Chapter 11

RF Planning and Optimization for LTE Networks

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Contents

11.1 Introduction

Long-term evolution (LTE) is the next generation in cellular technology to follow the current universal mobile telecommunication system/high-speed packet access (UMTS/HSPA)*. The LTE standard targets higher peak data rates, higher spectral efficiency, lower latency, flexible channel bandwidths, and system cost compared to its predecessor. LTE is considered to be the fourth generation (4G) in mobile communications [1, 2]. It is referred to as mobile multimedia, anywhere anytime, with global mobility support, integrated wireless solution, and customized personal service (MAGIC) [1]. LTE will be internet protocol (IP) based, providing higher throughput, broader bandwidth, and better handoff while ensuring seamless services across covered areas with multimedia support.

Enabling technologies for LTE are adaptive modulation and coding (AMC), multiple-input multiple-output systems (MIMO), and adaptive antenna arrays. LTE spectral efficiency will have a theoretical peak of 300 Mbps/20 MHz = 15 bits/Hz (with the use of MIMO capability), which is six times higher than 3G-based networks that have 3.1 Mbps/1.25 MHz = 2.5 bits/Hz [i.e., evolution data only, (EV-DO)]. LTE will have a new air interface for its radio access network (RAN), which is based on orthogonal frequency division multiple access (OFDMA) [3].

This chapter focuses on the radio frequency (RF) planning and optimization of 4G LTE cellular networks, or the so-called evolved universal terrestrial radio access networks (E-UTRAN) and discusses the physical layer modes of operation for the user equipment (UE) as well as base stations (BS) or the so called evolved node B

* Estimated first commercial deployment is in 2011 (from Qualcomm Inc., February 2009).

(eNB) subsystem. Frequency division duplexing (FDD) and time division duplexing (TDD) modes of operation and their frequency bands are also discussed and illustrated according to the 3GPP specification release 8, 36 series, as of September/December 2008.

RF aspects of cell planning such as cell types, diversity, antenna arrays and MIMO system operation to be used within this architecture will be discussed. Various wireless propagation models used to predict the signal propagation, strength, coverage and link budget are to be explained. The main performance and post deployment parameters are then discussed to assess the RF network performance and coverage. Model tuning according to field measurements is discussed to optimize the network performance. These will follow the standard recommendation for mobile and stationary users. All these aspects are essential for the RF planning process.

11.2 LTE Architecture and the Physical Layer

11.2.1 LTE Network Architecture

The LTE network architecture is illustrated in Figure 11.1. The data are exchanged between the UE and the base station (eNB) through the air interface. The eNB is part of the E-UTRAN where all the functions and network services are conducted. Whether it is voice packets or data packets, the eNB will process the data and route it accordingly. The main components of such a network are [4]:

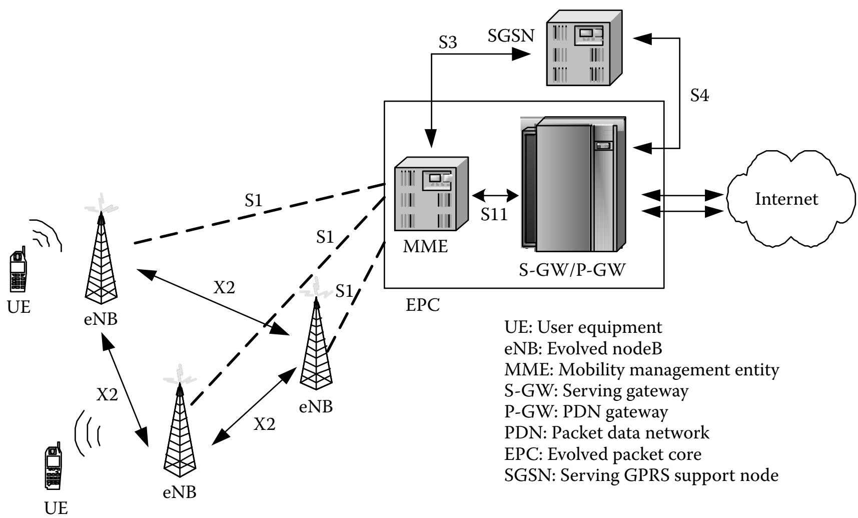

Figure 11.1 LTE network architecture.

- **User Equipment (UE):** This is the user device that is connected to the LTE network via the RF channel through the BS that is part of the eNB subsystem.
- **Evolved NodeB (eNB):** The eNB functionalities include radio resource management (RRM) for both uplink (UL) and downlink (DL), IP header compression and encryption of user data, routing of user data, selection of MME, paging, measurements, scheduling, and broadcasting.
- **Mobility Management Entity (MME):** This portion of the network is responsible for nonaccess stratum (NAS) signaling and security, tracking UE, handover selection with other MMEs, authentication, bearer management, core network (CN) node signaling, and packet data network (PDN) service and selection. The MME is connected to the S-GW via an S11 interface [5].
- **Serving Gateway (S-GW):** This gateway handles eNB handovers, packet data routing, quality of service (QoS), user UL/DL billing, lawful interception, and transport level packet marking. The S-GW is connected to the PDN gateway via an S5 interface.
- **PDN Gateway (P-GW):** This gateway is connected to the outside global network (Internet). This stage is responsible for IP address allocation, per-user packet filtering, and service level charging, gating, and rate enforcement.
- **Evolved Packet Core (EPC):** It includes the MME, the S-GW as well as the P-GW.

Logical, functional, and radio protocol layers are graphically illustrated in Figure 11.2. The logical nodes encompass the functional capabilities as well as radio protocols and interfaces. Interfaces S1–S11 as well as X2 are used to interconnect the various parts of the LTE network and are responsible for reliable packet routing and seamless integration. Details of such interfaces are discussed in the 3GPP specification and is discussed in this chapter. Radio protocol layers are the shaded ones in Figure 11.2. After a specific eNB is selected, a handover can take place based on measurements conducted at the UE and the eNB. The handover can take place between eNBs without changing the MME/SGW connection. After the handover is complete, the MME is notified about the new eNB connection. This is called an intra-MME/SGW handover. The exact procedures for this operation as well as inter-MME/SGW handover are discussed in detail in [4]. Handovers are conducted within layer-2 functionality (i.e., radio resource control (RRC)).

When comparing the new LTE standard release 8 to the currently deployed cellular systems in terms of maximum data rates, modulation schemes, multiplexing, among other system specific performance parameters, several improvements can be easily observed. Table 11.1 lists the major technologies and system performance for different networks evolved from 2.5G up to 4G. The North American system (based on CDMA) is shown in the shaded columns. The RF channel that connects the UE to the eNB is the focus of RF planning for LTE network design. The duplexing, multiplexing, modulation, and diversity are among the major aspects of the system

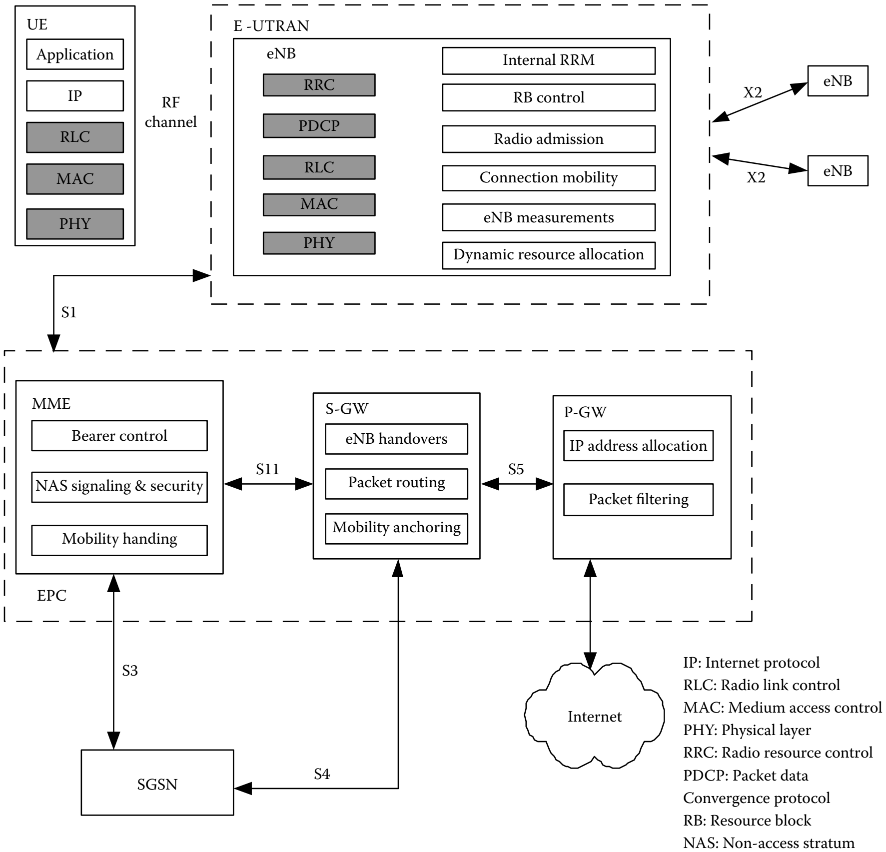

Figure 11.2 Logical, functional, and radio protocol layers for the LTE network.

architecture that affect the planning process. Also, the wireless propagation model, antenna types and number (LTE supports multiple antennas in the UE and eNB), and semiconductor technology used are key components in RF planning and design. The UE as well as the eNB (UL and DL) have to be designed, analyzed, deployed, and optimized in order achieve the system performance metrics defined within the standard.

