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Introduction and Background

Thomas Sälzer and Matthew Baker

1.1 The Context for the Long Term Evolution of UMTS

1.1.1 Historical Context

The Long Term Evolution of UMTS is just one of the latest steps in an advancing series of mobile telecommunications systems.

Arguably, at least for land-based systems, the series began in 1947 with the development of the concept of *cells* by the famous Bell Labs of the USA. The use of cells enabled the capacity of a mobile communications network to be increased substantially, by dividing the coverage area up into small cells each with its own base station operating on a different frequency.

The early systems were confined within national boundaries. They attracted only a small number of users, as the equipment on which they relied was expensive, cumbersome and power-hungry, and therefore was only really practical in a car.

The first mobile communication systems to see large-scale commercial growth arrived in the 1980s and became known as the 'First Generation' systems. The First Generation comprised a number of independently-developed systems worldwide (e.g. AMPS (Analogue Mobile Phone System, used in America), TACS (Total Access Communication System, used in parts of Europe), NMT (Nordic Mobile Telephone, used in parts of Europe) and J-TACS (Japanese Total Access Communication System, used in Japan and Hong Kong)), using analogue technology.

Global roaming first became a possibility with the development of the digital 'Second Generation' system known as GSM (Global System for Mobile Communications). The success of GSM was due in part to the collaborative spirit in which it was developed. By harnessing the creative expertise of a number of companies working together under the

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auspices of the European Telecommunications Standards Institute (ETSI), GSM became a robust, interoperable and widely-accepted standard.

Fuelled by advances in mobile handset technology, which resulted in small, fashionable terminals with a long battery life, the widespread acceptance of the GSM standard exceeded initial expectations and helped to create a vast new market. The resulting near-universal penetration of GSM phones in the developed world provided an ease of communication never previously possible, first by voice and text message, and later also by more advanced data services. Meanwhile in the developing world, GSM technology had begun to connect communities and individuals in remote regions where fixed-line connectivity was non-existent and would be prohibitively expensive to deploy.

This ubiquitous availability of user-friendly mobile communications, together with increasing consumer familiarity with such technology and practical reliance on it, thus provides the context for new systems with more advanced capabilities. In the following section, the series of progressions which have succeeded GSM is outlined, culminating in the development of the system currently known as LTE – the Long Term Evolution of UMTS (Universal Mobile Telecommunications System).

1.1.2 LTE in the Mobile Radio Landscape

In contrast to transmission technologies using media such as copper lines and optical fibres, the radio spectrum is a medium shared between different, and potentially interfering, technologies.

As a consequence, regulatory bodies – in particular, ITU-R (International Telecommunication Union, Radio Communication Sector) [1], but also regional and national regulators – play a key role in the evolution of radio technologies since they decide which parts of the spectrum and how much bandwidth may be used by particular types of service and technology. This role is facilitated by the *standardization* of families of radio technologies – a process which not only provides specified interfaces to ensure interoperability between equipment from a multiplicity of vendors, but also aims to ensure that the allocated spectrum is used as efficiently as possible, so as to provide an attractive user experience and innovative services.

The complementary functions of the regulatory authorities and the standardization organizations can be summarized broadly by the following relationship:

$$\text{Aggregated data rate} = \underbrace{\text{bandwidth}}_{\substack{\text{regulation and licences}\\ \text{(ITU-R, regional regulators)}}} \times \underbrace{\text{spectral efficiency}}_{\substack{\text{technology}\\ \text{and standards}}}$$

On a worldwide basis, ITU-R defines technology families and associates specific parts of the spectrum with these families. Facilitated by ITU-R, spectrum for mobile radio technologies is identified for the radio technologies which meet the ITU-R's requirements to be designated as members of the *International Mobile Telecommunications* (IMT) family. Effectively, the IMT family comprises systems known as 'Third Generation' (for the first time providing data rates up to 2 Mbps) and beyond.

From the technology and standards angle, there are currently three main organizations responsible for developing the standards meeting IMT requirements, and which are continuing to shape the landscape of mobile radio systems, as shown in Figure 1.1.

The uppermost evolution track shown in Figure 1.1 is that developed in the 3rd Generation Partnership Project (3GPP), which is currently the dominant standards development group for mobile radio systems and is described in more detail below.

Within the 3GPP evolution track, three multiple access technologies are evident: the 'Second Generation' GSM/GPRS/EDGE family[1] was based on Time- and Frequency-Division Multiple Access (TDMA/FDMA); the 'Third Generation' UMTS family marked the entry of Code Division Multiple Access (CDMA) into the 3GPP evolution track, becoming known as *Wideband* CDMA (owing to its 5 MHz carrier bandwidth) or simply WCDMA; finally LTE has adopted Orthogonal Frequency-Division Multiplexing (OFDM), which is the access technology dominating the latest evolutions of all mobile radio standards.

In continuing the technology progression from the GSM and UMTS technology families within 3GPP, the LTE system can be seen as completing the trend of expansion of service provision beyond voice calls towards a multiservice air interface. This was already a key aim of UMTS and GPRS/EDGE, but LTE was designed from the start with the goal of evolving the radio access technology under the assumption that all services would be packet-switched, rather than following the circuit-switched model of earlier systems. Furthermore, LTE is accompanied by an evolution of the non-radio aspects of the complete system, under the term 'System Architecture Evolution' (SAE) which includes the Evolved Packet Core (EPC) network. Together, LTE and SAE comprise the Evolved Packet System (EPS), where both the core network and the radio access are fully packet-switched.

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[1] The maintenance and development of specifications for the GSM family was passed to 3GPP from ETSI.

