Chapter 2

3GPP LTE System

2.1. LTE Features

UMTS networks worldwide are being upgraded to High Speed Packet Access (HSPA) in order to increase data rate and capacity for packet data. HSPA refers to the combination of High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA).
While HSDPA was introduced as a 3GPP release 5 feature, HSUPA is an important feature of 3GPP release 6.
However, even with the introduction of HSPA, evolution of UMTS has not reached its end. HSPA+ brings significant enhancements in 3GPP release 7 and 8. Objective is to enhance performance of HSPA based radio networks in terms of spectrum efficiency, peak data rate and latency. Important features of HSPA+ are downlink MIMO (Multiple Input Multiple Output), higher order modulation for uplink and downlink, improvements of layer 2 protocols, and continuous packet connectivity [7].

In order to ensure the competitiveness of UMTS for the next 10 years and beyond, concepts for UMTS Long Term Evolution (LTE) have been introduced in 3GPP release 8 [8]. Objective is a high-data-rate, low-latency and packet-optimized radio access technology. LTE is also referred to as EUTRA (Evolved UMTS Terrestrial Radio Access) or E-UTRAN (Evolved UMTS Terrestrial Radio Access Network).

LTE has ambitious requirements for data rate, capacity, spectrum efficiency, and latency. In order to fulfill these requirements, LTE is based on new technical principles. LTE uses new multiple access schemes on the air interface: OFDMA (Orthogonal Frequency Division Multiple Access) in downlink and SC-FDMA (Single Carrier Frequency Division Multiple Access) in uplink. Furthermore, MIMO antenna schemes form an essential part of LTE [1].
LTE includes an FDD (Frequency Division Duplex) mode of operation and a TDD (Time Division Duplex) mode of operation [2].

The target peak data rates for downlink and uplink in the LTE system were set at 100 Mbps and 50 Mbps respectively within a 20 MHz bandwidth [9] with the terminal has two receive antennas and one transmit antenna. The number of antennas used at the base station is more easily upgradeable by the network operator, and the first version of the LTE specifications has therefore been designed to support downlink MIMO operation with up to four transmit and receive antennas.

In terms of mobility, the LTE system is required to support communication with terminals moving at speeds of up to 350 km/h, or even up to 500 km/h depending on the frequency band [7]. These requirements mean that handover between cells has to be possible without interruption, in other words, with imperceptible delay and packet loss for voice calls, and with reliable transmission for data services.

These targets are to be achieved by the LTE system in typical cells of radius up to 5 km, while operation should continue to be possible for cell ranges of up to 100 km to enable wide-area deployments [9].

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

The LTE system is required to support transition from idle to active in less than 100 ms [7].

The LTE system capacity is dependent not only on the supportable throughput but also on the number of users simultaneously located within a cell which can be supported by the control signaling. For the latter aspect, the LTE system is required to support at least 200 active-state users per cell for spectrum allocations up to 5MHz, and at least 400 users per cell for wider spectrum allocations; only a small subset of these users would be actively receiving or transmitting data at any given time instant, depending, for example, on the availability of data to transmit and the prevailing radio channel conditions. An even larger number of non-active users may also be present in each cell, and therefore able to be paged or to start transmitting data with low latency [1].

As demand for suitable radio spectrum for mobile communications increases, LTE is required to be able to operate in a wide range of frequency bands and sizes of spectrum allocations in both uplink and downlink. LTE can use spectrum allocations ranging from 1.4 to 20 MHz. LTE provides also support for FDD, TDD.
The frequency bands where LTE will operate will be in both paired and unpaired spectrum, requiring flexibility in the duplex arrangement, so LTE supports both FDD and TDD. Release 8 of the 3GPP specifications for LTE includes fourteen frequency bands for FDD and eight for TDD. The paired bands for FDD operation are numbered from 1 to 14. The unpaired bands for TDD operation are numbered from 33 to 40 [10].

The following table summarizes the LTE specifications

Bandwidth	1.4,3,5,10 and 20 MHz
Maximum data rate	100 Mbps for DL and 50 Mbps for UL
Latency	100 msec
Mobility	Up to 350 Km/h
Duplex mode	FDD and TDD
Cell range	Up to 100 km radius

Table 2.1 LTE specifications

2.2. LTE Frame Structure

The LTE down Link (DL) radio frame structure for FDD consists of 10 sub-frames with total timing $T_{\mathrm{f}} = 307200 \cdot T_{\mathrm{s}} = 10\ \mathrm{ms}$ for the frame. Every sub-frame has two slots with timing = 0.5 msec for each slot. Each slot consists of 7 OFDM symbols with cyclic prefix for each OFDM symbol.
Figure 2.1 shows an example of (DL) radio frame structure for FDD with normal cyclic prefix [2].

2.3. LTE Signals and Channels

In figure 2.5 we can see the resource grid of the LTE down link sub-frame with $N_{\mathrm{RB}}^{\mathrm{UL}} N_{\mathrm{sc}}^{\mathrm{RB}}$ subcarriers where $N_{\mathrm{RB}}^{\min,\mathrm{UL}} = 6$ and $N_{\mathrm{RB}}^{\max,\mathrm{UL}} = 110$ is the smallest and largest uplink bandwidth,

