# MODULE 4

# Uplink Transport Channel Processing

There are major differences between downlink and uplink in LTE, including different transmission and multiple access schemes, and different types of channel and control information, which result, in different physical layer processing. Low complexity and high power efficiency are among the major factors for the transmitter design in the uplink. As a result, the multiple access in the uplink is based on SC-FDMA due to its low peak-to-average power ratio (PAPR) compared to OFDMA, which subsequently has an impact on the resource allocation and baseband signal generation. Due to the SC-FDMA nature of the uplink, each UE can only be allocated contiguous resource blocks, unlike downlink where each UE can be allocated non-contiguous resource blocks in order to extract frequency diversity gain. In addition, the uplink only supports a limited number of MIMO modes compared to the downlink.

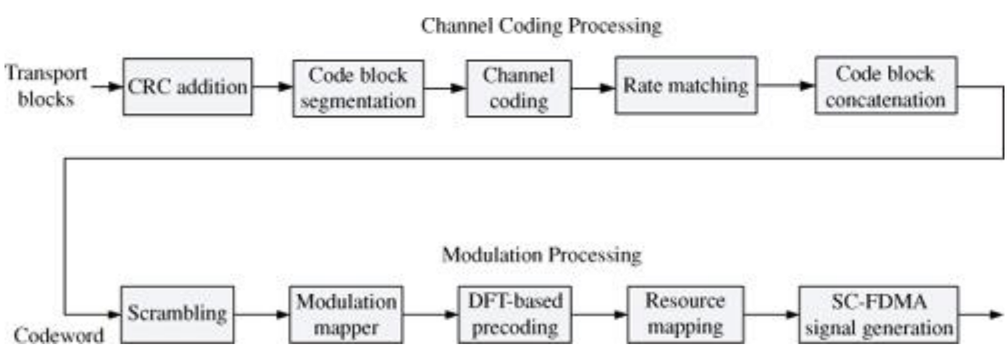
Nevertheless, there are similarities between the downlink and uplink transport channel processing. For example, the same channel coding processing is applied on both downlink and uplink shared channels and the time-frequency structure of the uplink resource blocks is similar to that of the downlink. There are also interactions between downlink and uplink transmissions. The downlink control information carries scheduling grants for the uplink transmission, while the uplink control information provides necessary information such as channel quality and channel rank for downlink scheduling and transport format selection.

In this chapter, we describe the physical layer processing of uplink transport channels and control information. First, an overview of the uplink transport channel processing is provided, highlighting the similarities and differences between the uplink and downlink processing. Then the channel processing of each individual uplink transport channel is described, including that of the control information and the reference signals. Finally, the H-ARQ protocol in the uplink is discussed.

# 8.1 UPLINK TRANSPORT CHANNEL PROCESSING OVERVIEW

The transport channel processing in the uplink is very similar to that of the downlink, which can be divided into two distinct steps, that is, channel coding and modulation, as shown in Figure 8.1. Since spatial multiplexing is not supported in the uplink, data streams from the MAC layer are presented to the encoding unit only one transport block every subframe. The codeword after encoding is passed to the symbol mapping unit where the bits are mapped onto complex valued symbols. Subsequently, the modulated symbols are processed to generate SC-FDMA signals and mapped onto the assigned resource blocks. In this section, we describe the general framework of channel processing, which is common to all uplink transport channels/control information. We will focus mostly on the specific features in the uplink that are different from that of the downlink. The features that are common between uplink and downlink can be found in Chapter 7.

**Figure 8.1** Overview of uplink transport channel processing.




## 8.1.1 Channel Coding Processing

The channel coding processing in the uplink is similar to that in the downlink, that is, it includes CRC addition, code block segmentation, channel coding, rate matching, and code block concatenation. The general channel coding processing was illustrated in Figure 7.2 in Chapter 7. The usage of the channel coding scheme and coding rate for the uplink shared channel and control information is specified in Table 8.1 and Table 8.2, respectively. The same turbo encoder used for downlink shared channels is also used for uplink shared channels. For control information, the channel coding scheme depends on the type of control information and also on the type of the physical channel that carries the control information. Unlike the downlink, the control information in the uplink can be mapped either to the Physical Uplink Shared Channel (PUSCH) or the Physical Uplink Control

Channel (PUCCH). Details about channel coding for control information in the uplink are discussed later in Section 8.3.1.

**Table 8.1** Usage of Channel Coding Scheme and Coding Rate for Uplink Transport Channels

| Transport Channel | Coding Scheme | Coding Rate |
|---|---|---|
| UL-SCH | Turbo coding | 1/3 |

**Table 8.2** Usage of Channel Coding Scheme and Coding Rate for Uplink Control Information

| Control Information | Coding Scheme | Coding Rate |
|---|---|---|
| UCI | Block coding | Variable |
| | Tail-biting convolutional coding | 1/3 |

## 8.1.2 Modulation Processing

For the modulation in the uplink, the various steps such as scrambling and modulation mapping are done in the same way as in the downlink. Unlike downlink, in uplink a UE-specific scrambling is applied in order to randomize the interference. Also, since spatial multiplexing is not supported in the uplink there is no layer mapping or MIMO precoding. The main difference from the downlink comes from the nature of the SC-FDMA-based transmission, which is different from the OFDMA-based transmission that is used in the downlink.

The generation of the SC-FDMA baseband signal is illustrated in Figure 8.2.

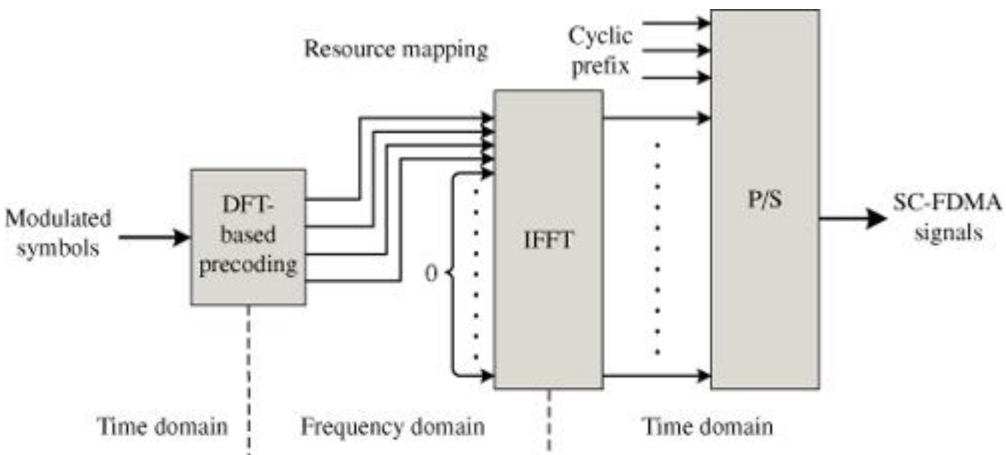
1. First, the DFT-based precoding is applied to the block of complex-valued modulation symbols, which transforms the time-domain signal into the frequency domain. In LTE, the DFT size is constrained to be products of the integers two, three, and five, which is a tradeoff between the complexity of the implementation and the flexibility on the assigned bandwidth. The DFT size also depends on the number of resource blocks assigned to the UE.
2. Then the output of the DFT-based precoder is mapped to the resource blocks that have been allocated for the transmission of the transport block. In LTE, only localized resource allocation is supported in the uplink, that is, contiguous resource blocks are assigned to each UE.
3. The baseband signal $s_l(t)$ in SC-FDMA symbol $l$ in an uplink slot is defined by:

(8.1)

$$s_l(t) = \sum_{k=-\lfloor N_{RB}^{UL} N_{sc}^{RB}/2 \rfloor}^{\lceil N_{RB}^{UL} N_{sc}^{RB}/2 \rceil - 1} a_{k^{(-)},l} \cdot e^{j2\pi(k+1/2)\Delta f(t - N_{CP,l} T_s)}$$

for $0 \le t < (N_{CP,l} + N) \times T_s$, where $k^{(-)} = k + \lfloor N_{RB}^{UL} N_{sc}^{RB}/2 \rfloor$, $N$ is the FFT size, $\Delta f$ = 15kHz, and $a_{k,l}$ is the content of resource element $(k, l)$. It is generated with an IFFT operation, after which the cyclic prefix (CP) is inserted. Different from the OFDM baseband signal in the downlink, the DC SC-FDMA subcarrier is used in the uplink. Direction conversion will introduce distortion in the DC subcarrier, and in LTE uplink all the subcarriers are shifted by half a subcarrier spacing to reduce this influence. The operation combining DFT-based precoding and IFFT applies to all uplink physical signals and physical channels except the physical random access channel.

**Figure 8.2** Generation of SC-FDMA baseband signals, where P/S denotes the parallel-to-serial converter.

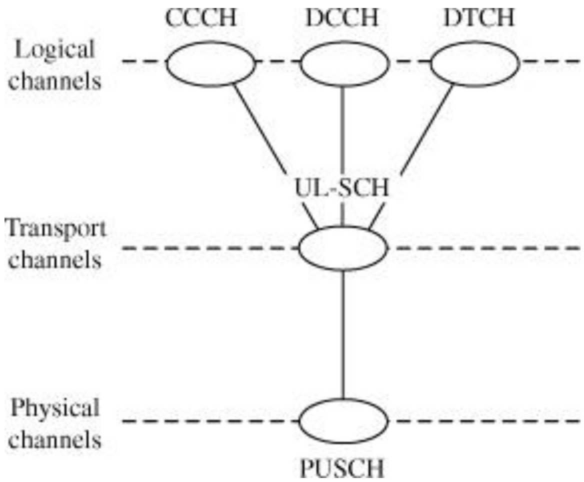



Note that the generation of the SC-FDMA signal shares the similar structure as that for the OFDMA signal, with an additional DFT operation.