The standardization of LTE and EPS does not mean that further development of the other radio access technologies in 3GPP has ceased. In particular, the enhancement of UMTS with new releases of the specifications continues in 3GPP, to the greatest extent possible while ensuring backward compatibility with earlier releases: the original 'Release 99' specifications of UMTS have been extended with high-speed downlink and uplink enhancements (HSDPA[2] and HSUPA[3] in Releases 5 and 6 respectively), known collectively as 'HSPA' (High-Speed Packet Access). HSPA has been further enhanced in Release 7 (becoming known as HSPA+) with higher-order modulation and, for the first time in a cellular communication system, multistream 'MIMO' operation (Multiple-Input Multiple-Output antenna system). Further enhancements of HSPA+ are being introduced in Release 8 in parallel to the first release of LTE (which for consistency is also termed Release 8). These backward-compatible enhancements will enable network operators who have invested heavily in the WCDMA technology of UMTS to generate new revenues from new features while still providing service to their existing subscribers using legacy terminals.

LTE is able to benefit from the latest understanding and technology developments from HSPA and HSPA+, especially in relation to optimizations of the protocol stack, while also being free to adopt radical new technology without the constraints of backward compatibility or a 5 MHz carrier bandwidth. However, LTE also has to satisfy new demands, for example in relation to spectrum flexibility for deployment. LTE can operate in Frequency-Division Duplex (FDD) and Time-Division Duplex (TDD) modes in a harmonized framework designed also to support the evolution of TD-SCDMA (Time-Division Synchronous Code Division Multiple Access), which has been developed in 3GPP as an additional branch of the UMTS technology path, essentially for the Chinese market.

The second path of evolution has emerged from the IEEE 802 LAN/MAN[4] standards committee, which created the '802.16' family as a broadband wireless access standard. This family is also fully packet-oriented. It is often referred to as *WiMAX*, on the basis of a so-called 'System Profile' assembled from the 802.16 standard and promoted by the WiMAX Forum. The WiMAX Forum also ensures the corresponding product certification. While the first version known as 802.16-2004 was restricted to fixed access, the following version 802.16e includes basic support of mobility and is therefore often referred to as 'mobile WiMAX'. However, it can be noted that in general the WiMAX family has not been designed with the same emphasis on mobility and compatibility with operators' core networks as the 3GPP technology family, which includes core network evolutions in addition to the radio access network evolution. Nevertheless, the latest generation currently under development by the IEEE, known as 802.16m, has similar targets to the likely future enhancements to LTE which are outlined in the concluding chapter of this book, Chapter 24.

A third evolution track shown in Figure 1.1 is led by a partnership organization similar to 3GPP and known as 3GPP2. Based on the American 'IS95' standard, which was the first mobile cellular communication system to use CDMA technology, CDMA2000 was developed and deployed mainly in the USA, Korea and Japan. Standardization in 3GPP2 has continued with parallel evolution tracks towards data-oriented systems (EV-DO), to a certain extent taking a similar path to the evolutions in 3GPP. Mirroring LTE, 3GPP2's latest

[2]High-Speed Downlink Packet Access.
[3]High-Speed Uplink Packet Access.
[4]Local Area Network/Metropolitan Area Network.

evolution is a new OFDM-based system called Ultra-Mobile Broadband (UMB), derived in part from a proprietary system known as 'Flash OFDM'.

The overall pattern is of an evolution of mobile radio towards flexible, packet-oriented, multiservice systems. The aim of all these systems is towards offering a mobile broadband user experience that can approach that of current fixed access networks such as Asymmetric Digital Subscriber Line (ADSL) and Fibre-To-The-Home (FTTH).

1.1.3 The Standardization Process in 3GPP

The collaborative standardization model which so successfully produced the GSM system became the basis for the development of the UMTS system. In the interests of producing truly global standards, the collaboration for both GSM and UMTS was expanded beyond ETSI to encompass regional Standards Development Organizations (SDOs) from Japan (ARIB and TTC), Korea (TTA), North America (ATIS) and China (CCSA), as shown in Figure 1.2.

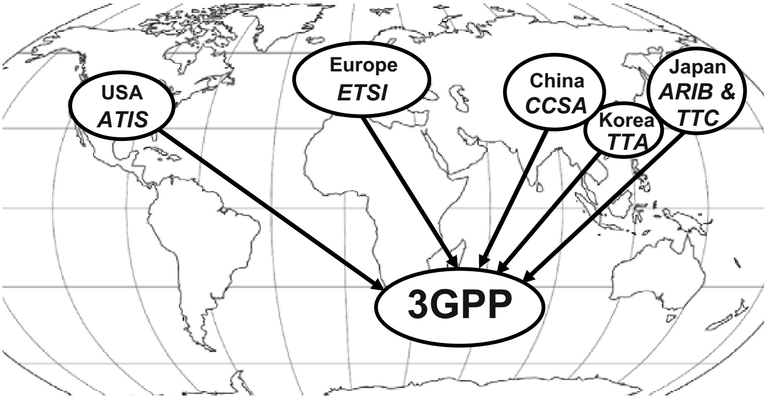

Figure 1.2 3GPP is a global partnership of six regional SDOs.

So the 3GPP was born, which by 2008 boasted over 300 individual member companies.

The successful creation of such a large and complex system specification as that for UMTS or LTE requires a well-structured organization with pragmatic working procedures. 3GPP is divided into four Technical Specification Groups (TSGs), each of which is comprised of a number of Working Groups (WGs) with responsibility for a specific aspect of the specifications as shown in Figure 1.3.

A distinctive feature of the working methods of these groups is the consensus-driven approach to decision-making. This facilitates open discussion and iterative improvement of technical proposals, frequently leading to merging of proposals from multiple companies in the quest for the optimal solution.

All documents submitted to 3GPP are publicly available on the 3GPP website,[5] including contributions from individual companies, technical reports and technical specifications.

[5] http://www.3gpp.org.