11.3 Duplexing, Coding, and Modulation in LTE

In LTE, time division duplexing (TDD) and frequency division duplexing (FDD) are supported. If the cellular system is using two different carrier frequencies for the UL and DL, then the duplexing is called FDD. In this case, both the UE and the eNB can transmit at the same time. For FDD, a channel separation is needed to reduce the interference between the UL and DL traffic. Another precaution should

Table 11.1 Characteristics of Different Cellular Networks

	2.5G		*3G*		*3.5G*		*4G*
	EDGE	*cdma2000*	*UMTS*[1]	*EV-DO*[2]	*HSDPA*	*EV-DV*	*LTE*
Channel bandwidth (MHz)	0.2	1.25	5	1.25	5, 10	1.25, 3.75	5, 10, 15, 20
Duplexing	FDD	FDD	FDD	FDD	FDD	FDD	FDD/TDD
Multiplexing	TDMA	TDMA	WCDMA	TD-CDMA	WCDMA	TD-CDMA	OFDM/ SCFDMA
Modulation	GMSK/8PSK	GMSK/8PSK	QPSK	QPSK/8PSK /16QAM	QPSK/ 16QAM/	QPSK/8PSK /16QAM	QPSK/ 16QAM/ 64QAM
Coding	C	CTC	CTC	CTC	CTC	CTC	CTC
Maximum data rate	(UL) 0.04	(UL) 0.05	(UL) 0.14	(UL) 1.8	(UL) 2	(UL) 1	(UL) 50
(Mbps)	(DL) 0.18	(DL) 0.38	(DL) 0.38	(DL) 3.1	(DL) 7.2	(DL) 3-5	(DL) 100[3]

1: Universal Mobile Telecommunications Systems R99
2: Evolution data optimized (EV-DO) REV A
3: No MIMO
GMSK: Gaussian minimum shift keying
QPSK: Quadrature phase shift keying
QAM: Quadrature amplitude modulation
TD-CDMA: Time division-synchronous CDMA
OFDMA: Orthogonal frequency division multiple access
SC-FDMA: Single carrier frequency division multiple access
CTC: Convolutional/Turbo coding

be taken in the RF chain design that should provide enough out-of-band rejection in the transceiver. This is accomplished using high-quality RF filters.

In TDD-based systems, the communication between the UE and the eNB is made in a simplex fashion, where one terminal is sending data and the other is receiving. With a short enough delay time, the operation might seem as if it was a simultaneous process. The amount of spectrum required for FDD and TDD is the same. Although FDD uses two bands of frequencies separated by a guard band, TDD uses a single band of frequency, but it needs twice as much bandwidth. Because TDD sends and receives data at different time slots, the antenna will be connected to the transmitter at one time and to the receiver chain at another. The presence of a high-quality, fast-operating RF switch is thus essential.

LTE FDD supports both full-duplex and half-duplex transmission. Table 11.2 shows the LTE frequency bands for FDD. There are 14 bands shown (out of 15 defined in [6], band 17 is not shown). The DL as well as the UL bands are presented with their respective channel numbers. The channel numbers are also identified as the evolved absolute radio frequency channel numbers (EARFCN). The carrier frequency in the DL and UL is calculated based on the assigned EARFCN from the eNB. Equations 11.1 and 11.2 relate the EARFCN to the carrier frequency used in megahertz.

$$f_{DL} = f_{DL_{\text{Low}}} + 0.1(N_{DL} - N_{DL-\text{offset}}) \tag{11.1}$$

$$f_{UL} = f_{UL_{\text{Low}}} + 0.1(N_{UL} - N_{UL-\text{offset}}) \tag{11.2}$$

The offset value for the DL ($N_{DL-\text{offset}}$) and UL ($N_{UL-\text{offset}}$) are found from Tables 11.2 and 11.3 for FDD and TDD, respectively. The offset value is the starting value of the channel numbers for the specific band (i.e., for E-UTRA band 7, the $N_{DL-\text{offset}}$ is 2750). The nominal channel spacing between two adjacent carriers will depend on the channel bandwidths, the deployment scenario, and the size of the frequency block available. This is calculated using the following:

$$\text{Nominal channel spacing} = \frac{(BW_{\text{channel}-1} + BW_{\text{channel}-2})}{2} \tag{11.3}$$

where $BW_{\text{channel}-1}$ and $BW_{\text{channel}-2}$ are the channel bandwidths of the two adjacent carriers. The FDD mode utilizes the frame structure Type 1 [4]. The frame duration is $T_f = 307200 \times T_s = 10$ ms for both UL and DL. The sampling time (T_s) is given by

$$T_s = \frac{1}{15000 \times 2048}\text{s}$$

The denominator of T_s comes from the OFDMA subcarrier spacing (15 kHz) and the number of fast fourier transform (FFT) points. Each Type 1 frame is divided into 10 equally sized subframes, each of which is in turn equally divided into two slots. Each slot consists of 12 subcarriers with 6-7 OFDMA symbols (called a resource block). Figure 11.3 shows the structure of a Type 1 radio frame for LTE in FDD mode.

Table 11.2 LTE FDD Frequency Bands and Channel Numbers

E-UTRAN Band	Downlink (DL) (UE Receive, eNB Transmit)		Channel Numbers (N_{DL})	Uplink (UL) (UE Transmit, eNB Receive)		Channel Numbers (N_{UL})
	f_{DL_Low} (MHz)	f_{DL_High} (MHz)		f_{UL_Low} (MHz)	f_{UL_High} (MHz)	
1	2110	2170	0–599	1920	1980	13000–13599
2	1930	1990	600–1199	1850	1910	13600–14199
3	1805	1880	1200–1949	1710	1785	14200–14949
4	2110	2155	1950–2399	1710	1755	14950–15399
5	869	894	2400–2649	824	849	15400–15649
6	875	885	2650–2749	830	840	15650–15749
7	2620	2690	2750–3449	2500	2570	15750–16449
8	925	960	3450–3799	880	915	16450–16799
9	1844.9	1879.9	3800–4149	1749.9	1784.9	16800–17149
10	2110	2170	4150–4749	1710	1770	17150–17749
11	1475.9	1500.9	4750–4999	1427.9	1452.9	17750–17999
12	728	746	5000–5179	698	716	18000–18179
13	746	756	5180–5279	777	787	18180–18279
14	758	768	5280–5379	788	798	18280–18379

Table 11.3 LTE TDD Frequency Bands and Channel Numbers

E-UTRAN Band	*Downlink (DL) (UE Receive, eNB Transmit)*		*Channel Numbers (N_{DL})*	*Uplink (UL) (UE Transmit, eNB Receive)*		*Channel Numbers (N_{UL})*
	f_{DL_Low} (MHz)	*f_{DL_High} (MHz)*		*f_{UL_Low} (MHz)*	*f_{UL_High} (MHz)*	
33	1900	1920	26000–26199	1900	1920	26000–26199
34	2010	2025	26200–26349	2010	2025	26200–26349
35	1850	1910	26350–26949	1850	1910	26350–26949
36	1930	1990	26950–27549	1930	1990	26950–27549
37	1910	1930	27550–27749	1910	1930	27550–27749
38	2570	2620	27750–28249	2570	2620	27750–28249
39	1880	1920	28250–28649	1880	1920	28250–28649
40	2300	2400	28650–29649	2300	2400	28650–29649

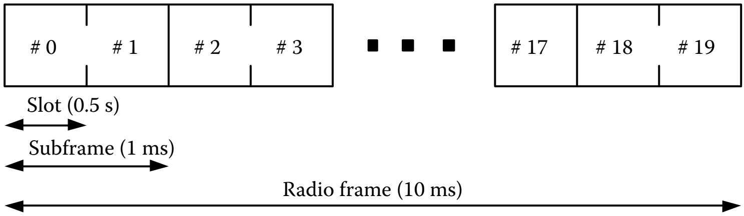

Figure 11.3 FDD frame type 1 structure.

For the TDD mode of operation, the frequency bands used and their respective channel numbers are illustrated in Table 11.3. There are 8 bands in TDD mode. Frame structure Type 2 is used for TDD duplexing. Each radio frame is 10 ms long. The frame consists of two 5-ms subframes. Each subframe is in turn divided into eight 1.5 ms slots and three special fields: downlink pilot time slot (DwPTS), guard period (GP), and uplink pilot time slot (UpPTS). The length of the combined three fields is 1 ms. Figure 11.4 shows the structure of a Type 2 radio frame.