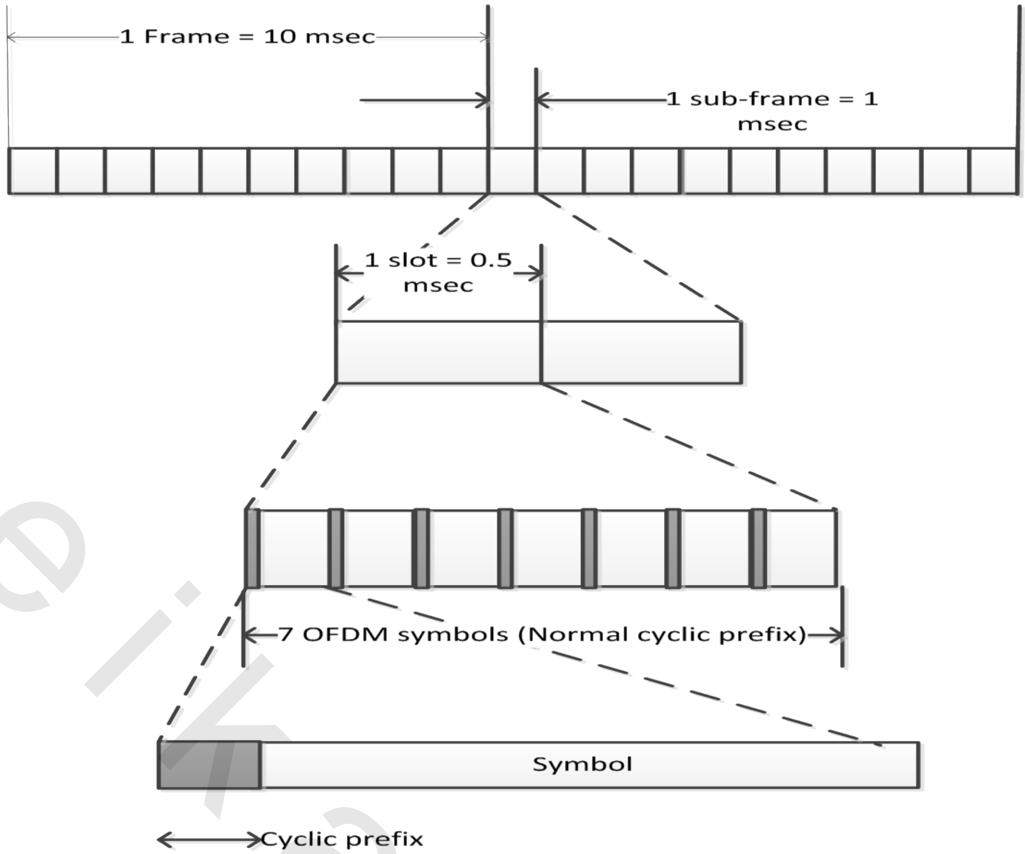

Figure 2.1 (DL) radio frame structure for FDD

respectively, supported by the current version of this specification. The set of allowed values for N_{RB}^{UL} is given in table 2.2.

channel BW (MHz)	1.4	3	5	10	15	20
N_{RB}	6	15	25	50	75	100

Table 2.2 Number of resource blocks in LTE

We can also explain in brief the downlink physical channels as follows

- Physical broadcast channel (PBCH)
    - The Physical Broadcast Channel (PBCH) is used to broadcast the Master Information Block (MIB) using the BCH transport channel and BCCH logical channel

- The PBCH is allocated in the central 72 subcarriers belonging to the first 4 OFDMA symbols of the second time slot of every 10 ms radio frame (time slot 1 in sub-frame 0. with time slot numbering starting from 0).

- The Physical Control Format Indicator Channel (PCFICH)
    - The Physical Control Format Indicator Channel (PCFICH) is used at the start of each 1 ms downlink sub-frame to signal the number of symbols used for the PDCCH.
- The Physical Downlink Control Channel (PDCCH)
    - The Physical Downlink Control Channel (PDCCH) is used to transfer Downlink Control Information (DCI).
    - The PCFICH signals the number of OFDMA symbols which can be occupied by the PDCCH. These symbols are always at the start of each downlink sub-frame.
    - Resource Elements allocated to the PDCCH are grouped into quadruplets (groups of 4 Resource Elements). The number of quadruplets available to the PDCCH is equal to the number of quadruplets within the set of OFDMA symbols signaled by the PCFICH, which have not already been allocated to the PCFICH, PHICH or Reference Signals.

We can summarize the downlink signals as follows

- Primary and secondary synchronization signals
    - Used to achieve radio frame, sub-frame, slot and symbol synchronization in the time domain.
    - The synchronization signals also used to estimate the physical-layer cell identity (N_{ID}^{cell}).
    - Primary synchronization signals is mapped as shown in figure 2.5 in the central 62 subcarriers belonging to the last symbol of time slots 0 and 10
    - Secondary synchronization signal is mapped as shown in figure 2.5 in the central 62 subcarriers belonging to the second to last symbol of time slots 0 and 10.
- Reference signals
    - Used in channel estimation to perform the demodulation process of the channels mentioned above.
    - It consists of three signals

1. Cell-specific downlink reference signals.

   Cell specific Reference Signals are broadcast across the entire cell. They are used to support CQI reporting and demodulation. It consists of reference symbols as explained in 6.10.1.1 in [2]. It is inserted within the first and third last 6 OFDM symbol of each slot and with a frequency-domain spacing of six subcarriers as shown in figure 2.2.