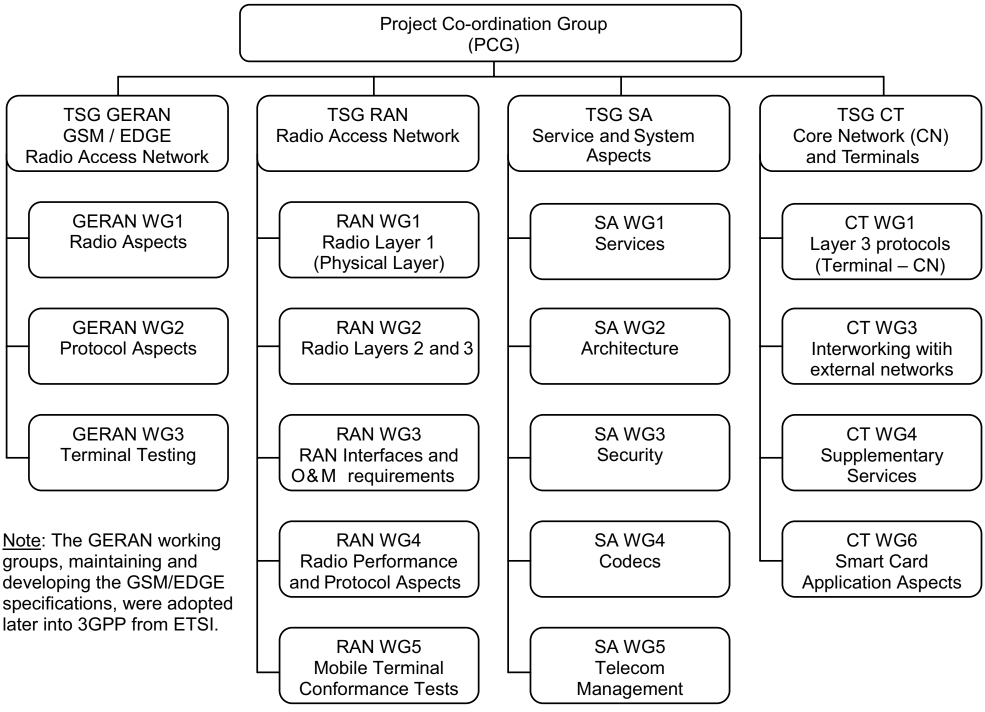

Figure 1.3 The Working Group structure of 3GPP. Reproduced by permission of © 3GPP.

In reaching consensus around a technology, the WGs take into account a variety of considerations, including but not limited to performance, implementation cost, complexity and compatibility with earlier versions or deployments. Simulations are frequently used to compare performance of different techniques, especially in the WGs focusing on the physical layer of the air interface and on performance requirements. This requires consensus first to be reached around the simulation assumptions to be used for the comparison, including, in particular, understanding and defining the scenarios of interest to network operators.

Formal voting is therefore rare in 3GPP, thus for the most part avoiding polarization of the contributing companies into factions, or bureaucratic stalemate situations which sometimes occur in standardization efforts.

The LTE standardization process was inaugurated at a workshop in Toronto in November 2004, when a broad range of companies involved in the mobile communications business presented their visions for the future evolution of the specifications to be developed in 3GPP. These visions included both initial perceptions of the *requirements* which needed to be satisfied, and proposals for *suitable technologies* to meet those requirements.

The requirements are reviewed in detail in Section 1.2, while the key technologies are introduced in Section 1.3.

1.2 Requirements and Targets for the Long Term Evolution

Discussion of the key requirements for the new LTE system led to the creation of a formal 'Study Item' in 3GPP with the specific aim of 'evolving' the 3GPP radio access technology to ensure competitiveness over a 10-year time-frame. Under the auspices of this Study Item, the requirements for LTE were refined and crystallized, being finalized in June 2005.

They can be summarized as follows:

- reduced delays, in terms of both connection establishment and transmission latency;
- increased user data rates;
- increased cell-edge bit-rate, for uniformity of service provision;
- reduced cost per bit, implying improved spectral efficiency;
- greater flexibility of spectrum usage, in both new and pre-existing bands;
- simplified network architecture;
- seamless mobility, including between different radio-access technologies;
- reasonable power consumption for the mobile terminal.

It can also be noted that network operator requirements for next generation mobile systems were formulated by the Next Generation Mobile Networks (NGMN) alliance of network operators [2], which served as an additional reference for the development and assessment of the LTE design. Such operator-driven requirements will also guide the development of the next phase of LTE, namely LTE-Advanced (see Chapter 24).

To address these objectives, the LTE system design covers both the radio interface and the radio network architecture. The main chapters of this book describe the technologies by which these targets are achieved, and even exceeded in some aspects, by the first version of the LTE system.

1.2.1 System Performance Requirements

Improved system performance compared to existing systems is one of the main requirements from network operators, to ensure the competitiveness of LTE and hence to arouse market interest. In this section, we highlight the main performance metrics used in the definition of the LTE requirements and its performance assessment.

Table 1.1 summarizes the main performance requirements to which the first release of LTE was designed. Many of the figures are given relative to the performance of the most advanced available version of UMTS, which at the time of the definition of the LTE requirements was HSDPA/HSUPA Release 6 – referred to here as the *reference baseline*. It can be seen that the target requirements for LTE represent a significant step from the capacity and user experience offered by the 'Third Generation' mobile communications systems which were being deployed at the time when LTE was being developed.

