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Introduction

We live in the era of a mobile data revolution. With the mass-market expansion of smartphones, tablets, notebooks, and laptop computers, users demand services and applications from mobile communication systems that go far beyond mere voice and telephony. The growth in data-intensive mobile services and applications such as Web browsing, social networking, and music and video streaming has become a driving force for development of the next generation of wireless standards. As a result, new standards are being developed to provide the data rates and network capacity necessary to support worldwide delivery of these types of rich multimedia application.

LTE (Long Term Evolution) and LTE-Advanced have been developed to respond to the requirements of this era and to realize the goal of achieving global broadband mobile communications. The goals and objectives of this evolved system include higher radio access data rates, improved system capacity and coverage, flexible bandwidth operations, significantly improved spectral efficiency, low latency, reduced operating costs, multi-antenna support, and seamless integration with the Internet and existing mobile communication systems.

In some ways, LTE and LTE-Advanced are representatives of what is known as a fourth-generation wireless system and can be considered an organic evolution of the third-generation predecessors. On the other hand, in terms of their underlying transmission technology they represent a disruptive departure from the past and the dawn of what is to come. To put into context the evolution of mobile technology leading up to the introduction of the LTE standards, a short overview of the wireless standard history will now be presented. This overview intends to trace the origins of many enabling technologies of the LTE standards and to clarify some of their requirements, which are expressed in terms of improvements over earlier technologies.

1.1 Quick Overview of Wireless Standards

In the past two decades we have seen the introduction of various mobile standards, from 2G to 3G to the present 4G, and we expect the trend to continue (see Figure 1.1). The primary mandate of the 2G standards was the support of mobile telephony and voice applications. The 3G standards marked the beginning of the packet-based data revolution and the support of Internet

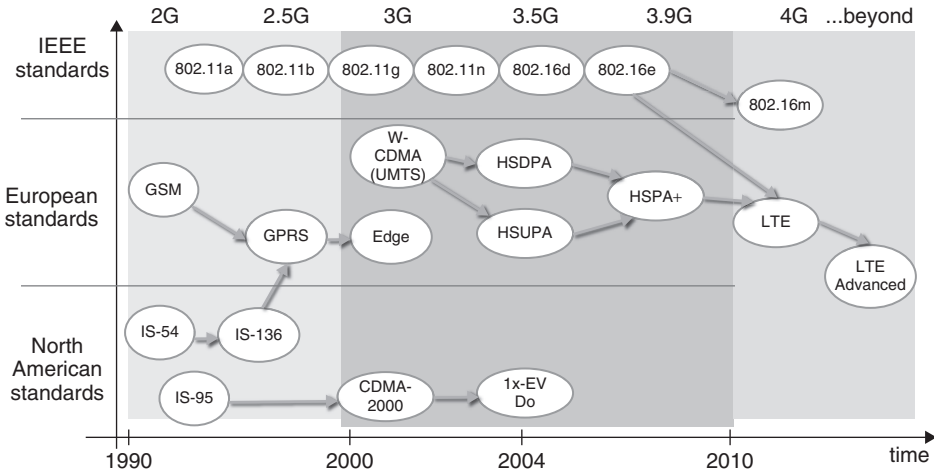


Figure 1.1 Evolution of wireless standards in the last two decades

applications such as email, Web browsing, text messaging, and other client-server services. The 4G standards will feature all-IP packet-based networks and will support the explosive demand for bandwidth-hungry applications such as mobile video-on-demand services.

Historically, standards for mobile communication have been developed by consortia of network providers and operators, separately in North America, Europe, and other regions of the world. The second-generation (2G) digital mobile communications systems were introduced in the early 1990s. The technology supporting these 2G systems were circuit-switched data communications. The GSM (Global System for Mobile Communications) in Europe and the IS-54 (Interim Standard 54) in North America were among the first 2G standards. Both were based on the Time Division Multiple Access (TDMA) technology. In TDMA, a narrowband communication channel is subdivided into a number of time slots and multiple users share the spectrum at allocated slots. In terms of data rates, for example, GSM systems support voice services up to 13 kbps and data services up to 9.6 kbps.

