# Chapter 2
# 3GPP Long Term Evolution

## 2.1 Introduction

### *2.1.1 Evolution and Environment of 3GPP Telecommunication Systems*

Terrestrial mobile telecommunications started in the early 1980s using various analog systems developed in Japan and Europe. The Global System for Mobile communications (GSM) digital standard was subsequently developed by the European Telecommunications Standards Institute (ETSI) in the early 1990s. Available in 219 countries, GSM belongs to the second generation mobile phone system. It can provide an international mobility to its users by using inter-operator roaming. The success of GSM promoted the creation of the Third Generation Partnership Project (3GPP), a standard-developing organization dedicated to supporting GSM evolution and creating new telecommunication standards, in particular a Third Generation Telecommunication System (3G). The current members of 3GPP are ETSI (Europe), ATIS(USA), ARIB (Japan), TTC (Japan), CCSA (China) and TTA (Korea). In 2010, there are 1.3 million 2G and 3G base stations around the world [6] and the number of GSM users surpasses 3.5 billion [25].

The existence of multiple vendors and operators, the necessity interoperability when roaming and limited frequency resources justify the use of unified telecommunication standards such as GSM and 3G. Each decade, a new generation of standards multiplies the data rate available to its user by ten (Fig. 2.1). The driving force behind the creation of new standards is the radio spectrum which is an expensive resource shared by many interfering technologies. Spectrum use is coordinated by International Telecommunication Union, Radio Communication Sector (ITU-R), an international organization which defines technology families and assigns their spectral bands to frequencies that fit the International Mobile Telecommunications (IMT) requirements. 3G systems including LTE are referred to as ITU-R IMT-2000.

M. Pelcat et al., *Physical Layer Multi-Core Prototyping*,
Lecture Notes in Electrical Engineering 171, DOI: 10.1007/978-1-4471-4210-2_2,

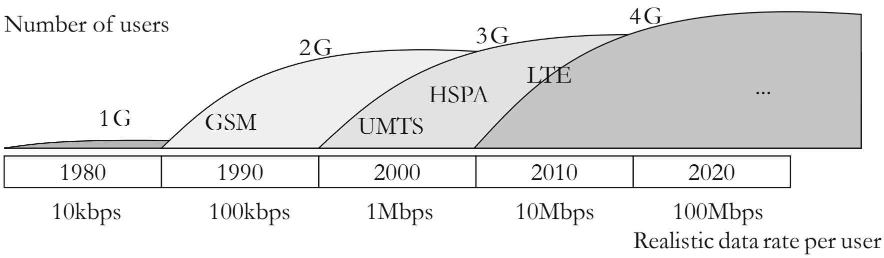



**Fig. 2.1** 3GPP standard generations

Radio access networks must constantly improve to accommodate the tremendous evolution of mobile electronic devices and internet services. Thus, 3GPP unceasingly updates its technologies and adds new standards. The goal of new standards is the improvement of key parameters, such as complexity, implementation cost and compatibility, with respect to earlier standards. Universal Mobile Telecommunications System (UMTS) is the first release of the 3G standard. Evolutions of UMTS such as High Speed Packet Access (HSPA), High Speed Packet Access Plus (HSPA+) or 3.5G have been released as standards due to providing increased data rates which enable new mobility internet services like television or high speed web browsing. The 3GPP Long Term Evolution (LTE) is the 3GPP standard released subsequent to HSPA+. It is designed to support the forecasted ten-fold growth of traffic per mobile between 2008 and 2015 [25] and the new dominance of internet data over voice in mobile systems. The LTE standardization process started in 2004 and a new enhancement of LTE named LTE-Advanced is currently being standardized.

### *2.1.2 Terminology and Requirements of LTE*

A LTE terrestrial base station computational center is known as an evolved NodeB or `eNodeB`, where a NodeB is the name of a UMTS base station. An eNodeB can handle the communication of a few base stations, with each base station covering a geographic zone called a cell. A cell is usually three-sectored with three antennas (or antenna sets) each covering 120 (Fig. 2.2). The user mobile terminals (commonly mobile phones) are called User Equipment (`UE`). At any given time, a UE is located in one or more overlapping cells and communicates with a preferred cell; the one with the best air transmission properties. LTE is a duplex system, as communication flows in both directions between UEs and eNodeBs. The radio link between the eNodeB and the UE is called the downlink and the opposite link between UE and its eNodeB is called uplink. These links are asymmetric in data rates because most internet services necessitate a higher data rate for the downlink than for the uplink. Fortunately, it is easier to generate a higher data rate signal in an eNodeB powered by mains than in UE powered by batteries.

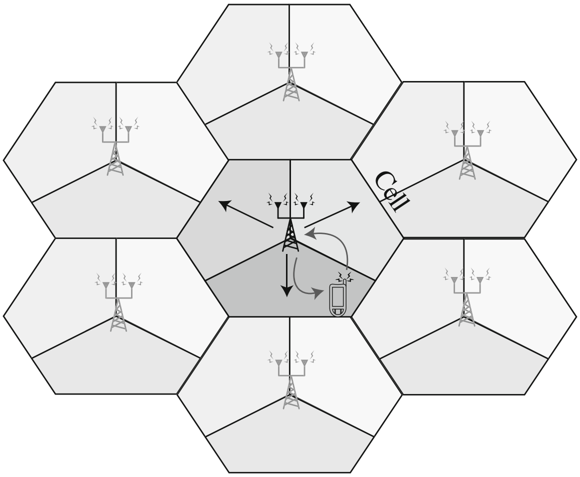



**Fig. 2.2** A three-sectored cell

In GSM, UMTS and its evolutions, two different technologies are used for voice and data. Voice uses a circuit-switched technology, i.e. a resource is reserved for an active user throughout the entire communication, while data is packet-switched, i.e. data is encapsulated in packets allocated independently. Contrary to these predecessors, LTE is a totally packet-switched network using Internet Protocol (IP) and has no special physical features for voice communication. LTE is required to coexist with existing systems such as UMTS or HSPA in numerous frequency configurations and must be implemented without perturbing the existing networks.

LTE Radio Access Network advantages compared with previous standards (GSM, UMTS, HSPA...) are [30]:

- `Improved data rates`. Downlink peak rate are over 100 Mbit/s assuming 2 UE receive antennas and uplink peak rate over 50Mbit/s. Raw data rates are determined by $Bandwidth * Spectral\ Efficiency$ where the bandwidth (in Hz) is limited by the expensive frequency resource and ITU-R regulation and the spectral efficiency (in bit/s/Hz) is limited by emission power and channel capacity (Sect. 2.3.1). Within this raw data rate, a certain amount is used for control, and so is hidden from the user. In addition to peak data rates, LTE is designed to ensure a high system-level performance, delivering high data rates in real situations with average or poor radio conditions.
- A `reduced` data transmission `latency`. The two-way delay is under 10 ms.
- A `seamless mobility` with handover latency below 100 ms; handover is the transition when a given UE leaves one LTE cell to enter another one. 100 ms has been shown to be the maximal acceptable round trip delay for voice telephony of acceptable quality [30].
- `Reduced cost per bit`. This reduction occurs due to an improved spectral efficiency; spectrum is an expensive resource. Peak and average spectral

efficiencies are defined to be greater than 5 and 1.6 bit/s/Hz respectively for the downlink and over 2.5 and 0.66 bit/s/Hz respectively for the uplink.

- A `high spectrum flexibility` to allow adaptation to particular constraints of different countries and also progressive system evolutions. LTE operating bandwidths range from 1.4 to 20 MHz and operating carrier bands range from 698 MHz to 2.7 GHz.
- A `tolerable mobile terminal power consumption` and a very low power idle mode.
- A `simplified network architecture`. LTE comes with the System Architecture Evolution (SAE), an evolution of the complete system, including core network.
- A `good performance for both Voice over IP` (VoIP) with small but constant data rates `and packet-based traffic` with high but variable data rates.
- A `spatial flexibility` enabling small cells to cover densely populated areas and cells with radii of up to 115 km to cover unpopulated areas.
- The support of `high velocity UEs` with good performance up to 120 km/h and connectivity up to 350 km/h.
- The management of up to `200 active-state users per cell` of 5 MHz or less and 400 per cell of 10 MHz or more.

Depending on the type of UE (laptop, phone...), a tradeoff is found between data rate and UE memory and power consumption. LTE defines 5 UE categories supporting different LTE features and different data rates.

LTE also supports data broadcast (television for example) with a spectral efficiency over 1 bit/s/Hz. The broadcasted data cannot be handled like the user data because it is sent in real-time and must work in worst channel conditions without packet retransmission.

Both eNodeBs and UEs have emission power limitations in order to limit power consumption and protect public health. An outdoor eNodeB has a typical emission power of 40–46 dBm (10–40 W) depending on the configuration of the cell. An UE with power class 3 is limited to a peak transmission power of 23 dBm (200 mW). The standard allows for path-loss of roughly between 65 and 150 dB. This means that For 5 MHz bandwidth, a UE is able to receive data of power from $-100$ to $-25$ dBm (0.1 pW to 3.2 $\mu$W).

### *2.1.3 Scope and Organization of the LTE Study*

The scope of this study is illustrated in Fig. 2.3. It concentrates on the Release 9 LTE physical layer in the eNodeB, i.e. the signal processing part of the LTE standard. 3GPP finalized the LTE Release 9 in December 2009. The physical layer (Open Systems Interconnection (OSI) layer 1) uplink and downlink baseband processing must share the eNodeB digital signal processing resources. The downlink baseband process is itself divided into channel coding that prepares the bit stream for transmission and

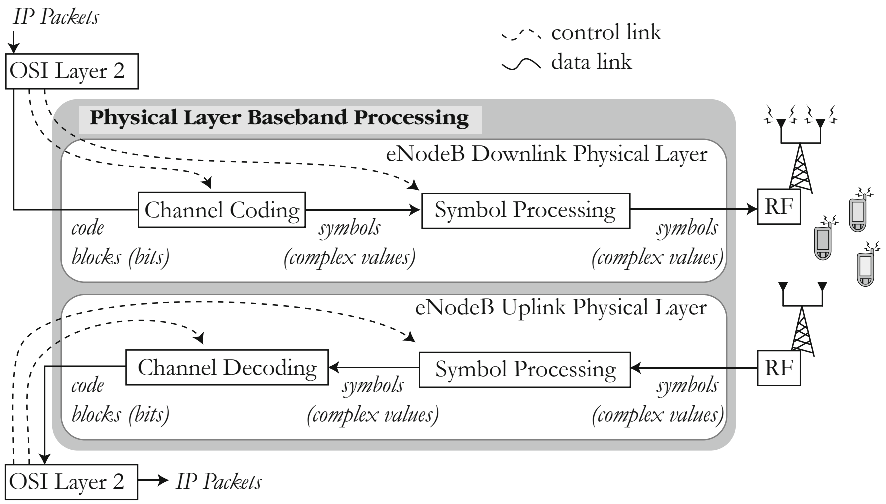



**Fig. 2.3** Scope of the LTE study

symbol processing that adapts the signal to the transmission technology. The uplink baseband process performs the corresponding decoding. To explain the interaction with the physical layer, a short description of LTE network and higher layers will be given (in Sect. 2.2). The OSI layer 2 controls the physical layer parameters.

The goal of this study is to address the most computationally demanding use cases of LTE. Consequently, there is a particular focus on the highest bandwidth of 20 MHz for both the downlink and the uplink. An eNodeB can have up to 4 transmit and 4 receive antenna ports while a UE has 1 transmit and up to 2 receive antenna ports. An understanding of the basic physical layer functions assembled and prototyped in the rapid prototyping section is important. For this end, this study considers only the baseband signal processing of the physical layer. For transmission, this means a sequence of complex values $z(t) = x(t) + jy(t)$ used to modulate a carrier in phase and amplitude are generated from binary data and for each antenna port. A single antenna port carries a single complex value $s(t)$ at a one instant in time and can be connected to several antennas.

$$s(t) = x(t)\cos(2\pi f t) + y(t)\sin(2\pi f t) \tag{2.1}$$

where f is the carrier frequency which ranges from 698 MHz to 2.7GHz. The receiver gets an impaired version of the transmitted signal. The baseband receiver acquires complex values after lowpass filtering and sampling and reconstructing the transmitted data.

An overview of LTE OSI layers 1 and 2 with further details on physical layer technologies and their environment is presented in the following sections. A complete description of LTE can be found in [20, 21] and [30]. Standard documents describing

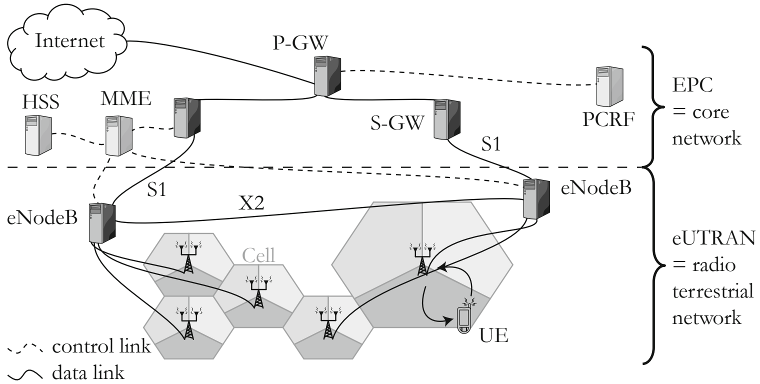



**Fig. 2.4** LTE system architecture evolution

LTE are available on the web. The UE radio requirements in [7], eNodeBs radio requirements in [8], rules for uplink and downlink physical layer in [9] and channel coding in [10] with rules for defining the LTE physical layer.