		Absolute requirement	Comparison to Release 6	Comment
Downlink	Peak transmission rate	> 100 Mbps	7 × 14.4 Mbps	LTE in 20 MHz FDD, 2 × 2 spatial multiplexing. Reference: HSDPA in 5 MHz FDD, single antenna transmission
	Peak spectral efficiency	> 5 bps/Hz	3 bps/Hz	
	Average cell spectral efficiency	> 1.6 – 2.1 bps/Hz/cell	3 – 4 × 0.53 bps/Hz/cell	LTE: 2 × 2 spatial multiplexing, Interference Rejection Combining (IRC) receiver [3]. Reference: HSDPA, Rake receiver [4], 2 receive antennas
	Cell edge spectral efficiency	> 0.04 – 0.06 bps/Hz/user	2-3 × 0.02 bps/Hz	As above, 10 users assumed per cell
	Broadcast spectral efficiency	> 1 bps/Hz	N/A	Dedicated carrier for broadcast mode
Uplink	Peak transmission rate	> 50 Mbps	5 × 11 Mbps	LTE in 20 MHz FDD, single antenna transmission. Reference: HSUPA in 5 MHz FDD, single antenna transmission
	Peak spectral efficiency	> 2.5 bps/Hz	2 bps/Hz	
	Average cell spectral efficiency	> 0.66 – 1.0 bps/Hz/cell	2 – 3 × 0.33 bps/Hz	LTE: single antenna transmission, IRC receiver [3]. Reference: HSUPA, Rake receiver [4], 2 receive antennas
	Cell edge spectral efficiency	> 0.02 – 0.03 bps/Hz/user	2 – 3 × 0.01 bps/Hz	As above, 10 users assumed per cell
System	User plane latency (two way radio delay)	< 10 ms	One fifth	
	Connection set-up latency	< 100 ms		Idle state → active state
	Operating bandwidth	1.4 – 20 MHz	5 MHz	(initial requirement started at 1.25 MHz)
	VoIP capacity	NGMN preferred target expressed in [2] is > 60 sessions/MHz/cell		

As mentioned above, HSPA technologies are also continuing to be developed to offer higher spectral efficiencies than were assumed for the reference baseline case. However, LTE has been able to benefit from avoiding the constraints of backward compatibility, enabling the inclusion of advanced MIMO schemes in the system design from the beginning, and highly flexible spectrum usage built around new multiple access schemes.

The requirements shown in Table 1.1 are discussed and explained in more detail below.

1.2.1.1 Peak Rates and Peak Spectral Efficiency

For marketing purposes, the first parameter by which different radio access technologies are usually compared is the peak per-user data rate which can be achieved. This peak data rate generally scales according to amount of spectrum used, and, for MIMO systems, according to the minimum of the number of transmit and receive antennas (see Section 11.1).

The peak rate can be defined as the maximum throughput per user assuming the whole bandwidth being allocated to a single user with the highest modulation and coding scheme and the maximum number of antennas supported. Typical radio interface overhead (control channels, pilot signals, guard intervals, etc.) is estimated and taken into account for a given operating point. For TDD systems, the peak rate is generally calculated for the downlink and uplink periods separately. This makes it possible to obtain a single value independent of the uplink/downlink ratio and a fair system comparison that is agnostic of the duplex mode. The maximum spectral efficiency is then obtained simply by dividing the peak rate by the used spectrum allocation.

The target peak data rates for downlink and uplink in the LTE system were set at 100 Mbps and 50 Mbps respectively within a 20 MHz bandwidth,[6] corresponding to respective peak spectral efficiencies of 5 and 2.5 bps/Hz. The underlying assumption here is that the terminal has two receive antennas and one transmit antenna. The number of antennas used at the base station is more easily upgradeable by the network operator, and the first version of the LTE specifications has therefore been designed to support downlink MIMO operation with up to four transmit and receive antennas. The MIMO techniques enabling high peak data rates are described in detail in Chapter 11.

When comparing the capabilities of different radio communication technologies, great emphasis is often placed on the peak data rate capabilities. While this is one indicator of how technologically advanced a system is and can be obtained by simple calculations, it may not be a key differentiator in the usage scenarios for a mobile communication system in practical deployment. Moreover, it is relatively easy to design a system that can provide very high peak data rates for users close to the base station, where interference from other cells is low and techniques such as MIMO can be used to their greatest extent. It is much more challenging to provide high data rates with good coverage and mobility, but it is exactly these latter aspects which contribute most strongly to user satisfaction.

In typical deployments, individual users are located at varying distances from the base stations, the propagation conditions for radio signals to individual users are rarely ideal, and moreover the available resources must be shared between many users. Consequently, although the claimed peak data rates of a system are genuinely achievable in the right conditions, it is rare for a single user to be able to experience the peak data rates for a sustained period, and the envisaged applications do not usually require this level of performance.

A differentiator of the LTE system design compared to some other systems has been the recognition of these ‘typical deployment constraints’ from the beginning. During the design process, emphasis was therefore placed not only on providing a competitive peak data rate for use when conditions allow, but also importantly on *system level performance*, which was evaluated during several performance verification steps.

System-level evaluations are based on simulations of multicell configurations where data transmission from/to a population of mobiles is considered in a typical deployment scenario. The paragraphs below describe the main metrics used as requirements for system level performance. In order to make these metrics meaningful, parameters such as the deployment scenario, traffic models, channel models and system configuration need to be thoroughly defined.

[6] Four times the bandwidth of a WCDMA carrier.

The key definitions used for the system evaluations of LTE can be found in an operator input document addressing the performance verification milestone in the LTE development process [5]. This document takes into account deployment scenarios and channel models agreed during the LTE Study Item [6], and is based on an evaluation methodology elaborated by NGMN NGMN operators in [7]. The reference deployment scenarios which were given special consideration for the LTE performance evaluation covered macrocells with base station separations of between 500 m and 1.7 km, as well as microcells using MIMO with base station separations of 130 m. A range of mobile terminal speeds were studied, focusing particularly on the range 3–30 km/h, although higher mobile speeds were also considered important.

1.2.1.2 Cell Throughput and Spectral Efficiency

Performance at the cell level is an important criterion, as it relates directly to the number of cell sites that a network operator requires, and hence to the capital cost of deploying the system. For LTE, it was chosen to assess the cell level performance with full-queue traffic models (i.e. assuming that there is never a shortage of data to transmit if a user is given the opportunity) and a relatively high system load, typically 10 users per cell.

The requirements at the cell level were defined in terms of the following metrics:

- Average cell throughput [bps/cell] and spectral efficiency [bps/Hz/cell].
- Average user throughput [bps/user] and spectral efficiency [bps/Hz/user].
- Cell-edge user throughput [bps/user] and spectral efficiency [bps/Hz/user]. The metric used for this assessment is the 5-percentile user throughput, obtained from the cumulative distribution function of the user throughput.