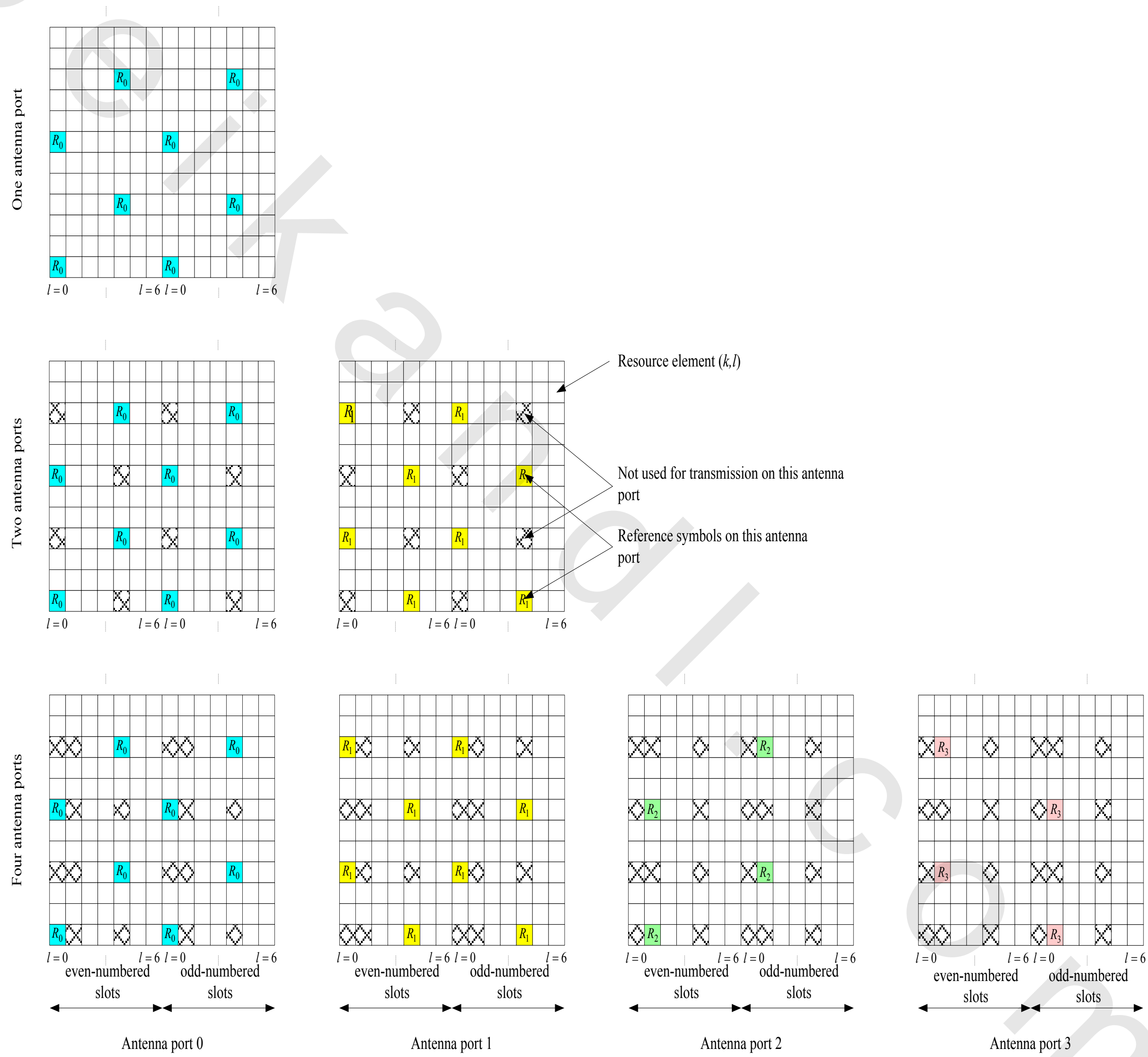

Figure 2.2 Mapping of cell specific reference signals (normal cyclic prefix).

2. UE specific Reference Signals

   UE specific Reference Signals can be directed towards individual UE using beam forming techniques.

   The UE-specific reference signals are then only transmitted within the resource blocks assigned for DL-SCH transmission to that specific UE.

   An example of mapping UE-specific reference signals is shown in figure 2.3.

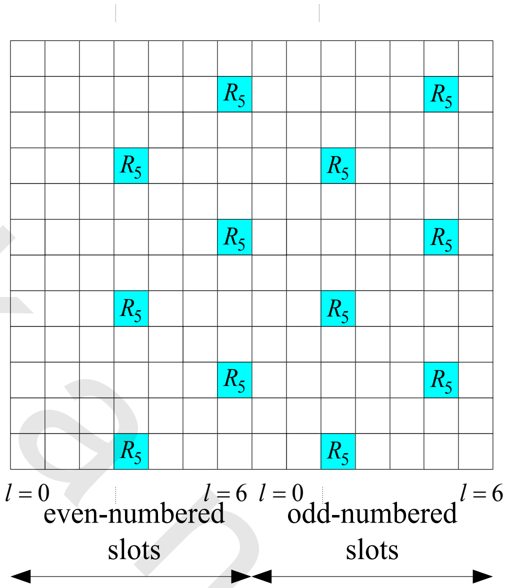

Figure 2.3 Mapping of UE-specific reference signals (normal cyclic prefix)

3. MBSFN Reference Signals

   They are used to support the channel estimation of Multimedia Broadcast Multicast Services (MBMS).

   MBMS aims to provide an efficient mode of delivery for both broadcast and multicast services over the core network.

   MBSFN is used to

- Increase received signal strength, especially at the border between cells involved in the MBSFN transmission.
- Reduce interference level at the border between cells involved in the MBSFN transmission, as the signals received from neighbor cells will not appear as interference but as useful signals.

  An MBSFN sub-frame consists of two parts:

- A unicast part

A bidirectional point-to-point transmission between the network and each of the multiple users

- An MBSFN part, to which the MCH is mapped.

  A downlink-only point-to-multipoint connection from the network to multiple terminals.

  More details about MBSFN sub-frame types are in [7].

