**LTE PHY Fundamentals**

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**DL Physical Channels**

- **DL-SCH:** The DownLink Shared CChannel is a channel used to transport down-link user data or Radio Resource Control (RRC) messages, as well as system information which are not transported via the Broadcast CChannel (BCH).

- **PBCH:** The Physical Broadcast CChannel carries the Master Information Block (MIB). It consists of a limited number of the most frequently transmitted parameters essential for initial access to the cell. The PBCH is designed for early detection by the UE, and cell-wide coverage.

- **PDSCH:** The Physical Downlink Shared CChannel is the main downlink data-bearing channel in LTE, used for all user data, as well as for broadcast system information which is not carried on the Physical Broadcast CChannel (PBCH). It is also used for paging messages.

- **PDCCH:** The Physical Downlink Control CChannel is a downlink control channel used to support efficient data transmission in LTE. A PDCCH carries a message known as Downlink Control Information (DCI), which includes transmission resource assignments and other control information for a UE or group of UEs. Many PDCCHs can be transmitted in a subframe.

- **PCFICH:** The Physical Control Format Indicator CChannel is a downlink physical channel that carries a Control Format Indicator (CFI) which indicates the number of OFDM symbols (i.e. normally 1, 2 or 3) used for transmission of downlink control channel information in each subframe.

- **PHICH:** The Physical Hybrid ARQ Indicator CChannel is a downlink physical channel that carries the Hybrid ARQ (HARQ) ACK/NACK information indicating whether the eNodeB has correctly received a transmission on the Physical Uplink Shared CChannel (PUSCH). Multiple PHICHs (for different UEs) are mapped to the same set of downlink resource elements. These constitute a PHICH group, where different PHICHs within the same PHICH group are separated through different complex orthogonal Walsh sequences.

**Design constraints**

The two basic principal physical parameters are the cyclic prefix length ($T_g$) and the sub-carrier spacing ($\Delta f$). There are several design constraints to select these two parameters, and the standard tries to find a trade-off with the optimal values holding the constraints.
First of all, Tu should be as larger than Tg as possible so the system has low overhead \((Tu >> Tg)\). It is important to keep in mind that Tu has to be sufficiently small to ensure that the channel does not vary within one OFDM symbol.

Tg has to be large enough to avoid Inter Symbol Interference (ISI). This is, Tg should be larger than the delay spread (Td) of the channel. LTE has different configurations depending on the type of channel through which the system is transmitting \((Tg > Td)\).

Finally, considering a mobile UE, there is going to be a deviation in frequency from the expected carrier frequency. This is due to the Doppler Effect. This deviation in frequency will have a maximum value of \(f_{\text{dmax}} = \frac{v}{\lambda_0}\), being \(\lambda_0\) the wavelength associated to the systems carrier frequency. Note that the Doppler Effect will be more noticeable at the further subcarriers from the DC component of the OFDM baseband system.

In order to attenuate the effects of Inter Carrier Interference (ICI), it is required that \(f_{\text{dmax}}/\Delta f << 1\). This implies that \(\Delta f\) has to be large enough to overcome ICI \((\Delta f >> f_{\text{dmax}})\).

Recall that \(Tu = 1/\Delta f\), so one has to find a trade-off between \(Tu/Tg\) and \(\Delta f\).

**Delay spread**

- **Urban environment (maximum delay spread of 15μs)**: Among the 3 possible configurations listed in the LTE standard, in this kind of environment the chosen parameters would be \(\Delta f = 15\text{KHz}\) and \(\text{CP} = 17\mu\text{s (Extended CP mode)}\). This value of \(\Delta f\) is the most common one and is determined in order to be able to serve users moving at a velocity of up to 500km/h. The chosen length of the cyclic prefix is enough to avoid ISI.
Indoor environment (maximum delay spread of 1μs): In this case, the chosen parameters would be $\Delta f = 15$KHz and $CP = 5$μs (Normal parametrization). Again, the chosen value of $\Delta f$ would be enough to cover speeds of up to 500km/h and a shorter CP is enough to avoid ISI with a delay spread of 1μs.

Mapping of reference signals

The cell-specific reference signals are pilot signals inserted into the downlink signal that are used by the UE to perform downlink channel estimation in order to perform coherent demodulation of the information-bearing parts of the downlink signal. These signals are modulated using QPSK to make them resilient to noise and errors and they carry one of the 504 different cell identities. They are also transmitted in a power boosted way (6dB more than surrounding data symbols) so they are easily detected, received and demodulated.

