either by using macro diversity (similar to eMBMS, where different cells transmit identical resource blocks simultaneously), or by merely letting the surrounding cells defer from transmitting any data at all at the instant when the cell edge user is scheduled by the controlling cell.

By introducing *higher order MIMO*, the eNodeB and the terminal may be equipped with more antennas. In the downlink up to 8x8 MIMO is supported, while the uplink adds support for 4x4 MIMO.

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The final LTE-Advanced feature is *relaying*, which aims at improving the coverage area / cell edge performance. One possibility is to use a relay node as a special eNodeB which uses LTE as its backhaul, also known as 'self-backhauling'. In this case the relay looks like a stationary terminal to the donor eNodeB, and like a regular eNodeB to the terminals connected to it.

4 Performance

When developing a mobile broadband network it is important to understand the performance the technology delivers under different conditions. Capacity is one important property which can be utilized in the dimensioning of the network, eg. to find the supported number of users with a given service requirement. User experience is also an important aspect. An example is the latency of the network, which reveals how suited it is with regard to delivering real-time services like VoIP and real-time gaming.

4.1 Data Capacity

The increase in required data capacity is characterized by an increasing number of users with ever higher bandwidth demands. As the wireless-data market grows (cf. Figure 1), deploying wireless technologies with high capacity will be of paramount importance. We start this section by a short discussion on peak rates and end user rates before we investigate the data capacity.

The maximum throughput the system can offer is referred to as the peak rate. For a single user to be able to reach the peak rate, he needs to experience favorable channel conditions and preferably be alone in the cell, ie. have access to all the cell resources. Moreover, both the base station and the terminal need to be equipped with sufficient processing resources. This is usually only the case for high end terminals. The peak rates for selected versions of HSPA and LTE are summarized in Table 3.

We observe that there is a big difference between LTE and HSPA peak rates; however, it should be noted that LTE is based on a 20 MHz channel, while HSPA is based on a 5 or 10 MHz channel.

Peak rates may be interesting for some special cases, eg. fixed line of sight links. However, for an operator in general, it is more interesting to investigate the expected end user rates. In Figure 13, predicted end user downlink rates for an LTE cellular network are illustrated as a function of the number of users.

The grey area in the figure shows the variation of user rates that may be experienced, from the worst case (bottom 5%, ie. cell edge) to the best case (peak rate in isolated cell). The orange dots show consolidated measurements at cell edge and average user throughput. Consequently, LSTI predicts that the average throughput of an LTE cell will be approximately 25 Mbps in busy hour, this must be shared between the users (eg. five active users get 5 Mbps each). Note that there is a large gap between this average throughput and the peak rate from Table 3. The green dots indicate design targets set by the NGMN[3].

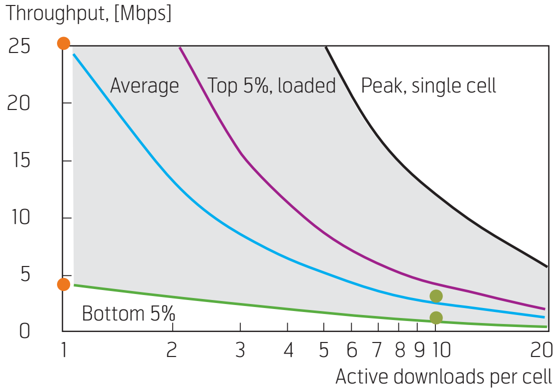

Figure 13 Typical end user data rates for LTE on downlink (Source: LSTI[2])

Technology	Uplink	Downlink
HSPA Rel-6	5.6 Mbps (QPSK)	14 Mbps (16QAM)
HSPA Rel-7	11 Mbps (16QAM)	21 Mbps (64QAM) 28 Mbps (16QAM+2x2 SU-MIMO)
HSPA Rel-8	11 Mbps (16QAM)	42 Mbps (64QAM+2x2 SU-MIMO) 42 Mbps (64QAM+DC-HSDPA)
HSPA Rel-9	23 Mbps (DC-HSUPA)	84 Mbps (DC-HSDPA+2x2 SU-MIMO)
LTE Rel-8	86 Mbps	172 Mbps (2x2 SU-MIMO)