## 2.2 From IP Packets to Air Transmission

### *2.2.1 Network Architecture*

LTE introduces a new network architecture named System Architecture Evolution (SAE) and is displayed in Fig. 2.4 where control nodes are grayed compared with data nodes. SAE is divided into two parts:

- The Evolved Universal Terrestrial Radio Access Network (`E-UTRAN`) manages the radio resources and ensures the security of the transmitted data. It is composed entirely of eNodeBs. One eNodeB can manage several cells. Multiple eNodeBs are connected by cabled links called X2 allowing handover management between two close LTE cells. For the case where a handover occurs between two eNodeBs not connected by a X2 link, the procedure uses S1 links and is more complex.
- The Evolved Packet Core (`EPC`) also known as core network, enables packet communication with internet. The Serving Gateways (`S-GW`) and Packet Data Network Gateways (`P-GW`) ensure data transfers and Quality of Service (QoS) to the mobile UE. The Mobility Management Entities (`MME`) are scarce in the network. They handle the signaling between UE and EPC, including paging information, UE identity and location, communication security, load balancing. The radio-specific control information is called Access Stratum (`AS`). The radio-independent link between core network and UE is called Non-Access Stratum (`NAS`). MMEs delegate the verification of UE identities and operator subscriptions to Home Subscriber Servers (`HSS`). Policy Control and charging Rules

Function (PCRF) servers check that the QoS delivered to a UE is compatible with its subscription profile. For example, it can request limitations of the UE data rates because of specific subscription options.

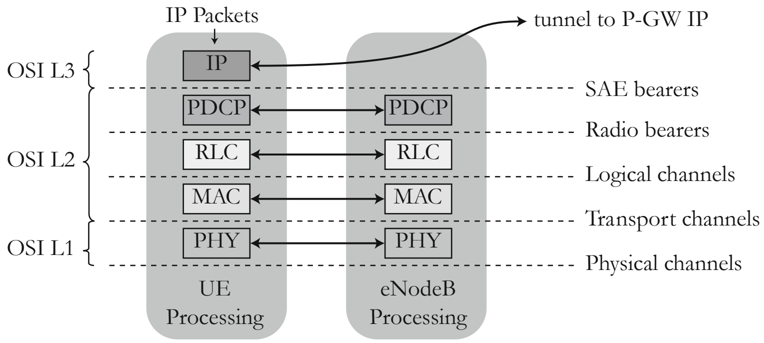
The details of eNodeBs and their protocol stack are now described.

### *2.2.2 LTE Radio Link Protocol Layers*

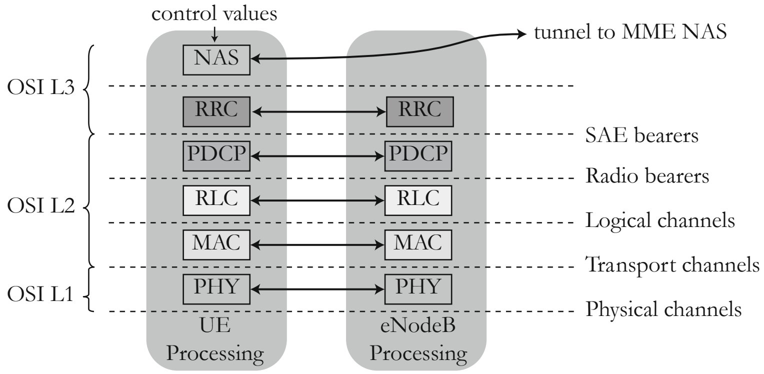
The information sent over a LTE radio link is divided in two categories: the user-plane which provides data and control information irrespective of LTE technology and the control-plane which gives control and signaling information for the LTE radio link. The protocol layers of LTE are displayed in Fig. 2.5 differ between user plane and control plane but the low layers are common to both planes. Figure 2.5 associates a unique OSI Reference Model number to each layer. layers 1 and 2 have identical functions in control-plane and user-plane even if parameters differ (for instance, the modulation constellation). Layers 1 and 2 are subdivided in:

- PDCP layer [14] or layer 2 Packet Data Convergence Protocol is responsible for data ciphering and IP header compression to reduce the IP header overhead. The service provided by PDCP to transfer IP packets is called a radio bearer. A radio bearer is defined as an IP stream corresponding to one service for one UE.
- RLC layer [13] or layer 2 Radio Link Control performs the data concatenation and then generates the segmentation of packets from IP-Packets of random sizes which comprise a Transport Block (TB) of size adapted to the radio transfer. The RLC layer also ensures ordered delivery of IP-Packets; Transport Block order can be modified by the radio link. Finally, the RLC layer handles a retransmission scheme of lost data through a first level of Automatic Repeat reQuests (ARQ). RLC manipulates logical channels that provide transfer abstraction services to the upper layer radio bearers. A radio bearer has a priority number and can have Guaranteed Bit Rate (GBR).
- MAC layer [12] or layer 2 Medium Access Control commands a low level retransmission scheme of lost data named Hybrid Automatic Repeat reQuest (HARQ). The MAC layer also multiplexes the RLC logical channels into HARQ protected transport channels for transmission to lower layers. Finally, the MAC layer contains the scheduler (Sect. 2.2.4), which is the primary decision maker for both downlink and uplink radio parameters.
- Physical layer [9] or layer 1 comprises all the radio technology required to transmit bits over the LTE radio link. This layer creates physical channels to carry information between eNodeBs and UEs and maps the MAC transport channels to these physical channels. The following sections focus on the physical layer with no distinction drawn between user and control planes.

Layer 3 differs in control and user planes. Its Control plane handles all information specific to the radio technology, with the MME making the upper layer decisions. The User plane carries IP data from system end to system end (i.e. from UE to




**(a)** User plane




**(b)** Control plane

**Fig. 2.5** Protocol layers of LTE radio link

P-GW). No further detail will be given on LTE non-physical layers. More information can be found in [20], p. 300 and [30], pp. 51 and 79.

Using both HARQ, employed for frequent and localized transmission errors, and ARQ, which is used for rare but lengthy transmission errors, results in high system reliability while limiting the error correction overhead. The retransmission in LTE is determined by the target service: LTE ensures different Qualities of Service (QoS) depending on the target service. For instance, the maximal LTE-allowed packet error loss rate is $10^{-2}$ for conversational voice and $10^{-6}$ for transfers based on Transmission Control Protocol (TCP) OSI layer 4. The various QoS imply different service priorities. For the example of a TCP/IP data transfer, the TCP packet retransmission system adds a third error correction system to the two LTE ARQs.

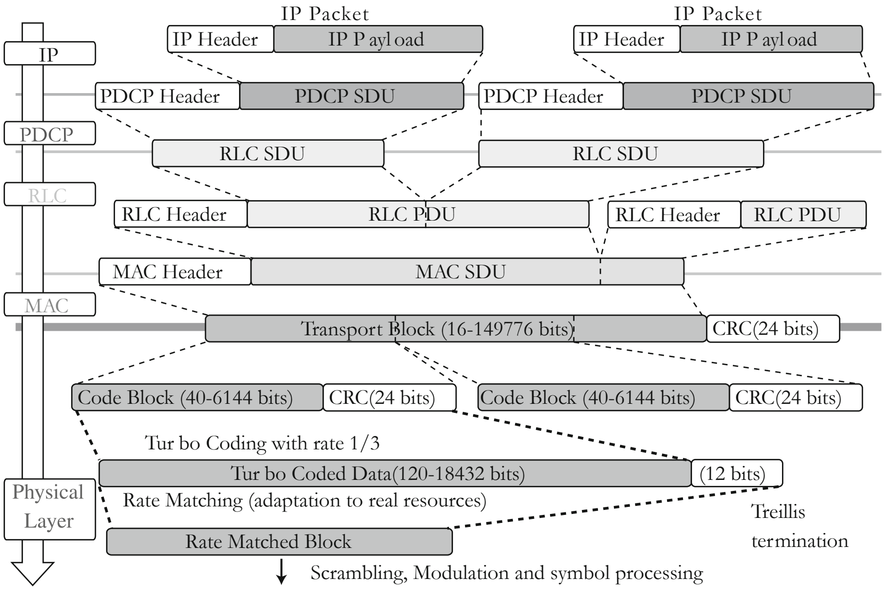



**Fig. 2.6** Data blocks segmentation and concatenation

### *2.2.3 Data Blocks Segmentation and Concatenation*

The physical layer manipulates bit sequences called Transport Blocks. In the user plane, many block segmentations and concatenations are processed layer after layer between the original data in IP packets and the data sent over air transmission. Figure 2.6 summarizes these block operations. Evidently, these operations do not reflect the entire bit transformation process including ciphering, retransmitting, ordering, and so on.

In the PDCP layer, the IP header is compressed and a new PDCP header is added to the ciphered Protocol Data Unit (PDU). In the RLC layer, RLC Service Data Units (SDU) are concatenated or segmented into RLC PDUs and a RLC header is added. The MAC layer concatenates RLC PDUs into MAC SDUs and adds a MAC header, forming a Transport Block, the data entity sent by the physical layer. For more details on layer 2 concatenation and segmentation, see [30], p. 79. The physical layer can carry downlink a Transport Blocks of size up to 149776 bits in 1 ms. This corresponds to a data rate of 149.776 Mbit/s. The overhead required by layer 2 and upper layers reduces this data rate. Moreover, such a Transport Block is only possible in very favorable transmission conditions with a UE capable of supporting the data rate. Transport Block sizes are determined from radio link adaptation parameters shown in the tables of [11], p. 26. An example of link capacity computing is given in Sect. 7.2.2. In the physical layer, Transport Blocks are segmented into Code Blocks

(CB) of size up to 6144 bits. A Code Block is the data unit for a part of the physical layer processing, as will be seen in Chap. 7.

### 2.2.4 MAC Layer Scheduler

The LTE MAC layer adaptive scheduler is a complex and important part of the eNodeB. It controls the majority of the physical layer parameters; this is the layer that the study will concentrate on in later sections. Control information plays a much greater role in LTE than in the previous 3GPP standards because many allocation choices are concentrated in the eNodeB MAC layer to help the eNodeB make global intelligent tradeoffs in radio access management. The MAC scheduler manages:

- the `radio resource allocation` to each UE and to each radio bearer in the UEs for both downlink and uplink. The downlink allocations are directly sent to the eNodeB physical layer and those of the uplink are sent via downlink control channels to the UE in uplink grant messages. The scheduling can be dynamic (every millisecond) or persistent, for the case of long and predictable services as VoIP.
- the `link adaptation` parameters (Sect. 2.3.5) for both downlink and uplink.
- the `HARQ` (Sect. 2.3.5.1) commands where lost Transport Blocks are retransmitted with new link adaptation parameters.
- the `Random Access Procedure` (Sect. 2.4.5) to connect UEs to a eNodeB.
- the `uplink timing alignment` (Sect. 2.3.4) to ensure UE messages do not overlap.

The MAC scheduler must take data priorities and properties into account before allocating resources. Scheduling also depends on the data buffering at both eNodeB and UE and on the transmission conditions for the given UE. The scheduling optimizes link performance depending on several metrics, including throughput, delay, spectral efficiency, and fairness between UEs.

## 2.3 Overview of LTE Physical Layer Technologies

### 2.3.1 Signal Air transmission and LTE

In [31], C. E. Shannon defines the capacity $C$ of a communication channel impaired by an Additive White Gaussian Noise (AWGN) of power N as:

$$C = B \cdot \log_2(1 + \frac{S}{N}) \tag{2.2}$$

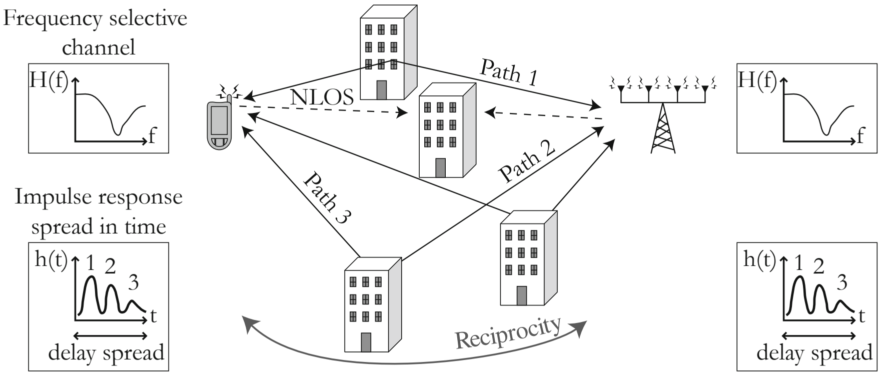



**Fig. 2.7** Radio propagation, channel response and reciprocity property

where C is in bit/s and S is the signal received power. The `channel capacity` is thus linearly dependent on bandwidth. For the largest possible LTE bandwidth, 20 MHz, this corresponds to 133 Mbit/s or 6.65 bit/s/Hz for a $S/N = 20$ dB Signal-to-Noise Ratio or SNR (100 times more signal power than noise) and 8 Mbit/s or 0.4 bit/s/Hz for a $-5$ dB SNR (3 times more noise than signal). Augmenting the transmission power will result in an increased capacity, but this parameter is limited for security and energy consumption reasons. In LTE, the capacity can be doubled by creating two different channels via several antennas at transmitter and receiver sides. This technique is commonly called Multiple Input Multiple Output (`MIMO`) or spatial multiplexing and is limited by control signaling cost and non-null correlation between channels. It may be noted that the LTE target peak rate of 100 Mbit/s or 5 bit/s/Hz is close to the capacity of a single channel. Moreover, the real air transmission channel is far more complex than its AWGN model. Managing this complexity while maintaining data rates close to the channel capacity is one of the great challenges of LTE deployment.

LTE signals are transmitted from terrestrial base stations using electromagnetic waves propagating at light speed. LTE cells can have a radii of up to 115 km, leading to a transmission latency of about 380 μs in both downlink and uplink directions. The actual value of this latency depends on the cell radius and environment. Compensation of this propagation time is performed by UEs and called `timing advance` ([30], p. 459).

