

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 in Releases 8 and 9.

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)¹ 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.

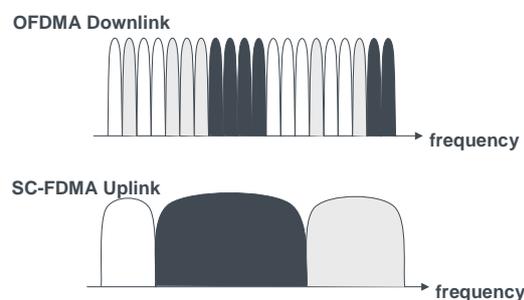


Figure 1.4: Frequency-domain view of the LTE multiple-access technologies.

OFDMA extends the multicarrier technology of 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 subdivision of the available bandwidth is exploited in sharing the subcarriers among multiple users.²

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.³ 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 wideband transmitted signal into multiple narrowband subcarriers, enabling inter-symbol interference to be largely constrained within a guard interval at the beginning of each symbol;

¹ OFDM technology was already well understood in 3GPP as a result of an earlier study of the technology in 2003–4.

² 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.

³ Digital Audio Broadcasting, Digital Video Broadcasting and Digital Mobile Broadcasting.

- 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 highlylinear 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. SCFDMA, which is explained in detail in Chapter 14, 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.

In Release 10, the uplink multiple access scheme is extended to allow multiple clusters of subcarriers in the frequency domain, as explained in Section 28.3.6.

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 spatial 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.

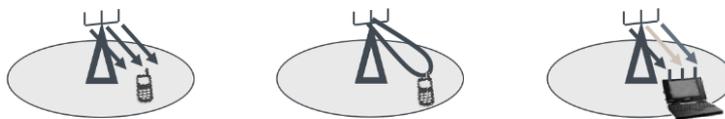


Figure 1.5: Three fundamental benefits of multiple antennas:
(a) diversity gain; (b) array gain; (c) spatial multiplexing gain.

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 the first release of LTE. The final system includes several complementary options which allow for adaptability according to the network deployment and the propagation conditions of the different users.

1.3.3 Packet-Switched Radio Interface

As has already been noted, LTE has been designed as a completely packet-oriented multiservice 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 included 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,

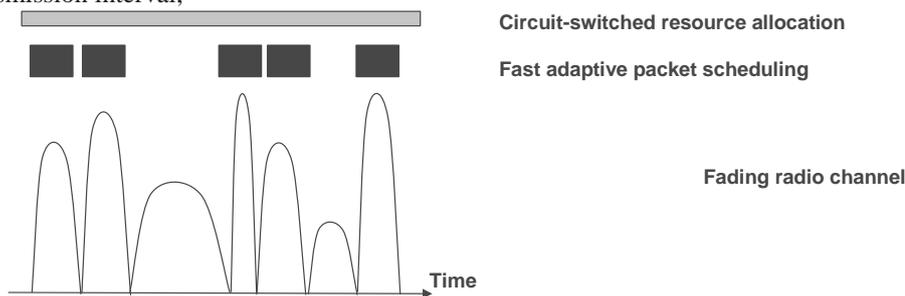


Figure 1.6: Fast scheduling and link adaptation.

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.

1.3.4 User Equipment Categories

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 supported functionality 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 supported functionality, as well as increased costs due to loss of economies of scale and increased complexity for testing the interoperability of many different configurations.

The first release of LTE was therefore 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.

The five Release 8 UE categories are summarized in Table 1.2. It can be seen that the highest category of Release 8 LTE UE possesses peak data rate capabilities far exceeding the LTE Release 8 targets. Full details are specified in [12].

Table 1.2: Categories of LTE user equipment in Releases 8 and 9.

	UE category				
	1	2	3	4	5
Supported downlink data rate (Mbps)	10	50	100	150	300
Supported uplink data rate (Mbps)	5	25	50	50	75
Number of receive antennas required	2	2	2	2	4
Number of downlink MIMO layers 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

Additional UE categories are introduced in Release 10, and these are explained in Section 27.5.