  MBSFN reference symbols are inserted within the MBSFN part of the MBSFN sub-frame as shown in figure 2.4

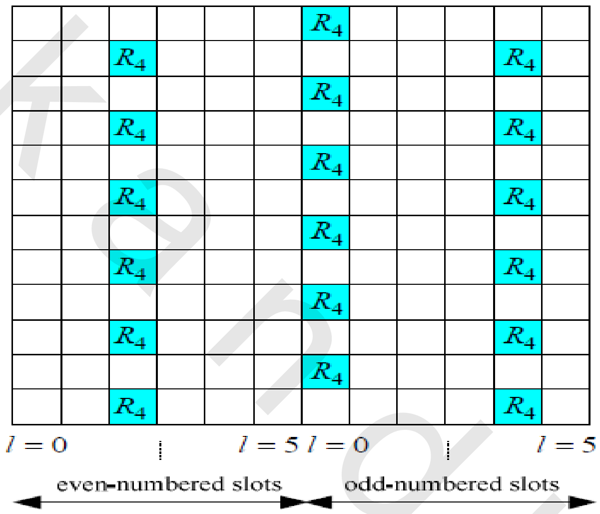

Figure 2.4 Mapping of MBSFN reference signals

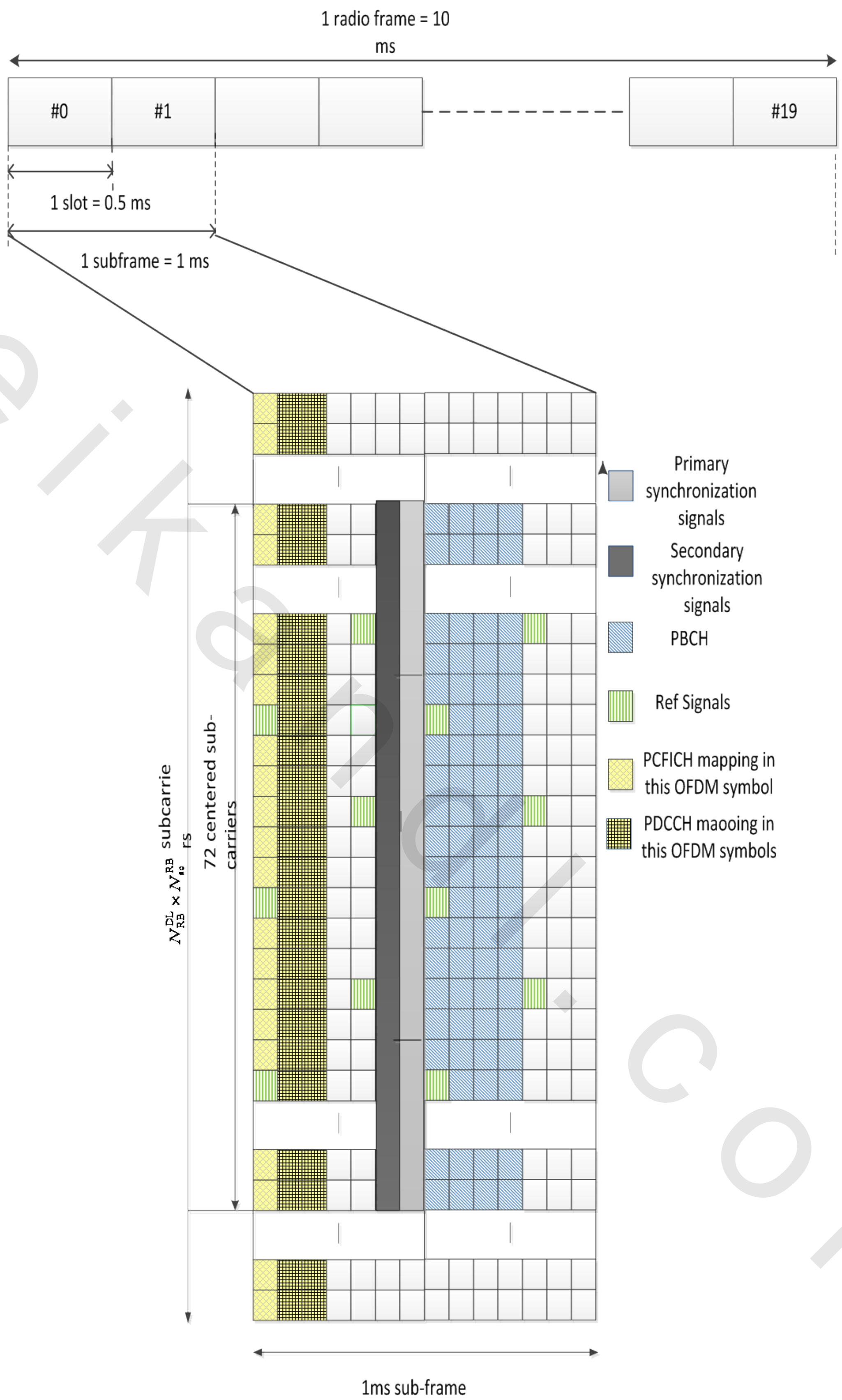

Figure 2.5 The resource grid of the LTE down link sub-frame

2.4. LTE Technologies

2.4.1. OFDMA and SC-FDMA

The downlink transmission scheme for E-UTRA FDD and TDD modes is based on conventional OFDM [1]. In an OFDM system, the available spectrum is divided into multiple carriers, called subcarriers. Each of these subcarriers is independently modulated by a low rate data stream. OFDM has several benefits including its robustness against multipath fading and its efficient receiver architecture.

In practice, the OFDM signal can be generated using IFFT (Inverse Fast Fourier Transform) digital signal processing. The IFFT converts a number N of complex data symbols used as frequency domain bins into the time domain signal.