For the UMTS Release 6 reference baseline, it was assumed that both the terminal and the base station use a single transmit antenna and two receive antennas; for the terminal receiver the assumed performance corresponds to a two-branch Rake receiver [4] with linear combining of the signals from the two antennas.

For the LTE system, the use of two transmit and receive antennas was assumed at the base station. At the terminal two receive antennas were assumed, but still only a single transmit antenna. The receiver for both downlink and uplink is assumed to be a linear receiver with optimum combining of the signals from the antenna branches [3]. In the uplink, higher per-user throughput should be achievable by also using multiple transmit antennas at the terminal, which will be considered for future releases of LTE.

The original requirements for the cell level metrics were only expressed as relative gains compared to the Release 6 reference baseline. The absolute values provided in Table 1.1 are based on evaluations of the reference system performance that can be found in [8] and [9] for downlink and uplink respectively.

1.2.1.3 Voice Capacity

Unlike full queue traffic (such as file download) which is typically delay-tolerant and does not require a guaranteed bit-rate, real-time traffic such as Voice over IP (VoIP) has tight delay constraints. It is important to set system capacity requirements for such services – a particular challenge in fully packet-based systems like LTE which rely on adaptive scheduling.

The system capacity requirement is defined as the number of satisfied VoIP users, given a particular traffic model and delay constraints. The details of the traffic model used for evaluating LTE can be found in [5]. Here, a VoIP user is considered to be in outage (i.e. not satisfied) if more than 2% of the VoIP packets do not arrive successfully at the radio receiver within 50 ms and are therefore discarded. This assumes an overall end-to-end delay (from mobile terminal to mobile terminal) below 200 ms. The system capacity for VoIP can then be defined as the number of users present per cell when more than 95% of the users are satisfied.

The NGMN group of network operators expressed a preference for the ability to support 60 satisfied VoIP sessions per MHz – an increase of two to four times what can typically be achieved in the Release 6 reference case. This is an area where there is scope for further enhancement of LTE in later releases.

1.2.1.4 Mobility and Cell Ranges

In terms of mobility, the LTE system is required to support communication with terminals moving at speeds of up to 350 km/h, or even up to 500 km/h depending on the frequency band. The primary scenario for operation at such high speeds is usage on high-speed trains – a scenario which is increasing in importance across the world as the number of high-speed rail lines increases and train operators aim to offer an attractive working environment to their passengers. These requirements mean that handover between cells has to be possible without interruption – in other words, with imperceptible delay and packet loss for voice calls, and with reliable transmission for data services.

These targets are to be achieved by the LTE system in typical cells of radius up to 5 km, while operation should continue to be possible for cell ranges of up to 100 km to enable wide-area deployments.

1.2.1.5 Broadcast Mode Performance

Although not available in the first release due to higher prioritization of other service modes, LTE is required to integrate an efficient broadcast mode for high rate Multimedia Broadcast/Multicast Services (MBMS) such as Mobile TV, based on a Single Frequency Network mode of operation as explained in detail in Chapter 14. This mode is able to operate either on a shared carrier frequency together with unicast transmissions, or on a dedicated broadcast carrier. To ensure efficient broadcast performance a requirement was defined for the dedicated carrier case.

In broadcast systems, the system throughput is limited to what is achievable for the users in the worst conditions. Consequently, the broadcast performance requirement was defined in terms of an achievable system throughput (bps) and spectral efficiency (bps/Hz) assuming a coverage of 98% of the nominal coverage area of the system. This means that only 2% of the locations in the nominal coverage area are in outage – where outage for broadcast services is defined as experiencing a packet error rate higher than 1%.

This broadcast spectral efficiency requirement was set to 1 bps/Hz [10].

1.2.1.6 User Plane Latency

User plane latency is an important performance metric for real-time and interactive services. On the radio interface, the minimum user plane latency can be calculated based on signalling analysis for the case of an unloaded system. It is defined as the average time between the first transmission of a data packet and the reception of a physical layer Acknowledgement (ACK). The calculation should include typical HARQ[7] retransmission rates (e.g. 0–30%). This definition therefore considers the capability of the system design, without being distorted by the scheduling delays that would appear in the case of a loaded system. The round-trip latency is obtained simply by multiplying the one-way user plane latency by a factor of two.

The LTE system is also required to be able to operate with an IP-layer one-way data-packet latency across the radio access network as low as 5 ms in optimal conditions. However, it is recognized that the actual delay experienced in a practical system will be dependent on system loading and radio propagation conditions. For example, HARQ plays a key role in maximizing spectral efficiency at the expense of increased delay while retransmissions take place, whereas maximal spectral efficiency may not be essential in situations when minimum latency is required.

1.2.1.7 Control Plane Latency and Capacity

In addition to the user plane latency requirement, call setup delay is required to be significantly reduced compared to existing cellular systems. This not only enables a good user experience but also affects the battery life of terminals, since a system design which allows a fast transition from an idle state to an active state enables terminals to spend more time in the low-power idle state.

Control plane latency is measured as the time required for performing the transitions between different LTE states. LTE is based on only two main states, 'RRC_IDLE' and 'RRC_CONNECTED' (i.e. 'active').

The LTE system is required to support transition from idle to active in less than 100 ms (excluding paging delay and Non-Access Stratum (NAS) signalling delay).

The LTE system capacity is dependent not only on the supportable throughput but also on the number of users simultaneously located within a cell which can be supported by the control signalling. For the latter aspect, the LTE system is required to support at least 200 active-state users per cell for spectrum allocations up to 5 MHz, and at least 400 users per cell for wider spectrum allocations; only a small subset of these users would be actively receiving or transmitting data at any given time instant, depending, for example, on the availability of data to transmit and the prevailing radio channel conditions. An even larger number of non-active users may also be present in each cell, and therefore able to be paged or to start transmitting data with low latency.