11.3.1 LTE Physical Channels

The following physical channels are used in the LTE architecture [4]:

- **Physical Broadcast Channel (PBCH):** The transport blocks are mapped into four subframes within a 40-ms interval and then decoded with no special signaling. This channel is used for correcting mobile frequencies, control channel structure, frame synchronization, and the like.
- **Physical Control Format Indicator Channel (PCFICH):** This channel is transmitted in every subframe and indicates the number of OFDMA symbols used for the PDCCH.
- **Physical Downlink Control Channel (PDCCH):** This channel carries the uplink scheduling information and informs the UE about resource

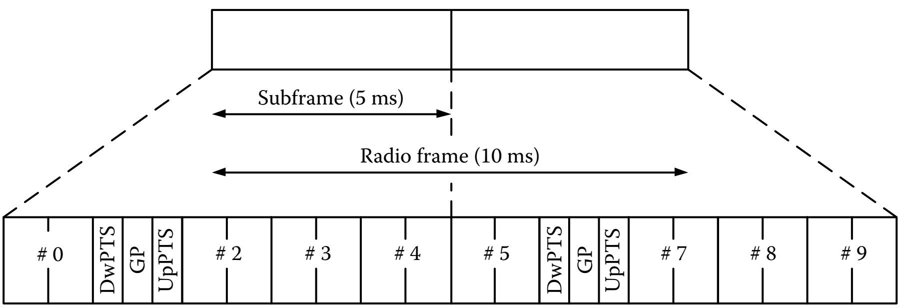

Figure 11.4 TDD frame type 2 structure.

allocation and hybrid automatic repeat request (HARQ) for the paging channel (PCH) and the downlink synchronization channel (DL-SCH).

- **Physical Hybrid ARQ Indicator Channel (PHICH):** This channel carries the HARQ of acknowledge/not-acknowledge (ACK/NACK) for the uplink transmissions.
- **Physical Downlink/Uplink Shared Channel (PDSCH/PUSCH):** This channel carries the DL synchronization channel (SCH) and UL-SCH as well as PCH information.
- **Physical Multicast Channel (PMCH):** This channel carries the multicast information.
- **Physical Uplink Control Channel (PUCCH):** This channel carries HARQ for the downlink transmissions, as well as scheduling requests and channel quality indicator (CQI) reports.
- **Physical Random Access Channel (PRACH):** This channel carries the random access preamble.

Three main procedures are given to the physical layer: cell search, power control, and link adaptation. In cell search, the DL synchronization and reference signals are tracked to acquire frequency and time synchronization, as well as the cell ID. Power control is used to control the output power spectral density from the UE. Finally, link adaptation will decide which modulation and coding schemes (bearers) are to be used based on the performed channel measurements and data coming from the eNB.

The physical layer maps the physical channels to transport channels for layer-2 processing. Layer-2 is divided into three sublayers: medium access control (MAC), radio link control (RLC), and packet data convergence protocol (PDCP). The MAC sublayer is responsible for mapping between transport and logical channels, scheduling reporting, error correction, priority handling, and padding. The RLC sublayer performs ARQ error correction, RLC reestablishment, passing protocol data units (PDUs) to upper layers and concatenation, segmentation, and reassembly of service data units (SDUs). The PDCP is responsible for header compression, ciphering and deciphering, data transfer, and PDU/SDU delivery [4].

11.3.2 Coding, Modulation, and Multiplexing

There are two levels of coding: source coding and channel coding. The former is used for data compression and the latter is used to minimize channel effects on transmitted symbols. Convolutional turbo coding (CTC) channel coding is used in LTE equipment. It has proven to enhance data transmission in complex fading channels. The coded blocks are then scrambled using a length 31 gold code (GC) sequence. Initialization on the sequence generator is made at the beginning of every frame. A GC sequence generator can be implemented using a linear feedback shift register (LFSR). A block of bits to be transmitted on the PBCH consists of 1920 bits with normal cyclic prefix (CP) is denoted by b. This block has to be scrambled with a cell-specific sequence prior to modulation. Let the GC sequence for this cell be denoted by C. The scrambling process is made according to Equation 11.4 [7,8]:

$$\tilde{b}(i) = b(i) \oplus C(i) \tag{11.4}$$

where $\oplus$ is the module-2 addition operator. To combat bursty channel errors in a multipath environment, the coded data is interleaved in such a way that the bursty channel is transformed into a channel with independent errors. Interleaving will spread the bursty errors in time so that they would appear independent of each other and then conventional error correcting mechanisms can be used to correct such errors. For more on interleaving and coding, please refer to [1,9].

Linear modulation schemes are used in LTE. M-ary digital modulation is utilized since the bit rate used is higher than the channel bandwidth assigned (300 Mbps data rate in a 20-MHz bandwidth). The modulation scheme is determined depending on the channel characteristics. In bad channel conditions, a low constellation modulation scheme is used, which is QPSK. Here, two bits are encoded into a single word (phase) for transmission. The 16-QAM and 64-QAM modulation schemes are used in better channel conditions, and the data are mapped into both phase and amplitude changes on the carrier frequency. The signal constellation of a QAM modulation consists of a square grid. The modulated signals contain a level based on the number of bits used. For 16-QAM, every 4 bits are given a signal value from the 16-level constellation. Figure 11.5 shows the difference between the QPSK and the 16-QAM signal constellations [7]. A 64-QAM modulation scheme follows that of the 16-QAM but instead encodes 6-bits into one signal level/phase compared to 4-bits in 16-QAM.

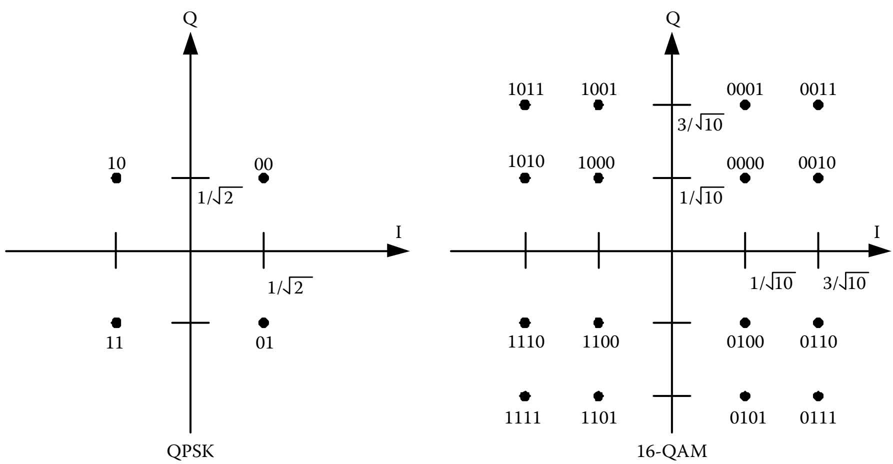

Figure 11.5 QPSK and 16-QAM signal constellations, gray coded. (From 3GPP TS 36.211, V8.4.0, E-UTRA "Physical Channels and Modulation," September 2008.) © 2008. 3GPP^{TM}.

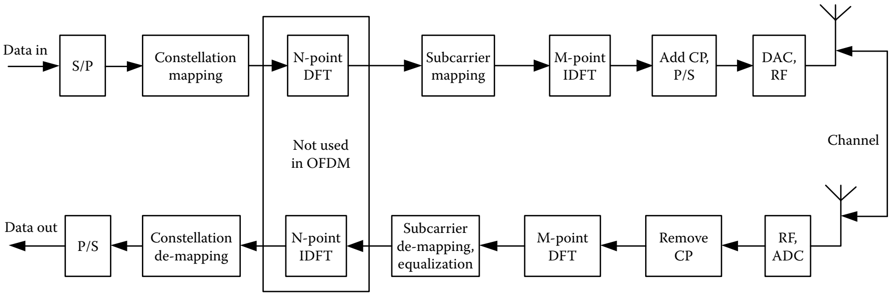

Figure 11.6 SC-FDMA/OFDMA tranceiver block diagram (DL/UL).

In LTE, adaptive modulation and coding (AMC) is implemented on the UL/DL streams according to channel conditions. Thus, the modulation scheme as well as the coding scheme are changed automatically for best transmission performance for the given channel conditions. Multicarrier multiplexing is attractive because a frequency-selective channel would appear as a flat-fading one for individual orthogonal carriers (subcarriers). Thus compensation for channel impairments would become easier to realize in hardware [1,9]. Two multiplexing schemes are used in the LTE architecture. OFDMA is used for the downlink and SC-FDMA is used for the uplink. Figure 11.6 shows a block diagram for a SC-OFDMA transceiver and the modification required to obtain that of an OFDMA [7].

CP is needed to overcome inter-symbol interference (ISI) that is introduced on the data by the wireless channel. The cyclic bit extension (adding a copy of the last data portion of the OFDMA symbol to the beginning of it instead of a guard band) to the FFT output adds a guard interval to the data to be transmitted.

In a typical OFDMA system block diagram (Figure 11.6), the serial input binary data is converted into a parallel (S/P) stream that is mapped into a complex constellation (modulation and coding) before being formatted for subcarrier mapping through an IFFT operation. This process is followed by the addition of a CP before being passed to a digital-to-analog converter (DAC). The data are then passed to the RF part and the antenna elements (in case if more than 1 is used, i.e., MIMO). In the receiver, the opposite sequence of operations is followed with the use of an FFT processor. A SC-FDMA system includes an extra FFT/IFFT operation in the transmitter/receiver, respectively. The size of the former FFT/IFFT processor is less than the latter one ($M > N$). This change in the signal chain of the system diagram gives several advantages of SC-FDMA over OFDMA. The major advantage of using SC-FDMA over OFDMA is the lower peak-to-average power ratio (PAPR) that minimizes problems to power amplifiers within the terminals. Thus, although the SC-FDMA will entail more signal processing complexity (which can be handled with today's DSP), it will allow the creation of cheaper UE (RF portion is still relatively expensive) and a better link budget because a lower PARP is achieved [10]. OFDMA is discussed in detail in [9, 11].