The GSM standard later evolved into the Generalized Packet Radio Service (GPRS), supporting a peak data rate of 171.2 kbps. The GPRS standard marked the introduction of the split-core wireless networks, in which packet-based switching technology supports data transmission and circuit-switched technology supports voice transmission. The GPRS technology further evolved into Enhanced Data Rates for Global Evolution (EDGE), which introduced a higher-rate modulation scheme (8-PSK, Phase Shift Keying) and further enhanced the peak data rate to 384 kbps.

In North America, the introduction of IS-95 marked the first commercial deployment of a Code Division Multiple Access (CDMA) technology. CDMA in IS-95 is based on a direct spread spectrum technology, where multiple users share a wider bandwidth by using orthogonal spreading codes. IS-95 employs a 1.2284 MHz bandwidth and allows for a maximum of 64 voice channels per cell, with a peak data rate of 14.4 kbps per fundamental channel. The IS-95-B revision of the standard was developed to support high-speed packet-based data transmission. With the introduction of the new supplemental code channel supporting high-speed packet data, IS-95-B supported a peak data rate of 115.2 kbps. In North America,

3GPP2 (Third Generation Partnership Project 2) was the standardization body that established technical specifications and standards for 3G mobile systems based on the evolution of CDMA technology. From 1997 to 2003, 3GPP2 developed a family of standards based on the original IS-95 that included 1xRTT, 1x-EV-DO (Evolved Voice Data Only), and EV-DV (Evolved Data and Voice). 1xRTT doubled the IS-95 capacity by adding 64 more traffic channels to achieve a peak data rate of 307 kbps. The 1x-EV-DO and 1x-EV-DV standards achieved peak data rates in the range of 2.4–3.1 Mbps by introducing a set of features including adaptive modulation and coding, hybrid automatic repeat request (HARQ), turbo coding, and faster scheduling based on smaller frame sizes.

The 3GPP (Third-Generation Partnership Project) is the standardization body that originally managed European mobile standard and later on evolved into a global standardization organization. It is responsible for establishing technical specifications for the 3G mobile systems and beyond. In 1997, 3GPP started working on a standardization effort to meet goals specified by the ITU IMT-2000 (International Telecommunications Union International Mobile Telecommunication) project. The goal of this project was the transition from a 2G TDMA-based GSM technology to a 3G wide-band CDMA-based technology called the Universal Mobile Telecommunications System (UMTS). The UMTS represented a significant change in mobile communications at the time. It was standardized in 2001 and was dubbed Release 4 of the 3GPP standards. The UMTS system can achieve a downlink peak data rate of 1.92 Mbps. As an upgrade to the UMTS system, the High-Speed Downlink Packet Access (HSDPA) was standardized in 2002 as Release 5 of the 3GPP. The peak data rates of 14.4 Mbps offered by this standard were made possible by introducing faster scheduling with shorter subframes and the use of a 16QAM (Quadrature Amplitude Modulation) modulation scheme. High-Speed Uplink Packet Access (HSUPA) was standardized in 2004 as Release 6, with a maximum rate of 5.76 Mbps. Both of these standards, together known as HSPA (High-Speed Packet Access), were then upgraded to Release 7 of the 3GPP standard known as HSPA+ or MIMO (Multiple Input Multiple Output) HSDPA. The HSPA+ standard can reach rates of up to 84 Mbps and was the first mobile standard to introduce a 2×2 MIMO technique and the use of an even higher modulation scheme (64QAM). Advanced features that were originally introduced as part of the North American 3G standards were also incorporated in HSPA and HSPA+. These features include adaptive modulation and coding, HARQ, turbo coding, and faster scheduling.