Table 3 Peak rates for selected HSPA and LTE versions [3GAmericas][1]

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[1] *HSPA is in general based on a 5 MHz carrier, except when DC is included (10 MHz). LTE peak rates are based on a 20 MHz carrier.*

[2] *The LTE/SAE Trial Initiative (LSTI) was launched 2007 and is a global collaborative technology trial initiative focused on accelerating the availability of commercial and interoperable next generation LTE mobile broadband systems (www.lstiforum.org).*

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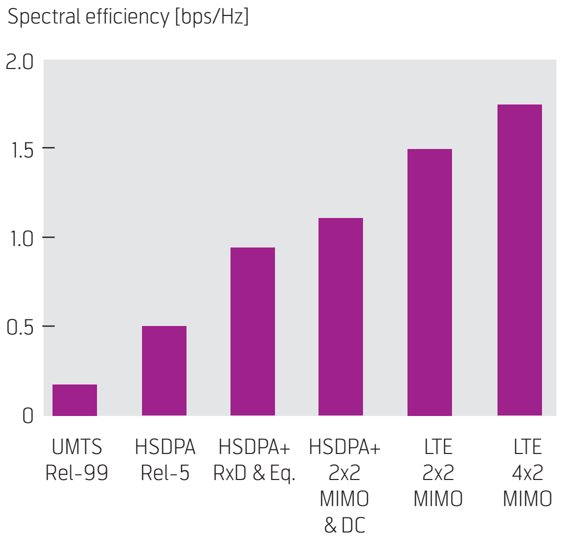

Figure 14 Downlink – average spectral efficiency [3GAmericas]

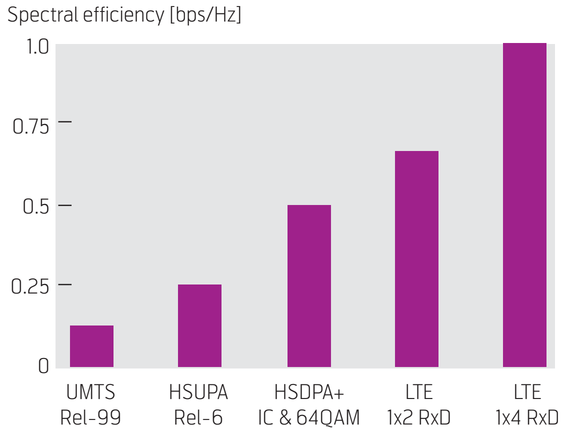

Figure 15 Uplink – average spectral efficiency [3GAmericas]

We now turn our attention towards data capacity, which is defined as the average accumulated data throughput offered (measured in Mbps per cell).To compare the data capacity of HSPA and LTE below we will use average spectral efficiency, defined as the average data rate of the cell divided by the bandwidth utilized. Keeping all other things equal (frequency band, amount of spectrum, site to site distance), an increase in spectral efficiency translates to a proportional increase in the number of users supported. Alternatively, if the number of users is kept constant, an increase in spectral efficiency makes it possible to increase throughput available to each user.

Figure 14 gives estimates of average spectral efficiency for different versions of HSPA and LTE downlink.

We have not included all possible capacity enhancing features and combinations in Figure 14, however a set of important features are chosen to illustrate some of the potential that lies in the future development.