Moreover, the signal can undergo several reflections before reaching its target. This effect is known as `multiple path propagation` and is displayed in Fig. 2.7. In the time domain, multiple reflections create a Channel Impulse Response (CIR) $h(t)$ with several peaks, each corresponding to a reflection. This effect elongates a received symbol in time and can cause Inter Symbol Interference (ISI) between two successive symbols. The ISI introduces a variable attenuation over the frequency band generating a frequency selective channel. For a given time and a given cell, there are frequency bands highly favorable to data transmission between the eNodeB and a given UE due to its position in space whereas these frequency bands may not be favorable to another UE.

Additional to channel selectivity, the environment parameters that compromise air transmission are fading, noise and interference. In LTE, the `frequency reuse factor` is 1, i.e. adjacent base stations of a single operator employ the same frequency carrier band. This choice complicates interference handling at cell edges. Ignoring interference, a single air transmission channel is usually modeled with channel convolution and additive noise, which gives in the discrete time domain:

$$y(n) = h(n) * x(n) + w(n), \tag{2.3}$$

where $n$ is the discrete time and $T_s$ is the sampling period, $x(n)$ and $y(n)$ are respectively the transmitted and received signals in discrete time, $h(n)$ is the channel impulse response (Fig. 2.7) and $w(n)$ is the noise. The equivalent in Fourier discrete domain gives:

$$Y(k) = H(k)X(k) + W(k), \tag{2.4}$$

where $k$ is the discrete frequency. In order to estimate $H(k)$, known reference signals (also called pilot signals) are transmitted. A reference signal cannot be received at the same time as the data it is aiding. Certain channel assumptions must be made, including slow modification over time. The time over which a Channel Impulse Response $h(t)$ remains almost constant is called `channel coherence time`. For a flat Rayleigh fading channel model at 2 GHz, modeling coherence time is about 5 ms for a UE speed of 20 km/h ([30], p. 576). The faster the UE moves, the faster the channel changes and the smaller the coherence time becomes.

The UE velocity also has an effect on radio propagation, due to the `Doppler effect`. For a carrier frequency of 2.5 GHz and a UE velocity of 130 km/h, the Doppler effect frequency shifts the signal up to 300 Hz ([30], p. 478). This frequency shift must be evaluated and compensated for each UE. Moreover, guard frequency bands between UEs are necessary to avoid frequency overlapping and Inter Carrier Interference (ICI).

Figure 2.7 shows a Non-line-of-sight (NLOS) channel, which occurs when the direct path is shadowed. Figure 2.7 also displays the property of `channel reciprocity`; the channels in downlink and in uplink can be considered to be equal in terms of frequency selectivity within the same frequency band. When downlink and uplink share the same band, channel reciprocity occurs, and so the uplink channel quality can be evaluated from downlink reception study and vice-versa. LTE technologies use channel property estimations $H(k)$ for two purposes:

- `Channel estimation` is used to reconstruct the transmitted signal from the received signal.
- `Channel sounding` is used by the eNodeBs to decide which resource to allocate to each UE. Special resources must be assigned to uplink channel soundings because a large frequency band exceeding UE resources must be sounded initially

by each UE to make efficient allocation decisions. The downlink channel sounding is quite straightforward, as the eNodeB sends reference signals over the entire downlink bandwidth.

Radio models describing several possible LTE environments have been developed by 3GPP (SCM and SCME models), ITU-R (IMT models) and a project named IST-WINNER. They offer tradeoffs between complexity and accuracy. Their targeted usage is hardware conformance tests. The models are of two kinds: matrix-based models simulate the propagation channel as a linear correlation (Eq. 2.3) while geometry-based models simulate the addition of several propagation paths (Fig. 2.7) and interferences between users and cells.

LTE is designed to address a variety of environments from mountainous to flat, including both rural and urban with Macro/Micro and Pico cells. On the other hand, Femtocells with very small radii are planned for deployment in indoor environments such as homes and small businesses. They are linked to the network via a Digital Subscriber Line (DSL) or cable.

### *2.3.2 Selective Channel Equalization*

The air transmission channel attenuates each frequency differently, as seen in Fig. 2.7. Equalization at the decoder site consists of compensating for this effect and reconstructing the original signal as much as possible. For this purpose, the decoder must precisely evaluate the channel impulse response. The resulting coherent detection consists of 4 steps:

1. Each transmitting antenna sends a known `Reference Signal` (RS) using predefined time/frequency/space resources. Additional to their use for channel estimation, RS carry some control signal information. Reference signals are sometimes called pilot signals.
2. The RS is decoded and the $H(f)$ (Eq. 2.4) is computed for the RS time/frequency/space resources.
3. $H(f)$ is interpolated over time and frequency on the entire useful bandwidth.
4. Data is decoded exploiting $H(f)$.

The LTE uplink and downlink both exploit coherent detection but employ different reference signals. These signals are selected for their capacity to be orthogonal with each other and to be detectable when impaired by Doppler or multipath effect. Orthogonality implies that several different reference signals can be sent by the same resource and still be detectable. This effect is called Code Division Multiplexing (CDM). Reference signals are chosen to have constant amplitude, reducing the transmitted Peak to Average Power Ratio (PAPR, [28]) and augmenting the transmission power efficiency. Uplink reference signals will be explained in 2.4.3 and downlink reference signals in 2.5.3.

As the transmitted reference signal $X_p(k)$ is known at transmitter and receiver, it can be localized and detected. The simplest least square estimation defines:

$$H(k) = (Y(k) - W(k))/X_p(k) \approx Y(k)/X_p(k). \quad (2.5)$$

$H(k)$ can be interpolated for non-RS resources, by considering that channel coherence is high between RS locations. The transmitted data is then reconstructed in the Fourier domain with $X(k) = Y(k)/H(k)$.

### 2.3.3 eNodeB Physical Layer Data Processing

Figure 2.8 provides more details of the eNodeB physical layer that was roughly described in Fig. 2.3. It is still a simplified view of the physical layer that will be explained in the next sections and modeled in Chap. 7.

In the `downlink data encoding`, `channel coding` (also named link adaptation) prepares the binary information for transmission. It consists in a Cyclic Redundancy Check (CRC) /turbo coding phase that processes Forward Error Correction (FEC), a rate matching phase to introduce the necessary amount of redundancy, a scrambling phase to increase the signal robustness, and a modulation phase that transforms the bits into symbols. The parameters of channel coding are named Modulation and Coding Scheme (MCS). They are detailed in Sect. 2.3.5. After channel coding, `symbol processing` prepares the data for transmission over several antennas and subcarriers. The downlink transmission schemes with multiple antennas are explained in Sects. 2.3.6 and 2.5.4 and the Orthogonal Frequency Division Multiplexing Access (OFDMA), that allocates data to subcarriers, in Sect. 2.3.4.

In the `uplink data decoding`, the `symbol processing` consists in decoding Single Carrier-Frequency Division Multiplexing Access (SC-FDMA) and equalizing signals from the different antennas using channel estimates. SC-FDMA is the uplink broadband transmission technology and is presented in Sect. 2.3.4. Uplink multiple antenna transmission schemes are explained in Sect. 2.4.4. After symbol processing, uplink `channel decoding` consists of the inverse phases of downlink channel coding because the chosen techniques are equivalent to the ones of downlink. HARQ combining associates the repeated receptions of a single block to increase robustness in case of transmission errors.

Next sections explain in details these features of the eNodeB physical layer, starting with the broadband technologies.

### 2.3.4 Multicarrier Broadband Technologies and Resources

LTE uplink and downlink data streams are illustrated in Fig. 2.9. The LTE uplink and downlink both employ technologies that enable a two-dimension allocation of resources to UEs in time and frequency. A third dimension in space is added by Multiple Input Multiple Output (MIMO) spatial multiplexing (Sect. 2.3.6). The eNodeB decides the allocation for both downlink and uplink. The uplink allocation decisions

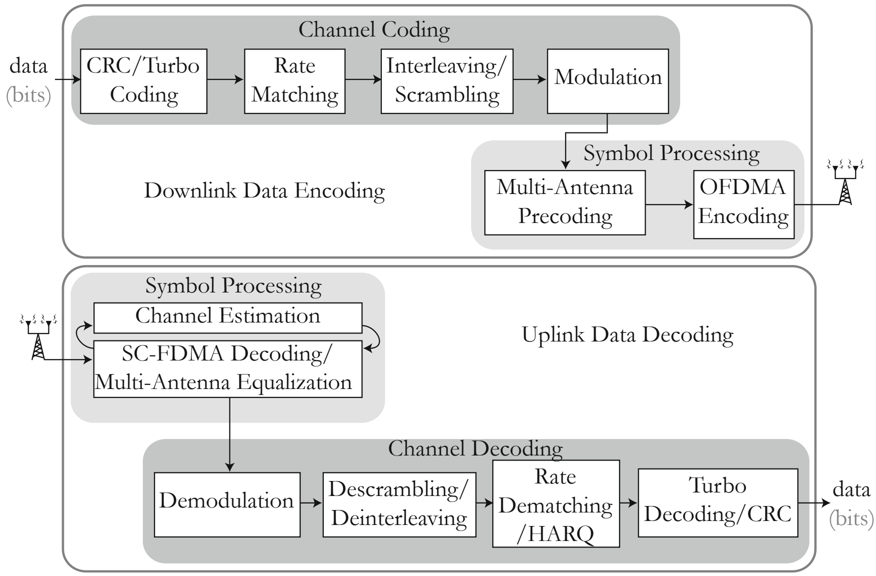



**Fig. 2.8** Uplink and downlink data processing in the LTE eNodeB

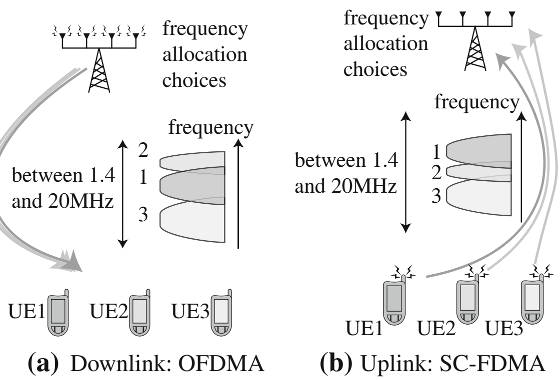



**Fig. 2.9** LTE downlink and uplink multiplexing technologies

must be sent via the downlink control channels. Both downlink and uplink bands have six possible bandwidths: 1.4, 3, 5, 10, 15, or 20 MHz.

#### 2.3.4.1 Broadband Technologies

The multiple subcarrier broadband technologies used in LTE are illustrated in Fig. 2.10. Orthogonal Frequency Division Multiplexing Access (`OFDMA`) employed for the downlink and Single Carrier-Frequency Division Multiplexing (`SC-FDMA`)

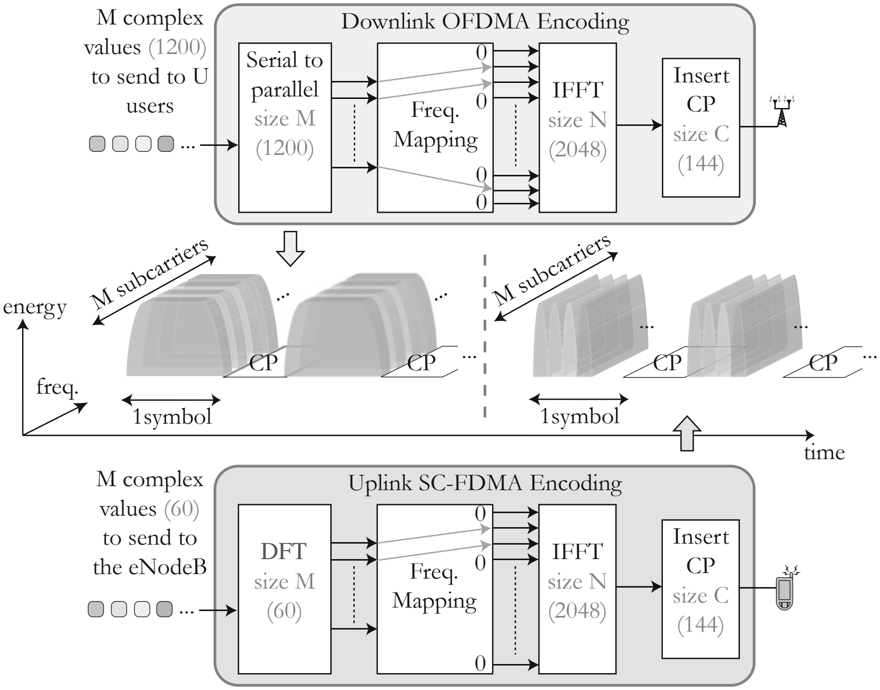



**Fig. 2.10** Comparison of OFDMA and SC-FDMA

is used for the uplink. Both technologies divide the frequency band into subcarriers separated by 15 kHz (except in the special broadcast case). The subcarriers are orthogonal and data allocation of each of these bands can be controlled separately. The separation of 15 kHz was chosen as a tradeoff between data rate (which increases with the decreasing separation) and protection against subcarrier orthogonality imperfection [1]. This imperfection occurs from the Doppler effect produced by moving UEs and because of non-linearities and frequency drift in power amplifiers and oscillators.

Both technologies are effective in limiting the impact of multi-path propagation on data rate. Moreover, the dividing the spectrum into subcarriers enables simultaneous access to UEs in different frequency bands. However, SC-FDMA is more efficient than OFDMA in terms of Peak to Average Power Ratio (PAPR, [28]). The lower PAPR lowers the cost of the UE RF transmitter but SC-FDMA cannot support data rates as high as OFDMA in frequency-selective environments.