1.2.2 Deployment Cost and Interoperability

Besides the system performance aspects, a number of other considerations are important for network operators. These include reduced deployment cost, spectrum flexibility and enhanced interoperability with legacy systems – essential requirements to enable deployment of LTE networks in a variety of scenarios and to facilitate migration to LTE.

[7] Hybrid Automatic Repeat reQuest – see Section 10.3.2.5.

1.2.2.1 Spectrum Allocations and Duplex Modes

As demand for suitable radio spectrum for mobile communications increases, LTE is required to be able to operate in a wide range of frequency bands and sizes of spectrum allocations in both uplink and downlink. LTE can use spectrum allocations ranging from 1.4 to 20 MHz with a single carrier and addresses all frequency bands currently identified for IMT systems by ITU-R [1] including those below 1 GHz.

This will in due course include deploying LTE in spectrum currently occupied by older radio access technologies – a practice often known as 'spectrum refarming'.

The ability to operate in both paired and unpaired spectrum is required, depending on spectrum availability. LTE provides support for FDD, TDD and half-duplex FDD operation in a unified design, ensuring a high degree of commonality which facilitates implementation of multimode terminals and allows worldwide roaming.

1.2.2.2 Inter-Working with Other Radio Access Technologies

Flexible interoperation with other radio access technologies is essential for service continuity, especially during the migration phase in early deployments of LTE with partial coverage, where handover to legacy systems will often occur.

LTE relies on an evolved packet core network which allows interoperation with various access technologies, in particular earlier 3GPP technologies (GSM/EDGE and UTRAN) as well as non-3GPP technologies (e.g. WiFi, CDMA2000 and WiMAX).

However, service continuity and short interruption times can only be guaranteed if measurements of the signals from other systems and fast handover mechanisms are integrated in the LTE radio access design. In its first releases LTE will thus support tight inter-working with all legacy 3GPP technologies and some non-3GPP technologies such as CDMA2000.

1.2.2.3 Terminal Complexity and Cost

A key consideration for competitive deployment of LTE is the availability of low-cost terminals with long battery life, both in stand-by and during activity. Therefore, low terminal complexity has been taken into account where relevant throughout the LTE system, as well as designing the system wherever possible to support low terminal power consumption.

1.2.2.4 Network Architecture Requirements

LTE is required to allow a cost-effective deployment by an improved radio access network architecture design including:

- flat architecture consisting of just one type of node, the base station, known in LTE as the *eNodeB*;
- effective protocols for the support of packet-switched services;
- open interfaces and support of multivendor equipment interoperability;
- efficient mechanisms for operation and maintenance, including self-optimization functionalities;

- support of easy deployment and configuration, for example for so-called home base stations (otherwise known as femto-cells).

1.3 Technologies for the Long Term Evolution

The fulfilment of the extensive range of requirements outlined above is only possible thanks to advances in the underlying mobile radio technology. As an overview, we outline here three fundamental technologies that have shaped the LTE radio interface design: *multicarrier* technology, *multiple-antenna* technology, and the application of *packet-switching* to the radio interface. Finally, we summarize the combinations of capabilities that are supported by different categories of LTE mobile terminal.

1.3.1 Multicarrier Technology

Adopting a multicarrier approach for multiple access in LTE was the first major design choice. After initial consolidation of proposals, the candidate schemes for the downlink were Orthogonal Frequency-Division Multiple Access (OFDMA)[8] and Multiple WCDMA, while the candidate schemes for the uplink were Single-Carrier Frequency-Division Multiple Access (SC-FDMA), OFDMA and Multiple WCDMA. The choice of multiple-access schemes was made in December 2005, with OFDMA being selected for the downlink, and SC-FDMA for the uplink. Both of these schemes open up the frequency domain as a new dimension of flexibility in the system, as illustrated schematically in Figure 1.4.

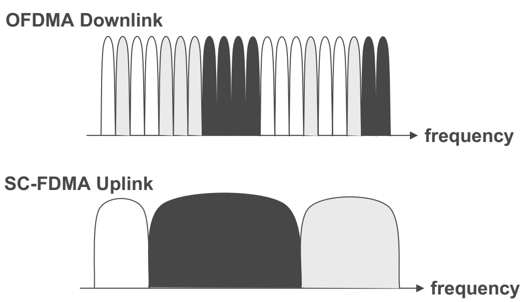

Figure 1.4 Frequency-domain view of the LTE multiple-access technologies.

OFDMA extends the multicarrier technology OFDM to provide a very flexible multiple-access scheme. OFDM subdivides the bandwidth available for signal transmission into a multitude of narrowband subcarriers, arranged to be mutually orthogonal, which either individually or in groups can carry independent information streams; in OFDMA, this

[8]OFDM technology was already well understood in 3GPP as a result of an earlier study of the technology in 2003–4.

subdivision of the available bandwidth is exploited in sharing the subcarriers among multiple users.[9]

This resulting flexibility can be used in various ways:

- Different spectrum bandwidths can be utilized without changing the fundamental system parameters or equipment design.
- Transmission resources of variable bandwidth can be allocated to different users and scheduled freely in the frequency domain.
- Fractional frequency re-use and interference coordination between cells are facilitated.

Extensive experience with OFDM has been gained in recent years from deployment of digital audio and video broadcasting systems such as DAB, DVB and DMB.[10] This experience has highlighted some of the key advantages of OFDM, which include:

- robustness to time-dispersive radio channels, thanks to the subdivision of the wide-band transmitted signal into multiple narrowband subcarriers, enabling inter-symbol interference to be largely constrained within a guard interval at the beginning of each symbol;
- low-complexity receivers, by exploiting frequency-domain equalization;
- simple combining of signals from multiple transmitters in broadcast networks.

These advantages, and how they arise from the OFDM signal design, are explained in detail in Chapter 5.