## 8.2 UPLINK SHARED CHANNELS

In this section, we describe the transport channel processing for Uplink Shared Channels (UL-SCH). In the uplink, the UL-SCH is the only transport channel that carries traffic data. As mentioned previously it can also be used to transfer control signals for higher layers. The channel mapping around the UL-SCH is shown in Figure 8.3.

**Figure 8.3** Channel mapping around the uplink shared channel.




## 8.2.1 Channel Encoding and Modulation

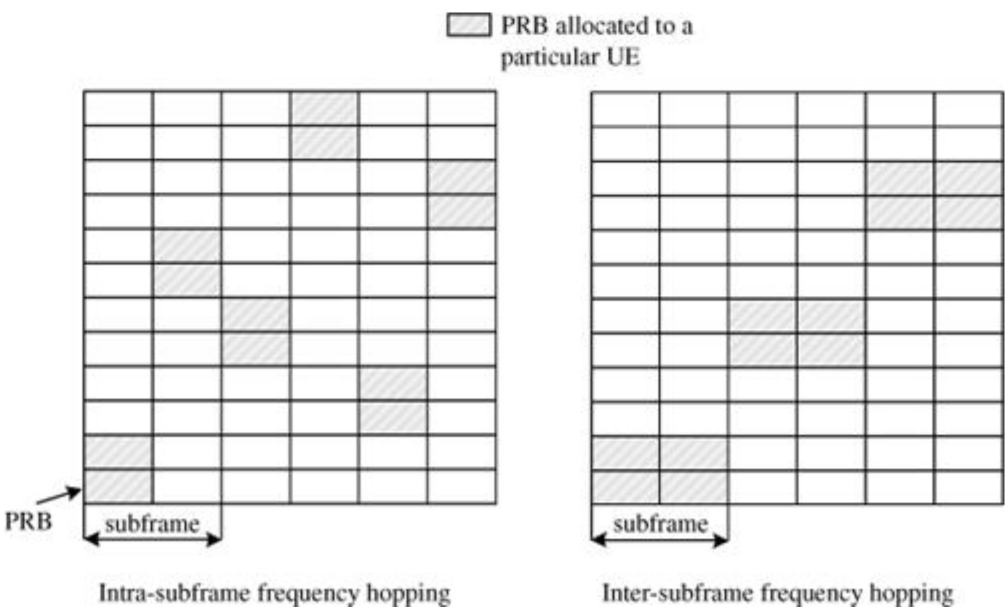
The channel coding scheme for data streams on the UL-SCH is the same as that for the DL-SCH. A rate 1/3 turbo encoder is used to encode the transport block. Effective code rates other than 1/3 are achieved by either puncturing or repetition of the encoded bits, depending on the transport block size, the modulation scheme, and the assigned radio resource. The encoded symbols are scrambled prior to modulation, which is done to randomize the interference. Instead of using a cell-specific scrambling as in the downlink, a UE-specific scrambling is applied in the uplink. The UL-SCH is mapped to the PUSCH, which supports QPSK, 16QAM, and 64QAM modulation schemes. The QPSK and 16QAM modulation schemes are mandatory and support for the 64QAM modulation is optional and depends on the UE capability. The modulation order and the redundancy version for the channel coding of the H-ARQ protocol are contained in the 5-bit "modulation and coding scheme and redundancy version" field ($I_{MCS}$) in the downlink control information (DCI) carried on the PDCCH with format 0.

## 8.2.2 Frequency Hopping

The resource mapper maps the complex-valued modulation symbols in sequence on to the physical resource blocks assigned for transmission of PUSCH. In LTE, only localized resource allocation is supported in the uplink due to its robustness to frequency offset compared to distributed resource allocation. Localized resource allocation also retains the single-carrier property in the uplink transmission. As a consequence, there is very little frequency diversity gain. On the contrary, in the downlink it is possible to allocate disjoint sets of resource blocks to a UE to extract some frequency diversity gain. To alleviate this issue, LTE supports frequency hopping on PUSCH, which provides additional frequency diversity gain in the uplink. Frequency hopping can also provide interference averaging when the system is not 100% loaded.

In LTE both *intra-subframe* and *inter-subframe* frequency hopping are supported, as illustrated in Figure 8.4. In intra-subframe hopping, the UE hops to another frequency allocation from one slot to another within the same subframe; in inter-subframe hopping, the frequency resource allocation changes from one subframe to another. Higher layers determine if the hopping is “inter-subframe” or “intra- and inter-subframe.” In general, “intra-subframe” hopping provides higher frequency diversity gain since this gain can be extracted over a single H-ARQ transmission, which always spans only one subframe. In the case of “inter-subframe” hopping, multiple H-ARQ transmissions are needed in order to extract the frequency diversity gain.

**Figure 8.4** Illustrations of frequency hopping on PUSCH.




If the single bit Frequency Hopping (FH) field in the corresponding PDCCH with DCI format 0 is set to 1, the UE shall perform PUSCH frequency hopping; otherwise, no PUSCH frequency hopping is performed.

• **No frequency hopping** If uplink frequency hopping is disabled (FH = 0), the set of physical resource blocks to be used for transmission is given by $n_{PRB} = n_{V\ RB}$, where $n_{V\ RB}$ is the virtual resource block index obtained from the uplink scheduling grant.

• **Frequency hopping** If uplink frequency hopping is enabled (FH = 1), there are two frequency hopping types. *Type 1 hopping* uses an explicit offset in the second slot, determined by parameters in DCI format 0. In *Type 2 hopping*, the set of physical resource blocks to be used for transmission is given by the scheduling grant together with a predefined hopping pattern.

The UE first determines the allocated resource blocks after applying all the frequency hopping rules, and then the data is mapped onto these resources.

## 8.2.3 Multiantenna Transmission

As discussed in Chapter 6, considering cost and complexity of the UE, LTE only supports a limited number of multiantenna transmission schemes in the uplink: a) transmit antenna selection and b) multiuser MIMO (MU-MIMO).

### Transmit Antenna Selection

With two or more transmit antennas at the UE, transmit antenna selection can be applied, which is able to provide spatial diversity gain. The multiantenna transmission at the UE depends on the signaling from higher layers.

• **No antenna selection** If transmit antenna selection is disabled or not supported by the UE, the UE shall transmit from antenna port 0.

• **Closed-loop (CL) antenna selection** If CL UE transmit antenna selection is enabled by higher layers, the UE shall perform transmit antenna selection in response to commands received via DCI format 0 from the eNode-B. The DCI format 0 is scrambled with the antenna selection mask as shown in Table 7.12 in Chapter 7, which enables the UE to determine which antenna port to select.

• **Open-loop (OL) antenna selection** If OL UE transmit antenna selection is enabled by higher layers, the transmit antenna to be selected by the UE is not specified. Although in this mode there is no closed-loop feedback from the eNode-B, the UE can determine the optimum antenna based on H-ARQ ACK/NAK feedbacks. The UE can transmit from antenna 0 for some time instance and then switch to antenna 1 for a next time instance. During both of these time instances, the UE also monitors the H-ARQ ACK/NAK ratio. If the ACK/NAK ratio in the time instance when antenna 0 was used is less than the ACK/NAK ratio for the time instance when antenna 1 was used, then clearly antenna 1 is a better choice and vice versa.

### MU-MIMO in Uplink

MU-MIMO is supported in the uplink, which is also referred to as “virtual” MIMO transmission. Two UEs transmit simultaneously on the same radio resource, forming a virtual MIMO channel, and the eNode-B separates the data streams for each UE, for example, using multiuser detection. This transmission mode provides a spatial multiplexing gain to increase the uplink spectrum efficiency, even with single-antenna UEs.

The MU-MIMO mode mainly affects the operation at eNode-B, as the Channel Quality Indicator (CQI) calculation and the scheduling process will change due to the interaction between data streams for different UEs. As the eNode-B can estimate the channel information from the uplink reference signal, it is capable of performing CQI calculation and scheduling without further feedback from UEs, which makes it easier to implement MU-MIMO in the uplink than in the downlink. For the eNode-B to differentiate and demodulate signals from the two UEs, orthogonal reference signals are assigned for each of them, which is discussed in Section 8.4.

## 8.3 UPLINK CONTROL INFORMATION

The Uplink Control Information (UCI) is to assist physical layer procedures by providing the following types of physical layer control information:

• Downlink CQI, which is used to assist the adaptive modulation and coding and the channel-dependent scheduling of the downlink transmission. The CQI indicates the highest modulation and coding rate that can be supported in the downlink with a 10% block error rate on the first H-ARQ transmission.