Figure 2.10 shows typical transmitter implementations of OFDMA and SC-FDMA using Fourier transforms. SC-FDMA can be interpreted as a linearly precoded OFDMA scheme, in the sense that it has an additional DFT processing preceding the conventional OFDMA processing. The frequency mapping of Fig. 2.10 defines the subcarrier accessed by a given UE.

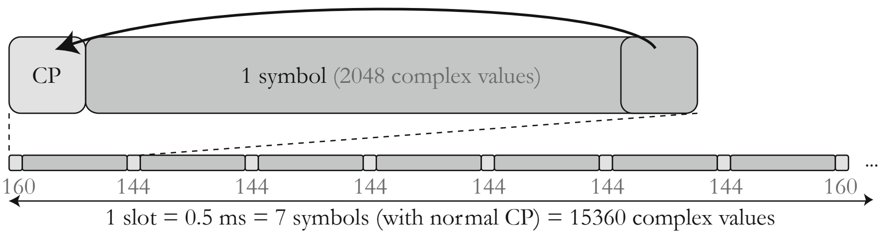



**Fig. 2.11** Cyclic prefix insertion

Downlink symbol processing consists of mapping input values to subcarriers by performing an Inverse Fast Fourier Transform (IFFT). Each complex value is then transmitted on a single subcarrier but spread over an entire symbol in time. This transmission scheme protects the signal from Inter Symbol Interference (ISI) due to multipath transmission. It is important to note that without channel coding (i.e. data redundancy and data spreading over several subcarriers), the signal would be vulnerable to frequency selective channels and Inter Carrier Interference (ICI). The numbers in gray (in Fig. 2.10) reflect typical parameter values for a signal of bandwidth of 20 MHz. The OFDMA encoding is processed in the eNodeB and the 1200 input values of the case of 20MHz bandwidth carry the data of all the addressed UEs. SC-FDMA consists of a small size Discrete Fourier Transform (DFT) followed by OFDMA processing. The small size of the DFT is required as this processing is performed within a UE and only uses the data of this UE. For an example of 60 complex values the UE will use 60 subcarriers of the spectrum (subcarriers are shown later to be grouped by 12). As noted before, without channel coding, data would be prone to errors introduced by the wireless channel conditions, especially because of ISI in the SC-FDMA case.

#### 2.3.4.2 Cyclic Prefix

The Cyclic Prefix (CP) displayed in Figs. 2.10 and 2.11 is used to separate two successive symbols and thus reduces ISI. The CP is copied from the end of the symbol data to an empty time slot reserved before the symbol and protects the received data from timing advance errors; the linear convolution of the data with the channel impulse response is converted into a circular convolution, making it equivalent to a Fourier domain multiplication that can be equalized after a channel estimation (Sect. 2.3.2). CP length in LTE is 144 $samples = 4.8\,\mu s$ (normal CP) or 512 $samples = 16.7\,\mu s$ in large cells (extended CP). A longer CP can be used for broadcast when all eNodeBs transfer the same data on the same resources, so introducing a potentially rich multi-path channel. Generally, multipath propagation can be seen to induce channel impulse responses longer than CP. The CP length is a tradeoff between the CP overhead and sufficient ISI cancellation [1].

#### 2.3.4.3 Time Units

Frequency and timing of data and control transmission is not decided by the UE. The eNodeB controls both uplink and downlink time and frequency allocations. The allocation base unit is a block of 1 ms per 180 kHz (12 subcarriers). Figure 2.12 shows 2 Physical Resource Blocks (PRB). A PRB carries a variable amount of data depending on channel coding, reference signals, resources reserved for control...

Certain time and frequency base values are defined in the LTE standard, which allows devices from different companies to interconnect flawlessly. The LTE time units are displayed in Fig. 2.12:

- A `basic time unit` lasts $T_s = 1/30720000\,\mathrm{s} \approx 33\,\mathrm{ns}$. This is the duration of 1 complex sample in the case of 20 MHz bandwidth. The sampling frequency is thus $30.72\,\mathrm{MHz} = 8 * 3.84\,\mathrm{MHz}$, eight times the sampling frequency of UMTS. The choice was made to simplify the RF chain used commonly for UMTS and LTE. Moreover, as classic OFDMA and SC-FDMA processing uses Fourier transforms, symbols of size power of two enable the use of FFTs and $30.72\,\mathrm{MHz} = 2048 * 15\,\mathrm{kHz} = 2^{11} * 15\,\mathrm{kHz}$, with 15 kHz the size of a subcarrier and 2048 a power of two. Time duration for all other time parameters in LTE is a multiple of $T_s$.
- A `slot` is of length $0.5\,\mathrm{ms} = 15360\,T_s$. This is also the time length of a PRB. A slot contains 7 symbols in normal cyclic prefix case and 6 symbols in extended CP case. A Resource Element (RE) is a little element of 1 subcarrier per one symbol.
- A `subframe` lasts $1\,\mathrm{ms} = 30720\,T_s = 2\,slots$. This is the minimum duration that can be allocated to a user in downlink or uplink. A subframe is also called Transmission Time Interval (TTI) as it is the minimum duration of an independently decodable transmission. A subframe contains 14 symbols with normal cyclic prefix that are indexed from 0 to 13 and are described in the following sections.
- A `frame` lasts $10\,\mathrm{ms} = 307200\,T_s$. This corresponds to the time required to repeat a resource allocation pattern separating uplink and downlink in time in case of Time Division Duplex (TDD) mode. TDD is defined below.

In the LTE standard, the subframe size of 1 ms was chosen as a tradeoff between a short subframe which introduces high control overhead and a long subframe which significantly increases the retransmission latency when packets are lost [3]. Depending on the assigned bandwidth, an LTE cell can have between 6 and 100 resource blocks per slot. In TDD, special subframes protect uplink and downlink signals from ISI by introducing a guard period ([9], p. 9).

#### 2.3.4.4 Duplex Modes

Figure 2.13 shows the duplex modes available for LTE. Duplex modes define how the downlink and uplink bands are allocated respective to each other. In Frequency Division Duplex (`FDD`) mode, the uplink and downlink bands are disjoint. The connection is then full duplex and the UE needs to have two distinct Radio Frequency (RF) processing chains for transmission and reception. In Time Division

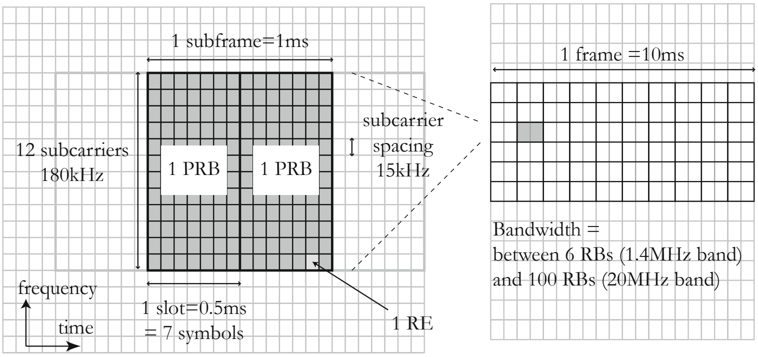



**Fig. 2.12** LTE time units

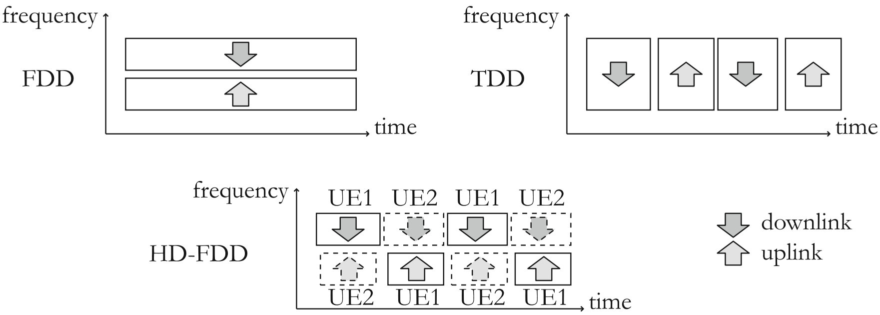



**Fig. 2.13** Different types of LTE duplex modes

Duplex (TDD) mode, the downlink and the uplink alternatively occupy the same frequency band. The same RF chain can then be used for transmitting and receiving but available resources are halved. In Half-Duplex FDD (HD-FDD) mode, the eNodeB is full duplex but the UE is half-duplex (so can have a single RF chain). In this mode, separate bands are used for the uplink and the downlink but are never simultaneous for a given UE. HD-FDD is already present in GSM.

ITU-R defined 17 FDD and 8 TDD frequency bands shared by LTE and UMTS standards. These bands are located between 698 and 2690 MHz and lead to very different channel behavior depending on carrier frequency. These differences must be accounted for during the calibration of base stations and UEs. The following Sections will focus on FDD mode.

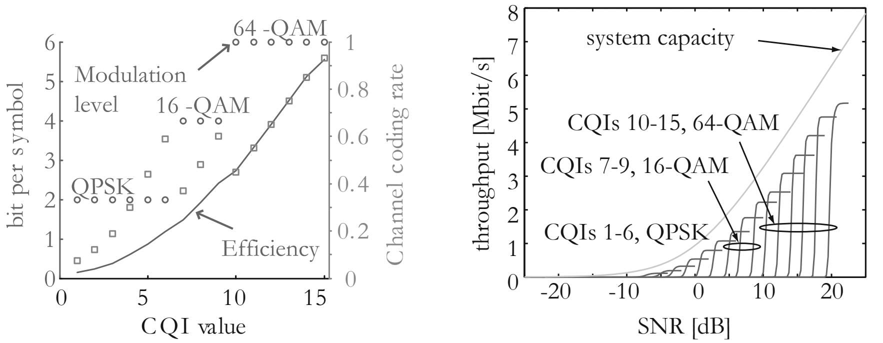
### 2.3.5 LTE Modulation and Coding Scheme

Within a single LTE cell, a given UE can experience different Signal-to-Interference plus Noise Ratio (SINR) depending on the radio properties of its environment: the distance of the base station antenna, the base station emission power, the interference of other users, the number of diversity antennas, and so on. Several LTE channel coding features are created in order to obtain data rates near channel capacity in every situation. Channel coding operations are usually very computationally complex operations, and parameters for optimization must be chosen with care. For the case of one antenna port, two LTE physical layer parameters can be modified to maximize the throughput. These parameters are called `Modulation and Coding Scheme` (MCS):

- The `channel coding rate` is a parameter which determines the amount of redundancy to add in the input signal to allow Forward Error Correction (FEC) processing. A higher redundancy leads to more robust signal at the cost of throughput.
- The `modulation scheme` refers to the way data symbols are associated to a set of transmit bits. A symbol is a complex value that is used to modulate a carrier for air transmission. Three schemes are available in LTE: QPSK, 16-QAM and 64-QAM. They associate 2, 4 and 6 bits respectively to a single symbol and this number of bits is the modulation level. Of the three modulation schemes, QPSK is the most robust for transmission errors but 64-QAM allows the highest throughput ([9], p. 79).

The downlink channel quality estimation required for downlink MCS scheme choice is more complex than for its uplink equivalent. However, the report of downlink channel quality is vital for the eNodeB when making downlink scheduling decisions. In FDD mode, no reciprocity of frequency selective fading between uplink and downlink channels can be used (Sect. 2.3.1). The UE measures downlink channel quality from downlink reference signals and then reports this information to its eNodeB. The UE report consists of a number between 0 and 15, generated by the UE, representing the channel capacity for a given bandwidth. This number is called CQI for `Channel Quality Indicator` and is sent to the eNodeB in the uplink control channel. The CQI influences the choice of resource allocation and MCS scheme. In Fig. 2.14a, the channel coding rate and modulation rate are plotted against CQI, and the global resulting coding efficiency. It may be seen that the coding efficiency can be gradually adapted from a transmission rate of 0.15 bits/resource element to 5.55 bits/resource element.

CQI reports are periodic, unless the eNodeB explicitly requests aperiodic reports. Periodic reports pass through the main uplink control channel known as the Physical Uplink Control CHannel (PUCCH, Sect. 2.4.2). When PUCCH resources are unavailable, the reports are multiplexed in the uplink data channel known as the Physical Uplink Shared CHannel (PUSCH, Sect. 2.4.2). Aperiodic reports are sent in the PUSCH when explicitly requested by the eNodeB. Periodic CQI reports have




**(a)** Link Adaptation Parameters for each CQI

**(b)** Link Adaptation Effect on the Throughput of a 1.4 MHz Cell

**Fig. 2.14** LTE link adaptation

a period between 2 and 160 ms. Periodic CQI reports contain one CQI if no spatial multiplexing is used or two CQI (one per rank) in the case of rank 2 downlink spatial multiplexing (Sect. 2.3.6). Aperiodic CQI modes exist including one CQI for the whole band and possibly an additional CQI for a set of preferred subbands ([11], p. 37). The choice of following the UE recommendation is given to the eNodeB. After receiving the UE report, the eNodeB sends data using the downlink data channel known as the Physical Downlink Shared Channel (PDSCH, Sect. 2.5.2). Control values are simultaneously transmitting in the main downlink control channel known as the Physical Downlink Control Channel (PDCCH, Sect. 2.5.2). These PDCCH control values carry Downlink Control Information (DCI) which include the chosen MCS scheme and HARQ parameters.

Figure 2.14b shows the effect of MCS on the throughput of a LTE transmission using a single antenna, a bandwidth of 1.4MHz, no HARQ and one UE. With only one UE in the cell, there can be no interference, so SINR is equal to SNR (Signal-to-Noise Ratio). The results were generated by the LTE simulator of Vienna University of Technology with a Additive White Gaussian Noise (AWGN) channel model and published in [24]. It may be seen that, for the studied channel model, a throughput close to the channel capacity can be achieved if the link adaptation is well chosen. It may also be noted that this choice is very sensitive to the SNR.