It can be shown that in an OFDM-based system an equidistant arrangement of reference symbols in the lattice structure achieves the minimum mean squared error estimate of the channel. Moreover, in the case of a uniform reference symbol grid, a ‘diamond shape’ in the time-frequency plane can be shown to be optimal.

The placing of these reference signals in the time-frequency lattice is constrained both in time and frequency.

Time domain requirements

The required spacing in the time domain between reference signals is forced by the Doppler Effect. The maximum Doppler frequency determines how fast the channel changes in time (coherence time $\tau_c \approx 1/f_{\text{dmax}}$). The LTE standard considers speeds of up to 500km/h. At a carrier frequency of 2GHz, this speed represents a maximum Doppler shift of $f_{\text{dmax}} \approx 950$Hz. Given Nyquist’s sampling theorem, the minimum sampling period required to reconstruct a channel with a Doppler shift of 950Hz is $T_{\text{min}} = 1/(2f_{\text{dmax}}) = 0.5$ms under the above assumptions. This implies that two reference symbols per slot are needed in the time domain in order to estimate the channel correctly.

Frequency domain requirements

The required spacing in the frequency domain between reference signals is forced by the Coherence Bandwidth of the channel. This bandwidth can be defined in different ways depending on the degree of decorrelation in percentage. For example, a 50% coherence bandwidth is defined as the separation in frequency such that the cross correlation between two frequency samples of the channel is 0.5.

The coherence bandwidth of the wireless channel is directly related to the Delay Spread ($\delta_\tau$) of the channel. The coherence bandwidth (50% and 90%) can be approximated as $B_{c,90\%} = 1/(50 \delta_\tau)$ and $B_{c,50\%} = 1/(5 \delta_\tau)$. The maximum r.m.s channel delay spread considered in the standard is 991 ns, corresponding to $B_{c,90\%} \approx 20$KHz and $B_{c,50\%} \approx 200$KHz.

In LTE the spacing between two reference symbols in frequency, in one RB, is 45 kHz, thus allowing the expected frequency domain variations of the channel to be resolved. Therefore, in the frequency direction there is one reference symbol every six subcarriers on each OFDM symbols which includes
reference symbol, but these are staggered so that within each Resource Block (RB) there is one reference symbol every 3 subcarriers.

**LTE FDD DL radio frame**

a) Radio frame structure (1.4MHz BW, 1 antenna port, CFI=2)

![LTE FDD DL radio frame diagram](image-url)

b) Overhead and peak rate throughput (64-QAM, 5.5547 bits per symbol)

**CFI=2**

Given the BW of 1.4MHz, there are only 6 RBs available. For CFI=2 the structure of the frame is the same as the one depicted in section (6.a). As can be seen above, there are 6x10=60 blocks of (1RB x 1 subframe), organized in 10 columns with 6 RB each one.

8 of the columns will be of the type a (shown above), 1 column of type a and 1 column of type c. Let’s compute the number of resource elements used for data and the ones used for control information per each time of column:
- **Column (a):** CFI + PBCH + reference + PSS/SSS= 2x12+6x12+4=100 control resource elements 12x14-100=68 data resource elements

- **Column (b):** CFI + reference + PSS/SSS= 2x12+2x12+6= 54 control resource elements 12x14-54=114 data resource elements

- **Column (c):** CFI + reference= 2x12+6=30 control resource elements 12x14-30=138 data resource elements

The **overhead** can be calculated as:

\[
\text{Total control} = (1 \times \text{column a}) \times (6 \times 100) + (1 \times \text{column b}) \times (6 \times 54) + (8 \times \text{columns c}) \times (6 \times 30) = 2364 \text{ resource elements}
\]

\[
\text{Total resource elements} = (6 \times 12) \times (10 \times 14) = 10080
\]

\[
\text{Overhead (CFI=2)} = 100 \times \left( \frac{2364}{10080} \right) = 23.45\%
\]

One information symbol can be allocated in each data resource element. The transmission is done by means of 64-QAM with an average of 5.5547 bits per symbol. The **peak rate throughput** is:

\[
\text{Total data} = (1 \times \text{column a}) \times (6 \times 68) + (1 \times \text{column b}) \times (6 \times 114) + (8 \times \text{columns c}) \times (6 \times 138) = 7716 \text{ resource elements}
\]

\[
\text{Peak rate} = \left( \frac{7716 \text{ symbols} \times 5.5547 \text{ bits/symbol}}{10\text{ms}} \right) = 4.28\text{Mbps}
\]