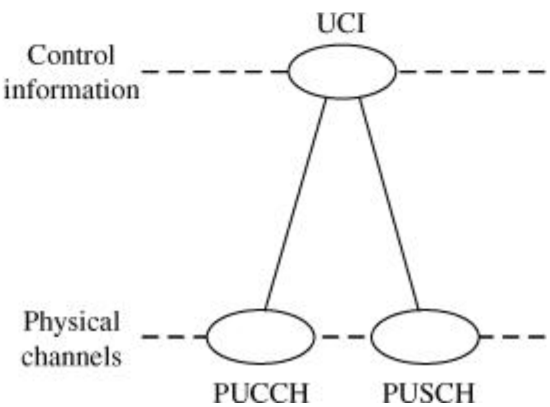
• H-ARQ acknowledgment (H-ARQ-ACK) associated with the downlink H-ARQ process.

• Scheduling Request (SR) to request radio resources for the uplink transmission.

• Precoding Matrix Indicator (PMI) and Rank Indication (RI) for downlink MIMO transmission. RI indicates the maximum number of layers that can be used for spatial multiplexing in the downlink, while PMI indicates the preferred precoding matrix.

The channel mapping for control information in the uplink is shown in Figure 8.5. Unlike the downlink, which has three different physical control channels, there is only one physical control channel defined for the UCI—the PUCCH. The UCI can also be mapped onto PUSCH when the UE has been assigned uplink radio resources. When this happens, the UCI is frequency-multiplexed with the UL-SCH data on the PUSCH unless the PUSCH carries a random access response grant or a retransmission as part of the contention-based random access procedure. When the UE does not have uplink allocation on the PUSCH, the UCI is transmitted on the PUCCH in the specifically assigned radio resource. In this section, we first describe the channel coding processing for the UCI, which depends on whether it is transmitted on PUCCH or PUSCH, and then modulation and resource mapping for the UCI are discussed. The physical layer procedures related to the UCI transmission such as the CQI and PMI/RI feedback are discussed in Chapter 9.

**Figure 8.5** Channel mapping for control information in the uplink.




## 8.3.1 Channel Coding for Uplink Control Information

As mentioned previously, the UCI can be transmitted on PUCCH, or on PUSCH if there is uplink assignment. The channel coding for UCI therefore depends on whether it is carried on the PUCCH or PUSCH. In addition, different types of control information are encoded differently, which allows individual adjustments of transmission energy using different coding rates.

**UCI on PUCCH**

When the UCI is transmitted on the PUCCH, three channel coding scenarios are considered: 1) the UCI contains CQI/PMI but not H-ARQ-ACK, 2) the UCI contains H-ARQ-ACK and/or SR but not CQI/PMI, and 3) the UCI contains both CQI/PMI and H-ARQ-ACK. The channel coding processing for each of these scenarios is described in the following:

• **Encoding CQI/PMI** The CQI/PMI is encoded using a (20, $N_{CQI}$) code, with codewords being a linear combination of the 13 basis sequences that are defined in Table 8.3, and $N_{CQI}$ is the number of CQI and PMI bits, which is discussed in Section 9.2. Denote $a_i$, $i$ = 1, ..., $N_{CQI}$ as the input channel quality bits, and the encoding is performed as:

(8.2)

$$b_i = \sum_{n=0}^{N_{CQI}} (a_n \cdot M_{i,n}) \bmod 2, \; i = 0, 1, \ldots, 19.$$

**Table 8.3** Basis Sequences for (20, *N*) Code

| $i$ | $M_{i,0}$ | $M_{i,1}$ | $M_{i,2}$ | $M_{i,3}$ | $M_{i,4}$ | $M_{i,5}$ | $M_{i,6}$ | $M_{i,7}$ | $M_{i,8}$ | $M_{i,9}$ | $M_{i,10}$ | $M_{i,11}$ | $M_{i,12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| 2 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |
| 3 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| 4 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 |
| 5 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 6 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |
| 7 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 |
| 8 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 |
| 9 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 |
| 10 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 11 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 |
| 12 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| 13 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 |
| 14 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |
| 15 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 16 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |
| 17 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |
| 18 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 19 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

• **Encoding H-ARQ-ACK and SR** The H-ARQ-ACK bits and SR indication are received from higher layers. Each positive acknowledgement (ACK) is encoded as a binary '1' while each negative acknowledgment (NAK) is encoded as a binary '0'. There is one H-ARQ-ACK bit for single-codeword transmission and two H-ARQ-ACK bits for two-codeword transmission (spatial multiplexing).

• **Encoding CQI/PMI + H-ARQ-ACK** When CQI/PMI and H-ARQ-ACK are transmitted in the same subframe, the following coding scheme is used:

– With the normal CP, the CQI/PMI is encoded using the (20, $N_{CQI}$) code as in (8.2), and then the H-ARQ-ACK bits are added at the end of the resulting codeword.

– With the extended CP, the CQI/PMI and H-ARQ-ACK are jointly encoded using the same (20, $N$) code as that for encoding CQI/PMI alone, with $N$ as the sum of CQI/PMI bits and H-ARQ-ACK bits.

Based on different types of control information carried on the PUCCH, there are six different PUCCH formats defined in LTE, as shown in Table 8.4. The parameter $M_{bit}$ is the number of encoded bits for each PUCCH format, which can be easily inferred from the channel coding scheme discussed above. For example, if the UCI carries CQI/PMI only, or carries CQI/PMI and H-ARQ-ACK with the extended CP, the (20, $N_{CQI}$) encoder is applied, so there are 20 coded bits, corresponding to PUCCH format 2. The SR is carried by the presence/absence of transmission of PUCCH from the UE, so there are no extra bits.

**Table 8.4** Supported PUCCH Formats

| PUCCH Format | Contents | $M_{bit}$ |
|---|---|---|
| 1 | Scheduling Request (SR) | N/A |
| 1a | H-ARQ-ACK, H-ARQ-ACK+SR | 1 |
| 1b | H-ARQ-ACK, H-ARQ-ACK+SR | 2 |
| 2 | CQI/PMI or RI, (CQI/PMI or RI)+H-ARQ-ACK (extended CP) | 20 |
| 2a | (CQI/PMI or RI)+H-ARQ-ACK (normal CP) | 21 |
| 2b | (CQI/PMI or RI)+H-ARQ-ACK (normal CP) | 22 |

**UCI on PUSCH with UL-SCH Data**

If there is uplink radio resource assigned to the UE, the UCI can be multiplexed with the UL-SCH data on the PUSCH channel and there is no need to send SR. In this case, the channel coding for H-ARQ-ACK, RI, and CQI/PMI is done independently. Different coding rates can be achieved by allocating different numbers of coded symbols, depending on the amount of allocated radio resource.

*Coding for H-ARQ-ACK*

For the FDD mode, there is one or two H-ARQ-ACK bits. For the TDD mode, two ACK/NAK feedback modes are supported,[1] with different information bits:

• ACK/NAK bundling, which consists of one or two bits of information

• ACK/NAK multiplexing, which consists of between one and four bits of information

Denote $N_{HARQ}$ as the number of H-ARQ-ACK bits. For $N_{HARQ} = 1$ or 2, the H-ARQ-ACK bits are first encoded into a $N_{HARQ}Q_m$-bit codeword, with the encoding specified in [2], where $Q_m$ is the modulation order and is equal to 2 for QPSK, 4 for 16QAM, and 6 for 64QAM.

• For both FDD and TDD ACK/NAK multiplexing with $N_{HARQ} \leq 2$, the output sequence from the channel encoder is obtained by concatenating multiple encoded H-ARQ-ACK blocks.

• For TDD with ACK/NAK bundling, the output sequence from the channel encoder is obtained by scrambling the concatenation of multiple encoded H-ARQ-ACK blocks with a specified scrambling sequence.

• For TDD with ACK/NAK multiplexing with $N_{HARQ} > 2$, the H-ARQ-ACK bits are encoded using a linear combination of a set of basis sequences.

*Coding for RI*

The mapping between the RI bits and the channel rank is shown in Table 8.5. Denote $N_{RI}$ as the number of RI bits. Similar to H-ARQ-ACK, the $N_{RI}$-bit RI is first encoded into an $N_{RI}Q_m$ codeword, and then multiple encoded RI blocks are concatenated to form a bit sequence.

**Table 8.5** RI Mapping

| RI Bits | Channel Rank |
|---|---|
| 0 | 1 |
| 1 | 2 |
| 0, 0 | 1 |
| 0, 1 | 2 |
| 1, 0 | 3 |
| 1, 1 | 4 |

*Coding for CQI/PMI*

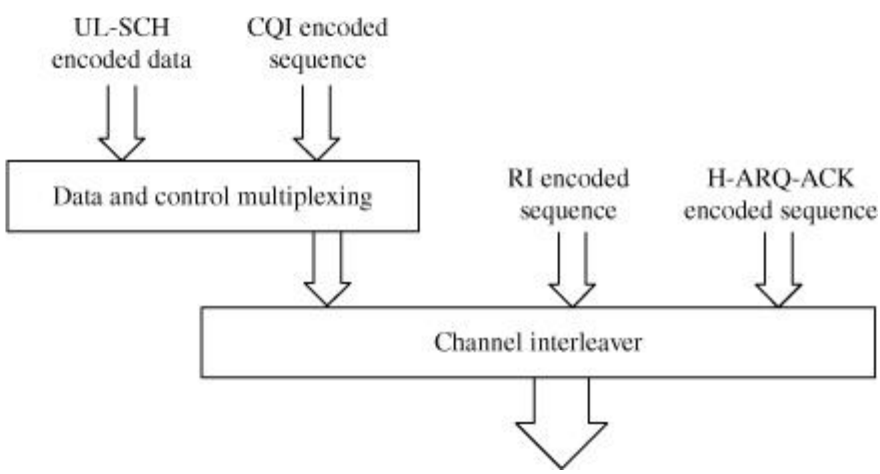
The coding scheme for CQI/PMI depends on the total number of CQI and PMI bits.