The techniques used to add redundancy and process Forward Error Correction (FEC) are different for control and data channels. The majority of control information in the PDCCH and the PUCCH use tail biting convolutional coding, sequence repetition and pruning while data channels (PDSCH, PUSCH) use turbo coding, sequence repetition and pruning ([29], p. 76).

The `convolutional code` used for control in LTE (Fig. 2.15a) has a 1/3 rate i.e. the code adds 2 redundant bits for each information bit. The encoder was chosen for its simplicity to allow to easier PDCCH decoding by UEs. Indeed, a UE needs to permanently decode many PDCCH PRBs, including many that are not intended for

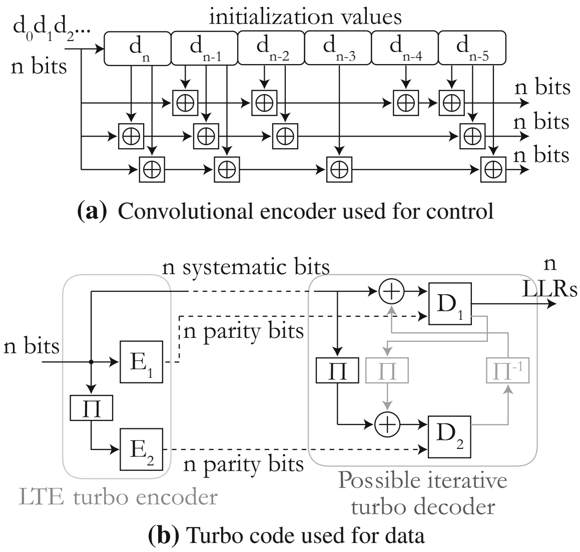



**Fig. 2.15** LTE forward error correction methods

decoding and so this permanent computation must be limited. Convolutional coding is well suited for a FEC system with small blocks because it is not necessary to start in a predefined state. Moreover, convolutional codes can be efficiently decoded using a Viterbi decoder [19]. The absence of predefined state is important because a predefined starting state has a cost in the encoded stream. Instead, the 6 last bits of the encoded sequence serve as starting state of the encoder, transforming a linear convolution into a circular convolution, in the same way as the Cyclic Prefix with the channel impulse response. This technique is named tail biting.

A `turbo code` [16] in LTE (Fig. 2.15b) introduces redundancy in all LTE transmitted data. It has a rate of 1/3 and consists of an interleaver and two identical rate-1 convolutional encoders $E_1$ and $E_2$. One convolutional encoder ($E_1$) processes the input data while the other convolutional encoder ($E_2$) processes a pseudo-randomly interleaved version of the same data. The turbo coder outputs a concatenation of its unmodified input (systematic bits) and the two convoluted signals (parity bits). The resulting output facilitates FEC because there is little probability of having a low Hamming weight (number of 1s in the bit stream), thus improving detection. Each Code Block is independently turbo coded. A Code Block size ranges from 40 to 6144 bits (Sect. 2.2.3). Turbo coding is very efficient for long Code Blocks but it necessitates 12 tail bits containing no information that reduce its efficiency for small blocks.

Turbo coding and decoding are two of the most demanding functions of the LTE physical layer. Special coprocessors for turbo coding and decoding are included in multi-core architectures intended to handle eNodeB physical layer computation. Turbo iterative decoders ([27] and Fig. 2.15b) contain two convolution decoders that calculate the A Posteriori Probability (APP) of their input. At each iteration of the decoder, the detection belief of the decoded bit increases. APPs are stored in Log Likelihood Ratio (LLR) integer values where the sign indicates the detected binary value (0 or 1) and the amplitude indicates the reliability of the detection. For each bit, the turbo decoder outputs an LLR. Such a decoder, manipulating not only raw bits but also detection belief, is called soft decision decoder. For the possibility of HARQ retransmissions, LLR values of preceding receptions are stored to allow the combination of the preceding with the new reception. This combining operation can increase the signal to noise ratio in a code block and hence increase the odds for a successful decoding by the Turbo decoder.

After convolutional or turbo coding, the bits enter a circular Rate Matching (RM) process where they are interlaced, repeated and pruned to obtain the desired coding rate (Fig. 2.14a) with an optimal amount of spread redundancy.

#### 2.3.5.1 Hybrid Automatic Repeat ReQuest

HARQ retransmission of lost blocks is a part of link adaptation. HARQ introduces redundancy in the signal to counteract the channel impairments. Moreover, HARQ is `hybrid` in the sense that each retransmission can be made more robust by a stronger modulation and by stronger channel coding.

An eNodeB has 3 ms after the end of a PUSCH subframe reception to process the frame, detect a possible reception error via Cyclic Redundancy Check (CRC) decoding and send back a NACK bit in the PDCCH. The uplink HARQ is synchronous in that a retransmission, if any, always appears 8 ms after the end of the first transmission. This fixed retransmission scheme reduces signaling in PUCCH. The repetitions can be adaptive (each one with a different MCS scheme), or not.

Downlink HARQ is consistently asynchronous and adaptive. There is at least 8 ms between two retransmissions of a Transport Block. It introduces more flexibility than the uplink scheme at the cost of signaling.

When a Transport Block is not correctly received, 8 different stop-and-wait processes are enabled, for both downlink and uplink receivers. This number of processes reduces the risk of the communication being blocked while waiting for HARQ acknowledgement, with the cost of memory to store the LLRs for each process (Sect. 2.3.5). Data from several repetitions are stored as LLRs and recombined, making HARQ hybrid.

### *2.3.6 Multiple Antennas*

In LTE, eNodeBs and UEs can use several antennas to improve the quality of wireless links:

- eNodeB baseband processing can generate up to 4 separate downlink signals. Each signal is allocated to an antenna port. The eNodeB can also receive up to 4 different uplink signals. Two antennas sending the same signal are processed at the baseband processing as a single antenna port.
- A UE can have 2 receive antennas and receive 2 different signals simultaneously. It can have 2 transmit antennas but the UE will switch between these antennas as it has only one RF amplifier.

Multiple transmit antennas ($N_T > 1$), receive antennas ($N_R > 1$) or both can improve link quality and lead to higher data rates with higher spectral efficiency. For a precise introduction to MIMO channel capacity, see [22]. Different multiple antenna effects can be combined:

- `Spatial diversity` (Fig. 2.16a) consists of using different paths between antenna sets to compensate for the selective frequency fading of channels due to multipath transmission. There are two modes of spatial diversity: transmission or reception. Transmission spatial diversity necessitates several transmit antennas. Combining several transmit antennas consists in choosing the right way to distribute data over several antennas. A common technique is named Space-Time Block Coding (STBC) where successive data streams are multiplexed in the channels and made as orthogonal as possible to enhance the reception diversity. The most common of these codes is Alamouti; it offers optimal orthogonality for 2 transmit antennas [15]. No such optimal code exists for more than 2 antennas. Reception spatial diversity (Fig. 2.16a) uses several receive antennas exploiting the diverse channels, by combining their signal with Maximal-Ratio Combining (MRC).
- `Spatial multiplexing gain`, sometimes called MIMO effect is displayed in Fig. 2.16b for the case $N_T = N_R = 2$. It consists of creating several independent channels in space, exploiting a good knowledge of the channels and reconstructing the original data of each channel. MIMO can increase the throughput by a factor of $\min(N_T, N_R)$ but this factor is never obtained in real life because multiple paths are never totally uncorrelated and channel estimation requires additional reference signals. MIMO actually takes advantage of the multipath scattering that spatial diversity tries to counteract.
- `Beamforming`, also called array gain, consists of creating constructive and destructive interference of the wavefront to concentrate the signal in a given spatial direction. This is displayed in Fig. 2.16c. These interferences are generated by several transmitting antennas precoded by factors named beam patterns.

Without spatial multiplexing, every PRB corresponding to a single UE has the same MCS. In downlink spatial multiplexing mode, two separate MCS can be used for two different Transport Blocks sent simultaneously to a UE. A more complex scheme was shown to greatly increase the control with only slightly higher data rates [2].

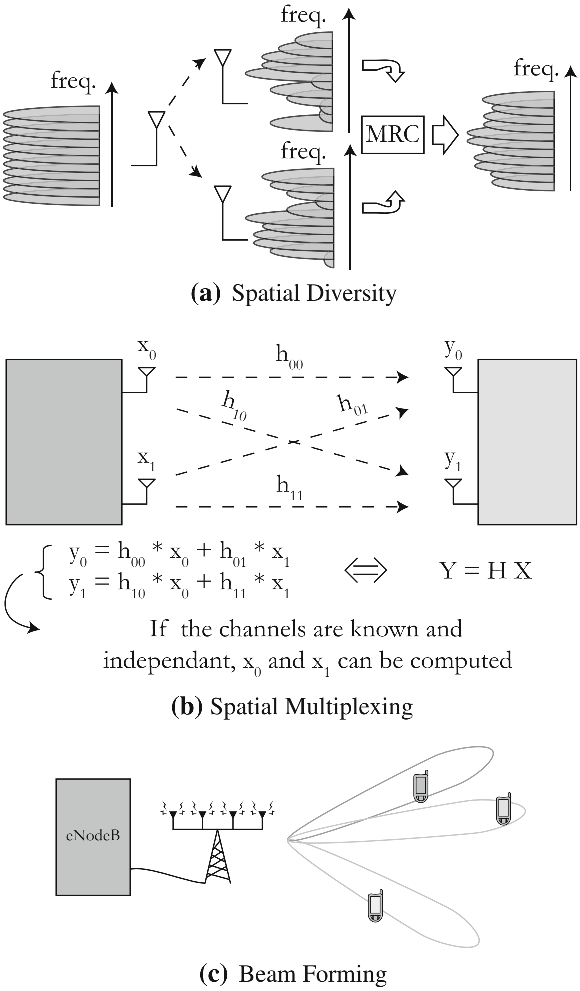



**Fig. 2.16** LTE link adaptation

## 2.4 LTE Uplink Features

### *2.4.1 Single Carrier-Frequency Division Multiplexing*

#### 2.4.1.1 Uplink Pilot Signals

The SC-FDMA presented earlier is also known as DFT-Spread Orthogonal Frequency Division Multiplexing (DFTS-OFDM). A discussion on uplink technology choices can be found in [18]. A SC-FDMA decoder in the eNodeB necessitates a channel

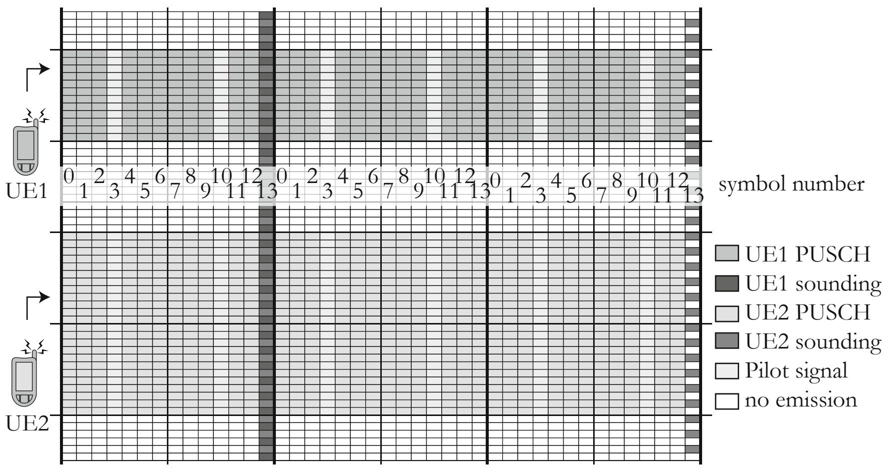



**Fig. 2.17** Reference signals location in the uplink resources

estimation to equalize the received signal. This channel estimation is performed sending Zadoff–Chu (ZC) sequences known to both the UE and the eNodeB. ZC sequences will be explained in Sect. 2.4.3. These sequences are called Demodulation Reference Signals (DM RS) and are transmitted on the center symbol of each slot (Fig. 2.17). The eNodeB also needs to allocate uplink resources to each UE based on channel frequency selectivity, choosing frequency bands that are most favorable to the UE. DM RS are only sent by a UE in its own frequency band; they do not predict if it is necessary to allocate new frequencies in the next subframe. This is the role of Sounding Reference Signal (SRS). The positions of DM RS and SRS in the uplink resource blocks is illustrated in Fig. 2.17.

DM RS are located in symbols 3 and 10 of each subframe. When explicitly requested by the eNodeB, SRS signals of ZC sequences are sent in the symbol 13 location. The SRS for a given UE is located every 2 subcarriers using the Interleaved FDMA (IFDMA) method. A 10-bit PDCCH message describes the time, period (between 2 and 320 ms) and bandwidth for the UE to send the SRS message. For more details on SRS, see [30], p. 370. As both DM RS and SRS are Constant Amplitude Zero AutoCorrelation (CAZAC) sequences, two UEs can send each their SRS using the same resources provided they use different cyclic shifts, making sequences orthogonal (Sect. 2.4.3). The eNodeB is then able to separate the two different pilot signals. Figure 2.17 displays an example of three subframes with UE 1 transmitting data on one fixed PRB with a SRS cycle of more than 2 ms and UE 2 sending data on two fixed PRBs with a SRS cycle of 2 ms.