11.4 Cell Planning

The aim of the cell planning engineer is to establish the proper radio network in terms of service coverage, QoS, capacity, cost, frequency use, equipment deployment, and performance. In order to plan a cellular radio network, the designer has to identify specifications, study the area under consideration and create a database with geographic information (GIS), analyze the population in the service area, create models (i.e., cell types, IDs, locations, etc.), and perform simulations and analysis using proper propagation scenarios and tools. Afterward, simulation and coverage results are analyzed, followed by cell deployment and drive testing. The results of field measurements are compared against the simulation model results, and the model is tuned for performance optimization. Each of the aforementioned stages in turn consist of a number of steps that need to be performed.

11.4.1 Coverage

Coverage planning is an important step in deploying a cellular network. This process includes the selection of the proper propagation model based on the area's terrain, clutter, and population. Propagation models (empirical models) are too simplistic to predict the signal propagation behavior in an accurate fashion; they provide us with some relatively good accuracy of how things would behave. Field measurements are the most accurate in predicting radio coverage in a certain area. For example, in buildings coverage will add about 16 to 20 dB of extra signal loss, and inside vehicle ones can increase the loss by an extra 3 to 6 dB [1].

Engineers rely on prediction tools to study and analyze the performance of the network for a geographic area via its coverage. In LTE, the air interface and radio signal electronics are going to be different than those already deployed (in terms of multiplexing, AMC, and MIMO capability for both the UE and eNB). Modeling and simulation using some current RF planning tools (i.e., Atoll [12]) for LTE cells will give a good idea about the coverage performance of a certain grid within a specific area. Based on the simulations made, the planning engineer would change eNB locations, add more towers, replace antenna types, add more sectors to some towers, and so on. Most cells are designed to be hexagonal in theory; in reality, this is not the case, as several factors affect the location selection decision (political, humanitarian, economical). Figure 11.7 shows simulated signal power levels (color coded) of four LTE RF cells in downtown Brussels, Belgium. Note the description of one of the sites where the frequency band and bandwidth are shown along with the RF equipment characteristics: antenna parameters, tower-mounted amplifier (TMA) characteristics, and feeder loss. This information is to be used in the link budget as well (Section 11.5.4).

11.4.2 Cell IDs

For LTE cells, the eNB antenna is 45 m tall in rural areas and 30 m tall in urban areas. Typically eNBs (or sites) in a macrocellular deployment are placed on a hexagonal

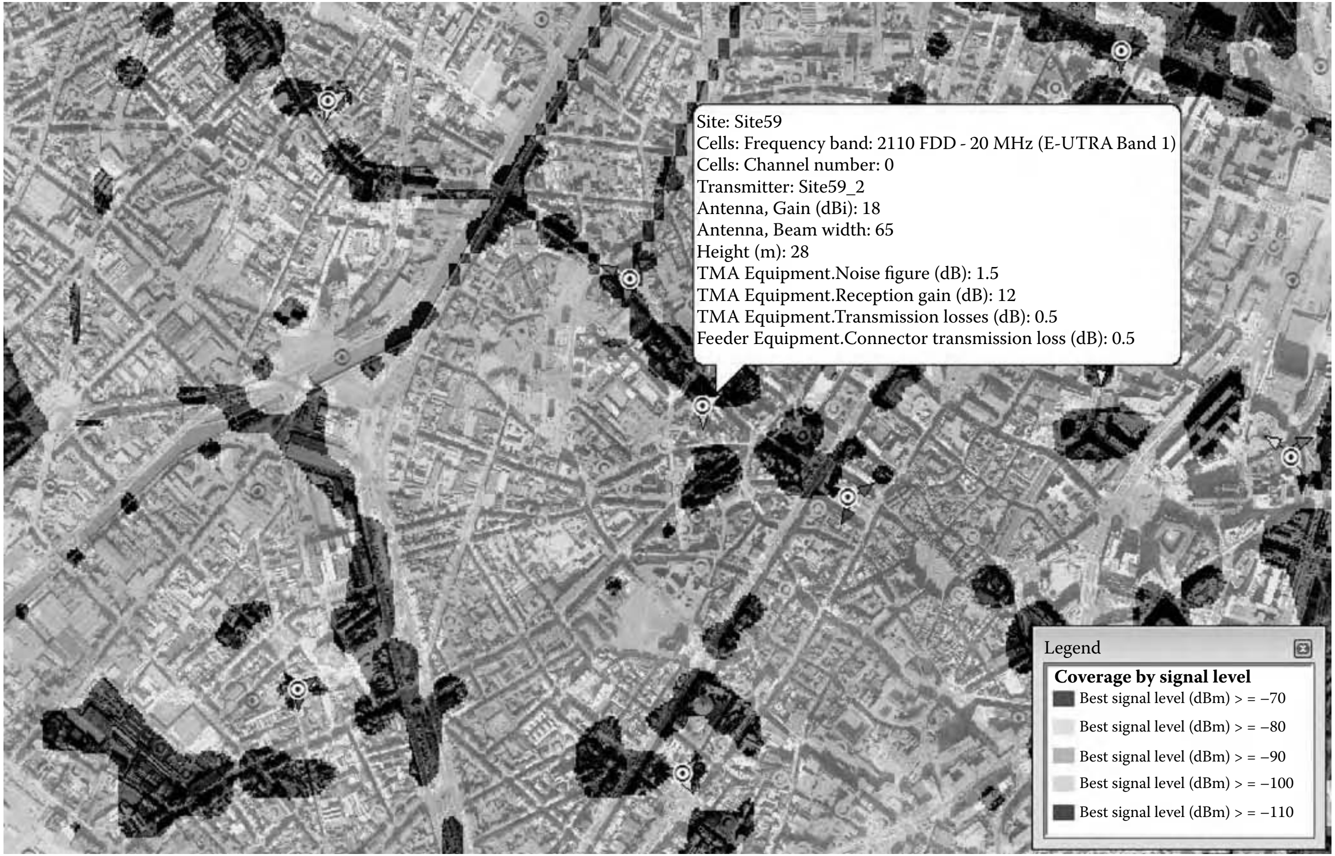

Figure 11.7 Atoll coverage example in downtown Brussels.

grid with an intersite distance of $3 \times R$, where $R = 500$ m is the cell radius. Each eNB has three sectors with an antenna placed at each sector. In a multioperator cellular layout, identical cell layouts for each network shall be applied, with second network sites located at first network cell edges [13].

In an LTE system, the same carrier frequency is used, and thus the system relies on scrambling and pseudo-noise (PN) codes to distinguish between users and sites as well as to establish synchronization between the UE and eNB. A cell ID and scrambling code is to be given to each site. There are 504 unique cell IDs that can be used within the LTE physical layer. These IDs are grouped into three 168 groups, each group contains three identities. The cell ID is found from:

$$N_{\text{cell}} = 3N_G + N_{ID} \tag{11.5}$$

where $N_G \in [0, 167]$ is the physical layer cell group ID, and $N_{ID} \in [0, 2]$ is the identification number within the group. N_{ID} is also used to pick one of the 64 Zandoff-Chu scrambling codes used for the primary and secondary synchronization channels (reference channels). A Zandoff-Chu sequence is a complex-orthogonal sequence that is used to give unique signatures to radio signals. Orthogonal codes are used to distinguish between radio transmissions and thus distinguish between surrounding eNBs. In UMTS, Walsh codes were used for this purpose. In LTE, Zandoff-Chu sequences are used. These give rise to constant amplitude radio signal after the scrambling process. A root Zandoff-Chu sequence can be found using:

$$d_u(n) = e^{-j}\frac{\pi u n(n+1)}{N_{zc}} \tag{11.6}$$

where, $N_{zc} = 63$ in LTE, and $0 \leq n \leq N_{zc}$; the root index u is related to N_{ID}. In the UE, GC sequences with different shifts are used based on the subscriber identity and the physical channel type [8].

For cell ID and scrambling code planning, several strategies exist based on minimum reuse distance, domain constraints, minimum E_c/I_0 levels, number of codes per cluster, etc. Several automatic scrambling code planning algorithms exist within RF planning packages that can be used as well. The fact that there are plenty of cell IDs that can be used allows for a large pool of sequences and thus a larger area between similar reused sequences. Some of these strategies are [12, 14]:

- **Cluster Reuse-Based Method**: This method assigns code sets according to a code set reuse pattern that is predefined (i.e, 13 cell clusters). Then, based on the propagation loss exponent and the processing gain of the radio scheme, the minimum reuse distance is found.
- **Graph Optimization Technique**: In this method, heuristic algorithms are used to assign cell IDs and scrambling codes by minimizing the number of sets to be used based on an optimization criteria. The algorithm first finds the inter-cell distances, and then starts automatic code assignments based on the optimization criteria and their priorities.

- **Distributed Per-cell/Per-site**: In the per-cell strategy, the pool of codes is distributed among as many cells as possible, thus increasing the minimum reuse distance. The distribution per site allocates a group of different codes to adjacent sites, and from these groups, one code per transmitter is assigned.