OFDMA allows the access of multiple users on the available bandwidth. Each user is assigned a specific time-frequency resource. As a fundamental principle of 3GPP LTE, the data channels are shared channels, i.e. for each transmission time interval of 1 ms, a new scheduling decision is taken regarding which users are assigned to which time/frequency resources during this transmission time interval.

While OFDMA is seen optimum to fulfil the LTE requirements in downlink, OFDMA properties are less favorable for the uplink. This is mainly due to weaker peak-to-average power ratio (PAPR) properties of an OFDMA signal, resulting in worse uplink coverage. Thus, the LTE uplink transmission scheme for FDD and TDD mode is based on SC-FDMA (Single Carrier Frequency Division Multiple Access) with cyclic prefix [11]. SC-FDMA signals have better PAPR properties compared to an OFDMA signal. This was one of the main reasons for selecting SC-FDMA as LTE uplink access scheme. The PAPR characteristics are important for cost-effective design of UE power amplifiers. Still, SC-FDMA signal processing has some similarities with OFDMA signal processing.

There are different schemes SC-FDMA signal generation. DFT-spread- OFDM (DFT-s-OFDM) has been selected for LTE.

For DFT-s-OFDM, a size-M DFT is first applied to a block of M modulation symbols. The DFT transforms the modulation symbols into the frequency domain. The result is mapped onto the available subcarriers. In LTE uplink, only localized transmission on consecutive subcarriers is allowed. An N-point IFFT where

N>M is then performed as in OFDM, followed by addition of the cyclic prefix and parallel to serial conversion.

2.4.2. Multiple Antenna (MIMO)

The use of multiple antenna technology allows the exploitation of the spatial-domain as another new dimension. This becomes essential in the quest for higher spectral efficiencies [1].

Multiple antennas can be used in a variety of ways, mainly based on three fundamental principles which are transmit diversity, beam forming and spatial multiplexing. We will discuss here the three principles in brief.

2.4.2.1. Transmit Diversity

Transmit diversity is radio communication using signals that originate from two or more independent sources that have been modulated with identical information-bearing signals and that may vary in their transmission characteristics at any given instant [7].

It can help overcome the effects of fading, outages, and circuit failures. When using diversity transmission and reception, the amount of received signal improvement depends on the independence of the fading characteristics of the signal as well as circuit outages and failures.

Considering antenna diversity, in many systems additional antennas may be expensive or impractical at the remote or even at the base station. In these cases, transmit diversity can be used to provide diversity benefit at a receiver with multiple transmit antennas only. With transmit diversity; multiple antennas transmit delayed versions of a signal, creating frequency-selective fading, which is equalized at the receiver to provide diversity gain.

Since transmit diversity with N antennas results in N sources of interference to other users, the interference environment will be different from conventional systems with one transmit antenna. Thus, even if transmit diversity has almost the same performance as receive diversity in noise-limited environments, the performance in interference-limited environments will differ.

2.4.2.2. Beamforming

Beamforming or spatial filtering is a signal processing technique used in sensor arrays for directional signal transmission or reception. This is achieved by combining elements in a phased array in such a way that signals at particular angles experience constructive interference while others experience destructive interference. Beamforming can be used at both the transmitting and receiving ends in order to achieve spatial selectivity. The improvement compared with omnidirectional reception/transmission is known as the receive/transmit gain (or loss).

Adaptive beamforming is used to detect and estimate the signal-of-interest at the output of a sensor array by means of optimal (e.g., least-squares) spatial filtering and interference rejection.

2.4.2.3. Spatial Multiplexing

Spatial multiplexing is a transmission technique in MIMO wireless communication to transmit independent and separately encoded data signals, so-called streams, from each of the multiple transmit antennas. Therefore, the space dimension is reused, or multiplexed, more than one time.

If the transmitter is equipped with N_t antennas and the receiver has N_r antennas, the maximum spatial multiplexing order (the number of streams) is,

$$N_s = \min(N_t, N_r)$$

If a linear receiver is used, this means that N_s streams can be transmitted in parallel, ideally leading to an N_s increase of the spectral efficiency (the number of bits per second and per Hz that can be transmitted over the wireless channel). The practical multiplexing gain can be limited by spatial correlation, which means that some of the parallel streams may have very weak channel gains.

In LTE we apply two types of precoding for spatial multiplexing, precoding for spatial multiplexing without cyclic delay diversity (CDD) and precoding for spatial multiplexing for large-delay CDD [2].

2.4.2.4. MIMO in LTE

According to [2] LTE supports the following multi-antenna transmission schemes or transmission modes

- Transmit diversity
- Closed-loop spatial multiplexing including codebook-based beam-forming
- Open-loop spatial multiplexing.

2.4.2.4.1. Transmit Diversity

As mentioned above, we send the same modulated codewords on more than one antenna (practically on two or four antenna) to overcome the effects of fading, outages and circuit failures.

Transmit diversity is performed on two stages. First the layer mapping shall be done according to Table 2.3. There is only one codeword and the number of layers υ is equal to the number of antenna ports P used for transmission of the physical channel [2].