**CFI=3**

With CFI=3, the number of data and control resource elements in each column changes as follows:

- **Column (a):** CFI + PBCH + reference + PSS/SSS= 3x12+6x12+4=112 control resource elements 12x14-112= 56 data resource elements

- **Column (b):** CFI + reference + PSS/SSS= 3x12+2x12+6= 66 control resource elements 12x14-66=102 data resource elements

- **Column (c):** CFI + reference= 3x12+6=42 control resource elements 12x14-42=126 data resource elements

\[
\text{Total control} = 1 \times (6 \times 112) + 1 \times (6 \times 66) + 8 \times (6 \times 42) = 3084 \text{ resource elements}
\]

\[
\text{Total resource elements} = (6 \times 12) \times (10 \times 14) = 10080
\]

\[
\text{Overhead (CFI=2)} = 100 \times \left( \frac{3084}{10080} \right) = 30.59\%
\]

\[
\text{Total data} = (1 \times \text{column a}) \times (6 \times 56) + (1 \times \text{column b}) \times (6 \times 102) + (8 \times \text{columns c}) \times (6 \times 126) = 6996 \text{ resource elements}
\]

\[
\text{Peak rate} = \left( \frac{6996 \text{ symbols} \times 5.5547 \text{ bits/symbol}}{10\text{ms}} \right) = 3.89\text{Mbps}
\]
CFI=4

With CFI=4, the number of data and control resource elements in each column changes as follows:

- **Column (a):**  
  CFI + PBCH + reference + PSS/SSS = 4x12+6x12+4=124 control resource elements  
  12x14-124= 44 data resource elements

- **Column (b):**  
  CFI + reference + PSS/SSS= 4x12+2x12+6= 78 control resource elements  
  12x14-78= 90 data resource elements

- **Column (c):**  
  CFI + reference= 4x12+6=54 control resource elements  
  12x14-54= 114 data resource elements

Total control=1x(6x124)+1x(6x78)+8x(6x54)=3804 resource elements  
Total resource elements=(6x12)x(10x14)=10080

**Overhead (CFI=2)= 100 x (3804/10080)=37.74%**

Total data=(1 column a)x(6x44)+(1 column b)x(6x90)+(8 columns c)x(6x114)=6276 resource elements

**Peak rate= (6276 symbols x 5.5547 bits/symbol)/10ms= 3.48 Mbps**

So, the final results are as shown in the table:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CFI</th>
<th>Overhead [%]</th>
<th>Peak rate [Mbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>23.45</td>
<td>4.28</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>30.59</td>
<td>3.89</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>37.74</td>
<td>3.48</td>
</tr>
</tbody>
</table>
LTE FDD DL radio frame (BW=20MHz)

a) Radio frame structure (20MHz BW, 4 antenna ports, CFI=2)

Given 20MHz of available spectrum, there are 100 Resource Blocks available. Note that the 6 central ones contain PBCH, PSS/SSS, CFI and the reference signals (for a 4 antenna port configuration) while The remaining 94 RBs contain only CFI and the reference signals.

b) Overhead and peak rate throughput (64-QAM, 5.5547 bits per symbol)
CFI=1

Let's recalculate the amount of data and control block per each kind of subframe:

- **Column (a):**  
  CFI + PBCH + reference + PSS/SSS = 1x12+6x12+12=96 control resource elements  
  12x14-96= 72 data resource elements

- **Column (b):**  
  CFI + reference + PSS/SSS= 1x12+2x12+20= 56 control resource elements  
  12x14-64= 112 data resource elements

- **Column (c):**  
  CFI + reference= 1x12+20=32 control resource elements  
  12x14-40= 136 data resource elements

The **overhead** can be calculated as:

\[
\text{Total control} = (1 \text{ column a})x(6x96)+(1 \text{ column b})x(6x56)+(8 \text{ columns c})x(6x32) + \\
+ (94 \text{ columns c})x32=32528 \text{ resource elements} \\
\text{Total resource elements}=(100x12)x(10x14)=168000
\]