• If the payload size $N_{CQI}$ is less than or equal to 11 bits, the CQI/PMI bits are first encoded using a (32, $N_{CQI}$) block code, with the codewords as a linear combination of 11 length-32 basis sequences given in [2]. The 11 basis sequences allow encoding a maximum of 11 CQI/PMI bits. The encoded CQI/PMI block is $b_0$, $b_1$, ..., $b_{31}$, and then the output bit sequence $q_0$, $q_1$, ..., $q_Q$ is obtained by circular repetition of the encoded block as $q_i = b_{(i \bmod 32)}$, where $i = 1, 2, ..., Q$. The length of the output sequence ($Q$) depends on the assigned radio resource for PUSCH.

• If $N_{CQI} > 11$, first a CRC is added, and then the tail-biting convolutional code with rate 1/3 described in Section 7.1.1 is used as the coding scheme.

After channel encoding, the CQI encoded sequence is multiplexed with the UL-SCH data, the output of which is interleaved with the RI and H-ARQ-ACK encoded sequence as depicted in Figure 8.6. The multiplexing ensures that control and data information bits are mapped to different modulation symbols. The channel interleaving, together with resource mapping, is to ensure that H-ARQ-ACK information is present on both slots in a subframe and is mapped to the radio resource around the uplink demodulation reference signals. It is done in this way since the H-ARQ ACK/NAK bits are not transmitted with much protection and placing them close to the reference signal ensures that they are decoded properly at the eNode-B.

**Figure 8.6** Multiplexing of data and control information on the PUSCH channel.




*UCI on PUSCH Without UL-SCH Data*

For this case, the channel coding for CQI, RI, and H-ARQ-ACK information is performed in the same manner as if the UCI is transmitted with UL-SCH data, and then the coded sequences are interleaved. The same interleaver as in Figure 8.6 is applied without the UL-SCH data.

## 8.3.2 Modulation of PUCCH

When the UCI is transmitted on the PUSCH, the modulation scheme is determined by the scheduler in the MAC layer. In this subsection, we focus on the scenario when the UCI is transmitted on the PUCCH, that is, no uplink resource is assigned to the UE. The modulation scheme and the number of bits per subframe for different PUCCH formats are specified in Table 8.6. All PUCCH formats use a cyclic shift of a based sequence to transmit in each SC-FDMA symbol, so UCI from multiple UEs can be transmitted on the same radio resource through code division multiplexing (CDM).

**Table 8.6** Modulation for Different PUCCH Formats

| PUCCH Format | Modulation Scheme | $M_{bit}$ |
|---|---|---|
| 1 | N/A | N/A |
| 1a | BPSK | 1 |
| 1b | QPSK | 2 |
| 2 | QPSK | 20 |
| 2a | QPSK+BPSK | 21 |
| 2b | QPSK+QPSK | 22 |

**PUCCH Formats 1, 1a, and 1b**

The PUCCH formats 1a and 1b are used to transmit H-ARQ-ACK and/or SR, without CQI bits. When both ACK/NAK and SR are transmitted in the same subframe, a UE shall transmit the ACK/NAK on its assigned ACK/NAK PUCCH resource for a negative SR transmission and transmit the ACK/NAK on its assigned SR PUCCH resource for a positive SR transmission. As shown in Table 8.4, one or two explicit bits are transmitted, respectively, the modulation for which is described in Table 8.7, resulting in a complex-valued symbol $d(0)$. For PUCCH format 1, the SR information is carried by the presence/absence of transmission of the PUCCH from the UE, that is, the on-off keying is applied. When there is an SR, $d(0) = 1$.

**Table 8.7** Modulation Symbol $d(0)$ for PUCCH Formats 1*a* and 1*b*

| PUCCH Format | $b(0),b(M_{bit}-1)$ | $d(0)$ |
|---|---|---|
| 1a | 0 | 1 |
| | 1 | −1 |
| 1b | 00 | 1 |
| | 01 | −j |
| | 10 | j |
| | 11 | −1 |

Then $d(0)$ is multiplied with a cyclically shifted sequence with length 12, corresponding to 12 subcarriers in each uplink radio resource block. The Zadoff-

Chu sequence[2] is used as the base sequence. This achieves frequency-domain CDM and the cyclic shift varies between symbols and slots within a subframe to randomize inter-cell interference. The resulting symbol block is scrambled and block-wise spread with an orthogonal sequence in the time domain, where the sequence length depends on the number of symbols available for transmission in each slot. In this way, multiple UEs' PUCCHs are multiplexed on the same time-frequency resource using frequency-domain and time-domain CDM.

**PUCCH Formats 2, 2a, and 2b**

As specified in Table 8.4, in each subframe the number of bits for format 2, 2a, or 2b is $M_{bit} \geq 20$. The block of the first 20 bits, $b(0), ..., b(19)$, shall be scrambled with a UE-specific scrambling sequence, producing a block of scrambled bits $\tilde{b}(0), \ldots, \tilde{b}(19)$. Then the scrambled bits will be QPSK modulated, resulting in a block of complex-valued modulation symbols $d(0), ..., d(9)$. Similar to formats 1, 1a, and 1b, each of these complex-valued symbols is multiplied with a length-12 cyclically shifted version of a Zadoff-Chu sequence. This allows PUCCHs from multiple UEs to be transmitted on the same resource block with CDM.

For PUCCH formats 2a and 2b that apply only for normal CP, the extra bits $b(20)$, $b(M_{bit} - 1)$ represent ACK/NAK information. The modulation of these H-ARQ-ACK bits are described in Table 8.8. The resulting modulated symbol $d(10)$ will be used in the generation of the reference signal for PUCCH format 2a and 2b, from which the eNode-B can decode the ACK/NAK information.

**Table 8.8** Modulation symbol $d(10)$ for PUCCH formats 2*a* and 2*b*

| PUCCH Format | $b(20), b(M_{bit}-1)$ | $d(10)$ |
|---|---|---|
| 2a | 0 | 1 |
| | 1 | −1 |
| 2b | 00 | 1 |
| | 01 | −j |
| | 10 | j |
| | 11 | −1 |

## 8.3.3 Resource Mapping

The PUCCH is never transmitted simultaneously with the PUSCH from the same UE, that is, the PUCCH is time-division multiplexed with the PUSCH from the same UE. This is done in order to retain the single-carrier property of SC-FDMA.

However, the PUCCH can be frequency-division multiplexed with the PUSCH from other UEs in the same subframe. For frame structure type 2 (the TDD mode), the PUCCH is not transmitted in the UpPTS field, which is only for the transmission of uplink sounding reference signals or random access. If the UE has not been assigned any uplink resource for the UL-SCH transmission, a certain set of uplink resources are assigned for the transmission of the PUCCH. The PUCCH uses one resource block in each of the two slots in a subframe.

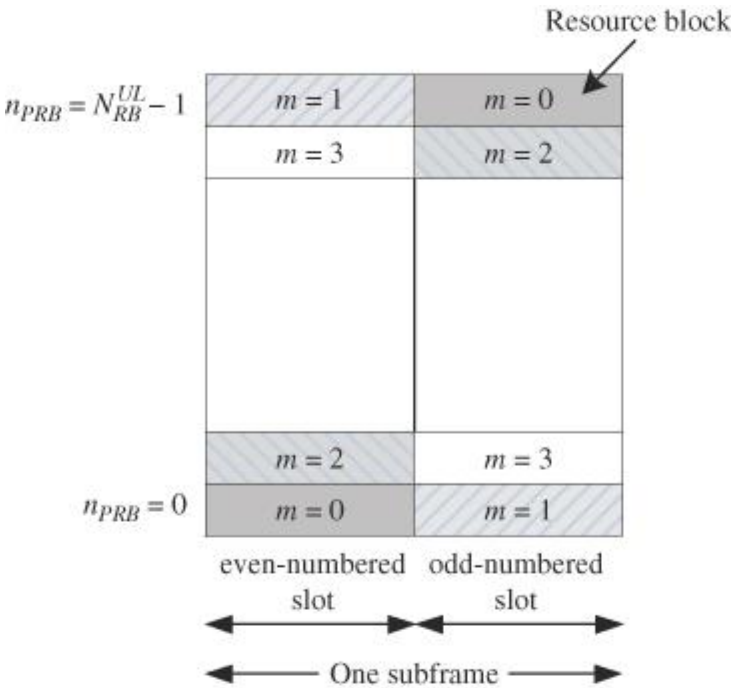
The physical resource blocks to be used for PUCCH transmission in slot $n_s$ are given by:

(8.3)

$$n_{PRB} = \begin{cases} \lfloor \frac{m}{2} \rfloor & \text{if } (m + n_s \bmod 2) \bmod 2 = 0 \\ N_{RB}^{UL} - 1 - \lfloor \frac{m}{2} \rfloor & \text{if } (m + n_s \bmod 2) \bmod 2 = 1 \end{cases}$$

where the parameter *m* depends on the PUCCH format. According to this rule, the mapping of PUCCH to physical resource blocks in one subframe is shown in Figure 8.7 for different values of *m*. We see that the PUCCH is transmitted at the bandwidth edge, which is to provide the contiguous bandwidth in the middle for data transmission as only localized resource allocation is allowed in the uplink. In addition, the frequency hopping between different slots provides frequency diversity. The PUCCH symbols are mapped to resource elements not used for reference signal transmission. The resource mapping of PUCCH symbols within each slot, together with reference symbols, is discussed in Section 8.4.2.