Number of layers	Number of code words	Codeword-to-layer mapping $i = 0,1,...,M_{\text{symb}}^{\text{layer}} - 1$	
2	1	$x^{(0)}(i) = d^{(0)}(2i)$ $x^{(1)}(i) = d^{(0)}(2i+1)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)}/2$
4	1	$x^{(0)}(i) = d^{(0)}(4i)$ $x^{(1)}(i) = d^{(0)}(4i+1)$ $x^{(2)}(i) = d^{(0)}(4i+2)$ $x^{(3)}(i) = d^{(0)}(4i+3)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)}/4$

Table 2.3 Codeword-to-layer mapping for transmit diversity

The second stage is precoding. For transmission on two antenna ports, $p \in \{0,1\}$, the output $y(i) = \left[y^{(0)}(i) \quad y^{(1)}(i)\right]^T$, $i = 0,1,...,M_{\text{symb}}^{\text{ap}} - 1$ of the precoding operation is defined by

$$\begin{bmatrix} y^{(0)}(2i) \\ y^{(1)}(2i) \\ y^{(0)}(2i+1) \\ y^{(1)}(2i+1) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 & j & 0 \\ 0 & -1 & 0 & j \\ 0 & 1 & 0 & j \\ 1 & 0 & -j & 0 \end{bmatrix} \begin{bmatrix} \text{Re}\left(x^{(0)}(i)\right) \\ \text{Re}\left(x^{(1)}(i)\right) \\ \text{Im}\left(x^{(0)}(i)\right) \\ \text{Im}\left(x^{(1)}(i)\right) \end{bmatrix} \quad (1)$$

for $i = 0,1,...,M_{\text{symb}}^{\text{layer}} - 1$ with $M_{\text{symb}}^{\text{ap}} = 2M_{\text{symb}}^{\text{layer}}$.

You can refer to 6.3.4.3 for transmission on four antenna ports.

2.4.2.4.2. Closed-loop Spatial Multiplexing

As mentioned above, the spatial multiplexing technique is used to increase the spectral efficiency, as spatial multiplexing implies that multiple streams or ‘ layers ’ are transmitted in parallel, thereby allowing for higher data rates within a given bandwidth.
The layer mapping shall be done according to table 2.4. One or two codewords are mapped to the layers. The number of layers υ is less than or equal to the number of antenna ports P used for transmission of the physical channel. The case of a single codeword mapped to two layers is only applicable when the number of antenna ports is 4.

Number of layers	**Number of code words**	**Codeword-to-layer mapping** $i = 0,1,\dots,M_{\text{symb}}^{\text{layer}}-1$	
1	1	$x^{(0)}(i) = d^{(0)}(i)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)}$
2	2	$x^{(0)}(i) = d^{(0)}(i)$ $x^{(1)}(i) = d^{(1)}(i)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)} = M_{\text{symb}}^{(1)}$
2	1	$x^{(0)}(i) = d^{(0)}(2i)$ $x^{(1)}(i) = d^{(0)}(2i+1)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)}/2$
3	2	$x^{(0)}(i) = d^{(0)}(i)$ $x^{(1)}(i) = d^{(1)}(2i)$ $x^{(2)}(i) = d^{(1)}(2i+1)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)} = M_{\text{symb}}^{(1)}/2$
4	2	$x^{(0)}(i) = d^{(0)}(2i)$ $x^{(1)}(i) = d^{(0)}(2i+1)$ $x^{(2)}(i) = d^{(1)}(2i)$ $x^{(3)}(i) = d^{(1)}(2i+1)$	$M_{\text{symb}}^{\text{layer}} = M_{\text{symb}}^{(0)}/2 = M_{\text{symb}}^{(1)}/2$

Table 2.4 Codeword-to-layer mapping for spatial multiplexing

The precoding for closed loop spatial multiplexing is performed according to

$$\begin{bmatrix} y^{(0)}(i) \\ \vdots \\ y^{(P-1)}(i) \end{bmatrix} = W(i) \begin{bmatrix} x^{(0)}(i) \\ \vdots \\ x^{(\upsilon-1)}(i) \end{bmatrix} \qquad (2)$$

Where the precoding matrix $W(i)$ is of size $P \times \upsilon$ and $i = 0,1,\dots,M_{\text{symb}}^{\text{ap}}-1$, $M_{\text{symb}}^{\text{ap}} = M_{\text{symb}}^{\text{layer}}$.

For spatial multiplexing, the values of $W(i)$ shall be selected among the precoder elements in the codebook configured in the eNodeB and the UE. You can refer to 6.3.4.2.3 in [2] for more information about codebook.

The UE may report a recommended number of layers (expressed as a Rank Indication , RI), as well as a recommended pre-coder matrix (Pre-coder-Matrix Indication , PMI) corresponding to that number of layers, depending on estimates of the downlink channel conditions. The network may, or may not, follow the UE recommendation when transmitting to the terminal. When not following the UE recommendation, the network must explicitly inform the UE what pre-coder matrix is used for the subsequent downlink transmission.

2.4.2.4.3. Open-loop Spatial Multiplexing

Open-loop spatial multiplexing does not rely on any detailed pre-coder recommendation being fed back from the UE and does not require any explicit pre-coder information being signaled to the UE from the network.

The layer mapping of the open-loop spatial multiplexing is performed like the closed-loop. The precoding is performed according to

$$\begin{bmatrix} y^{(0)}(i) \\ \vdots \\ y^{(P-1)}(i) \end{bmatrix} = W(i)D(i)U \begin{bmatrix} x^{(0)}(i) \\ \vdots \\ x^{(\upsilon-1)}(i) \end{bmatrix} \qquad (3)$$

where the precoding matrix $W(i)$ is of size $P \times \upsilon$ and $i = 0,1,\ldots,M_{\text{symb}}^{\text{ap}} - 1$, $M_{\text{symb}}^{\text{ap}} = M_{\text{symb}}^{\text{layer}}$. The diagonal size-$\upsilon \times \upsilon$ matrix $D(i)$ supporting cyclic delay diversity and the size-$\upsilon \times \upsilon$ matrix U are both given by Table 2.5 for different numbers of layers υ.

The values of the precoding matrix $W(i)$ shall be selected among the precoder elements in the codebook configured in the eNodeB and the UE. You can refer to 6.3.4.2.3 in [2] for more information about codebook.