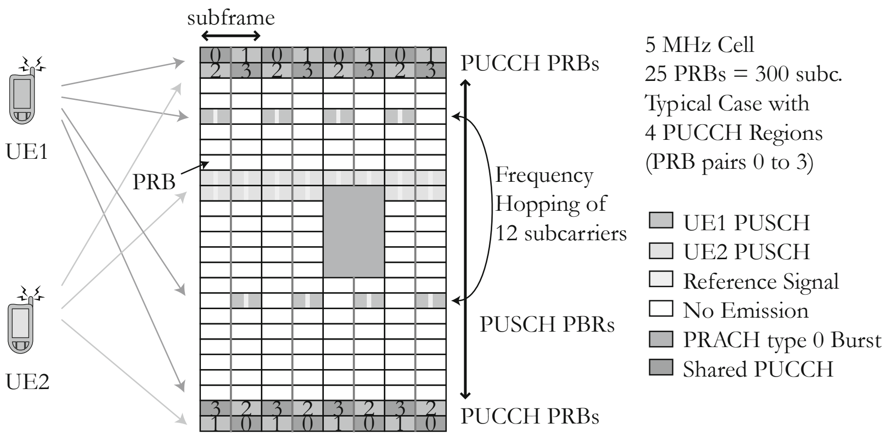



**Fig. 2.18** Uplink channels

## *2.4.2 Uplink Physical Channels*

Uplink data and control streams are sent using three physical channels allocated on the system bandwidth:

- The `Physical Uplink Shared Channel` (PUSCH) carries all the data received by a eNodeB from its UEs. It can also carry some control. LTE PUSCH only supports localized UE allocations, i.e. all PRBs allocated to a given UE are consecutive in frequency.
- The `Physical Uplink Control Channel` (PUCCH) carries the major part of the transmitted control values via uplink.
- `Physical Random Access Channel` (PRACH) carries the connection requests from unconnected UEs.

Figure 2.18 illustrates the localization of the physical channels for the example of a 5 MHz cell. The PUCCH is localized on the edges of the bandwidth while PUSCH occupies most of the remaining PRBs. PUCCH information with redundancy is sent on pairs of PRBs called regions (indexed in Fig. 2.18), where the two PRBs of a region are located on opposite edges. This technique is called frequency hopping and protects the PUCCH against localized frequency selectivity. There are typically 4 PUCCH regions per 5 MHz band. However, the eNodeB can allocate the PUSCH PRBs in PUCCH regions if they are not needed for control. Multiple UE control values can be multiplexed in PUCCH regions via Code Division Multiplexing (CDM).

Uplink decisions are generally taken by the eNodeB MAC scheduler and transmitted via downlink control channels. Consequently, the UEs are not required to send back these eNodeB decisions to the eNodeB, thus reducing the overhead of the PUCCH. 7 PUCCH region formats are defined according to the kind of information carried. The PUCCH contains the requests for more uplink data resources via an uplink Scheduling Request bit (SR), and the Buffer Status Reports (BSR) signals the amount of pending data from the UE PUSCH to the eNodeB. The PUCCH also signals the UE preferences for downlink Modulation and Coding Scheme (MCS, Sect. 2.3.5) including:

- `Hybrid Automatic Repeat reQuest` (HARQ), Acknowledgement (ACK), or Non Acknowledgement (NACK) are stored in 1 or 2 bits and require HARQ retransmissions if data was lost and the Cyclic Redundancy Check (CRC) was falsely decoded.
- A `Channel Quality Indicator` (CQI, Sect. 2.3.5) consists of 20 bits transporting indicators of redundancy 1 or 2 which recommend a MCS to the eNodeB for each transmitted Transport Block.
- `MIMO Rank Indicator` (RI) and `Precoding Matrix Indicator` (PMI) bits which recommend a multiple antenna scheme to the eNodeB (Sect. 2.3.6).

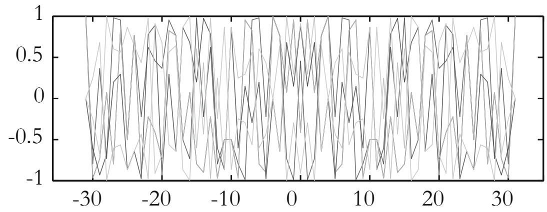
The PUCCH carries this control information periodically. If no PRB is available in the PUCCH channel, the PUSCH can carry some control information. Additionally, the eNodeB can request additional aperiodic CQI and link adaptation reports. These reports are sent in PUSCH and can be much more complete than periodic reports (up to 64 bits).

The PRACH is allocated periodically over 72 subcarriers (6 PRBs, Fig. 2.18). Employing 72 subcarriers is favorable because it has the widest bandwidth available for all LTE configurations between 1.4 MHz and 20 MHz. The PRACH burst can last between 1 and 3 subframes depending on the chosen mode; long modes are necessary for large cells. The PRACH period depends on the adjacent cell configurations and is typically several subframes. See Sect. 2.4.5 and [30], p. 421 for more details on the PRACH.

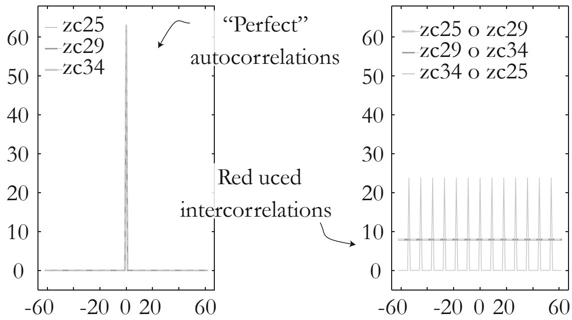
The uplink is shared between several transmitting UEs with different velocities and distances to the eNodeB. Certain precautions must be taken when multiple UEs are transmitting simultaneously, one of which is the `timing advance`. Timing advance consists of sending data with the corrected timing, so compensating for the propagation time and allowing the synchronization of all data received at the eNodeB. The correct timing advance is evaluated using the timing received from the PRACH bursts.

### *2.4.3 Uplink Reference Signals*

In uplink communication, a Demodulation Reference Signal (DM RS) is constructed from a set of complex-valued Constant Amplitude Zero AutoCorrelation (CAZAC) codes known as Zadoff–Chu (ZC) sequences [17, 26]. ZC sequences are computed with the formula:




**(a)** ZC Sequences Real and Imaginary Parts




**(b)** ZC Sequences Auto and Crosscorrelation magnitudes

**Fig. 2.19** Length-63 Zadoff–Chu sequences with index 25, 29 and 34

$$z_q(n) = \exp\left(\frac{-j\pi qn(n+1)}{N_{ZC}}\right) \tag{2.6}$$

where $n$ is the sample number, $q$ is the sequence index ranging from 1 to $N_{ZC} - 1$, and $N_{ZC}$ is the sequence size. Three ZC sequences of length 63 with indexes 25, 29 and 34 are illustrated in Fig. 2.19. Their amplitude and the amplitude of their Fourier transform are constant, keeping low the PAPR of their transmission (Fig. 2.19a). All three sequences have an autocorrelation close to the Dirac function, enabling the creation of several orthogonal sequences from a single sequence using cyclic shifts. It may also be noted that the cross correlation between two ZC sequences with different indices is small compared to the autocorrelation peak (Fig. 2.19b). Consequently, two sequences can be decoded independently when sent simultaneously as long as their indices or cyclic shifts are different.

Each uplink DM RS of length $N_P$ consists of a ZC sequence with the highest prime size smaller than $N_P$. The ZC sequence is cyclically extended to $N_P$ elements and then cyclically shifted by $\alpha$ elements. For the smallest DM RS sizes of 12 and 24 elements, special codes replace ZC sequences because they outperform the ZC sequences in these cases ([30], p. 361). DM RS primarily serve to estimate the channel. They also carry information in their sequence index $q$ and cyclic shift $\alpha$, namely an ID to determine which destination eNodeB of the DM RS and to identify the transmitting UE for the case of Multi-User MIMO (MU-MIMO, Sect. 2.4.4). Indices and shifts are vital in preventing UEs and cells from interfering with each other.

ZC sequences are used elsewhere in LTE systems, in particular as Sounding Reference Signal (SRS, 2.5.5) and in random access procedure (Sect. 2.4.5).

### 2.4.4 Uplink Multiple Antenna Techniques

In the first release of LTE, UEs are limited to one transmission amplifier. Uplink single-user spatial multiplexing is thus not possible but multiple UE antennas can still be exploited for better system throughput. Firstly, UEs can optionally have two transmit antennas and switch between them depending on the channel quality. This method known as `antenna selection` necessitates one SRS signal per antenna to report on channel quality. This increase in diversity must be weighed against the cost of this additional SRS signal in overhead

Secondly, `reception spatial diversity` (Sect. 2.3.6) is often exploitable because the majority of eNodeBs have several receive antennas, each of which have known channel responses $h_i$. Naming the received values:

$$y = hx, \tag{2.7}$$

where each antenna stream has already been equalized (Sect. 2.3.2) and thus $h = [h_1 h_2 ... h_N]^T$ is the vector of channel responses, each being a scalar and $x = [x_1 x_2 ... x_N]^T$ and $y = [y_1 y_2 ... y_N]^T$ are the transmitted and received signal vectors across N antennas. The MRC detected signal is given by:

$$\hat{x} = \frac{h^H y}{h^H h} \tag{2.8}$$

where $\hat{x}$ is the complex detected symbol. MRC favors antennas which can receive high power signals.

Thirdly, `Multi-User MIMO` (MU-MIMO) also called Spatial Division Multiple Access (SDMA) consists of allocating the same resources to 2 UEs in the eNodeB and using the channel differences in frequency selectivity between UEs to separate the signals while decoding. Using MIMO can greatly increase the data rate and only requires special processing in the eNodeB. It necessitates orthogonal uplink DM RS reference sequences with different cyclic shift to independently evaluate the channel of each UE. Eight different DM RS cyclic shifts are defined in LTE for this purpose. This scheme is often called Virtual MU-MIMO because no added complexity is required at the UE: it is not necessary for the UE to know it shares the same resources with another UE. The complexity increases only at eNodeB side.

A 2 × 2 MU-MIMO scheme is equivalent to that shown in Fig. 2.14b but with the transmit antennas connected to separate UEs. Spatial multiplexing decoding, also known as MIMO detection, consists of reconstructing an estimate vector $\hat{x}$ of the sent signal vector $x$ from $y$ and $H$ (Fig. 2.14b) in the eNodeB. The four channels in $H$ can be considered to be flat fading (not frequency selective) because they have been individually equalized upon reception (Sect. 2.3.2); the channel is thus constant over all SC-FDMA subcarriers. The two most common low complexity linear MIMO detectors are that of `Zero Forcing` (ZF) and of `Minimum Mean-Square Error` (MMSE). In the ZF method, where $\hat{x} = Gy$ is the vector of detected symbols and y is the vector of received symbols, $G$ is computed as the pseudo inverse of $H$:

$$G = (H^H H)^{-1} H^H. \tag{2.9}$$

The ZF method tends to amplify the transmission noise. The MMSE method is a solution to this problem, with:

$$G = (H^H H + \sigma^2 I)^{-1} H^H. \tag{2.10}$$

where $\sigma^2$ is the estimated noise power and I the identity matrix. Many advanced MIMO decoding techniques [23, 32] exist, notably including Maximum Likelihood Receiver (MLD) and Sphere Decoder (SD).

### *2.4.5 Random Access Procedure*

The random access procedure is another feature of the uplink. While preceding features enabled high performance data transfers from connected UEs to eNodeBs, the random access procedure connects a UE to a eNodeB. It consists of message exchanges initiated by an uplink message in the `PRACH` channel (Sect. 2.4.2). It has two main purposes: synchronizing the UE to the base station and scheduling the UE for uplink transmission. The random access procedure enables a UE in idle mode to synchronize to a eNodeB and become connected. It also happens when a UE in connected mode needs to resynchronize or to perform a handover to a new eNodeB. The scheduling procedures uses the MME (Sect. 2.2.1) which is the network entity managing paging for phone calls. When a phone call to a given UE is required, the MME asks the eNodeBs to send paging messages with the UE identity in the PDCCH. The UE monitors the PDCCH regularly even in idle mode. When paging is detected, it starts a random access procedure. The random access procedure starts when the UE sends a PRACH signal.

Special time and frequency resources are reserved for the PRACH. Depending on the cell configuration, a PRACH can have a period from 1 to 20 ms. The signal has several requirements. One is that an eNodeB must be able to separate signals from several UEs transmitted in the same allocated time and frequency window. Another constraint is that the eNodeB must decode the signal rapidly enough to send back a Random Access Response (RAR) in PDSCH. A typical time between the end of PRACH reception and RAR is 4 ms ([30], p. 424). The PRACH message must also be well protected against noise, multipath fading and other interference in order to be detectable at cell edges. Finally, the resources dedicated to PRACH must induce a low overhead.

The chosen PRACH signals are ZC sequences of length 839, except in the special TDD format 4, which is not treated here. Good properties for ZC sequences are explained in Sect. 2.4.3 where their use in reference signals is described. A set of 64 sequences (called signatures) is attributed to each cell (out of 838 sequences in total). A signature is a couple $(n_S, n_{CS})$ where $n_S \leq N_S \leq 64$ is the root index and $n_{CS} \leq N_{CS} \leq 64$ is the cyclic shift so that $N_{CS} = \lceil 64/N_S \rceil$. A combination of a root and a cyclic shift gives a unique signature out of 64. A tradeoff between a high number of roots and a high number of cyclic shifts must be made. It will be seen that for more cyclic shifts, the easier the decoding becomes (Sect. 7.3). Each eNodeB broadcasts the first of its signatures and the other signatures are deduced by the UE from a static table in memory ([9], p. 39). A UE sends a PRACH message, by sending one of the 64 signatures included in the eNodeB signature set.