Another important wireless application that has been a driving force for higher data rates and spectral efficiency is the wireless local area network (WLAN). The main purpose of WLAN standards is to provide stationary users in buildings (homes, offices) with reliable and high-speed network connections. As the global mobile communications networks were undergoing their evolution, IEEE (Institute of Electrical and Electronics Engineers) was developing international standards for WLANs and wireless metropolitan area networks (WMANs). With the introduction of a family of WiFi standards (802.11a/b/g/n) and WiMAX standards (802.16d/e/m), IEEE established Orthogonal Frequency Division Multiplexing (OFDM) as a promising and innovative air-interface technology. For example, the IEEE 802.11a WLAN standard uses the 5 GHz frequency band to transmit OFDM signals with data rates of up to 54 Mb/s. In 2006, IEEE standardized a new WiMAX standard (IEEE 802.16m) that introduced a packet-based wireless broadband system. Among the features of WiMAX are scalable bandwidths up to 20 MHz, higher peak data rates, and better spectral efficiency profiles than were being offered by the UMTS and HSPA systems at the time. This advance essentially kicked off the effort by 3GPP to introduce a new wireless mobile standard that could compete with the WiMAX technology. This effort ultimately led to the standardization of the LTE standard.

Table 1.1 Peak data rates of various wireless standards introduced over the past two decades

Technology	Theoretical peak data rate (at low mobility)
GSM	9.6 kbps
IS-95	14.4 kbps
GPRS	171.2 kbps
EDGE	473 kbps
CDMA-2000 (1xRTT)	307 kbps
WCDMA (UMTS)	1.92 Mbps
HSDPA (Rel 5)	14 Mbps
CDMA-2000 (1x-EV-DO)	3.1 Mbps
HSPA+ (Rel 6)	84 Mbps
WiMAX (802.16e)	26 Mbps
LTE (Rel 8)	300 Mbps
WiMAX (802.16m)	303 Mbps
LTE-Advanced (Rel 10)	1 Gbps

1.2 Historical Profile of Data Rates

Table 1.1 summarizes the peak data rates of various wireless technologies. Looking at the maximum data rates offered by these standards, the LTE standard (3GPP release 8) is specified to provide a maximum data rate of 300 Mbps. The LTE-Advanced (3GPP version 10) features a peak data rate of 1 Gbps.

These figures represent a boosts in peak data rates of about 2000 times above what was offered by GSM/EDGE technology and 50–500 times above what was offered by the W-CDMA/UMTS systems. This remarkable boost was achieved through the development of new technologies introduced within a time span of about 10 years. One can argue that this extraordinary advancement is firmly rooted in the elegant mathematical formulation of the enabling technologies featured in the LTE standards. It is our aim in this book to clarify and explain these enabling technologies and to put into context how they combine to achieve such a performance. We also aim to gain insight into how to simulate, verify, implement, and further enhance the PHY (Physical Layer) technology of the LTE standards.

1.3 IMT-Advanced Requirements

The ITU has published a set of requirements for the design of mobile systems. The first recommendations, released in 1997, were called IMT-2000 (International Mobile Telecommunications 2000) [1]. These recommendations included a set of goals and requirements for radio interface specification. 3G mobile communications systems were developed to be compliant with these recommendations. As the 3G systems evolved, so did the IMT-2000 requirements, undergoing multiple updates over the past decade [2].

In 2007, ITU published a new set of recommendations that set the bar much higher and provided requirements for IMT-Advanced systems [3]. IMT-Advanced represents the

requirements for the building of truly global broadband mobile communications systems. Such systems can provide access to a wide range of packet-based advanced mobile services, support low- to high-mobility applications and a wide range of data rates, and provide capabilities for high-quality multimedia applications. The new requirements were published to spur research and development activities that bring about a significant improvement in performance and quality of services over the existing 3G systems.