Number of layers υ	U	$D(i)$
1	$[1]$	$[1]$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & e^{-j2\pi/2}\end{bmatrix}$	$\begin{bmatrix}1 & 0\\ 0 & e^{-j2\pi i/2}\end{bmatrix}$
3	$\frac{1}{\sqrt{3}}\begin{bmatrix}1 & 1 & 1\\ 1 & e^{-j2\pi/3} & e^{-j4\pi/3}\\ 1 & e^{-j4\pi/3} & e^{-j8\pi/3}\end{bmatrix}$	$\begin{bmatrix}1 & 0 & 0\\ 0 & e^{-j2\pi i/3} & 0\\ 0 & 0 & e^{-j4\pi i/3}\end{bmatrix}$
4	$\frac{1}{2}\begin{bmatrix}1 & 1 & 1 & 1\\ 1 & e^{-j2\pi/4} & e^{-j4\pi/4} & e^{-j6\pi/4}\\ 1 & e^{-j4\pi/4} & e^{-j8\pi/4} & e^{-j12\pi/4}\\ 1 & e^{-j6\pi/4} & e^{-j12\pi/4} & e^{-j18\pi/4}\end{bmatrix}$	$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & e^{-j2\pi i/4} & 0 & 0\\ 0 & 0 & e^{-j4\pi i/4} & 0\\ 0 & 0 & 0 & e^{-j6\pi i/4}\end{bmatrix}$

Table 2.5 Open-loop spatial multiplexing arrays

2.4.3. Carrier Aggregation (LTE-A)

Carrier aggregation is used in LTE-Advanced in order to increase the bandwidth, and thereby increase the bit-rate [12]. Carrier aggregation can be used for both FDD and TDD. Each aggregated carrier is referred to as a component carrier (CC). The component carrier can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz and a maximum of five component carriers can be aggregated, hence the maximum aggregated bandwidth is 100 MHz. In FDD the number of aggregated carriers can be different in DL and UL.

The easiest way to arrange aggregation would be to use contiguous component carriers within the same operating frequency band (as defined for LTE), so called intra-band contiguous. This might not always be possible, due to operator frequency allocation scenarios. For non-contiguous allocation it could either be intra-band, i.e. the component carriers belong to the same operating frequency band, but have a gap, or gaps, in between, or it could be inter-band, in which case the component carriers belong to different operating frequency bands.

2.5. LTE DL Block Diagram

The processing for DL-SCH transmission is shown in figure 2.6, with transport blocks from the MAC layer. It can be explained as follows

2.5.1. CRC Insertion

24-bit CRC is calculated and appended to each transport block. The CRC allows for receiver The CRC allows for receiver side detection of errors in the decoded transport block. The corresponding error indication is then used by the downlink hybrid-ARQ protocol as a trigger for requesting retransmissions.

2.5.2. Code-block Segmentation

Code-block segmentation implies that the transport block is segmented into smaller code blocks that match the set of code-block sizes defined for the Turbo coder.

Code-block segmentation also implies that an additional (24 bits) CRC is calculated and appended to each code block. Having a CRC per code block allows for early detection of correctly decoded code blocks and corresponding early termination of the iterative decoding of that code block.

The transport-block CRC adds additional error-detection capabilities and thus reduces the risk for undetected errors in the decoded transport block.

2.5.3. Turbo Coding

The Turbo encoding uses a parallel concatenated convolutional code (PCCC) with two 8-state rate 1/2, eight-state constituent encoders, implying an overall code rate of 1/3.

The input to the second constituent encoder is interleaved using an internal turbo code interleaver as shown in [13].

2.5.4. Rate-matching and Physical-layer Hybrid-ARQ

The task of the rate-matching and physical-layer hybrid-ARQ functionality is to extract, from the blocks of code bits delivered by the channel encoder, the exact set of bits to be transmitted within a given TTI.

The outputs of the Turbo encoder (systematic bits, first parity bits, and second parity bits) are first separately interleaved. The interleaved bits are then inserted into what can be described as a circular buffer with the systematic bits inserted first, followed by alternating insertion of the first and second parity bits.

The bit selection then extracts consecutive bits from the circular buffer to the extent that fits into the assigned resource. The set of bits to extract depends on the redundancy version corresponding to different starting points for the extraction of coded bits from the circular buffer

2.5.5. Scrambling

LTE downlink scrambling implies that the block of code bits delivered by the hybrid-ARQ functionality is multiplied (*exclusive-or* operation) by a bit-level *scrambling sequence* . In general, scrambling of the coded data helps to ensure that the receiver-side decoding can fully utilize the processing gain provided by the channel code.

In LTE, downlink scrambling is applied to all transport channels. The scrambling sequences shoud be different for neighbor cells (cell-specific scrambling) to ensure interference randomization between the cells.

This is achieved by having the scrambling depend on the physical-layer cell identity.

2.5.6. Modulation, Layer Mapping and Precoding

The downlink data modulation transforms the block of scrambled bits to a corresponding block of complex modulation symbols. The set of modulation schemes supported for the LTE downlink includes QPSK, 16QAM, and 64QAM, corresponding to two, four, and six bits per modulation symbol, respectively.

The modulation mapping output (one or two codewords) are mapped and precoded as mentioned in 2.4.2.4. for transmit diversity, open loop and closed loop spatial multiplexing.

2.5.7. Resource Element Mapping

The resource element mapping maps the symbols to be transmitted on each antenna port to the resource elements of the set of resource blocks assigned by the MAC scheduler for transmission of the transport block(s) to the terminal.

The MAC scheduler defines virtual resource blocks. Virtual resource blocks and physical resource blocks are of equal size. The scheduler always uses virtual resource blocks for defining user allocations. There are two different types of virtual resource blocks:

- Localized virtual resource blocks.
- Distributed virtual resource blocks.