**Overhead (CFI=2)= 100 x (32528/168000)=19.36%**

One information symbol can be allocated in each data resource element. The transmission is done by means of 64-QAM with an average of 5.5547 bits per symbol. The **peak rate throughput** is:

\[
\text{Total data} = (1 \text{ column a})x(6x72)+(1 \text{ column b})x(6x112)+(8 \text{ columns c})x(6x136) + \\
+ (94 \text{ columns c})x136=135472 \text{ resource elements} \\
\text{Peak rate}= 4 \times (135472 \text{ symbols \times 5.5547 bits/symbol})/10\text{ms}= 301 \text{ Mbps}
\]

CFI=2

Let's recalculate the amount of data and control block per each kind of subframe:

- **Column (a):**  
  CFI + PBCH + reference + PSS/SSS = 2x12+6x12+8=104 control resource elements  
  12x14-104= 64 data resource elements

- **Column (b):**  
  CFI + reference + PSS/SSS = 2x12+2x12+16= 64 control resource elements  
  12x14-64= 104 data resource elements

- **Column (c):**  
  CFI + reference = 2x12+16=40 control resource elements  
  12x14-40= 128 data resource elements

The **overhead** can be calculated as:

\[
\text{Total control} = (1 \text{ column a})x(6x104)+(1 \text{ column b})x(6x64)+(8 \text{ columns c})x(6x40) + \\
+ (94 \text{ columns c})x40=40528 \text{ resource elements} \\
\text{Total resource elements}=(100x12)x(10x14)=168000
\]
One information symbol can be allocated in each data resource element. The transmission is done by means of 64-QAM with an average of 5.5547 bits per symbol. The peak rate throughput is:

$$\text{Total data=} \left(1 \text{ column a}\right) \times \left(6 \times 64\right) + \left(1 \text{ column b}\right) \times \left(6 \times 104\right) + \left(8 \text{ columns c}\right) \times \left(6 \times 128\right) + \left(94 \times 10 \text{ columns c}\right) \times 128 = 127472 \text{ resource elements}$$

$$\text{Peak rate=} \frac{4 \times (127472 \text{ symbols} \times 5.5547 \text{ bits/symbol})}{10 \text{ ms}} = 283.23 \text{ Mbps}$$

**CFI=3**

Let's recalculate the amount of data and control block per each kind of subframe:

- **Column (a):** CFI + PBCH + reference + PSS/SSS = 3x12+6x12+8=116 control resource elements
  
  12x14-116 = 52 data resource elements

- **Column (b):** CFI + reference + PSS/SSS = 3x12+2x12+16 = 76 control resource elements
  
  12x14-76 = 92 data resource elements

- **Column (c):** CFI + reference = 3x12+16 = 52 control resource elements
  
  12x14-52 = 116 data resource elements

The overhead can be calculated as:

$$\text{Total control=} \left(1 \text{ column a}\right) \times \left(6 \times 116\right) + \left(1 \text{ column b}\right) \times \left(6 \times 76\right) + \left(8 \text{ columns c}\right) \times \left(6 \times 52\right) + \left(94 \times 10 \text{ columns c}\right) \times 52 = 52528 \text{ resource elements}$$

$$\text{Total resource elements=} \left(100 \times 12\right) \times \left(10 \times 14\right) = 168000$$

$$\text{Overhead (CFI=2)=} \frac{100 \times (52528/168000)}{\text{=} 31.27\%}$$

One information symbol can be allocated in each data resource element. The transmission is done by means of 64-QAM with an average of 5.5547 bits per symbol. The peak rate throughput is:

$$\text{Total data=} \left(1 \text{ column a}\right) \times \left(6 \times 52\right) + \left(1 \text{ column b}\right) \times \left(6 \times 92\right) + \left(8 \text{ columns c}\right) \times \left(6 \times 116\right) + \left(94 \times 10 \text{ columns c}\right) \times 116 = 115472 \text{ resource elements}$$

$$\text{Peak rate=} \frac{4 \times (115472 \text{ symbols} \times 5.5547 \text{ bits/symbol})}{10 \text{ ms}} = 256.56 \text{ Mbps}$$

So, the final results are as shown in the table:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CFI</th>
<th>Overhead [%]</th>
<th>Peak rate [Mbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>19.36</td>
<td>301</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>24.12</td>
<td>283.23</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>31.27</td>
<td>256.56</td>
</tr>
</tbody>
</table>

We observe that, as stated in the standard, the peak bit-rate of LTE is about 300 Mbps.