One of the prominent features of IMT-Advanced is the enhanced peak data for advanced services and applications (100 Mbps for high mobility and 1 Gbps for low mobility). These requirements were established as targets for research. The LTE-Advanced standard developed by 3GPP and the mobile WiMAX standard developed by IEEE are among the most prominent standards to meet the requirements of the IMT-Advanced specifications. In this book, we focus on the LTE standards and discuss how their PHY specification is consistent with the requirements of the IMT-Advanced.

1.4 3GPP and LTE Standardization

The LTE and LTE-Advanced are developed by the 3GPP. They inherit a lot from previous 3GPP standards (UMTS and HSPA) and in that sense can be considered an evolution of those technologies. However, to meet the IMT-Advanced requirements and to keep competitive with the WiMAX standard, the LTE standard needed to make a radical departure from the W-CDMA transmission technology employed in previous standards. LTE standardization work began in 2004 and ultimately resulted in a large-scale and ambitious re-architecture of mobile networks. After four years of deliberation, and with contributions from telecommunications companies and Internet standardization bodies all across the globe, the standardization process of LTE (3GPP Release 8) was completed in 2008. The Release 8 LTE standard later evolved to LTE Release 9 with minor modifications and then to Release 10, also known as the LTE-Advanced standard. The LTE-Advanced features improvements in spectral efficiency, peak data rates, and user experience relative to the LTE. With a maximum peak data rate of 1 Gbps, LTE-Advanced has also been approved by the ITU as an IMT-Advanced technology.

1.5 LTE Requirements

LTE requirements cover two fundamental components of the evolved UMTS system architecture: the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and the Evolved Packet Core (EPC). The goals of the overall system include the following:

- Improved system capacity and coverage
- High peak data rates
- Low latency (both user-plane and control-plane)
- Reduced operating costs
- Multi-antenna support
- Flexible bandwidth operations
- Seamless integration with existing systems (UMTS, WiFi, etc.).

As a substantial boost in mobile data rates is one of the main mandates of the LTE standards, it is useful to review some of the recent advances in communications research as

well as theoretical considerations related to the maximum achievable data rates in a mobile communications link. We will now present some highlights related to this topic, inspired by an excellent discussion presented in Reference [4].

1.6 Theoretical Strategies

Shannon's fundamental work on channel capacity states that data rates are always limited by the available received signal power or the received signal-to-noise-power ratio [5]. It also relates the data rates to the transmission bandwidths. In the case of low-bandwidth utilization, where the data rate is substantially lower than the available bandwidth, any increase of the data rate will require an increase in the received signal power in a proportional manner. In the case of high-bandwidth utilization, where data rates are equal to or greater than the available bandwidth, any increase in the data rate will require a much larger relative increase in the received signal power unless the bandwidth is increased in proportion to the increase in data rate.

A rather intuitive way to increase the overall power at the receiver is to use multiple antennas at the receiver side. This is known as receive diversity. Multiple antennas can also be used at the transmitter side, in what is known as transmit diversity. A transmit diversity approach based on beamforming uses multiple transmit antennas to focus the transmitted power in the direction of the receiver. This can potentially increase the received signal power and allow for higher data rates.

However, increasing data rates by using either transmit diversity or receive diversity can only work up to a certain point. Beyond this, any boost in data rates will start to saturate. An alternative approach is to use multiple antennas at both the transmitter and the receiver. For example, a technique known as spatial multiplexing, which exploits multiple antennas at the transmitter and the receiver sides, is an important member of the class of multi-antenna techniques known as MIMO. Different types of MIMO technique, including open-loop and closed-loop spatial multiplexing, are used in the LTE standard.

Beside the received signal power, another factor directly impacting on the achievable data rates of a mobile communications system is the transmission bandwidth. The provisioning of higher data rates usually involves support for even wider transmission bandwidths. The most important challenge related to wider-band transmission is the effect of multipath fading on the radio channel. Multipath fading is the result of the propagation of multiple versions of the transmitted signals through different paths before they arrive at the receiver. These different versions exhibit varying profiles of signal power and time delays or phases. As a result, the received signal can be modeled as a filtered version of the transmitted signal that is filtered by the impulse response of the radio channel. In the frequency domain, a multipath fading channel exhibits a time-varying channel frequency response. The channel frequency response inevitably corrupts the original frequency-domain content of the transmitted signal, with an adverse effect on the achievable data rates. In order to adjust for the effects of channel frequency selectivity and to achieve a reasonable performance, we must either increase the transmit power, reduce our expectations concerning data rates, or compensate for the frequency-domain distortions with equalization.