Going from UMTS Release 99 to HSDPA, we observe that the spectral efficiency increases by approximately a factor of three. Advanced receivers at the user terminal, ie. equalization and receiver diversity (RxD), will further double HSDPA spectral efficiency. Dual carrier HSPA will offer a further gain in spectral efficiency of around 10 per cent by facilitating opportunistic scheduling in the frequency domain. Introducing 2x2 MIMO for HSPA will further increase spectral efficiency by about 20 per cent. The average spectral efficiency for the first LTE version is estimated to 1.5 bps/Hz, resulting in an average data rate of 30 Mbps for a 20 MHz bandwidth. The difference from the estimate of 25 Mbps in Figure 13 can be explained by the fact that LSTI looked at a single user case, ie. no opportunistic scheduling gain included.

In Figure 15 estimates are given of average spectral efficiency for different versions of HSPA and LTE uplink.

HSUPA gives a significant increase in uplink spectral efficiency compared to UMTS Release 99. Moreover, since HSUPA usually is interference limited, introducing interference cancelling at the base station will give a large increase in capacity. The estimates from Figure 15 predict a doubling of the spectral efficiency. If we look to LTE, the SC-FDMA based uplink is orthogonal by design, ie. LTE has much less own cell interference in the uplink. Combined with frequency dependent scheduling this gives LTE a superior average spectral efficiency.

Increased spectral efficiency comes at a price; it generally implies greater complexity for both user and base station equipment. Complexity can arise from the increased number of calculations performed to process signals or from additional hardware components. Hence, operators and vendors must balance market needs against network and equipment costs. Actually, one reason for the OFDM technology to be very attractive is that it allows higher spectral efficiency with lower overall complexity.

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[3] *Next Generation Mobile Networks (NGMN) is an alliance of operators that intends to complement and support the work within standardization bodies by providing a coherent view of what the operator community is going to require in the decade beyond 2010 (www.ngmn.org).*

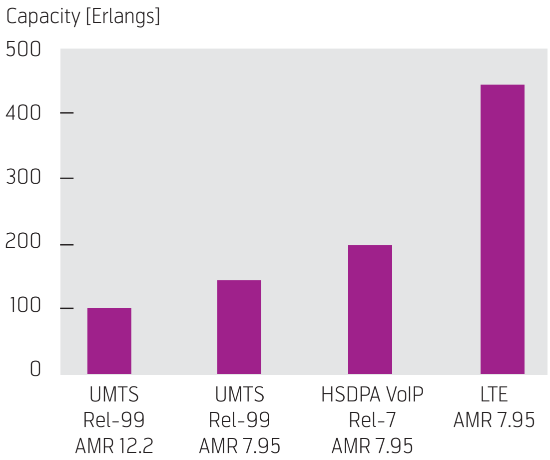

Figure 16 Voice capacity [3GAmericas]

4.2 Voice Capacity

A big difference between HSPA and LTE is that HSPA is based on legacy UMTS and thus has a legacy CS domain available for voice. For LTE there is no longer a CS domain, ie. it is an all IP architecture. Consequently, all voice over LTE must be based on VoIP. For more information on this see Section 3.1.3 and Section 3.2.3.

Figure 16 shows the voice capacity in Erlangs[4] for a 10 MHz scenario. The speech codec utilized is the *Adaptive Multi-Rate* (AMR) audio codec, which supports a range of coding rates (12.2 kbps and 7.95 kbps studied in Figure 16).

From the figure we observe how the capacity increases as the codec rate decreases and the radio technology becomes more advanced. It should be noted that the gains observed when going from CS to VoIP are not related specifically to the use of VoIP, but can be attributed to advances in radio techniques applied to the data channels. Many of these advances may also be applied to current CS modes. Consequently, there are other factors than the radio interface that are driving the migration to packet voice. Among these benefits is a consolidated IP core network for operators and sophisticated multimedia applications for users.

4.3 Latency

Low network latency is important to create a good user experience. Keeping the latency for user data (user plane) low is essential for delivering interactive services like real-time gaming and VoIP. User plane latency is usually characterized by the *Round Trip Time* (RTT), defined as the time it takes data to traverse the network and back. A common way of measuring the RTT is by using the ping utility as illustrated in Figure 17.