**Figure 8.7** Mapping to physical resource blocks for PUCCH.




## 8.4 UPLINK REFERENCE SIGNALS

In LTE there are two types of reference signals defined in the uplink:

• **Demodulation reference signals,** which are transmitted on uplink resources assigned to the UE, are for coherent demodulation of data and control information at the eNode-B. As PUCCH cannot be transmitted simultaneously with PUSCH, there are demodulation reference signals defined for each of them, that is, there are demodulation reference signals for PUSCH and demodulation reference signals for PUCCH.

• **Sounding reference signals** are wideband reference signals for the eNode-B to measure uplink channel quality information for uplink resource allocation. They are not associated with the transmission of PUSCH or PUCCH.

The reason for having two types of reference signals in the uplink is because, unlike the downlink, the demodulation reference signals in uplink are only transmitted on subcarriers assigned to the UE and therefore cannot provide sufficient wideband channel quality information for resource allocation, particularly over the resource blocks that are not allocated to the UE. Unlike the downlink, the reference signal in the uplink cannot be transmitted at the same time as user data. Instead, the uplink reference signals are time-division multiplexed with the uplink data on the assigned subcarriers. In this way, the power level of the reference signal can be different from that of the data symbol as they are transmitted over different SC-FDMA symbols, so the PAPR is minimized over each SC-FDMA symbol.

### 8.4.1 Reference Signal Sequence

Both the demodulation reference signal and the sounding reference signal are defined by a cyclic shift of the same base sequence. The generation of the base sequence depends on the reference signal sequence length, which is $M_{sc}^{RS} = mN_{sc}^{RB}$ with $1 \leq m \leq N_{RB}^{max,UL}$, where *m* is the size of the resource blocks assigned to the UE.

• If $m \geq 3$ (the UE is assigned three resource blocks or more), the base sequence is based on prime-length Zadoff-Chu sequences that are cyclically extended to the desired length.

• For $m = 1$ or $m = 2$, the base sequence is of the form $e^{j\varphi(n)\pi/4}$, where $0 \leq n \leq M_{sc}^{RS} - 1$ and the value of $\varphi(n)$ is given in [1].

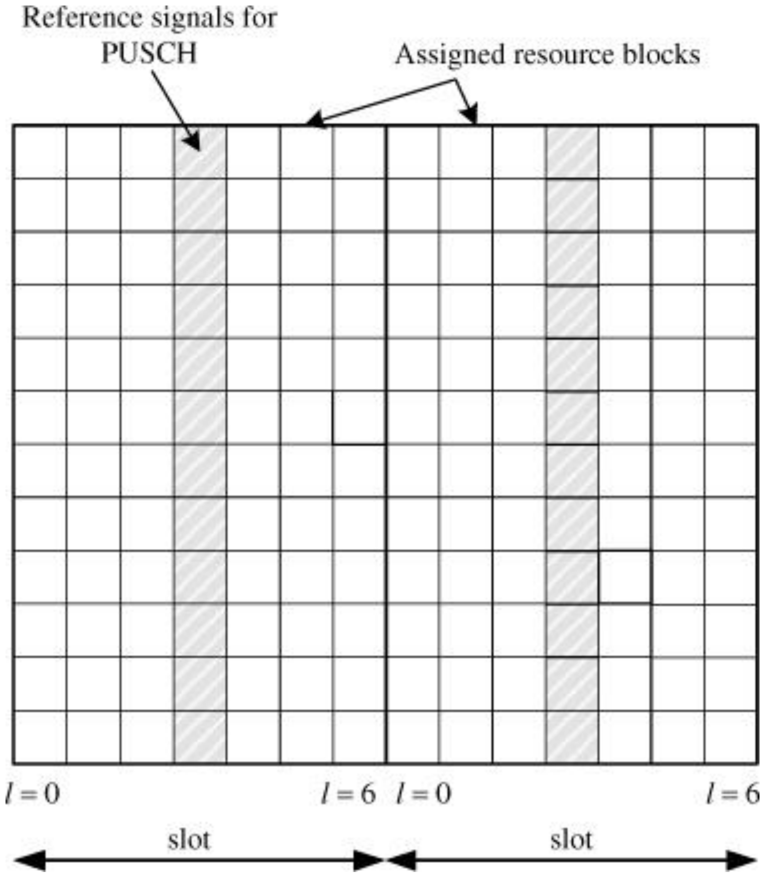
Multiple reference signals can then be created by different shifts of the same base sequence. As the Zadoff-Chu sequence has the property that cyclic shifted versions of the same sequence are orthogonal to each other, generating reference signals in such a manner can reduce inter-cell interference for the reference signal transmission. The orthogonality of reference signals within the same cell is obtained via frequency-domain multiplexing, as the reference signals for each UE are only carried in resource blocks assigned to that UE. The reference signal in the uplink is always UE-specific.

### 8.4.2 Resource Mapping of Demodulation Reference Signals

The resource mapping of the demodulation reference signal is different for PUSCH and PUCCH channels. In addition, different from the downlink, the reference signals are inserted in the time domain, which is to preserve the low PAPR property of SC-FDMA.

For PUSCH, the demodulation reference signal sequence is mapped to resource elements $(k, l)$ with $l = 3$ for normal CP and $l = 2$ for extended CP, with increasing order first in *k* and then in the slot number. An example of demodulation reference signal mapping for PUSCH is shown in Figure 8.8, with the normal CP.

**Figure 8.8** Resource mapping of demodulation reference signals for PUSCH with the normal CP.

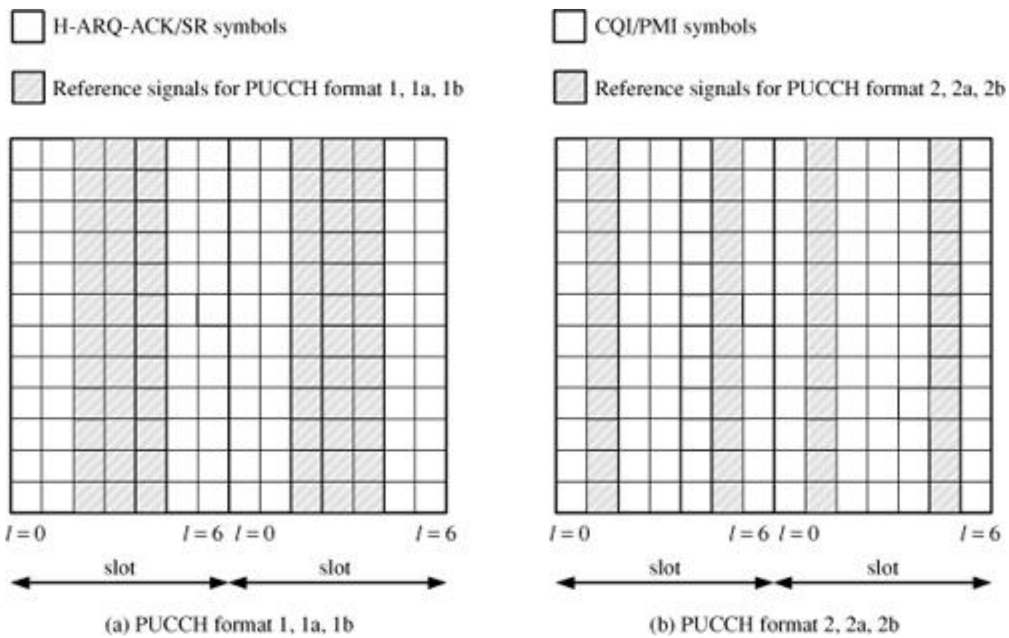



As shown in Section 8.3, PUCCH supports six different formats, and the resource mapping to SC-FDMA symbols for different formats is listed in Table 8.9. Note that the number of PUCCH demodulation reference symbols are different for different formats, which is related to the number of control symbols for each format. For example, as discussed in Section 8.3.2, there are 10 CQI/PMI modulated symbols for PUCCH format 2/2a/2b, and there are 2 reference symbols in each slot as shown in Table 8.9, so there are a total of 14 symbols that fill the whole subframe, which is of 14 SC-FDMA symbols. As PUCCH format 1/1a/1b has fewer information bits than PUCCH format 2/2a/2b, there are more reference symbols for format 1/1a/1b than there are for format 2/2a/2b, which can be used to improve the channel estimation performance. The resource mapping of PUCCH demodulation reference signals, together with PUCCH symbols, which are modulated as in Section 8.3.2, is shown in Figure 8.9 with the normal CP. Note that due to the resource mapping of PUCCH, the two consecutive slots shown in Figure 8.9(a) and 8.9(b) are at the two edges of the whole bandwidth, as in Figure 8.7.