11.4.3 Cell Types

Third-generation cellular networks utilize three cell types: macro, micro, and pico based on their coverage area and user capacity [15]. In LTE as well as WiMAX, a fourth type is introduced to serve a single household—femtocell. According to [16], these four cell types are defined as:

- **Macrocells**: The largest cell types that cover areas in kilometers. These eNBs can serve thousands of users simultaneously. They are very expensive due to their high installation costs (cabinet, feeders, large antennas, 30–50 m towers, etc). The cells have three sectors and constitute the heart of the cellular network. Their transmitting power levels are very high (5–40 W).
- **Microcells**: Provide a smaller coverage area than macrocells, and are added to improve coverage in dense urban areas. They serve hundreds of users and have lower installation costs than macrocells. You can find them on the roofs of buildings, and they can have three sectors as well, but without the tower structure. They transmit several watts of power.
- **Picocells**: Used to provide enhanced coverage in an office like environment. They can serve tens of users and provide higher data rates for the covered area. The 3G networks use picocells to provide the anticipated high data rates. They have a much smaller form factor than microcells and are even cheaper. Their power levels are in the range of 20 to 30 dBm.
- **Femtocells**: Introduced for use with 4G systems (LTE and WiMAX). They are extremely cheap and serve a single house/small office. Their serving capacity does not exceed 10 users, with power levels less than 20 dBm. A femtocell will provide a very high DL and UL data rates, and thus provide multi-Mbps per user, thus accomplishing MAGIC (see Section 11.1, Introduction).

11.4.4 Multiple-Input Multiple-Output Systems (MIMO)

MIMO systems are one of the major enabling technologies for LTE. They will allow higher data rate transmission through the use of multiple antennas at the receiver/transmitter. Let the number of transmitting antennas be M_T and the number of receiving antennas be N_R where $N_R \geq M_T$.

In a single-input single-output system (SISO)—used in current cellular systems, 3G and 3.5G—the maximum channel capacity is given by the Shannon-Hartley relationship:

$$C \approx B \times \log_2(1 + SNR_{\text{avg}}) \tag{11.7}$$

where C is the channel capacity in bits per second (bps), B is the channel bandwidth in Hz, and SNR_{avg} is the average signal-to-noise ratio at the receiver. In the SISO case, $M_T = N_R = 1$. In a MIMO case, the channel capacity becomes [1]:

$$C \approx B \times \log_2(1 + M_T \times N_R \times SNR_{\text{avg}}) \tag{11.8}$$

thus obtaining an $M_T N_T$ fold increase in the average SNR and increasing channel capacity. If $N_R \geq M_T$, we can send different signals within the same bandwidth and still decode them correctly at their corresponding receivers. For each channel (transmitter-receiver), its capacity will be given as:

$$C_{\text{single}-CH} \approx B \times \log_2\left(1 + \frac{N_R}{M_T} \times SNR_{\text{avg}}\right) \tag{11.9}$$

In the same bandwidth, we will have M_T dedicated channels (M_T transmitting antennas), resulting in an M_T-fold increase in capacity:

$$C \approx M_T B \times \log_2\left(1 + \frac{N_R}{M_T} \times SNR_{\text{avg}}\right) \tag{11.10}$$

Hence, with respect to the transmitting antennas we obtain a linear increase in the system capacity. It is very important in a MIMO system to identify the correlation matrices between the transmit/receive antennas, as well as the channel propagation conditions. Based on the transmit (M_T) and receive (N_R) number of antennas, a correlation matrix of $M_T \times N_R$ will be obtained. As an example, the spatial correlation matrix, R_{spatial} for a 2 × 2 MIMO system is given by:

$$R_{\text{spatial}} = R_{eNB} \bigotimes R_{UE} = \begin{bmatrix} 1 & \alpha \\ \alpha^* & 1 \end{bmatrix} \bigotimes \begin{bmatrix} 1 & \beta \\ \beta^* & 1 \end{bmatrix} = \begin{bmatrix} 1 & \beta & \alpha & \alpha\beta \\ \beta^* & 1 & \alpha\beta^* & \alpha \\ \alpha^* & \alpha^*\beta & 1 & \beta \\ \alpha^*\beta^* & \alpha^* & \beta^* & 1 \end{bmatrix} \tag{11.11}$$

where $\bigotimes$ is the Kronecker product operator, and R_{eNB} and R_{UE} are the eNB and UE correlation matrices, respectively. The other combinations of 1 × 2, 2 × 4, and 4 × 4 are listed in [6]. Values for α and β depend on the environment under consideration as defined by the standard. α can take one of the values in (0, 0.3, 0.9), whereas β can be one of the values (0, 0.9, 0.9) for the slow-, medium- and high-delay spread environments, respectively. Figure 11.8 shows a simplified MIMO system block diagram.

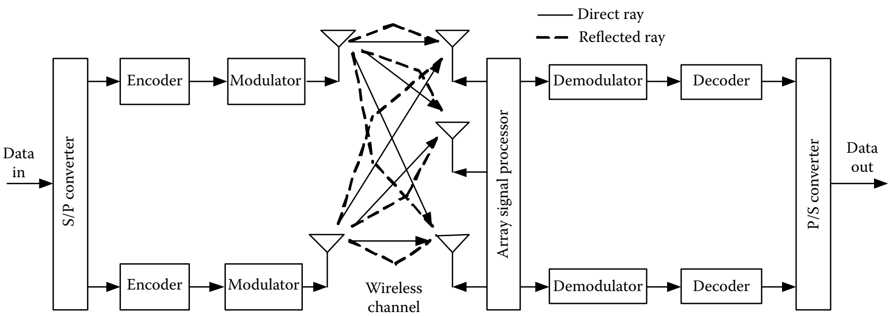

Figure 11.8 A MIMO system block diagram (simplified).

11.4.5 Diversity

For MIMO-based systems, different kinds of diversity techniques are used. MIMO-based diversity systems can be described as follows [12]:

- **Transmit Diversity**: The signal to be transmitted is forwarded and sent over all antennas, the same signal that is sent on all transmit antennas reaches the receiver, and the combined signal level will be higher if only one transmit antenna was used, making it more interference resistant. Transmit diversity will increase the carrier-to-interference plus noise ratio (CINR) level, and is used at cell locations with low CINR (i.e., further from eNB toward the cell edges).
- **Spatial Multiplexing**: Different signals are passed to different transmit antennas in this diversity technique. If the transmit terminal has M antennas and the receive terminal had N antennas, the throughput through the transmit-receiver link can be increased by [min(M, N)]. This diversity technique will increase the channel throughput provided that good CINR levels exist.
- **Adaptive MIMO Switching**: This technique allows switching between transmit diversity and spatial multiplexing based on the environment conditions. If the CINR exceeds a certain threshold, spatial multiplexing is chosen to provide the user with higher throughput. On the other hand, if CINR is below the defined threshold, transmit diversity is picked to improve user reception by choosing to operate at a lower throughput.

11.4.6 Antenna Arrays

Antenna arrays are used to provide directional radiation characteristics and higher gain to the transmitted/received signal. The outputs of individual antenna elements within the array are combined to provide a certain desired radiation pattern and gain. The more directional the antenna array, the narrower the half power beam width becomes. Relationships between these parameters are of importance to the antenna design engineer and is found in [17]. Another important parameter for cellular antennas is their polarity. Vertical polarization is used in cellular systems.

The eNB antenna gain within a macrocell in urban and rural areas is to be between 12 and 15 dBi, including the feeder losses within the bands of operation. These gain values are important in formulating the RF link budget of the system and in determining the coverage power levels. The antenna radiation pattern to be used for each sector within the three-sector cell site is given by [13]

$$A(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right] \tag{11.12}$$

where θ_{3dB} is the 3-dB (half power) beam width; in this case, it is 65°, $-180^\circ \leq \theta \leq 180^\circ$, and A_m is the maximum attenuation of 20 dB between the main lobe and the highest side lobe in the antenna gain pattern. The UE does not have such a directional pattern and will use an omnidirectional antenna for UL, whereas it will have the option of using one, two, or four antennas for downlinking. It is believed that the first UE prototypes are to have two antennas. Such antennas will have omnidirectional radiation patterns to receive as much signal power as possible. Its gain is assumed to be 0 dBi.

With proper use of adaptive techniques, the weighting of signal levels coming out of each antenna element with optimized coefficients gives better signal-to-noise ratio (SNR), interference reduction, and source signal tracking. This is called antenna beam forming (BF). If BF is utilized, the eNB antenna array can keep the main lobe in the direction of the UE, thus providing maximum antenna gain. This means higher SNR (CINR) levels, and thus better throughput and higher data transmission rates. Five predefined angles for BF have been suggested [0°, 30°, 45°, 60°, 70°] along with their image (negative) angles. The weights for the antenna array can be stored in a lookup table in the antenna electronics, or can be achieved using an RF butler matrix.

11.5 Propagation Modeling

In wireless communications, a multipath channel is the one that describes the medium between the UE and the eNB. A multipath channel is characterized by the delay profile that is characterized by the RMS delay spread and the maximum delay spanned by the tapped-delay-line taps, along with the Doppler spread. Four environments are defined for LTE: extended pedestrian (low delay profile), extended vehicular (medium delay profile), extended typical urban (high delay spread), and the high-speed train (nonfading). This section presents the four propagation scenarios supported in the LTE standard, followed by the propagation channel models used. Statistical and deterministic channel modeling is presented. Creation of the LTE link budget is discussed as well.