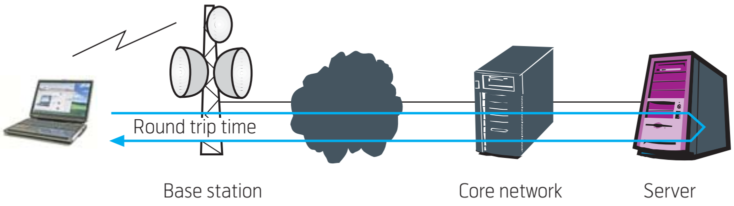

Figure 17 Ping utility is used to measure the Round Trip Time

Each successive data technology typically reduces latency. Moreover, ongoing improvements including fine tuning of network design will reduce the latency further. Figure 18 shows the typical latency of HSPA and LTE networks.

The values shown in Figure 18 reflect measurements of commercially deployed technologies. Some vendors have reported significantly lower values in networks using their equipment.

In addition to the user plane latency, low control plane latency is important to achieve a high user satisfaction. The control plane latency is defined as the time the user terminal takes to move from idle mode (battery saving mode) to active mode. Reducing this latency has been a priority when designing LTE, and the design goal of 100 ms is fulfilled in measurements published by the LSTI.

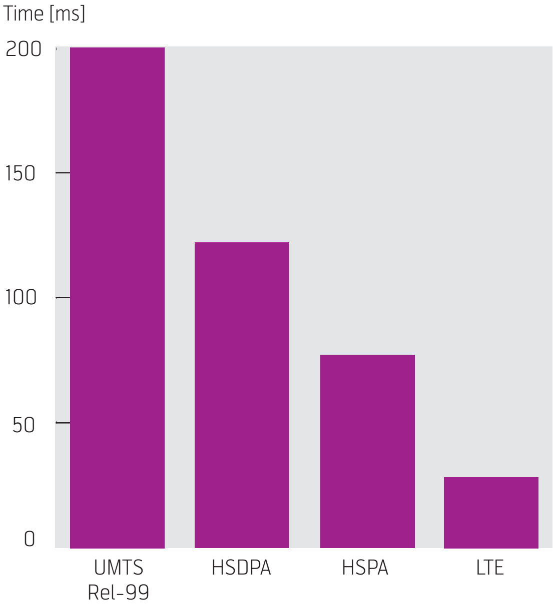

Figure 18 RTT for HSPA and LTE networks [3GAmericas]

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[4] *Erlang is a dimensionless unit used to characterize offered load for a communication system. In this context it can be interpreted as the number of simultaneous voice users supported.*

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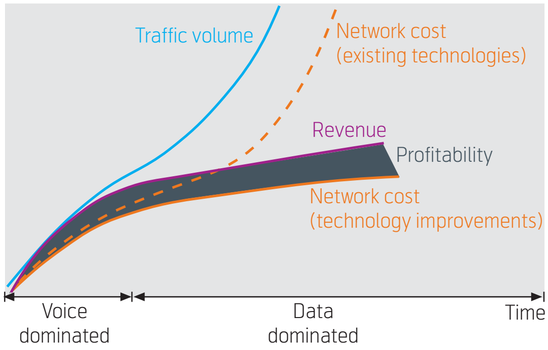

Figure 19 Operator challenge when going from a voice dominated to a data dominated regime

5 Drivers and Deployment

There are different reasons for operators to go for new technology, often referred to as drivers. The most prominent drivers for mobile broadband technology are discussed in the next subsection. Closely linked with the drivers are the deployment trends, ie. the combination of technology, frequency bands and usage. When discussing these trends, it is important to keep in mind that harmonization of bands across national borders is desirable due to roaming between operators. Deployment trends for HSPA and LTE are discussed in the last subsection.

5.1 Drivers for HSPA and LTE

Technology drivers may differ from market to market; the focus here will be on a developed market which already has some mobile broadband offerings, as for example the Nordic region.