Many channel-equalization techniques have been proposed to counter the effects of multipath fading. Simple time-domain equalization methods have been shown to provide adequate performance for transmission over transmission bandwidths of up to 5 MHz. However, for

LTE standards and other mobile systems that provision for wider bandwidths of 10, 15, or 20 MHz, or higher, the complexity of the time-domain equalizers become prohibitively large. In order to overcome the problems associated with time-domain equalization, two approaches to wider-band transmission have been proposed:

- The use of multicarrier transmission schemes, where a wider band signal is represented as the sum of several more narrowband orthogonal signals. One special case of multicarrier transmission used in the LTE standard is the OFDM transmission.
- The use of a single-carrier transmission scheme, which provides the benefits of low-complexity frequency-domain equalization offered by OFDM without introducing its high transmit power fluctuations. An example of this type of transmission is called Single-Carrier Frequency Division Multiplexing (SC-FDM), which is used in the LTE standard as the technology for uplink transmission.

Furthermore, a rather straightforward way of providing higher data rates within a given transmission bandwidth is the use of higher-order modulation schemes. Using higher-order modulation allows us to represent more bits with a single modulated symbol and directly increases bandwidth utilization. However, the higher bandwidth utilization comes at a cost: a reduced minimum distance between modulated symbols and a resultant increased sensitivity to noise and interference. Consequently, adaptive modulation and coding and other link adaptation strategies can be used to judiciously decide when to use a lower- or higher-order modulation. By applying these adaptive methods, we can substantially improve the throughput and achievable data rates in a communications link.

1.7 LTE-Enabling Technologies

The enabling technologies of the LTE and its evolution include the OFDM, MIMO, turbo coding, and dynamic link-adaptation techniques. As discussed in the last section, these technologies trace their origins to well-established areas of research in communications and together help contribute to the ability of the LTE standard to meet its requirements.

1.7.1 OFDM

As elegantly described in Reference [6], the main reasons LTE selects OFDM and its single-carrier counterpart SC-FDM as the basic transmission schemes include the following: robustness to the multipath fading channel, high spectral efficiency, low-complexity implementation, and the ability to provide flexible transmission bandwidths and support advanced features such as frequency-selective scheduling, MIMO transmission, and interference coordination.

OFDM is a multicarrier transmission scheme. The main idea behind it is to subdivide the information transmitted on a wideband channel in the frequency domain and to align data symbols with multiple narrowband orthogonal subchannels known as subcarriers. When the frequency spacing between subcarriers is sufficiently small, an OFDM transmission scheme can represent a frequency-selective fading channel as a collection of narrowband flat fading subchannels. This in turn enables OFDM to provide an intuitive and simple way of estimating

the channel frequency response based on transmitting known data or reference signals. With a good estimate of the channel response at the receiver, we can then recover the best estimate of the transmitted signal using a low-complexity frequency-domain equalizer. The equalizer in a sense inverts the channel frequency response at each subcarrier.

1.7.2 SC-FDM

One of the drawbacks of OFDM multicarrier transmission is the large variations in the instantaneous transmit power. This implies a reduced efficiency in power amplifiers and results in higher mobile-terminal power consumption. In uplink transmission, the design of complex power amplifiers is especially challenging. As a result, a variant of the OFDM transmission known as SC-FDM is selected in the LTE standard for uplink transmission. SC-FDM is implemented by combining a regular OFDM system with a precoding based on Discrete Fourier Transform (DFT) [6]. By applying a DFT-based precoding, SC-FDM substantially reduces fluctuations of the transmit power. The resulting uplink transmission scheme can still feature most of the benefits associated with OFDM, such as low-complexity frequency-domain equalization and frequency-domain scheduling, with less stringent requirements on the power amplifier design.