11.5.1 Propagation Environments

Multipath channel characteristics can be described by a combination of a delay spread profile, the Doppler spectrum, and the effect of multiple antennas in a MIMO system through the use of correlation matrices. The delay spread profile can be modeled as a tapped delay line with predefined delay elements and relative power contributions. There are four propagation scenarios in LTE [6]:

1. **Extended Pedestrian A Model**: This model covers walking users with speeds up to 3 km/h. The tapped delay line model consists of 7-taps with delays $\in$ [0, 30, 70, 90, 110, 190, 410] ns, and relative power $\in$ [0.0, −1.0, −2.0, −3.0, −8.0, −17.2, −20.8] dB. The maximum Doppler shift is 5 Hz.
2. **Extended Vehicular A Model**: This model covers moving vehicles with speeds up to 50 km/h. The model consists of 9-taps with delays $\in$ [0, 30, 150, 310, 370, 710, 1090, 1730, 2510] ns and relative power $\in$ [0.0, −1.5, −1.4, −3.6, −0.6, −9.1, −7.0, −12.0, −16.9] dB. The maximum Doppler shift is between 5 and 70 Hz.
3. **Extended Typical Urban Model**: This model covers moving vehicles with speeds up to 90 km/h. The model consists of 9-taps with delays $\in$ [0, 50, 120, 200, 230, 500, 1600, 2300, 5000] ns and relative power $\in$ [−1.0, −1.0, −1.0, 0.0, 0.0, 0.0, −3.0, −5.0, −7.0] dB. The maximum Doppler shift is between 70 and 300 Hz.
4. **High-Speed Train**: This model covers train users with speeds of 300 km/h. This is considered a nonfading model with a 1-tap delay line. The maximum Doppler shift is 750 Hz.

11.5.2 Empirical/Statistical Path Loss Models

Path loss models are important in the RF planning phase to be able to predict coverage and link budget among other important performance parameters. These models are based on the frequency band, type of deployment area (urban, rural, suburban, etc.), and type of application. Two path loss models for macro/microcell propagation are listed in [13] that are accurate if used beyond 100 m distances from the site for both urban and rural areas. Table 11.4 lists the most widely used propagation models in current cellular systems. Most of these models are a fusion of empirical formulas extracted from field measurements and some statistical prediction models. Three of the listed models that will be used in LTE are discussed in detail in the rest of this section.

11.5.2.1 Okumura-Hata

The Okumura-Hata model is a widely used wireless cellular propagation model that can predict channel behavior in the 150 to 2200 MHz range. It covers distances from 1 to 20 km. The model has three environment formulas:

Table 11.4 Commonly used Wireless Channel Propagation Models

Model	*Frequency (MHz)*	*Recommended use*
COST-231	800–2000	0.02 < *d* < 5 km, UMTS, GSM1800, LTE
Erceg-Greenstein	1900–6000	0.1 < *d* < 8 km, Fixed WiMAX
IMT-2000	800–2800	Indoor office, vehicular, outdoor to indoor
ITU-526	30–1000	Fixed receivers
ITU-529	300–1500	1 < *d* < 100 km, GSM900, CDMA2000, LTE
Okumura-Hata	150–2200	1 < *d* < 20 km, GSM900, CDMA2000, LTE
WLL	30–10000	Fixed receivers, Microwave Links, WiMAX

IMT: International Mobile Telecommunication
ITU: International Telecommunication Union
WLL: Wireless Local Loop

- **Typical Urban**

$$L_{P(\text{urban})} = 69.55 + 26.16\log(f_c) + [44.9 - 6.55\log(h_{BS})]Log(d) \\ -13.82\log(h_{BS}) - a(h_{UE}) \quad \text{dB} \tag{11.13}$$

where f_c is the carrier frequency $400 \leq f_c \leq 2200$ MHz, $h_{BS} \in [30, 200]$ m and $h_{UE} \in [1, 10]$ m are the base station and mobile station heights, respectively, $d \in [1, 20]$ km is the distance between the BS and UE, and $a(h_{UE})$ is the UE antenna height correction factor. For $f_c \geq 400$ MHz, $a(h_{UE})$ given by:

$$a(h_{UE}) = \begin{cases} 3.2[\log(11.75h_{UE})]^2 - 4.97 & \text{Dense urban} \\ [1.1\log(f_c) - 0.7]h_{UE} - [1.56\log(f_c) - 0.8] & \text{Urban} \end{cases} \tag{11.14}$$

- **Typical Suburban:**

$$L_{P(\text{suburban})} = L_{P(\text{urban})} - 2\left[\log\left(\frac{f_c}{28}\right)^2 - 5.4\right] \quad \text{dB} \tag{11.15}$$

- **Rural:**

$$L_{P(\text{rural})} = L_{P(\text{urban})} + 18.33\log(f_c) - 4.78[\log(f_c)]^2 - 40.94 \quad \text{dB} \tag{11.16}$$

11.5.2.2 COST-231

Cooperation in science and technology (COST-231) is one of the models anticipated to be used for LTE channel prediction. It covers frequencies from 800 to 2000 MHz, and distances from the BS starting at 20 m and up to 5 km. It is widely used in Europe for the GSM 1800-MHz system. The model is valid for $h_{BS} \in [4, 50]$ m and $h_{UE} \in [1, 3]$ m. The path loss formula is given by:

$$L_P = 32.4 + 20\log(d) + 20\log(f_c) + L_{rts} + L_m \quad \text{dB} \tag{11.17}$$

where L_{rts} and L_m are the rooftop to street diffraction and scatter factor and multi-screen loss, respectively. The formulas for these two factors are given by:

$$L_{rts} = 10\log(f_c) + 20\log(h_r - h_{UE}) + L_{\phi} - 10\log(W) - 16.9 \quad \text{dB} \tag{11.18}$$

$$L_m = L_{BS2B} + K_a + K_d\log(d) + K_f\log(f_c) - 9\log(b) \tag{11.19}$$

where, h_r is the average building height, W is the street width, b is the distance between adjacent buildings, L_{ϕ} is the loss due to the incident angle relative to the street, and L_{BS2B} is the loss factor due to the difference between the BS and average building height. The various relationships are given by (all in dB)

$$L_{\phi} = \begin{cases} -10 + 0.354\phi, & 0 \leq \phi \leq 35^\circ; \\ 2.5 + 0.075(\phi - 35), & 35 \leq \phi \leq 55^\circ; \\ 4 - 0.114(\phi - 55), & 55 \leq \phi \leq 90^\circ. \end{cases} \tag{11.20}$$

$$L_{BS2B} = \begin{cases} -18\log(11 + h_{BS} - h_r), & h_{BS} \geq h_r; \\ 0, & h_{BS} < h_r. \end{cases} \tag{11.21}$$

$$K_a = \begin{cases} 54, & h_{BS} > h_r; \\ 54 - 0.8h_{BS}, & d \geq 500m,\ h_{BS} \leq h_r; \\ 54 - 0.8h_{BS}\left(\frac{d}{500}\right), & d < 500m,\ h_{BS} \leq h_r. \end{cases} \tag{11.22}$$

$$K_d = \begin{cases} 18, & h_{BS} < h_r; \\ 18 - \frac{15(h_{BS} - h_r)}{h_{UE} - h_r}, & h_{BS} \geq h_r. \end{cases} \tag{11.23}$$

$$K_f = \begin{cases} 4 + 0.7\left(\frac{f_c}{925} - 1\right), & \text{midsize city/suburban;} \\ 4 + 1.5\left(\frac{f_c}{925} - 1\right), & \text{metro area.} \end{cases} \tag{11.24}$$

11.5.2.3 IMT-2000

International mobile telecommunications (IMT-2000) is the standard that includes the system requirements for 3G-based cellular systems from which UMTS is derived. This standard has the following several propagating environment models for outdoor and indoor channels [1]:

- **Indoor Environment**: This model covers indoor scenarios with small cells and low transmit power levels. It is suitable for RMS delay spread values of 35 to 460 ns. It uses a log-normal shadowing with a 12-dB standard deviation. The path loss is given by:

$$L_{P(\text{indoor})} = 37 + 30\log(d) + 18.3n^{\left[\frac{n+2}{n+1}-0.46\right]} \quad \text{dB} \tag{11.25}$$

  where d is the distance between the transmitter and receiver stations, and n is the number of floors.
- **Pedestrian and Outdoor-to-Indoor Environment:** The model uses small cells, with low transmit power levels, and RMS delay spread of 100 to 800 ns. It covers only nonline of sight (NLOS) scenarios, and utilizes a log-normal shadowing with a 10-dB standard deviation. The path loss is given by:

$$L_{P(\text{ped-out2in})} = 40\log(d) + 30\log(f_c) + 49 \quad \text{dB} \tag{11.26}$$

- **Vehicular Environment:** The model covers large cells and higher transmit power levels, with an RMS delay spread of 4 to 12 μs. A log-normal shadowing with a 10-dB standard deviation is used. The path loss formula is given by:

$$\begin{aligned} L_{P(\text{vehicle})} = {} & 40\left(1 - 4\times 10^{-2}\Delta h_{BS}\right)\log(d) - 18\log(\Delta h_{BS}) \\ & + 21\log(f_c) + 80 \quad \text{dB} \end{aligned} \tag{11.27}$$

  where Δh_{BS} is the BS antenna height measured from the average rooftop level of the vehicle in meters.