The LTE specifications deliberately avoid large numbers of optional features for the UEs, preferring to take the approach that if a feature is sufficiently useful to be worth including in the specifications then support of it should be mandatory. Nevertheless, a very small number of optional Release 8 features, whose support is indicated by each UE by specific signalling, are listed in [12]; such features are known as ‘UE capabilities’. Some additional UE capabilities are added in later releases.

In addition, it is recognized that it is not always possible to complete conformance testing and Inter-Operability Testing (IOT) of every mandatory feature simultaneously for early deployments of LTE. Therefore, the development of conformance test cases for LTE was prioritized according to the likelihood of early deployment of each feature. Correspondingly, *Feature Group Indicators* (FGIs) are used for certain groups of lower priority mandatory features, to enable a UE to indicate whether IOT has been successfully completed for those features; the grouping of features corresponding to each FGI can be found in Annex B.1 of [13]. For UEs of Release 9 and later, it becomes mandatory for certain of these FGIs to be set to indicate that the corresponding feature(s) have been implemented and successfully tested.

1.3.5 From the First LTE Release to LTE-Advanced

As a result of intense activity by a larger number of contributing companies than ever before in 3GPP, the specifications for the first LTE release (Release 8) had reached a sufficient level of completeness by December 2007 to enable LTE to be submitted to ITU-R as a member of the IMT family of radio access technologies. It is therefore able to be deployed in IMT-designated spectrum, and the first commercial deployments were launched towards the end of 2009 in northern Europe.

Meanwhile, 3GPP has continued to improve the LTE system and to develop it to address new markets. In this section, we outline the new features introduced in the second LTE release, Release 9, and those provided by LTE Release 10, which begins the next significant step known as LTE-Advanced.

Increasing LTE’s suitability for different markets and deployments was the first goal of Release 9. One important market with specific regulatory requirements is North America. LTE Release 9 therefore provides improved support for Public Warning Systems (PWS) and some accurate positioning methods (see Chapter 19). One positioning method uses the Observed Time Difference of Arrival (OTDOA) principle, supported by specially designed new reference signals inserted in the LTE downlink transmissions. Measurements of these positioning reference signals received from different base stations allow a UE to calculate its position very accurately, even in

locations where other positioning means such as GPS fail (e.g. indoors). Enhanced Cell-ID-based techniques are also supported.

Release 9 also introduces support for a broadcast mode based on Single Frequency Network type transmissions (see Chapter 13).

The MIMO transmission modes are further developed in Release 9, with an extension of the Release 8 beamforming mode to support two orthogonal spatial layers that can be transmitted to a single user or multiple users, as described in Section 11.2.2.3. The design of this mode is forward-compatible for extension to more than two spatial layers in Release 10.

Release 9 also addresses specific deployments and, in particular, low power nodes (see Chapter 24). It defines new requirements for pico base stations and home base stations, in addition to improving support for Closed Subscriber Groups (CSG). Support for selfoptimization of the networks is also enhanced in Release 9, as described in Chapter 25.

1.3.5.1 LTE-Advanced

The next version of LTE, Release 10, develops LTE to LTE-Advanced. While LTE Releases 8 and 9 already satisfy to a large extent the requirements set by ITU-R for the IMT-Advanced designation [14] (see Section 27.1), Release 10 will fully satisfy them and even exceed them in several aspects where 3GPP has set more demanding performance targets than those of ITU-R. The requirements for LTE-Advanced are discussed in detail in Chapter 27.

The main Release 10 features that are directly related to fulfilment of the IMT-Advanced requirements are:

- Carrier aggregation, allowing the total transmission bandwidth to be increased up to 100 MHz (see Chapter 28);
- Uplink MIMO transmission for peak spectral efficiencies greater than 7.5 bps/Hz and targeting up to 15 bps/Hz (see Chapter 29);
- Downlink MIMO enhancements, targeting peak spectral efficiencies up to 30 bps/Hz (see Chapter 29).

Besides addressing the IMT-Advanced requirements, Release 10 also provides some new features to enhance LTE deployment, such as support for relaying (see Chapter 30), enhanced inter-cell interference coordination (see Chapter 31) and mechanisms to minimize the need for drive tests by supporting extended measurement reports from the terminals (see Chapters 25 and 31).