**Table 8.9** Demodulation Reference Signal Location for Different PUCCH Formats

| PUCCH Format | Set of Values for $l$ | |
|---|---|---|
| | Normal Cyclic Prefix | Extended Cyclic Prefix |
| 1, 1a, 1b | 2,3,4 | 2,3 |
| 2 | 1,5 | 3 |
| 2a, 2b | 1,5 | N/A |

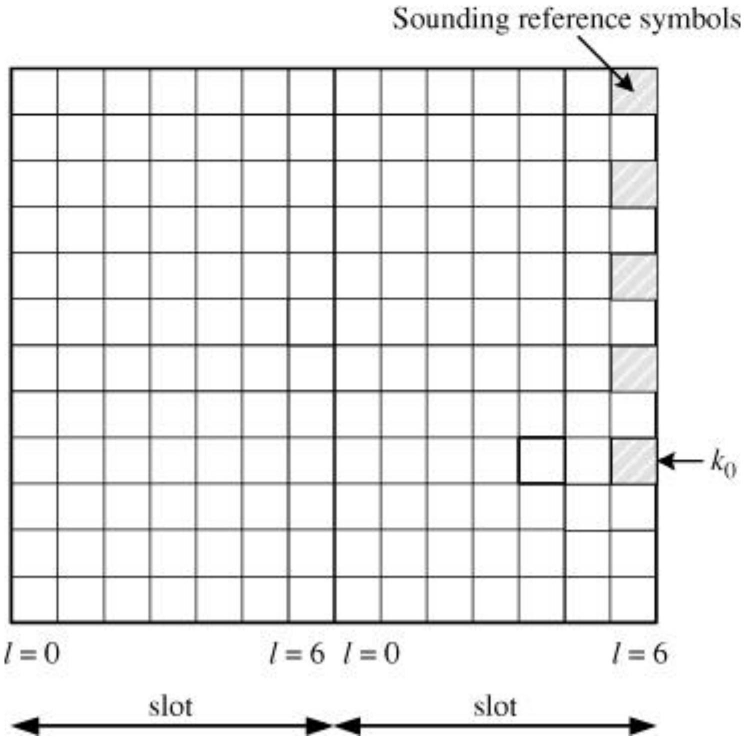
**Figure 8.9** Resource mapping of demodulation reference signals for PUCCH with the normal CP.




## 8.4.3 Resource Mapping of Sounding Reference Signals

For the FDD mode, the sounding reference signal is transmitted in the last SC-FDMA symbol in the specified subframe. For the TDD mode, the sounding reference signal is transmitted only in configured uplink subframes or the UpPTS field in the special subframe. The subframes in which the sounding reference signals are transmitted are indicated by the broadcast signaling, and there are 15 different configurations. In the frequency domain, the mapping starts from the position $k_0$, which is determined by system parameters, and fills every other subcarrier. The bandwidth of sounding reference signals is configured by higher layers and also depends on the system bandwidth. An example of resource mapping of sounding reference signals is shown in Figure 8.10.

**Figure 8.10** An example of resource mapping of sounding reference signals, with the normal CP.




The uplink channel sounding procedure is discussed in Section 9.4. By allocating every other subcarrier to a UE for the sounding reference signal, the system allows two UEs to use the same resource for sounding. The second UE uses the subcarriers not used by the first UE.

## 8.5 RANDOM ACCESS CHANNELS

The uplink random access procedure is used during initial access or to re-establish uplink synchronization. Details about the random access procedure is provided in Chapter 9. In this section, we describe the random access channel that carries random access preambles.

As shown in Figure 8.11, the random access preamble consists of a CP of length $T_{CP}$ and a sequence part of length $T_{SEQ}$. As uplink synchronization may not be established prior to the random access procedure, a Guard Time (GT) is also needed to account for the round trip propagation delay between the UE and the eNode-B. The values of $T_{CP}$ and $T_{SEQ}$ depend on the cell size and base station implementation. There are five different preamble formats defined in LTE, specified in Table 8.10, where $T_s = 1/(15000 \times 2048)$ sec. Format 0 is for normal cells; format 1, also known as the extended format, is used for large cells; format 2 and format 3 use repeated preamble sequences to compensate for increased path loss, and are used for small cells and large cells, respectively; format 4 is defined for frame structure type 2 only.

**Figure 8.11** The random access preamble format.

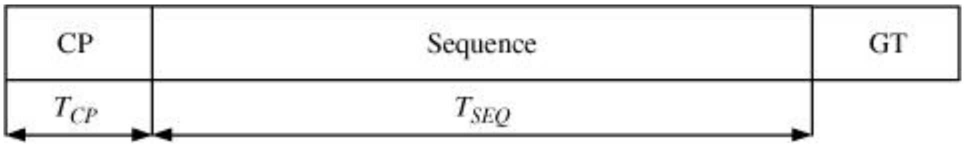



**Table 8.10** Random Access Preamble Parameters

| Preamble Format | $T_{CP}$ | $T_{SEQ}$ |
|---|---|---|
| 0 | $3168 \cdot T_s$ | $24576 \cdot T_s$ |
| 1 | $21024 \cdot T_s$ | $24576 \cdot T_s$ |
| 2 | $6240 \cdot T_s$ | $2 \cdot 24576 \cdot T_s$ |
| 3 | $21024 \cdot T_s$ | $2 \cdot 24576 \cdot T_s$ |
| 4 | $448 \cdot T_s$ | $4096 \cdot T_s$ |

The random access preambles are generated from Zadoff-Chu sequences, which are similar to reference signals. The network configures the set of preamble sequences that the UE is allowed to use. In each cell, there are 64 available preambles, which are generated from one or several root Zadoff-Chu sequences. Due to the zero cross-correlation between different cyclic shifts of the same Zadoff-Chu sequence, there is no intra-cell interference from multiple random access attempts using different preambles in the same cell.

The transmission of a random access preamble is restricted to certain time and frequency resources. The Physical Random Access Channel (PRACH) resources within a radio frame are indicated by a PRACH configuration index, which is given by higher layers. For frame structure type 1 with preamble format 0–3, there is at most one random access resource per subframe; for frame structure type 2 with preamble format 0–4, there might be multiple random access resources in an uplink subframe depending on the uplink/downlink configuration.

In the frequency domain, the random access burst occupies a bandwidth corresponding to six consecutive resource blocks (72 subcarriers) in a subframe or a set of consecutive subframes. The PRACH uses a different subcarrier spacing ($\Delta f_{RA}$) than other physical channels, which is listed in Table 8.11 together with the preamble sequence length $N_{ZC}$. Note that the data symbol subcarrier spacing $\Delta f$ = 15kHz is an integer multiple of the PRACH subcarrier spacing $\Delta f_{RA}$. This is to minimize the orthogonality loss in the frequency domain and can also reuse the IFFT/FFT component.

**Table 8.11** Parameters for Random Access Preamble

| Preamble Format | $\Delta f_{RA}$ | $N_{ZC}$ | $\varphi$ |
|---|---|---|---|
| 0–3 | 1.25 kHz | 839 | 7 |
| 4 | 7.5 kHz | 139 | 2 |

The baseband signal generation for the PRACH is different from other uplink physical channels, and no DFT-based precoding is applied, as the DFT of a Zadoff-Chu sequence is also a Zadoff-Chu sequence. The continuous-time random access signal is defined by:

(8.4)

$$s(t) = \beta \sum_{k=0}^{N_{ZC}-1} \sum_{n=0}^{N_{ZC}-1} x_{u,v}(n) \cdot e^{-j\frac{2\pi nk}{N_{ZC}}} \cdot e^{j2\pi(k+\varphi+K(k_0+1/2))\Delta f_{RA}(t-T_{CP})},$$

where $0 \leq t \leq (T_{SEQ} + T_{CP})$ and:

• $\beta$ is an amplitude scaling factor for power control;

• $x_{u,v}(n)$ is the $u$th root Zadoff-Chu sequence with cyclic shift $v$;

• $\varphi$ is a fixed offset determining the frequency-domain location of the random preamble within the physical resource blocks, given in Table 8.11;

• $K = \Delta f / \Delta f_{RA}$ accounts for the difference in subcarrier spacing between the random access preamble and uplink data transmission;

• $k_0 = n_{PRB}^{RA} N_{sc}^{RB} - N_{RB}^{UL} N_{sc}^{RB}/2$ controls the random access preamble location in the frequency domain, with $0 \leq n_{PRB}^{RA} \leq (N_{RB}^{UL} - 6)$ as the physical resource block number configured by higher layers.

## 8.6 H-ARQ IN THE UPLINK

As in the downlink, the H-ARQ retransmission protocol is also used in the LTE uplink, so the eNode-B has the capability to request retransmissions of incorrectly received data packets. For the uplink H-ARQ process, the corresponding ACK/NAK information is carried on the PHICH, for which the coding and modulation processing was discussed in Chapter 7.

LTE uplink applies the synchronous H-ARQ protocol, that is, the retransmissions are scheduled on a periodic interval unlike downlink where the scheduler determines the timing of retransmissions. Synchronous retransmission is preferred in the uplink because it does not require to explicitly signal the H-ARQ process number so there is less protocol overhead. The number of H-ARQ processes and the time interval between the transmission and retransmission depend on the duplexing mode and the H-ARQ operation type, discussed later in this section.

There are two types of H-ARQ operation in the uplink: the non-subframe bundling operation (normal H-ARQ operation), and the subframe bundling operation (also called TTI[3] bundling), in which four redundancy versions are transmitted over four consecutive uplink subframes. This essentially is the same as sending four H-ARQ retransmissions back to back without waiting for the H-ARQ ACK/NAK feedback. When TTI bundling is used, the eNode-B waits for four TTIs to receive and decode the four redundancy versions jointly before sending an H-ARQ ACK/NAK over the PHICH in the downlink. Similar to the downlink, the N-channel Stop-and-Wait protocol is used in the uplink.