By contrast, the transmitter design for OFDM is more costly, as the Peak-to-Average Power Ratio (PAPR) of an OFDM signal is relatively high, resulting in a need for a highly-linear RF power amplifier. However, this limitation is not inconsistent with the use of OFDM for *downlink* transmissions, as low-cost implementation has a lower priority for the base station than for the mobile terminal.

In the uplink, however, the high PAPR of OFDM is difficult to tolerate for the transmitter of the mobile terminal, since it is necessary to compromise between the output power required for good outdoor coverage, the power consumption, and the cost of the power amplifier. SC-FDMA, which is explained in detail in Chapter 15, provides a multiple-access technology which has much in common with OFDMA – in particular the flexibility in the frequency domain, and the incorporation of a guard interval at the start of each transmitted symbol to facilitate low-complexity frequency-domain equalization at the receiver. At the same time, SC-FDMA has a significantly lower PAPR. It therefore resolves to some extent the dilemma of how the uplink can benefit from the advantages of multicarrier technology while avoiding excessive cost for the mobile terminal transmitter and retaining a reasonable degree of commonality between uplink and downlink technologies.

As mentioned above, during the early stages of the development of LTE another multicarrier based solution to the multiple access scheme was also actively considered – namely multiple WCDMA carriers. This would have had the advantage of reusing existing

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[9]The use of the frequency domain comes in addition to the well-known time-division multiplexing which continues to play an important role in LTE.

[10]Digital Audio Broadcasting, Digital Video Broadcasting and Digital Mobile Broadcasting.

technology from the established UMTS systems. However, as the LTE system is intended to remain competitive for many years into the future, the initial benefits of technology reuse from UMTS become less advantageous in the long-term; continuation with the same technology would have missed the opportunity to embrace new possibilities and to benefit from OFDM with its flexibility, low receiver complexity and high performance in time-dispersive channels.

1.3.2 Multiple Antenna Technology

The use of multiple antenna technology allows the exploitation of the spatial-domain as another new dimension. This becomes essential in the quest for higher spectral efficiencies. As will be detailed in Chapter 11, with the use of multiple antennas the theoretically-achievable spectral efficiency scales linearly with the minimum of the number of transmit and receive antennas employed, at least in suitable radio propagation environments.

Multiple antenna technology opens the door to a large variety of features, but not all of them easily deliver their theoretical promises when it comes to implementation in practical systems. Multiple antennas can be used in a variety of ways, mainly based on three fundamental principles, schematically illustrated in Figure 1.5:

- **Diversity gain.** Use of the space-diversity provided by the multiple antennas to improve the robustness of the transmission against multipath fading.

- **Array gain.** Concentration of energy in one or more given directions via precoding or beamforming. This also allows multiple users located in different directions to be served simultaneously (so-called multi-user MIMO).

- **Spatial multiplexing gain.** Transmission of multiple signal streams to a single user on multiple spatial layers created by combinations of the available antennas.

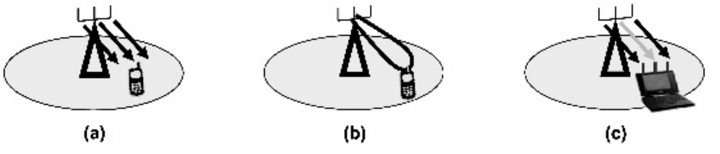

Figure 1.5 Three fundamental benefits of multiple antennas: (a) diversity gain; (b) array gain; (c) spatial multiplexing gain.

A large part of the LTE 'Study Item' phase was therefore dedicated to the selection and design of the various multiple antenna features to be included in LTE. The final system includes several complementary options which allow for adaptability according to the deployment and the propagation conditions of the different users.

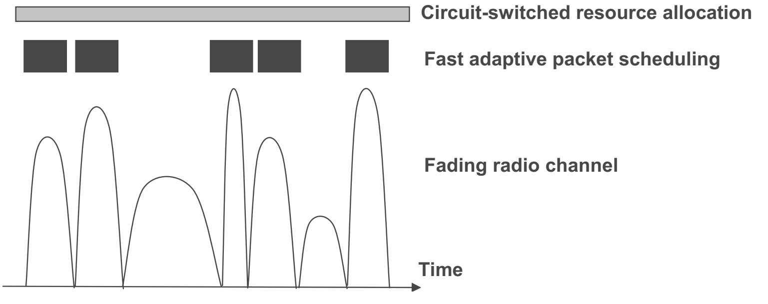

Figure 1.6 Fast scheduling and link adaptation.

1.3.3 Packet-Switched Radio Interface

As has already been noted, LTE has been designed as a completely packet-oriented multi-service system, without the reliance on circuit-switched connection-oriented protocols prevalent in its predecessors. In LTE, this philosophy is applied across all the layers of the protocol stack.

The route towards fast packet scheduling over the radio interface was already opened by HSDPA, which allowed the transmission of short packets having a duration of the same order of magnitude as the coherence time of the fast fading channel, as shown in Figure 1.6. This calls for a joint optimization of the physical layer configuration and the resource management carried out by the link layer protocols according to the prevailing propagation conditions. This aspect of HSDPA involves tight coupling between the lower two layers of the protocol stack – the MAC (Medium Access Control layer; see Chapter 4) and the physical layer. In HSDPA, this coupling already includes features such as fast channel state feedback, dynamic link adaptation, scheduling exploiting multi-user diversity, and fast retransmission protocols.

In LTE, in order to improve the system latency the packet duration was further reduced from the 2 ms used in HSDPA down to just 1 ms. This short transmission interval, together with the new dimensions of frequency and space, has further extended the field of cross-layer techniques between the MAC and physical layers to include the following techniques in LTE:

- adaptive scheduling in both the frequency and spatial dimensions;
- adaptation of the MIMO configuration including the selection of the number of spatial layers transmitted simultaneously;
- link adaptation of modulation and code-rate, including the number of transmitted codewords;
- several modes of fast channel state reporting.

These different levels of optimization are combined with very sophisticated control signalling, which proved to be one of the significant challenges in turning the LTE concept into a working system.