1.7.3 MIMO

MIMO is one of the key technologies deployed in the LTE standards. With deep roots in mobile communications research, MIMO techniques bring to bear the advantages of using multiple antennas in order to meet the ambitious requirements of the LTE standard in terms of peak data rates and throughput.

MIMO methods can improve mobile communication in two different ways: by boosting the overall data rates and by increasing the reliability of the communication link. The MIMO algorithms used in the LTE standard can be divided into four broad categories: receive diversity, transmit diversity, beamforming, and spatial multiplexing. In transmit diversity and beamforming, we transmit redundant information on different antennas. As such, these methods do not contribute to any boost in the achievable data rates but rather make the communications link more robust. In spatial multiplexing, however, the system transmits independent (nonredundant) information on different antennas. This type of MIMO scheme can substantially boost the data rate of a given link. The extent to which data rates can be improved may be linearly proportional to the number of transmit antennas. In order to accommodate this, the LTE standard provides multiple transmit configurations of up to four transmit antennas in its downlink specification. The LTE-Advanced allows the use of up to eight transmit antennas for downlink transmission.

1.7.4 Turbo Channel Coding

Turbo coding is an evolution of the convolutional coding technology used in all previous standards with impressive near-channel capacity performance [7]. Turbo coding was first introduced in 1993 and has been deployed in 3G UMTS and HSPA systems. However, in these

standards it was used as an optional way of boosting the performance of the system. In the LTE standard, on the other hand, turbo coding is the only channel coding mechanism used to process the user data.

The near-optimal performance of turbo coders is well documented, as is the computational complexity associated with their implementation. The LTE turbo coders come with many improvements, aimed at making them more efficient in their implementation. For example, by appending a CRC (Cyclic Redundancy Check) checking syndrome to the input of the turbo encoder, LTE turbo decoders can take advantage of an early termination mechanism if the quality of the code is deemed acceptable. Instead of following through with a fixed number of decoding iterations, the decoding can be stopped early when the CRC check indicates that no errors are detected. This very simple solution allows the computational complexity of the LTE turbo decoders to be reduced without severely penalizing their performance.

1.7.5 Link Adaptation

Link adaptation is defined as a collection of techniques for changing and adapting the transmission parameters of a mobile communication system to better respond to the dynamic nature of the communication channel. Depending on the channel quality, we can use different modulation and coding techniques (adaptive modulation and coding), change the number of transmit or receive antennas (adaptive MIMO), and even change the transmission bandwidth (adaptive bandwidth). Closely related to link adaptation is channel-dependent scheduling in a mobile communication system. Scheduling deals with the question of how to share the radio resources between different users in order to achieve more efficient resource utilizations. Typically, we need to either minimize the amount of resources allocated to each user or match the resources to the type and priority of the user data. Channel-dependent scheduling aims to accommodate as many users as possible, while satisfying the best quality-of-service requirements that may exist based on the instantaneous channel condition.

1.8 LTE Physical Layer (PHY) Modeling

In this book we will focus on digital signal processing in the physical layer of the Radio Access networks. Almost no discussion of the LTE core networks is present here, and we will leave the discussion of higher-layer processing such as Radio Resource Control (RRC), Radio Link Control (RLC), and Medium Access Control (MAC) to another occasion.

Physical layer modeling involves all the processing performed on bits of data that are handed down from the higher layers to the PHY. It describes how various transport channels are mapped to physical channels, how signal processing is performed on each of these channels, and how data are ultimately transported to the antenna for transmission.