## 8.6.1 The FDD Mode

For the FDD mode, there are eight parallel H-ARQ processes in the uplink for the non-subframe bundling operation, and four H-ARQ processes for the subframe bundling operation. For the FDD mode with the normal H-ARQ operation, upon detection of an NAK in subframe $n$, the UE retransmits the corresponding PUSCH in subframe $n + 4$; for the FDD mode with the subframe bundling operation, upon detection of an NAK in subframe $n - 5$, the UE retransmits the corresponding first PUSCH transmission in the bundle in subframe $n + 4$.

## 8.6.2 The TDD Mode

For the TDD mode, the number of H-ARQ processes is determined by the DL/UL configuration, listed in Table 8.12.

- For TDD UL/DL configurations 1–6 and the normal H-ARQ operation, upon detection of an NAK in subframe $n$, the UE retransmits in subframe $n + k$, with $k$ given in Table 8.13.
- For TDD UL/DL configuration 0 and the normal H-ARQ operation, upon detection of an NAK in subframe $n$, the UE will retransmit in subframe $n + 7$ or $n + k$ with $k$ given in Table 8.13, which depends on the UL index field in DCI and the value of $n$.

• For TDD UL/DL configurations 1 and 6 with subframe bundling, upon detection of an NAK in subframe $n - l$ with $l$ given in Table 8.14, the UE retransmits the corresponding first PUSCH transmission in the bundle in subframe $n + k$, with $k$ given in Table 8.13.

• For TDD UL/DL configuration 0 and the subframe bundling operation, upon detection of an NAK in subframe $n - l$ with $l$ given in Table 8.14, the UE retransmits in subframe $n + 7$ or $n + k$ with $k$ given in Table 8.13, depending on the UL index field in DCI and the value of $n$.

**Table 8.12** Number of Synchronous UL H-ARQ Processes for TDD

| TDD UL/DL Configuration | Number of H-ARQ Processes for Normal H-ARQ Operation | Number of H-ARQ Processes for Subframe Bundling Operation |
|---|---|---|
| 0 | 7 | 3 |
| 1 | 4 | 2 |
| 2 | 2 | N/A |
| 3 | 3 | N/A |
| 4 | 2 | N/A |
| 5 | 1 | N/A |
| 6 | 6 | 3 |

**Table 8.13** The Value of $k$ for TDD Configurations 0–6

| TDD UL/DL Configuration | DL Subframe Number $n$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| 0 | 4 | 6 | | | | 4 | 6 | | | |
| 1 | | 6 | | | 4 | | 6 | | | 4 |
| 2 | | | | 4 | | | | | 4 | |
| 3 | 4 | | | | | | | | 4 | 4 |
| 4 | | | | | | | | | 4 | 4 |
| 5 | | | | | | | | | 4 | |
| 6 | 7 | 7 | | | | 7 | 7 | | | 5 |

**Table 8.14** The Value of $l$ for TDD Configurations 0, 1, and 6

| TDD UL/DL Configuration | DL Subframe Number $n$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| 0 | 9 | 6 | | | | 9 | 6 | | | |
| 1 | | 2 | | | 3 | | 2 | | | 3 |
| 6 | 5 | 5 | | | | 6 | 6 | | | 8 |

# Physical Layer Procedures and Scheduling

In previous chapters, we have described the hierarchical channel structure, the physical radio resource structure, and transport channel processing of the LTE radio interface. In this chapter, we specify the physical layer procedures that provide crucial services to higher layers. Dynamic channel-dependent scheduling and MIMO transmission, including open-loop (OL) and closed-loop (CL) MIMO modes, are two key features of LTE that provide high-spectrum efficiency, both of which require specific feedback support and signaling. Channel Quality Indicator (CQI) feedback and channel sounding provide channel quality information (signal to noise ratio) for downlink and uplink, respectively. The Rank Indicator (RI) and Precoder Matrix Indicator (PMI) feedback are reported from UEs to support the different MIMO modes and enable dynamic switching between them. However, resources in the uplink are limited, so keeping the overhead low requires careful design of uplink reporting. In this chapter we also describe the various aspects of the different scheduling algorithms that are enabled in LTE. The type of scheduling used depends on the nature of the data traffic and its QoS requirements. In this chapter we also discuss the synchronization procedures used by the UE through cell search and random access procedures.

We first describe feedback procedures to enable dynamic scheduling, adaptive MIMO transmission, including H-ARQ ACK/NAK feedback, CQI reporting, and RI and PMI feedback. For uplink scheduling, channel sounding provides uplink channel quality information at the eNode-B and buffer status reporting from UEs are discussed. Then the signaling required for the dynamic scheduling of data traffic and semi-persistent scheduling of VoIP services are described. Finally, the network access procedure and uplink power control are discussed.

## 9.1 HYBRID-ARQ FEEDBACK

In LTE, the H-ARQ protocol is applied to improve the transmission reliability over the wireless channel, as discussed in Section 7.7 and Section 8.6 for downlink and uplink, respectively, also tutored in Chapter 2 (Section 2.6.4). The LTE downlink employs the asynchronous adaptive H-ARQ protocol, for which the retransmissions are scheduled in a similar fashion to the first transmission, i.e., the TTI and resource allocation for the retransmission is dynamically determined by the scheduler. In the uplink, synchronous adaptive H-ARQ protocol is used, for which the retransmissions are automatically scheduled after a certain time window and the UE does not need to send the H-ARQ process number. This reduces the amount of signaling overhead in the uplink. With different frame structures, the H-ARQ feedback is different for FDD and TDD modes. In this section, we discuss the H-ARQ feedback for both downlink and uplink transmissions.

### 9.1.1 H-ARQ Feedback for Downlink (DL) Transmission

For H-ARQ transmissions in the downlink, UEs need to feed back the associated ACK/NAK information on PUCCH or PUSCH. One ACK/NAK bit is transmitted in case of single-codeword downlink transmission, while two ACK/NAK bits are transmitted in case of two-codeword downlink transmission. For two-codeword transmission, codeword swap is enabled by a 1-bit transport block to codeword swap flag, which allows both codewords to experience similar channel conditions after H-ARQ retransmission when the channel is static or experiences little or no variation between subsequent H-ARQ transmissions. The coding and modulation for ACK/NAK bits were discussed in Section 8.3.

For the FDD mode, the UE transmits H-ARQ-ACK in subframe $n$ for a PDSCH transmission in subframe $n - 4$. When both H-ARQ-ACK and Scheduling Request (SR) are transmitted in the same subframe, i.e., with PUCCH format 1a or 1b, a UE shall transmit the H-ARQ-ACK on its associated H-ARQ-ACK PUCCH resource for a negative SR transmission and transmit the H-ARQ-ACK on its assigned SR PUCCH resource for a positive SR transmission.

For the TDD mode, in asymmetric uplink/downlink cases with more downlink subframes than uplink subframes, it may happen that more than one acknowledgment needs to be sent in a certain UL subframe. Therefore, H-ARQ reporting is different from the FDD mode. For TDD, two ACK/NAK feedback modes are supported by higher layer configuration:

• ACK/NAK bundling using PUCCH format 1a or 1b, which is the default mode and consists of one or two bits of information

• ACK/NAK multiplexing using PUCCH format 1b, which consists of between one and four bits of information

The feedback of H-ARQ-ACK in the UL subframe $n$ corresponds to the detection of the PDSCH transmission within subframe(s) $n - k$, where the parameter $k$ is different for different UL/DL configurations and different subframes, and $k \in K$ with $K$ specified in Table 9.1. We see that for some UL/DL configurations and in some subframes multiple acknowledgments are needed, with a maximum number of 4, so the number of information bits for ACK/NAK multiplexing is between one and four. For ACK/NAK bundling, multiple acknowledgments are combined by a logical AND operation, and then the bundled 1 or 2 ACK/NAK bits are transmitted using PUCCH format 1a and PUCCH format 1b, respectively.

**Table 9.1** Downlink Association Set Index $K$ : $\{k_0, k_1, ..., k_{M-1}\}$ for TDD

| TDD UL/DL Configuration | Subframe $n$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 0 | | | 6 | | 4 | | | 6 | | 4 |
| 1 | | | 7,6 | 4 | | | 7,6 | 4 | | |
| 2 | | | 8,7,4,6 | | | | 8,7,4,6 | | | |
| 3 | | | 7,6,11 | 6,5 | 5,4 | | | | | |
| 4 | | | 12,8,7,11 | 6,5,4,7 | | | | | | |
| 5 | | | TBD | | | | | | | |
| 6 | | | 7 | 7 | 5 | | 7 | 7 | | |

## 9.1.2 H-ARQ Indicator for Uplink (UL) Transmission

For the uplink H-ARQ process, as spatial multiplexing of transport blocks is not supported, only a single-bit H-ARQ Indicator (HI) needs to be sent to each scheduled UE, which is carried on the PHICH physical channel. The coding and modulation for HI were discussed in Section 7.3.2.