In developed markets, the trend is that the mobile traffic is going from voice dominated to data dominated. Furthermore, it is generally accepted that the price per volume of data traffic should be lower than that of voice traffic. One consequence is that the traffic volume is increasing dramatically (cf. Figure 1), while at the same time the revenue is flattening out. Hence, it will be crucial for the operators to be able to build and maintain a cost-efficient high capacity network. Consequently, this demand for a cost efficient high capacity network is the main technology driver. Figure 19 illustrates the challenge described.

Better user experience is also a driver that is worth noting. As seen in the performance section, the new technologies offer increased throughputs and reduced latency. To keep a successful business it is important to provide a service offering that is attractive to the customers. This driver is tightly linked to the increased capacity demand driver.

The terminal situation is also important for the success and feasibility of a new technology. The network technology is of no use if the corresponding terminals are not available in the market. In the case of mobile broadband it is possible to push USB dongles and data cards together with subscriptions. Consequently, if the terminals are available from the vendors' side, the operator can to a large extent actively help increase the terminal penetration.

Competition and market positioning may also be an important driver for a technology transition. What other local or global actors do can influence an operators' decision on the next technology transition and may 'force' a technology transition at an earlier stage than seen from a pure market demand perspective.

5.2 Frequency Bands and Deployment Trends

From physics we know that the attenuation a signal is exposed to when travelling through space increases with increasing frequency. The same goes for penetration into buildings, ie. lower frequencies reach further. Consequently, the lower frequency bands are very popular for developing coverage since they require fewer sites to cover a given area. On the other hand, when building for capacity, higher frequencies can be utilized since the site grid is not determined by coverage but rather the capacity demand in the area.

If we look at HSPA, most systems operate in the IMT-2000 core band around 2.1 GHz. Due to the relatively high frequency this is usually thought of as a capacity band. However, HSPA can also be deployed at lower frequency bands such as 850 MHz and 900 MHz to build coverage. It should be noted that these bands have been utilized by 2G technology and a refarming of the frequency band will be needed. This is discussed in more detail in Section 5.2.1.

LTE can be deployed in existing 2G and 3G spectrum, or in new spectrum such as the digital dividend and 2.6 GHz, currently being allocated in many parts of the world. If we look to Asia, initial deployments in Japan use 800 MHz, 1.5 GHz and 1.7 GHz depending on the operator. As for HSPA, there is high interest in opportunities for LTE deployments using frequencies released by spectrum refarming. Regarding the digital dividend, there are great expectations in Europe and elsewhere to access additional UHF bands. This will enable global and efficient deployment of LTE over large geographical areas. For more information on frequency spectrum for MBB the reader is referred to the paper by Trosby et al. in this issue [Trosby10].

When an operator starts deploying a new mobile technology generation the legacy network will typically still be operative for some time. As an example,

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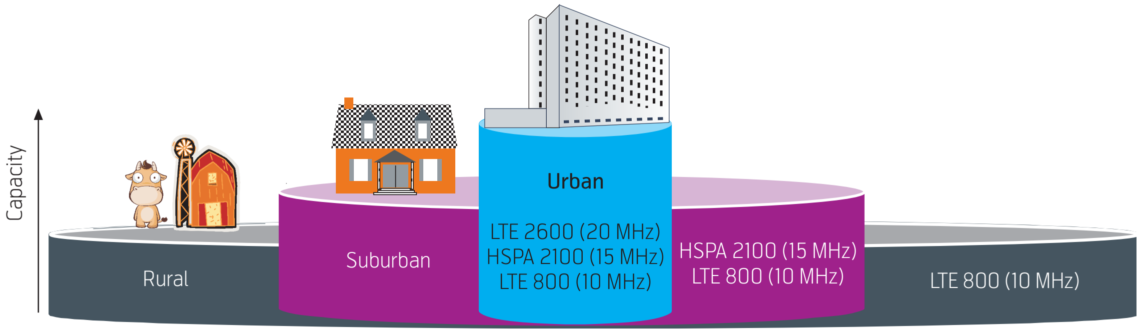