For example, Figure 1.2 illustrates the PHY model for the LTE downlink transmission. First, the data is multiplexed and encoded in a step known as Downlink Shared Channel processing (DL-SCH). The DL-SCH processing chain involves attaching a CRC code for error detection, segmenting the data into smaller chunks known as subblocks, undertaking channel-coding operations based on turbo coding for the user data, carrying out a rate-matching operation that selects the number of output bits to reflect a desired coding rate, and finally reconstructing the codeblocks into codewords. The next phase of processing is known as physical downlink

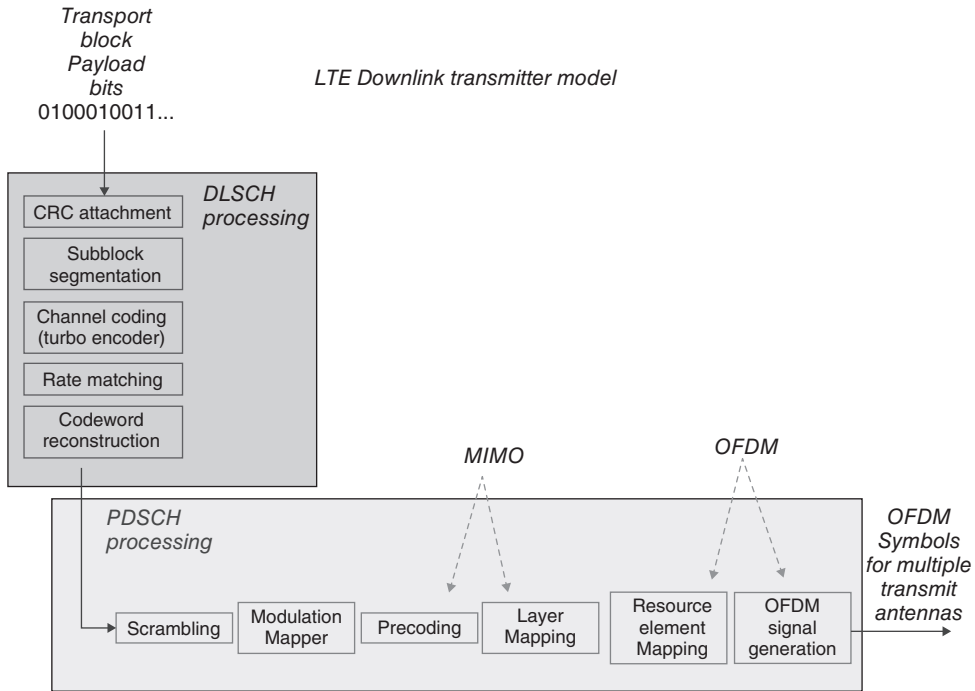


Figure 1.2 Physical layer specifications in LTE

shared channel processing. In this phase, the codewords first become subject to a scrambling operation and then undergo a modulation mapping that results in a modulated symbol stream. The next step comprises the LTE MIMO or multi-antenna processing, in which a single stream of modulated symbols is subdivided into multiple substreams destined for transmission via multiple antennas. The MIMO operations can be regarded as a combination of two steps: precoding and layer mapping. Precoding scales and organizes symbols allocated to each substream and layer mapping selects and routes data into each substream to implement one of the nine different MIMO modes specified for downlink transmission. Among the available MIMO techniques implemented in downlink transmission are transmit diversity, spatial multiplexing, and beamforming. The final step in the processing chain relates to the multicarrier transmission. In downlink, the multicarrier operations are based on the OFDM transmission scheme. The OFDM transmission involves two steps. First, the resource element mapping organizes the modulated symbols of each layer within a time–frequency resource grid. On the frequency axis of the grid, the data are aligned with subcarriers in the frequency domain. In the OFDM signal-generation step, a series of OFDM symbols are generated by applying inverse Fourier transform to compute the transmitted data in time and are transported to each antenna for transmission.

In my opinion, it is remarkable that such a straightforward and intuitive transmission structure can combine all the enabling technologies so effectively that they meet the diverse and stringent IMT-Advanced requirements set out for the LTE standardization. By focusing on PHY modeling, we aim to address challenges in understanding the development of the digital signal processing associated with the LTE standard.