A PRACH message occupies 6 consecutive PRBs in the frequency domain, regardless of the cell bandwidth, during 1–3 subframes. This allocation is shown in Fig. 2.18. A UE sends PRACH messages without knowing the timing advance. A Cyclic Prefix (CP) large enough to cover the whole round trip must be used to protect the message from ISI with previous symbol. A slightly bigger Guard Time (GT) with no transmission must also be inserted after sending the PRACH message to avoid ISI with next symbol. GT must be greater than the sum of round trip and maximum delay spread to avoid overlap between a PRACH message and the subsequent signal. Depending on the cell size, the constraints on CP and GT sizes are different. Five modes of PRACH messages exist allowing adaption to the cell configuration ([11], p. 31). The smallest message consists of the 839 samples of one signature sent in one subframe over $800\,\mu s = 30720 * 0.8\, T_S = 24576\, T_S$ with CP and GP of about 100 $\mu$s. This configuration works for cells with a radius under 14 km and thus a round trip time under $14 * 2/300000 = 93\,\mu s$. The longest message consists of 1697 samples (twice the 839 samples of one signature) sent in 3 subframes over $1600\,\mu s = 30720 * 1.6\, T_S = 49152\, T_S$ with CP and GP of about 700 $\mu$s. This configuration is adapted to cells with a radius up to 100 km and thus a round trip time up to $100 * 2/300000 = 667\,\mu s$.

In 100 km cells, the round trip time can be almost as long as the transmitted signature. Thus no cyclic shift can be applied due to the ambiguity when receiving the same root with different cyclic shifts: the signal could result from separate signatures or from UEs with different round trips. The smaller the cell is, the more cyclic shifts can be used for one root resulting in a less complex decoding process and greater orthogonality between signatures (see auto and intercorrelations in Fig. 2.19b).

In the frequency domain, the six consecutive PRBs used for PRACH occupy $6 * 0.180 = 1.08$ MHz. The center band of this resource is used to send the 839 signature samples separated by 1.25 kHz. When the guard band is removed from the signal, it may be seen that the actual usable band is $839 * 1.25 = 1048.75$ kHz.

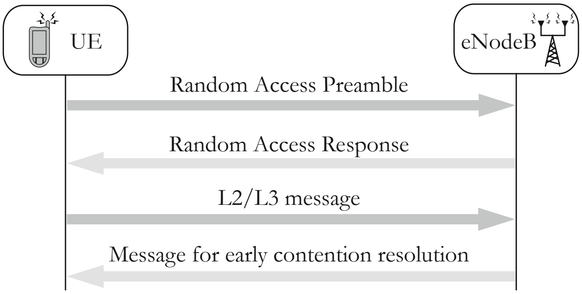



**Fig. 2.20** Contention-based random access procedure

Two modes of random access procedure exist: the most common is the contention-based mode in which multiple UEs are permitted to send a PRACH signal in the same allocated time and frequency window. Contention-free mode is the other possibility and for this case, the eNodeB ensures that only a single UE can send a given ZC sequence for a given time and frequency window. The contention-free mode will not be presented here; see [30] for more details.

Figure 2.20 illustrates the contention-based random access procedure. Within the UE, the physical layer first receives a PRACH message request from upper layers with a PRACH starting frequency and mode, message power and parameters (root sequences, cyclic shifts...). A temporary unique identity called Random Access Radio Network Temporary Identifier (RA-RNTI) identifies the PRACH time and frequency window. Then, the UE sends a PRACH message using the given parameters. The UE monitors the PDCCH messages in subframes subsequent to the PRACH burst and if the RA-RNTI corresponding to that UE is detected, the corresponding PDSCH PRBs are decoded and RAR information is extracted. If no PDCCH message with the RA-RNTI of the UE is detected, the random access procedure has failed, and so a new PRACH message will be scheduled. More details on PRACH can be found in [11], p. 16.

An 11-bit timing advance is sent by the eNodeB to the UE within the RAR message ([11], p. 8). This timing advance is derived from the downlink reception of the previous downlink message, and ranges from 0 to 0.67 ms (the round trip in a 100 km cell) with a unit of 16 $T_s = 0.52\ \mu$s. When the position of the UE is changed, its timing advance alters. Timing advance updates can be requested by the eNodeB in MAC messages if a modification of the reference signal reception timing is measurable by the eNodeB. These update messages are embedded in PDSCH data.

In the RAR, the eNodeB allocates uplink resources and a Cell Radio Network Temporary Identifier (C-RTNI) to the UE. The first PUSCH resource granted to the UE is used to send L2/L3 messages carrying the random access data: these include connection and/or scheduling requests, and the UE identifier.

The final step in the contention-based random access procedure is the downlink contention resolution message in which the eNodeB sends the UE identifier corresponding to the successful PRACH connection. A UE which does not receive

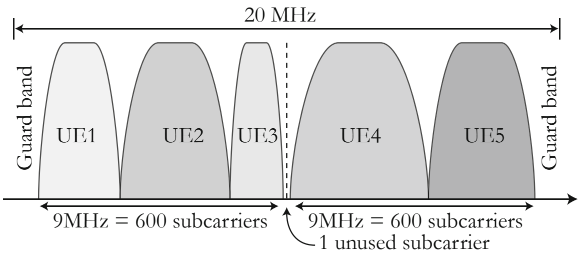



**Fig. 2.21** Baseband spectrum of a fully-loaded 20 MHz LTE downlink

a message which includes its own identifier will conclude that the random access procedure has failed, and will restart the procedure.

## 2.5 LTE Downlink Features

### *2.5.1 Orthogonal Frequency Division Multiplexing Access*

In contrast to uplink communications, a single entity, the eNodeB, handles the transmission over the whole bandwidth for the downlink. Transmission over a wide frequency band (up to 20MHz) and use of several antennas (4 or more) is possible because eNodeBs are powered by mains electricity and so the RF constraints are reduced compared to a UE. Consequently, a higher PAPR is allowed in the downlink than in the uplink ([30], p. 122).

Figure 2.21 displays the frequency use of a fully-loaded 20 MHz LTE downlink with localized UE allocation. A total bandwidth of 18 MHz is effectively used by the 1200 subcarriers, with the central subcarrier left unused because it may be "polluted" by RF oscillator leakage. The transmitted signal must fit within the transmission mask defined in [9]. Depending on bandwidth, the number of subcarriers varies according to Table 2.1. The number of PRBs per slot ranges from 6 in a 1.4 MHz cell to 100 in a 20 MHz cell. A configuration of 110 PRBs per slot in a 20 MHz cell with guard band reduction is also possible to increase data rates at the cost of a more complex radio frequency management. The number of subcarriers in the sampling band is a function of power of 2 (except for the 15 MHz case). A consequence of a subcarrier number power of two is that OFDMA and SC-FDMA baseband processing (Sect. 2.3.4) can be executed faster by employing the Fast Fourier Transform (FFT) algorithm to convert data into the Fourier domain.

Figure 2.22 shows that non-contiguous PRBs can be allocated to a UE using the downlink communication stream, enhancing protection against frequency selectivity at the cost of increasing control information. Frequency hopping between two PRBs in a single frame (for the case where two UEs exchange their PRBs) can also

**Table 2.1** LTE downlink bandwidth configurations

| | | | | | | |
|---|---|---|---|---|---|---|
| Bandwidth(MHz) | 1.4 | 3 | 5 | 10 | 15 | 20 |
| Resource blocks per slot | 6 | 15 | 25 | 50 | 75 | 100 |
| Number of data subcarriers | 72 | 180 | 300 | 600 | 900 | 1200 |
| Used bandwidth (MHz) | 1.08 | 2.25 | 4.5 | 9 | 13.5 | 18 |
| Minimal sampling rate (MHz) | 1.92 | 3.84 | 7.68 | 15.36 | 23.04 | 30.72 |
| Number of subcarriers in sampling band | 128 | 256 | 512 | 1024 | 1536 | 2048 |

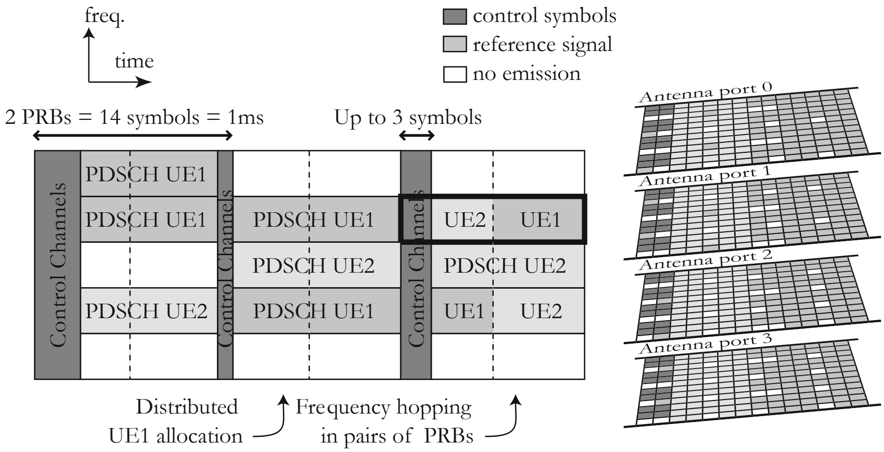



**Fig. 2.22** Downlink multiple user scheduling and reference signals

reinforce this protection [4]. Note that all PRBs associated with a single UE have identical modulation and coding schemes because little gain increase is seen if PRBs of one UE have different modulation and coding schemes [2]. Figure 2.22 also shows the downlink cell specific reference signals that are inserted in symbols 0, 1 and 4 of each slot. Antenna ports 1 and 2 insert 4 reference values each per slot. Antenna ports 3 and 4 insert only 2 reference values each per slot. For each additional antenna, a reference signal overhead is added but multiple antennas can bring significant gain compensating for this throughput reduction (Sect. 2.3.6). The maximum possible reference signal overhead is: $(2*4+2*2)/(7*12) = 14.3\,\%$. Reference signals must be interpolated to be used in coherent decoding; they must consequently reflect most of the channel properties by covering the entire time/frequency resources. Using the channel coherence bandwidth and channel coherence time worst case estimation, the diamond shape localization of reference signals was chosen as a tradeoff between overhead and channel estimation accuracy. Downlink RS are length-31 Gold sequences (Sect. 2.5.3) initialized with the transmitting cell identifier. An eNodeB can send additional UE-specific RS (for beam forming) or broadcast RS (for broadcasted data) ([30], p. 163).

### 2.5.2 Downlink Physical Channels

Like in uplink communications, the downlink bits are transmitted through several physical channels allocated to specific physical resources:

- The `Physical Broadcast Channel` (PBCH) broadcasts basic information about the cell. It is a low data rate channel containing the Master Information Block (MIB), which includes cell bandwidth, system frame number. It is sent every 10 ms and has significant redundancy on the 72 central subcarriers of the bandwidth (Sect. 2.5.5).
- The `Physical Downlink Control Channel` (PDCCH) is the main control channel, carrying Downlink Control Information (DCI [30], p. 195). There are ten formats of DCI each requiring 42 to 62 bits. Each format signals PRB allocations for uplink and downlink, as well as UE power control information, the Modulation and Coding Scheme (MCS, Sect. 2.3.5) and request for CQI (Sect. 2.3.5). Every downlink control channels is located at the beginning of the subframe, in symbol 1, 2 or 3. Downlink MCS is chosen using UE reports in PUCCH (Sect. 2.4.1) but the eNodeB has the liberty to choose a MCS independent of the UE recommendation.
- The `Physical Control Format Indicator Channel` (PCFICH) is a physical channel protected with a high level of redundancy, indicating how many PDCCH symbols (1, 2 or 3) are sent for each subframe. Certain exceptions in the number of control symbols exist for broadcast and small band modes. This channel is transmitted in symbol 0, "stealing" resources from PDCCH.
- The `Physical Downlink Shared Channel` (PDSCH) is the only data channel, which carries all user data. There are seven PDSCH transmission modes, which are used depending multiple antenna usage, as decided by the eNodeB (Sect. 2.5.4). The transmission mode is part of the DCI sent in PDCCH. PDSCH also infrequently carries System Information Blocks (SIB) to complete the MIB information of the cell in PBCH channel.
- The `Physical Hybrid ARQ Indicator Channel` (PHICH) carries uplink HARQ ACK/NACK information, which request retransmission of uplink data when the Cyclic Redundancy Check (CRC) was incorrectly decoded (Sect. 2.3.5.1). CRC is added to an information block to detect infrequent errors, producing a small amount of redundancy. This process is called Forward Error Correction (FEC, Sect. 2.3.5). PHICH is sent using the same symbols as PDCCH.
- The `Physical Multicast Channel` (PMCH) is used to broadcast data to all UEs via Multimedia Broadcast and Multicast Services (MBMS). This special mode was especially created to broadcast television, and is not considered in this document.

A UE must constantly monitor the control channels (PDCCH, PCFICH, PHICH). Due to the compact localization of control channels in the first few symbols of each subframe, a UE can execute some "micro sleeps" between two control zones, and thus save power when no PRB with the identifier of the UE was detected in

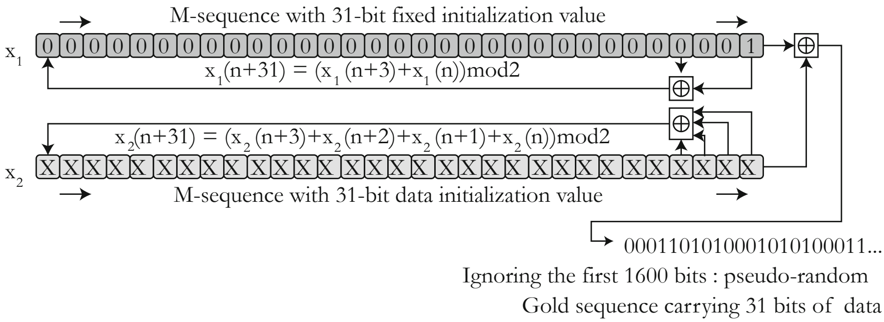



**Fig. 2.23** Gold pseudo random sequence generation

the subframe. Special modulation and coding schemes are used for control channels. PDCCH is scrambled, and adds bitwise length-31 Gold sequences, equivalent to those used in downlink reference signals, initialized with UE identifier. Gold sequences are specific bit sequences that are explained in the next section. Several MU-MIMO UEs can receive PDCCH on the same PRBs using Code Division Multiplexing (CDM). PBCH and PDCCH are coded with convolutional code instead of turbo code because convolutional codes are better suited for small blocks (Sect. 2.3.5 and [30], p. 237).