Localized virtual RBs are equal to physical RBs. Therefore, localized virtual RBs address physical RBs directly. Distributed RB mapping enables the usage of frequency diversity without scheduling distributed RBs directly. Distributed virtual RBs split a physical RB at the slot boundary into two halves. The first half of the scheduled distributed virtual RB directly equals the physical RBs. The second slot is hopped to another second slot of another UE which is virtually scheduled in the distributed way. There is one hopping gap between the scheduled RBs at system bandwidths smaller 50 RBs and two gaps at systems with a larger number of RBs.

2.5.8. OFDM Signal Generation

Applying IFFT to the resource grid to generate the OFDM time domain symbols which are transmitted.

The basic principle of OFDM is to divide the available spectrum into narrowband parallel channels referred to as subcarriers and transmit information on these parallel channels at a reduced signaling rate. The goal is to let each channel experience almost flat-fading simplifying the channel equalization process.

Each subcarrier is modulated by a data symbol and after applying the IFFT a cyclic prefix Extension is performed.

The last part of the OFDM signal is added as cyclic prefix (CP) in the beginning of the OFDM signal. The cyclic prefix length is generally chosen to accommodate the maximum delay spread of the wireless channel. The addition of the cyclic prefix makes the transmitted OFDM signal periodic and helps in avoiding inter-OFDM symbol and inter-subcarrier.

The baseband signal within an OFDM symbol can be written as

$$s(n) = \sum_{k=0}^{N-1} S(k) e^{j2\pi kn/N} \tag{4}$$

Where N represents the number of subcarriers, S (k) complex modulation symbol transmitted on the k^{th} subcarrier.

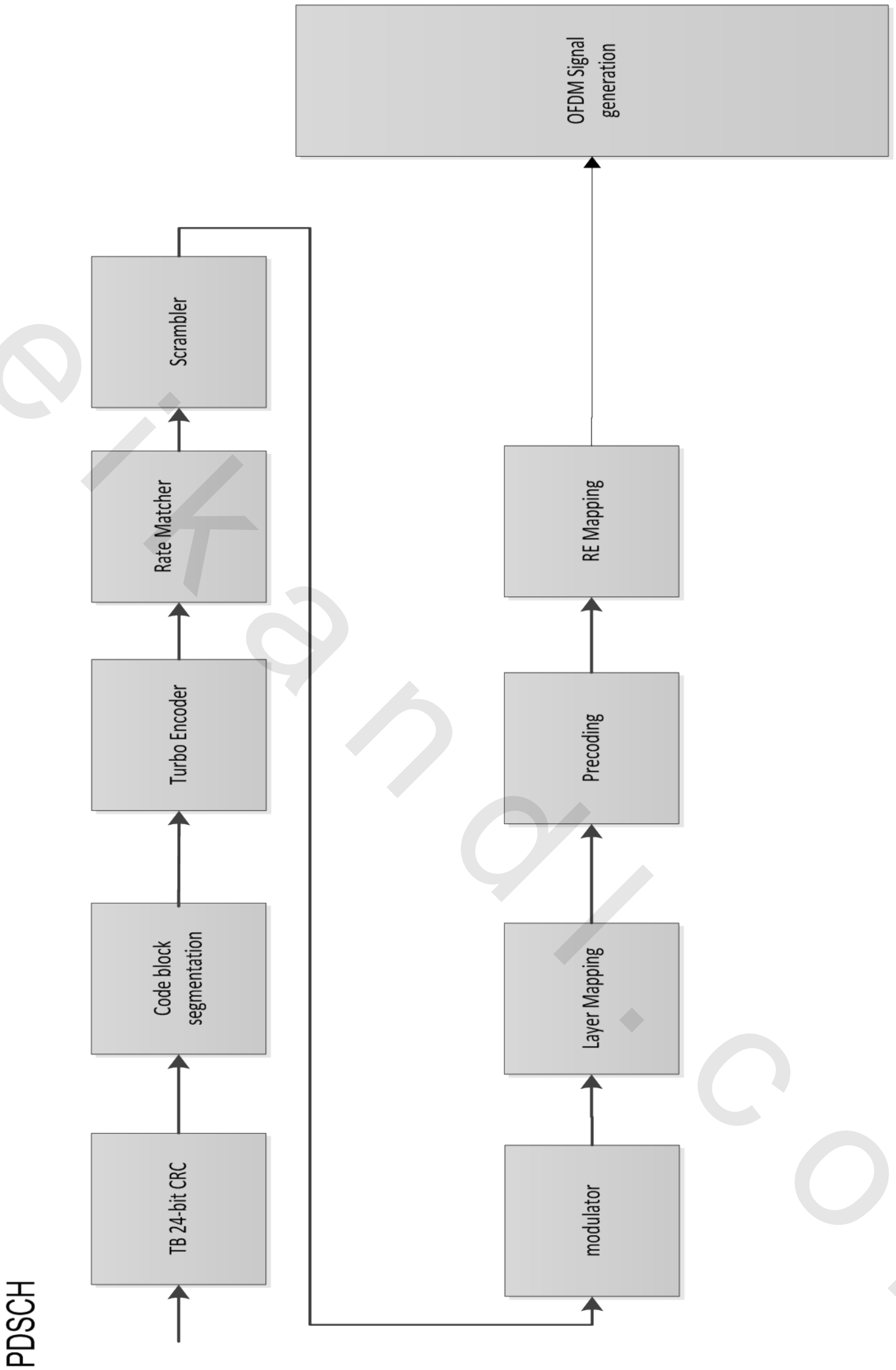

Figure 2.6 DLSCH block diagram