Figure 20 Example of mobile broadband deployment

4G is standing on the doorstep to being deployed, and most operators are not planning to switch off 2G for quite some time yet. Consequently, at a given point in time an operator will have a portfolio of technologies and frequency bands. In Figure 20 we show an example of how the deployment strategy can look for a mobile broadband operator that owns both 800 MHz and 2.6 GHz spectrum in addition to 2.1 GHz spectrum.

5.2.1 Case Study: UMTS900 through refarming

Traditionally the 900 MHz band has been the core 2G band in Europe. However, there is a very strong momentum for deploying mobile broadband in this band to help operators efficiently extend coverage by leveraging the advantages of lower frequencies. This becomes especially important for operators that do not get access to 800 MHz spectrum (cf. Figure 20).

So far, most attention has been on HSPA for 900 MHz, often referred to as UMTS900. Providing full coverage using 2.1 GHz is very expensive and takes too long time for many mobile network operators. For the same coverage, the number of sites required using 900 MHz is significantly lower, also resulting in a reduced rollout time. Theoretical analysis suggests a reduction of up to 60 per cent in the number of sites. Indoor coverage is also improved with 900 MHz. Technical specifications for HSPA in the 900 MHz band were completed by 3GPP in December 2005, and all the large network vendors have HSPA available for 900 MHz. The cost savings experienced by the Finnish operator Elisa when developing UMTS900 compared to UMTS in the 2.1 GHz band are estimated to 50-70 per cent [GSA1].

Moving all users from one technology to another over night is not feasible, eg. due to the terminal situation. When introducing HSPA in the 900 MHz band it needs to coexist with 2G for some time. This introduces several technical challenges; some of the challenges for GSM/HSPA coexistence are discussed below:

- In principle, if HSPA and GSM are co-sited they can share antennas. However, there are some challenges; ie. network planning strategies are very different and individual optimization of antenna direction is desirable. Therefore, the operator ends up with a trade-off; savings obtained by only needing one antenna versus suboptimal network planning due to restrictions on antenna direction.

- The reuse of GSM site locations is not straightforward. HSPA sites need their coverage to be well confined, otherwise capacity will be severely limited. As such, in areas where the GSM grid is characterized by a high degree of overlap, not all GSM site locations can be reused for HSPA. The solution could be to build new sites solely for HSPA coverage.

- Between sites that have only GSM (eg. cities where all frequency resources are needed for GSM) and sites with HSPA, an isolation distance is needed. In the worst case, this distance might be 40 km, but optimization measures and local topology conditions can shorten this considerably.

- When spectrum usage goes from GSM to HSPA, an increased interference level and dropped call rate should be expected in the GSM network. To counter against such degradation, GSM performance enhancing features can be deployed to better control the interference. This deployment is of course not without costs.

6 Concluding Remarks

This paper has discussed the mobile broadband radio access networks HSPA and LTE. Both systems make use of the latest advances within wireless communications as eg. MIMO and opportunistic scheduling. The main technical differences between the two can be summarized as; the multiple access scheme (WCDMA versus OFDM-based), the larger bandwidths utilized by LTE, and the flat all-IP architec-

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ture adopted by LTE. Both technologies are evolving and new features are added through standardization; however, only LTE is made an IMT-Advanced technology and may in that respect be viewed as more future proof than HSPA. Looking at the performance, it is obvious that LTE will have a slight performance gain over HSPA, however the gain is better characterized as an evolution than a revolution. When it comes to deployment it seems like the initial frequency bands, at least in Europe, will be 900 MHz (HSPA) and 800 MHz (LTE) for coverage and 2.1 GHz (HSPA) and 2.6 GHz (LTE) for capacity.

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