1.3.4 User Equipment Capabilities

The whole LTE system is built around the three fundamental technologies outlined above, combined with a new flat network architecture. Together, these technologies enable the targets set out in Section 1.2 to be met. By exploiting these technologies to the full, it would be possible for all LTE terminals, known as User Equipment (UE), to reach performance exceeding the peak transmission rates and spectral efficiencies.

However, in practice it is important to recognize that the market for UEs is large and diverse, and there is therefore a need for LTE to support a range of categories of UE with different capabilities to satisfy different market segments. In general, each market segment attaches different priorities to aspects such as peak data rate, UE size, cost and battery life. Some typical trade-offs include the following:

- Support for the highest data rates is key to the success of some applications, but generally requires large amounts of memory for data processing, which increases the cost of the UE.
- UEs which may be embedded in large devices such as laptop computers are often not significantly constrained in terms of acceptable power consumption or the number of antennas which may be used; on the other hand, other market segments require ultra-slim hand-held terminals which have little space for multiple antennas or large batteries.

The wider the range of UE categories supported, the closer the match which may be made between a UE's capabilities and the requirements of a particular market segment. However, support for a large number of UE categories also has drawbacks in terms of the signalling overhead required for each UE to inform the network about its capabilities, as well as increased costs due to loss of economies of scale and increased complexity for testing the interoperability of many different configurations.

The LTE system has therefore been designed to support a compact set of five categories of UE, ranging from relatively low-cost terminals with similar capabilities to UMTS HSPA, up to very high-capability terminals which exploit the LTE technology to the maximum extent possible and exceed the peak data rate targets.

The capabilities of the five categories are summarized in Table 1.2.

It can be seen that the highest category of LTE UE possesses peak data rate capabilities far exceeding the LTE targets.

1.4 From Theory to Practice

As a result of intense activity by a larger number of contributing companies than ever before in 3GPP, the study phase finally closed in September 2006, just two years after the LTE inauguration workshop. It had been shown that fulfilment of the agreed requirements for LTE was feasible, and the process of finalizing the technical choices and drafting a complete version of the specifications for the LTE was able to begin. By December 2007, although significant areas of detail remained to be defined, the specifications had reached a sufficient level of completeness to enable LTE to be submitted to the ITU-R as a member of the IMT family of radio access technologies, and therefore able to be deployed in IMT-designated spectrum.

Table 1.2 Categories of LTE user equipment.

	UE category				
	1	2	3	4	5
Maximum downlink data rate (Mbps)	10	50	100	150	300
Maximum uplink data rate (Mbps)	5	25	50	50	75
Number of receive antennas required	2	2	2	2	4
Number of downlink MIMO streams supported	1	2	2	2	4
Support for 64QAM modulation in downlink	✔	✔	✔	✔	✔
Support for 64QAM modulation in uplink	✖	✖	✖	✖	✔
Relative memory requirement for physical layer processing (normalized to category 1 level)	1	4.9	4.9	7.3	14.6

Thus the advances in theoretical understanding and technology which underpin the LTE specifications are destined for practical exploitation. This book is written with the primary aim of illuminating the transition from this underlying academic progress to the realization of useful advances in the provision of mobile communication services. Particular focus is given to the physical layer of the Radio Access Network (RAN), as it is here that many of the most dramatic technical advances are manifested. This should enable the reader to develop an understanding of the background to the technology choices in the LTE system, and hence to understand better the LTE specifications and how to implement them.[11]

Part 1 of the book sets the radio interface in the context of the network architecture and protocols, as well as explaining the new developments in these areas which distinguish LTE from previous systems.

In Part 2, the physical layer of the RAN downlink is covered in detail, beginning with an explanation of the theory of the new downlink multiple access technology, OFDMA, in Chapter 5. This sets the context for the details of the LTE downlink design in Chapters 6 to 9. As coding, link adaptation and multiple antenna operation are of fundamental importance in fulfilling the LTE requirements, two chapters are then devoted to these topics, covering both the theory and the practical implementation in LTE.

Chapters 12 and 13 show how these techniques can be applied to the system-level operation of the LTE system, focusing on applying the new degrees of freedom to multi-user scheduling, interference coordination and radio resource management.

Finally for the downlink, Chapter 14 covers broadcast operation – a mode which has its own unique challenges in a cellular system but which is nonetheless important in enabling a range of services to be provided to the end user.

Part 3 addresses the physical layer of the RAN uplink, beginning in Chapter 15 with an introduction to the theory behind the new uplink multiple access technology, SC-FDMA. This is followed in Chapters 16 to 20 with an analysis of the detailed uplink structure

[11] The explanations in this book are based on the first version of the LTE specifications, known as Release 8, as at the time of writing. Although most aspects of the specifications were stable at this time, it should be noted that the specifications are regularly updated, and the reader should always refer to the specification documents themselves for the definitive details.

and operation, including the design of the associated procedures for random access, timing control and power control which are essential to the efficient operation of the uplink.

This leads on to Part 4, which examines a number of aspects of the LTE system which arise specifically as a result of it being a mobile cellular system. Chapter 21 provides a thorough analysis of the characteristics of the radio propagation environments in which LTE systems will be deployed, since an understanding of the propagation environment underpins much of the technology adopted for the LTE specifications. The new technologies and bandwidths adopted in LTE also have implications for the radio-frequency implementation of the mobile terminals in particular, and some of these are analysed in Chapter 22. The LTE system is designed to operate not just in wide bandwidths but also in a diverse range of spectrum allocation scenarios, and Chapter 23 therefore addresses the different duplex modes applicable to LTE and the effects that these may have on system design and operation.

Finally, Part 5 recognizes that the initial version of the LTE system will not terminate the long process of advancement of mobile communications. Chapter 24 takes us beyond the initial version of LTE to consider some of the ways in which the evolution is already continuing towards LTE-Advanced, in response to the latest challenges posed by the ITU-R and by the ever-higher expectations of end-users.

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