### *2.5.3 Downlink Reference Signals*

In downlink communication, three types of reference signals are sent: cell specific, UE specific and broadcast specific RS (2.5.1). Only the cell specific RS, which are the most common are considered in this study. Downlink RS are constructed from length-31 Gold sequences. `Gold sequences` are generated using 31-bit shift registers and exclusive ORs (Fig. 2.23). $x_1$ and $x_2$ are called maximum length sequences or M-sequences, and are spectrally flat pseudo-random codes but can carry up to 31 bits of data. While $x_1$ initial value is a constant, $x_2$ initial value carries the data. In order for two Gold codes with close initialization to be orthogonal, the 1600 first outputs are ignored. The resulting signal shift improves the code PAPR and the two Gold codes from different eNodeBs are orthogonal, enabling a UE to decode the signal reliably [5]. The PAPR of reference signals is very important because the reference signals are often power boosted compared to data.

The initialization value of a Gold sequence is generated from the physical layer cell identity number, the slot number within the radio frame, the symbol number within the slot, and an indicator of normal or extended CP. The Gold sequence bits are QPSK modulated and transmitted on RS allocated resources. The same length-31 Gold bit sequences are used for scrambling data over the frequency band in Sect. 2.5.1.

### *2.5.4 Downlink Multiple Antenna Techniques*

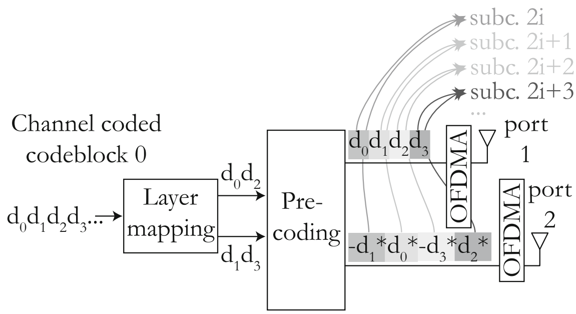
LTE PDSCH can combine spatial diversity, MIMO and beam forming (Sect. 2.3.6). Two successive processes map the data to the eNodeB multiple antenna ports:

1. The `code block to layer mapping` associates each code block with one or two layers ([9], p. 47). A layer is a set of bits that is multiplexed in frequency or in space with other layers. In LTE Release 9, two code blocks can be multiplexed simultaneously and the number of layers used is called Rank Indicator (RI) and is between 1 and 4. If two code blocks are sent simultaneously in the same resource, spatial multiplexing is exploited (Sect. 2.3.6).
2. The `precoding` jointly processes each element of the layers to generate the $n_T$ antenna port signals. It consists of multiplying the vector containing one element from each of the RI layers with a complex precoding matrix $W$. An antenna port can be connected to several antennas but these antennas will send an identical signal and so be equivalent to a single antenna with improved frequency selectivity due to diversity. The number of antenna ports $n_T$ is 1, 2 or 4. In LTE, precoding matrices are chosen in a set of predefined matrices called a "codebook" ([9], p. 48). Each matrix has an index call Precoding Matrix Indicator (PMI) in the current codebook.

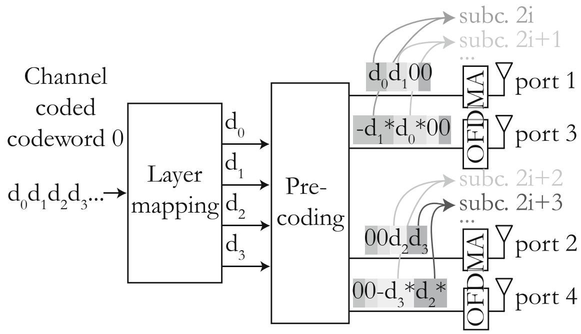
Figure 2.24 illustrates the layer mapping and precoding for `spatial diversity` for different numbers of RI and $n_T$. `Space-Frequency Block Coding` (SFBC) is used to introduce redundancy between several subcarriers. SFBC is simply introduced by temporally separating the values such as Space-Time Block Coding (STBC, Sect. 2.3.6) prior to the IFFT which is executed during OFDMA encoding. In Fig. 2.24a, one Code Block is sent to two antennas via two layers. The precoding matrix used to introduce SFBC follows the Alamouti scheme [15]. In Fig. 2.24b, a derived version of the Alamouti scheme is adapted for transmission diversity with SFBC over four antenna ports. Of every four values, two are transmitted using a pair of antenna ports with certain subcarriers and the two remaining values are transmitted on the other pair of antennas over different subcarriers. Antenna ports are not treated identically: antenna ports 3 and 4 transmit less reference signal so due to the resulting poorer channel estimation, these ports must not be paired together.

There are 7 PDSCH modes defining how the eNodeB exploits multiple antennas in its communication with a UE:

1. In `transmission mode 1`, no multiple antenna technique is used.
2. In `transmission mode 2`, there are several antennas but no spatial multiplexing. One Transport Block is sent per TTI with antenna diversity (Fig. 2.24a and b).
3. In `transmission mode 3`, open loop spatial multiplexing (MIMO) is used, i.e. the UE does not feed back information that would enable UE-specific precoding (i.e. beam forming). This precoding scheme is known as Cyclic Delay Diversity (CDD). It is equivalent to sending each subcarrier in a different direction, increasing frequency diversity of each transmitted Code Block.




**(a)** SFBC with one Codeword, 2 Layers and 2 Antennas

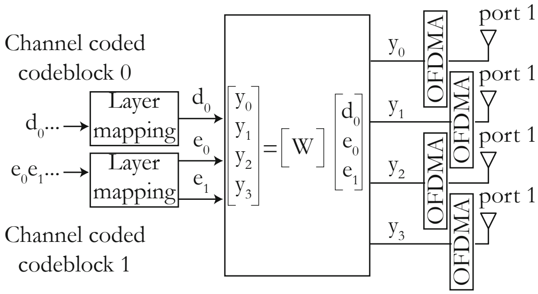



**(b)** SFBC with one Codeword, 4 Layers and 4 Antennas

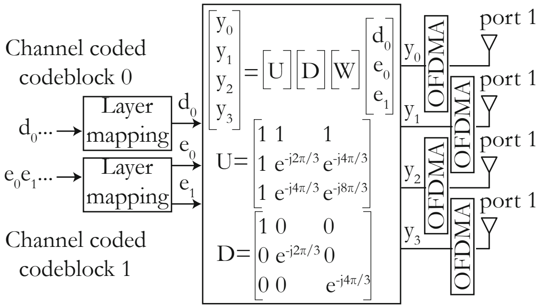
**Fig. 2.24** Layer mapping and precoding for spatial diversity with different multi-antenna parameters

4. In transmission mode 4, closed loop spatial multiplexing (MIMO) is used. The UE feeds back a RI and a PMI to advise the eNodeB to form a beam in its direction, i.e. by using the appropriate transmit antennas configuration. It also reports one Channel Quality Indicator (CQI) per rank, allowing the eNodeB to choose the MCS for each Transport Block.
5. In transmission mode 5, MU-MIMO is used (Sect. 2.4.4). Each of two UEs receives one of two transmitted Transport Blocks in a given resource with different precoding matrixes.
6. In transmission mode 6, there is no spatial multiplexing (rank 1) but UE precoding feedback is used for beamforming.
7. Transmission mode 7 corresponds to a more accurate beam forming using UE-specific downlink reference signals.

Examples of closed loop and open loop `spatial multiplexing` encoding are illustrated in Fig. 2.25. In Fig. 2.25a, the closed loop is used: the UE reports a PMI to assist in the eNodeB choice of a good precoding matrix $W$. In Fig. 2.25b, there is no UE feedback, so the two multiplexed code blocks are transmitted with a maximum




**(a)** Closed loop spatial multiplexing with two Codewords, 3 Layers, 4 Antennas




**(b)** Open loop spatial multiplexing with two Codeword, 3 Layers and 4 Antennas

**Fig. 2.25** Layer mapping and precoding for spatial multiplexing with different multiantenna parameters

transmission diversity configuration with CDD. While matrix $U$ mixes the layers, matrix $D$ creates different spatial beams for each subcarrier which is equivalent to sending each subcarrier in a different directions. Finally, $W$ is the identity matrix for two antenna ports and a table of predefined matrices used successively for four antenna ports. The objective of $W$ is to decorrelate more the spatial layers.

A UE knows the current transmission mode from the associated PDCCH format. MIMO detectors for the LTE downlink are located in the UEs; the ZF or MMSE techniques presented in Sect. 2.4.4 are used for the decoding. This topic is not within the scope of this study. More information on LTE downlink MIMO detectors can be found in [33].

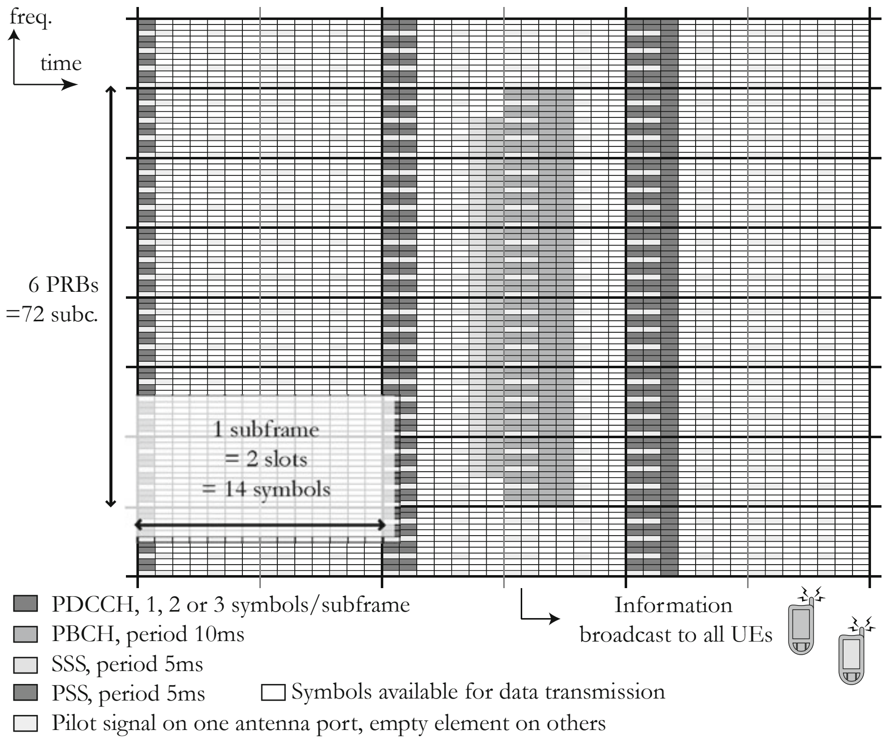



**Fig. 2.26** Downlink PSS, SSS, RS and PBCH localization in subframes

### *2.5.5 UE Synchronization*

Synchronizing the UE with the eNodeB is a prerequisite to data exchanges. A UE will monitor the eNodeB downlink synchronization signals when it requires a new connection (initial synchronization) or during a handover (new cell identification). The synchronization signals communicate the time basis as well as the cell identifier, bandwidth, cyclic prefix length and cell duplex mode. Four types of downlink signals must be decoded by the UE for synchronization: the Primary Synchronization Signal (PSS), the Secondary Synchronization Signal (SSS), the Physical Broadcast Channel (PBCH) and the downlink Reference Signal (RS). These signals give a UE information about the cell identity and parameters, as well as the quality of the channel.

1. The `Primary Synchronization Signal` (PSS) consists of a Zadoff–Chu (ZC) sequence with length $N_{ZC}$ 63 and index $q$ 25, 29 or 34. These sequences are illustrated in Fig. 2.19. The middle value is "punctured" to avoid using the DC subcarrier and so is sent twice in each frame using the 62 central subcarriers (Fig. 2.26). A ZC length of 63 enables fast detection using a 64 point FFT

and using 62 subcarriers ≤ 6 PRBs makes the PSS identical for all bandwidth configurations between 6 and 110 PRBs. $q$ gives the cell identity group (0 to 2) which is usually used to distinguish between the three sectors of a three-sectored cell (Sect. 2.1.2).

2. The `Secondary Synchronization Signal` (SSS) consists of a length-31 M-sequence, equivalent to the one used to generate Gold sequences (Sect. 2.5.3), duplicated and interleaved after different cyclic shifts. The 62 values obtained are used for Binary Phase Shift Keying (BPSK, 1 bit per symbol) coded and sent like PSS. The signal is initialized with a single cell identifier of a possible 168 which is used by a given UE to distinguish between adjacent cells. The cyclic shift gives the exact start time of the frames. The channel response knowledge contained in the PSS enables the UE to evaluate the channel for coherent detection of SSS.
3. The `Physical Broadcast Channel` (PBCH) (Sect. 2.5.1) is read only during initial synchronization to retrieve basic cell information.
4. `Downlink RS` (Sect. 2.5.3) is decoded to evaluate the current channel impulse response and the potential of a handover with a new cell identification and better channel properties.

The localization of PSS, SSS and PBCH in FDD mode with normal cyclic prefix is shown in Fig. 2.26. In this cell configuration, the 62 values of PSS and SSS are sent in the center of subframe symbols 6 and 5 respectively and repeated twice in a radio frame, i.e. every 5 ms. The PBCH is sent over 72 subcarriers and 4 symbols once in each radio frame. The relative positions of PSS and SSS communicate to UEs the type of duplex mode (TDD, FDD or HD-FDD) and CP length of the cell.

This section detailed the features of the LTE physical layer. Next section introduces the concept of dataflow Model of Computation and details the models that are used in this study to represent the LTE eNodeB physical layer processing.

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