11.5.3 Deterministic Path Loss Models

The previous section discussed three of the most widely used empirical/statistical path loss models used in 3G models that will also be used in LTE. These models are derived from extensive measurement scenarios from which the wireless channel is described by probability functions of statistical parameters. Empirical/statistical models provide general results. Another group is based on deterministic channel modeling. The channel characteristics are obtained by tracing the reflected, diffracted, and scattered rays based on a specific geometry with a database what includes the sizes of the physical objects and their material properties. Deterministic models have the advantage of providing very accurate, site-specific results that are reproducible. However, they suffer from the need of more model specific data and computation time [18–20].

Three-dimensional (3D) ray tracing is a deterministic channel modeling method that has proven to give good accuracy for indoor MIMO channels [19]. It is based on the combination of geometrical optics and the uniform theory of diffraction (GO/UTD). After specifying transmitter and receiver locations, a shouting-and-bouncing algorithm is used to obtain the electric field $\vec{E}_i$ (amplitude, phase, polarization, direction of departure (DOD), direction of arrival (DOA), delay spread, etc.) from the ith transmitter antenna to the jth receiver antenna. The path loss can be found [20] as follows:

$$L_j = 20\log\left(\frac{\lambda}{4\pi}\frac{|\vec{E}_{\mathbf{T}}|}{|\vec{E}_{\mathbf{0}}|}\right) \tag{11.28}$$

$$\vec{E}_{\mathbf{T}} = \sqrt{\sum_{i=1}^{n} \vec{E}_{\mathbf{i}}^{\mathbf{2}}} \tag{11.29}$$

where $\vec{E}_{\mathbf{T}}$ is the total received electric field, n is the number of received rays (paths), $\vec{E}_{\mathbf{0}}$ is the transmitted electric field, and L_j is the jth receiver antenna. Because 3D ray tracing will provide all the parameter values of the propagating signal for a transmitter/receiver path, the channel impulse response can be constructed and used to predict other channel effects on the transmitted waveform.

11.5.4 Link Budget

The fact that the LTE radio channel is adaptive according to channel variations as well as having the option of using MIMO at the UE and eNB makes the link budget formulation dynamic as well. The channel bandwidth and the measurements made at the UE and eNB also vary the noise density. A link budget is formed by specifying the power levels from the output of the transmitter module right before the antenna feeders, through the antenna, passing the wireless channel (fading, diffraction, shadowing, interference, noise), to the receiving antenna, feeders, and finally the input point of the receiver module.

In a spread-spectrum based communication system, the spreading of the data introduces an extra gain called the processing gain. The value of the processing is gain is given by $G_P = \frac{R_{\text{code}}}{R_{\text{data}}}$ where R_{code} is the code sequence chipping rate, and R_{data} is the data rate of the transmitted signal. The processing gain should be included in the link budget calculation. The geometry factor (G-factor), which describes the desired signal levels to inter-/intra-cell interference plus noise, should also be accounted for in the link budget (same as the CINR). Table 11.5 presents the minimum specified transmit and receive power levels for the UE and eNB in FDD mode of operation. These levels depend on the E-UTRA band of operation as

Table 11.5 Power Levels for Link Budget, UE, and BS in FDD Mode

		UE	*BS*	*Level*
Transmit	Maximum Transmit Power	23	43	dBm
	Cable/Interconnect Losses	0.5–2	0.5–2	dB
	Noise Figure	9	5	dB
	Antenna Again	0	12–15	dB
Receive	Antenna Gain	0	12–15	dB
	Noise Figure	9	5	dB
	Cable/Interconnect Losses	0.5–2	0.5–2	dB
	Sensitivity (min, BW = 10 MHz)	−94	−101.5	dBm

well as the operating BW and modulation scheme. The reference sensitivity is the minimum mean power applied to the antenna ports at which throughput shall meet the minimum requirements for the specified channel. For QPSK transmission, sensitivity is based on ≥95% throughput level from the absolute maximum. No MIMO gain is shown in the table, and the output powers are based on the active ON state of the UE/eNB. For other levels and modes of operation, refer to [6,13,21]. Table 11.6 show a simple link budget calculation for a 64 Kbps UL with the use

Table 11.6 Sample UL Budget for Four Resource Blocks with 720 KHz BW and 128 Kbps Operation, FDD Model

UE	a. Max. transmit power	23	dBm
	b. Cable losses	0.5–2	dB
	c. Body loss	0	dB
	d. Antenna again	0	dBi
	e. EIRP	21	dBm, (a − b − c + d)
eNB	f. Antenna gain	15	dBi
	g. Feeder loss	2	dB
	h. Noise figure (NF)	5	dB
	i. Thermal noise	−110.4	dBm, (KTB)
	j. Receiver noise floor	−105.4	dBm, (h + i)
	k. CINR	−5	dB, From simulations
	l. Receiver sensitivity	−106.8	dBm, or (j + k)
	m. Max. channel loss	140.8	dB (e + f − g − l)

Note: 1. KTB = Boltzmann's Constant × Temperature in degrees Kelvin (290) × Bandwith in hertz.
2. Receiver sensitivity (i) was used from [21]. Also it can be calculated from j + k in Table 11.6. The value used is based on the minimum sensitivity value required for 1.4 MHz BW in [21].

Table 11.7 Sample DL Budget for 10 MHz BW and 1 Mbps Operation, FDD Mode

eNB	a. Max. transmit power	43	dBm
	b. Feeder losses	2	dB
	c. Antenna again	15	dBi
	d. EIRP	66	dBm, (a − b + c)
UE	e. Antenna gain	0	dBi
	f. Body loss	0	dB
	g. Cable loss	2	dB
	h. Noise figure (NF)	9	dB
	i. Thermal noise	−104	dBm (KTB)
	j. Receiver noise floor	−95	dBm (h + i)
	k. CINR	−5	From simulations
	l. Receiver sensitivity	−91	dBm, or (j + k)
	m. Max. channel loss	155	dB (d + e − f − g − l)

Note: 1. KTB = Boltzmann's constant × temperature in degrees Kelvin (290) × Bandwdth in hertz.
2. Receiver sensitivity (i) was used from Table 11.5. It can also be calculated from j + k in Table 11.7. The value used is based on the minimum sensitivity requirement value listed in [6] for 10 MHz BW.

of two resource blocks. While Table 11.7 shows a simple DL budget with 1 Mbps, and a bandwidth of 10 MHz. The CINR values depend on the levels of interference and the modulation and coding combination used. These can be extracted from cite specific simulations. The effective isotropic radiated power (EIRP) is the power level exiting the UE/eNB when transmitting. The maximum channel loss calculated at the end of the link budget is the maximum level of power loss through the channel below which the receiver will not be able to capture the received signal, and a call will be dropped. Any of the channel models presented in the previous sections can be used to determine the maximum distance between the UE and the eNB for a certain configuration.

The presence of neighboring cells, users and other networks increases the interference and noise levels. There are certain threshold levels for the CINR at the UE and eNB below which the service cannot be granted. The coexistence of LTE with other 2G and 3G networks dictates the need for careful design procedures and tighter interference requirements. The LTE standard identifies the adjacent channel interference ratio (ACIR) and the adjacent channel leakage ratio (ACLR) as two bandwidth dependent parameters that are monitored and describe the amount of interference and its impact on the DL and UL throughput. Several simulation examples and scenarios can be found in [15].

11.5.5 CW Testing

Continuous wave (CW) testing, also called CW drive testing, is essential to the RF planning process and deployment of cellular networks. A CW test should be conducted to examine the signal levels in the area of interest: indoor, outdoor, and in vehicle. There are two types of drive tests:

1. **CW Drive**: A CW drive test is conducted through different routes in the area to be covered before the network is deployed. A transmit antenna is placed in the location of interest (future site), and is configured to transmit an unmodulated carrier at the frequency channel of choice. A vehicle with receiver equipment is used to collect and log the received signal levels.
2. **Optimization Drive**: This drive test is conducted after the cellular network is in operation (different call durations, data uploads, and data downloads). Thus, the modulated data signal is transmitted and then collected by the on-vehicle receiver equipment, then the data are analyzed for different performance parameters like reference channels (similar to the pilot in 3G systems), power measurements, scrambling codes, block error rates, and error vector magnitudes.

11.5.6 Model Tuning

Model tuning is the step that follows CW testing. The logged CW data are used to come up with a tuning factor for the initially picked propagation model used for the area under investigation. Propagation model optimization/tuning is performed using various curve fitting and optimization algorithms that are proprietary to the planning tool, and after the process is complete, statistical performance measures are obtained to illustrate the effect of optimization on the model behavior in terms of the mean, standard deviation, and RMS error. This process will provide a mode accurate channel model.