1.9 LTE (Releases 8 and 9)

The introduction of the first release of the LTE standard was the culmination of about four years of work by 3GPP, starting in 2005. Following an extensive study of various technologies capable of delivering on the requirements set for the LTE standard, it was decided that the air interface transmission technology of the new standard would be based on OFDM in downlink and SC-FDM in uplink. The full specifications, including various MIMO modes, were then incorporated in the standard. The first version of the LTE standard (3GPP version 8) was released in December 2008. Release 9 came in December 2009; it included relatively minor enhancements such as Multimedia Broadcast/Multicast Services (MBMS) support, location services, and provisioning for base stations that support multiple standards [4].

1.10 LTE-Advanced (Release 10)

The LTE-Advanced was released in December 2010. LTE-Advanced is an evolution of the original LTE standard and does not represent a new technology. Among the technologies added to the LTE standard to result in the LTE-Advanced were carrier aggregation, enhanced downlink MIMO, uplink MIMO, and relays [4].

1.11 MATLAB[®] and Wireless System Design

In this book, we use MATLAB to model the PHY of the LTE standard and to obtain insight into its simulation and implementation requirements. MATLAB is a widely used language and a high-level development environment for mathematical modeling and numerical computations. We also use Simulink, a graphical design environment for system simulations and model-based design, as well as various MATLAB toolboxes – application-specific libraries of components that make the task of modeling applications in MATLAB easier. For example, in order to model communications systems we use functionalities from the Communication System Toolbox. The toolbox provides tools for the design, prototyping, simulation, and verification of communications systems, including wireless standards in both MATLAB and Simulink.

Among the functionalities in MATLAB that are introduced in this book are the new System objects. System objects are a set of algorithmic building blocks suitable for system design available in various MATLAB toolboxes. They are self-documented algorithms that make the task of developing MATLAB testbenches to perform system simulations easier. By covering a wide range of algorithms, they also eliminate the need to recreate the basic building blocks of communications systems in MATLAB, C, or any other programming language. System objects are designed not only for modeling and simulation but also to provide support for implementation. For example, they have favorable characteristics that help accelerate simulation speeds and support C/C++ code generation and fixed-point numeric, and a few of them support automatic HDL (Hardware Description Language) code generation.

1.12 Organization of This Book

The thesis of this book is that by understanding its four enabling technologies (OFDMA, MIMO, turbo coding, and link adaptation) the reader can obtain an adequate understanding of the PHY model of the LTE standard. Chapter 2 provides a short overview of the technical specifications of the LTE standard. Chapter 3 provides an introduction to the tools and features

in MATLAB that are useful for the modeling and simulation of mobile communications systems. In Chapters 4–7, we treat each of the OFDM, MIMO, modulation, and coding and link adaptation techniques in detail. In each chapter, we create models in MATLAB that iteratively and progressively build up components of the LTE PHY based on these techniques. Chapter 8, on system-level specifications and performance evaluation, discusses various channel models specified in the standard and ways of performing system-level qualitative and quantitative performance analysis in MATLAB and Simulink. It also wraps up the first part of the book by putting together a system model and showing how the PHY of the LTE standard can be modeled in MATLAB based on the insight obtained in the preceding chapters.

The second part deals with practical issues such as simulation of the system and implementation of its components. Chapter 9 includes discussion on how to accelerate the speed of our MATLAB programs using a variety of techniques, including parallel computing, automatic C code generation, GPU (Graphics Progressing Unit) processing, and the use of more efficient algorithms. In Chapter 10, we discuss related implementation issues such as automatic C/C++ code generation from the MATLAB code, target environments, and code optimizations, and how these affect the programming style. We also discuss fixed-point numerical representation of data as a prerequisite for hardware implementation and its effect on the performance of various modeling components. Finally, in Chapter 11, we summarize our discussions and highlight directions for future work.

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