11.6 Network Performance Parameters

11.6.1 Performance Parameters

Several types of parameter measurements are made at the UE or the eNB. These measurements are used to quantify the network performance and thus will aid in the adaptation of the appropriate coding/modulation as well as the link/cell traffic and capacity. In idle mode, eNB broadcasts the measurements within messages in the frame protocol. To initiate a specific measurement from the UE, the eNB transmits an "RRC connection configuration message" to the UE, along with the measurement type and ID, objects, command, quantity, and reporting criteria. The UE performs the measurement and responds to the eNB request with the measurement ID and results via a "measurement report message" [21–23]. Some of the most common performance metrics in LTE are:

- **Received Signal Strength Indicator (RSSI)**: This measures the wideband received power within the specified channel bandwidth. This measurement is performed on the broadcast control channel (BCCH) carrier. The measurement reference point is the UE antenna connector. This measurement is easy to perform, as it does not need any data decoding, rather it shows whether a strong signal is present or not. It does not give any details about the channel or signal structure.
- **Received Signal Code Power (RSCP)**: measures the received power on one code on the primary common-pilot channel (CPICH). If the measurement is made while the equipment is in spatial multiplexing, the measured code power from each antenna is recorded, and then all are summed together. If transmit diversity is chosen, the largest measurement from all antennas is picked. The measurement reference point is the UE antenna connector.
- $\boldsymbol{E_c/N_0(E_c/I_0)}$: This is the received energy per chip divided by the noise power density (E_c/N_0) (interference power density E_c/I_0) in the band. When spatial multiplexing is used, the individual received energy per chip is measured for each antenna, and then summed together. The sum is divided by the noise power density in the band of operation. If transmit diversity is used, the measured E_c/N_0 for antenna i should not be lower than the corresponding RSCP level. The measurement reference point is the UE antenna connector. Usually the E_c/I_0 level is indicated as the interference levels are more profound and affect signal quality than noise levels (i.e., thermal noise).
- **Block Error Rate (BLER)**: This is used to measure error blocks within a specific channel transmission as a measure of transmission quality. This is performed on the transport and dedicated channels (TCH, DCH).
- **Carrier–Interference Plus Noise Ratio Power Level [CINR ($\boldsymbol{C/(I+N)}$)]**: The CINR is measured in both the UE and eNB to determine the radio bearer to be used based on some predefined set of thresholds. The radio bearer defines which modulation and coding scheme to use for the data to be transmitted. The higher the CINR, the higher the spectrum efficiency by using a higher constellation modulation and coding scheme. The calculation of CINR is more involved than the RSSI, and it provides a better indication on the channel and signal qualities. CINR is sometimes referred to as the *G*-factor.
- **Error Vector Magnitude (EVM)**: It measures of the difference between the measured symbol coming out of the equalizer to that of the reference. The square root ratio of the mean error vector power to the mean power of the reference symbol is defined as EVM. The required EVM percentage over all bandwidths of operation performed over all the resource blocks and subframes for LTE is based on the modulation scheme used. Thus, for QPSK, 16-QAM, and 64-QAM modulation is given by 17.5%, 12.5%, and 8%, respectively.

11.6.2 Traffic

Traffic intensity is a measure of the average number of calls taking place at a specific time interval. The traffic intensity (I) is usually measured in Erlangs. One Erlang represents a call with an average duration of 1 hour.

$$I = \frac{\sum_{i=1}^{N_c} t_i}{T} = \frac{N_c \bar{t}_i}{T} \tag{11.30}$$

where N_c is the total number of calls, t_i is the holding time for user i, T is the monitoring time interval, and $\bar{t}_i$ is the average holding time for user i. A call that cannot be completed because the connecting equipments are busy (fully utilized) is termed as a blocked call. Several probability distribution models (formulas) are used based on the way calls are handled. In the USA, the Poisson's formula is used, while in Europe and Asia the Erlang-B formula is used. Each formula has its own assumptions based on the way the calls originate and processed [1]. The Poisson's formula results in higher blocking rates than the Erlang-B one for a given traffic load.

The actual cellular network performance in terms of traffic and capacity depend on the eNB transceivers capacity as well as the average Erlangs per subscriber. The user might be blocked from service if its CINR level is below the minimum threshold as well [21]. In LTE, dynamic scheduling for the UL and DL is included in the MAC of the eNB. It takes into account the traffic volume and the QoS of each connected UE. Only service granted UE are allowed to transmit. Resources are allocated based on the radio channel condition measurements (CQI) and layer-2 measurements. These measurements will assign scheduling, load balancing and transmission priorities per traffic class [4, 5]. Layer-2 measurements are discussed in detail in [24]. The QoS class identifier (QCI) and the allocation and retention priority (ARP) are two parameters that control node specific parameters and control bearer level packet forwarding, scheduling weights, queue management, and priority levels to establish/modify such requests and whether to grant or decline them in the presence of resource limitations.

11.6.3 Measurement Types

The LTE is still in its early stages, as no actual deployments of the system has been reported in any part of the world. Several experiments are taking place as we speak. WiMAX, on the other hand, has been deployed in several regions around the world. The radio interface for LTE and WiMAX are similar in several aspects, the main difference being the use of SC-FDMA for the UL radio interface compared to an OFDMA interface for WiMAX. The measurement of signal levels and performance parameters in a complex system with MIMO capability is not a trivial task.

Although RF giants like Agilen, and Keithley, among others in the measurement arena, provide complete integrated solutions for RF planning engineers to test their networks, the engineer should know what to look for and how to read, interpret, and analyze the measurements conducted with proper setup procedures. There are generally two types of measurements involved: measurements of the prototype and measurements of the deployed network. Although the former is essential to make sure that the designed equipment satisfy the specification requirements in the laboratory environment, the latter provides an actual field characterization of the developed equipment.

- **Predeployment/Prototyping**: The measurements performed in this stage are aimed to show compliance of the developed equipment (UE/eNB) with the technology requirements. For LTE, laboratory measurements should reflect as much of the actual field environment as possible. Thus, several RF equipment vendors are providing MIMO channel emulators that can give close estimates of the RF propagation channel to be encountered by the LTE terminals. Vector signal generators (VSG) are used to generate LTE modulated signals, and vector signal analyzers (VSA) analyze the signals and provide all necessary information and performance measures at the receiver [25].
- **Postdeployment**: The measurements performed in this stage are made in two steps, as mentioned in Section 11.5.5. A CW test drive is made to check the coverage scenario, then a detailed test with active network traffic is performed to log performance metrics such as the EVM, subcarriers, spreading codes, signal strength, I/Q imbalance and errors, frequency shifts, cell ID, timing offset, and the like [26].

11.7 Postdeployment Optimization and Open Issues

11.7.1 Postdeployment Optimization

As with all currently deployed cellular networks, whether it be a 2G GSM network or even a 3G UMTS one, an LTE network will have to be optimized after deployment to provide better coverage, throughput, lower latency and seamless integration as the specification asks for. The optimization process contains several steps. It starts with data drive testing as mentioned in Section 11.5.5, where all performance parameters are tested and logged in the field after the network is active. This test should also include the different coverage/propagation scenarios along with their respective models (e.g., pedestrian, vehicular, indoor). The field data will then be used to tune the models for better network performance and coverage.

Based on the collected data, RF planning engineers analyze the performance and maybe decide to add more eNBs for coverage, mainly pico and femtocells, in the areas that show degraded power levels or data throughput. Femtocells will be used in LTE, as they will provide service for households and small businesses. Usually, the optimization process is an iterative one with no specific steps involved, rather than a set of consistent procedures that characterizes network performance and coverage in a certain area; actions are taken accordingly.

11.7.2 Open Issues

There are several open issues that original equipment manufacturers (OEMs) has to take into account when designing LTE terminals and equipment. Some of the issues are being addressed, whereas others are still under extensive investigation. Here, we identify some of these open issues in two categories: UE and eNB.

11.7.2.1 UE

There are several challenges that has to be overcome in implementing LTE UE. The use of MIMO technology dictates the use of highly reliable and complex equalization techniques. In a worse-case scenario, and using a minimum-mean-square-error (MMSE) technique, the equalization might consume 1500 MIPS (million instructions per second) performed on 600 subcarriers. This poses a challenge in performing parallel computations, minimizing power consumption and silicon area. Memory requirements for coding and decoding is also a challenge that needs to be overcome [27, 28].

11.7.2.2 eNB

Although designers always try to minimize power consumption and silicon area in their designs, there are less stringent requirements at the eNB side. The challenges with complexities of hardware also exist within the eNB equipment. However, there are other challenging aspects that have to be solved such as using BF to improve DL performance. BF needs the use of antenna arrays, which require the use of adaptive algorithms and electronics to be able to operate in real time and automatically. The fact that BF will coexist within MIMO system is also a challenge. The coexistence with legacy systems like 2G and 3G networks in the vicinity is another obstacle to be overcome (4G-3G, 4G-2G). This coexistence will increase interference levels and raises the thesholds of noise and interference. The LTE specification specifies strict intermodulation levels due to this network coexistence. There are stringent requirements within it that details the compliance levels within legacy systems bands that OEMs should pay attention to.

11.8 Conclusion

LTE-based cellular networks are anticipated to be deployed in 2011. Such complex networks need careful design and planning. This chapter touched on the physical layer (air interface) of such a network and discussed the RF planning process. Adaptive coding and modulation schemes as well as OFDMA multiplexing were presented to explain the physical layer interface and operation. The planning engineer should be aware of the channel models, MIMO system operation, and performance parameters and metrics to analyze and study the network behavior. Three statistical propagation channel models were discussed in detail (Okumura-Hata, Cost-231, and IMT-2000), as was the deterministic ray tracing method to identify the main parameters used for modeling the LTE channel. A coverage example was provided, using a simulation tool that incorporates MIMO systems. Measurement types and methods for pre- and postnetwork deployment were highlighted. The four propagation scenarios listed in the LTE specification were presented. Finally, some of the challenges on the UE and eNB sides were discussed.

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