For the FDD mode, an ACK/NAK received on the PHICH assigned to a UE in subframe $n$ is associated with the PUSCH transmission in subframe $n - 4$. For the TDD mode, different from the feedback for downlink transmission, there is no problem to transmit multiple acknowledgments on PHICH, as discussed in Section 7.3.2. For UL/DL configurations 1–6, an ACK/NAK received on the PHICH in subframe $n$ is associated with the PUSCH transmission in the subframe $n - k$ as indicated in Table 9.2. For TDD with UL/DL configuration 0:

1. If there is PUSCH transmission in subframe 4 or 9, an ACK/NAK received on the PHICH in subframe $n$ is associated with the PUSCH transmission in the subframe $n - 6$.
2. Otherwise, an ACK/NAK received on the PHICH in subframe $n$ is associated with the PUSCH transmission in the subframe $n - k$ with $k$ indicated in Table 9.2.

**Table 9.2** The Value of $k$ for TDD Configurations 0–6

| TDD UL/DL Configuration | DL Subframe Number $n$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 0 | 7 | 4 | | | | 7 | 4 | | | |
| 1 | | 4 | | | 6 | | 4 | | | 6 |
| 2 | | | | 6 | | | | | 6 | |
| 3 | 6 | | | | | | | | 6 | 6 |
| 4 | | | | | | | | | 6 | 6 |
| 5 | | | | | | | | | 6 | |
| 6 | 6 | 4 | | | | 7 | 4 | | | 6 |

## 9.2 CHANNEL QUALITY INDICATOR (CQI) FEEDBACK

The Channel Quality Indicator (CQI) contains information sent from a UE to the eNode-B to indicate a suitable downlink transmission data rate, i.e., a Modulation and Coding Scheme (MCS) value. CQI is a 4-bit integer and is based on the observed signal-to-interference-plus-noise ratio (SINR) at the UE. The CQI estimation process takes into account the UE capability such as the number of antennas and the type of receiver used for detection. This is important since for the same SINR value the MCS level that can be supported by a UE depends on these various UE capabilities, which needs to be taken into account in order for the eNode-B to select an optimum MCS level for the transmission. The CQI reported values are used by the eNode-B for downlink scheduling and link adaptation, which are important features of LTE.

LTE supports wideband and subband CQI reporting. A wideband CQI value is a single 4-bit integer that represents an *effective* SINR as observed by the UE over the entire channel bandwidth. With wideband CQI, the variation in the SINR across the channel due to frequency selective nature of the channel is masked out. Therefore, frequency selective scheduling where a UE is placed only in resource blocks with high SINR is not possible with wideband CQI reporting. To support frequency selective scheduling, each UE needs to report the CQI with a fine frequency granularity, which is possible with subband CQI reporting. A subband CQI report consists of a vector of CQI values where each CQI value is representative of the SINR observed by the UE over a subband. A subband is a collection of $n$ adjacent Physical Resource Blocks (PRBs) where the value of $n$ can be 2, 3, 4, 6, or 8 depending on the channel bandwidth and the CQI feedback mode. The various CQI feedback modes are discussed in further detail later in Section 9.2.2.

One of the critical aspects of designing the CQI feedback mechanism for LTE is the optimization between the downlink system performance and the uplink bandwidth consumed by the feedback mechanism. The wideband CQI is the most efficient in terms of uplink bandwidth consumption since it requires only a single 4-bit feedback. However, this is not the optimum feedback mechanism since frequency selective scheduling cannot be done using a wideband CQI feedback. On the other hand, subband CQI feedback requires more uplink bandwidth but is more efficient since it allows for a frequency selective scheduling, which maximizes the multiuser diversity gain of an OFDMA system. Wideband CQI is the preferred mode to use for high speeds where the channel changes rapidly since frequent subband reporting would exhaust a large portion of the uplink bandwidth. Wideband CQI is also the preferred mode for services such as VoIP where a large number of simultaneous UEs are supported and latency is more critical than the overall throughput since VoIP is typically a low data rate application with very strict latency requirement. The LTE standard does not specify how to select between wideband and subband CQI reporting depending on the UE speed or the QoS requirements of the application. It is left up to the equipment manufacturer to develop their proprietary algorithms in order to accomplish this.

In this section, we first describe the CQI estimation, and then move on to detailed discussion about different CQI reporting modes.

## 9.2.1 A Primer on CQI Estimation

Downlink cell-specific reference signals as discussed in Section 7.6.1 are used by each UE to estimate the MIMO channel from the eNode-B. The estimated MIMO channel along with the known reference signal is then used to calculate the other-cell interference level. The UE uses the estimated channel and interference plus noise variance to compute the SINR on the physical resource element (PRE) carrying the reference signal. The UE computes SINR samples over multiple OFDM symbols and subcarriers, which are then used to calculate an *effective SINR*. The effective SINR is given as:

(9.1)

$$\mathrm{SINR}_{\mathrm{eff}} = \alpha_1 I^{-1}\left(\frac{1}{N}\sum_{k=1}^{N} I\left(\frac{\mathrm{SINR}_k}{\alpha_2}\right)\right)$$

where $N$ is the number of samples. The function $I(\cdot)$ maps the SINR to a performance metric that is averaged over all the samples, and $I^{-1}(\cdot)$ is its inverse. The parameters $\alpha_1$ and $\alpha_2$ adapt to different modulation and coding schemes. The most commonly used functions for $I$ are

• Identity function: $I(\gamma) = \gamma$;

• Shannon capacity: $I(\gamma) = \log_2(1 + \gamma)$;

• Exponential Effective SINR Mapping (EESM): $I(\gamma) = e^{-\gamma}$;

• Mutual Information Equivalent SINR Mapping (MIESM) or modulation constrained capacity:

(9.2)

$$I(\gamma) = \log_2(M) + \frac{1}{2\pi M}\sum_{m=1}^{M-1}\int e^{-\gamma(y-x_m)^2}\log_2\left\{\frac{e^{-\gamma(y-x_m)^2}}{\sum_{k=0}^{M-1} e^{-\gamma(y-x_k)^2}}\right\}dy,$$

where $M$ is the size of the modulation alphabet (4 for QPSK, 16 for 16QAM, and 64 for 64QAM), and $x_m$ are the modulation symbols.

The EESM and the mutual information-based methods are preferred since they have been shown to give a more accurate estimate of the channel quality [6].

In the case of wideband CQI feedback, the UE measures the SINR from the reference signal over all the PRBs, and then computes its CQI based on the effective SINR across the entire channel bandwidth. On the other hand, for subband CQI the UE measures the SINR over the PRBs contained in the given subband, and then computes the CQI. A subband is a set of $k$ contiguous PRBs where $k$ is semi-statically configured by higher layers. The set of subbands ($S$) a UE shall evaluate for CQI reporting spans the entire downlink system bandwidth. Note that the last subband in the set $S$ may have fewer than $k$ contiguous PRBs depending on $N_{RB}^{DL}$. The number of subbands for a system bandwidth given by $N_{RB}^{DL}$ is determined by:

(9.3)

$$N = \lceil N_{RB}^{DL}/k \rceil.$$

If a UE reports a CQI value for a particular subband, it is called *subband feedback*; if a UE reports a single CQI value for the set $S$, i.e., the whole system bandwidth, it is called *wideband feedback*.

Based on the estimated effective SINR, the UE picks the CQI index that indicates the highest MCS level (modulation and code rate) that can be supported with a 10% BLER on the first H-ARQ transmission. The CQI feedback is used by the eNode-B to select an optimum PDSCH transport block with a combination of modulation scheme and transport block size corresponding to the CQI index that could be received with target block error probability after the first H-ARQ transmission. While this target block error probability is left open as an implementation choice, typical values are in the range of 10–25%. It should be noted that the target BLER of the transmission is not the same as the BLER of 10% based on which the CQI is computed. Thus, the eNode-B needs to take this into account while selecting the optimum transport block size. If the achieved block error rate is not equal to the target value based on the H-ARQ ACK/NAK ratio, then a fudge factor can be added to the CQI to ensure that the selection of the block size based on the CQI leads to the desired target block error rate. A positive fudge factor implies a more aggressive transport block size selection, whereas a negative fudge factor implies a more conservative transport block size selection.

The supported CQI indices and their interpretations are given in Table 9.3. In total, there are 16 CQI values, which require a 4-bit CQI feedback. In Table 9.3, the efficiency for a given CQI index is calculated as:

(9.4)

$$\text{efficiency} = Q_m \times \text{code rate},$$

**Table 9.3** 4-Bit CQI Table

| CQI Index | Modulation | Code Rate × 1024 | Efficiency |
|---|---|---|---|
| 0 | out of range | | |
| 1 | QPSK | 78 | 0.1523 |
| 2 | QPSK | 120 | 0.2344 |
| 3 | QPSK | 193 | 0.3770 |
| 4 | QPSK | 308 | 0.6016 |
| 5 | QPSK | 449 | 0.8770 |
| 6 | QPSK | 602 | 1.1758 |
| 7 | 16QAM | 378 | 1.4766 |
| 8 | 16QAM | 490 | 1.9141 |
| 9 | 16QAM | 616 | 2.4063 |
| 10 | 64QAM | 466 | 2.7305 |
| 11 | 64QAM | 567 | 3.3223 |
| 12 | 64QAM | 666 | 3.9023 |
| 13 | 64QAM | 772 | 4.5234 |
| 14 | 64QAM | 873 | 5.1152 |
| 15 | 64QAM | 948 | 5.5547 |

where $Q_m$ is the number of bits in the modulation constellation. Taking CQI index 4 as an example, as $Q_m = 2$ for QPSK, we have

$$\text{efficiency} = 2 \times \frac{308}{1024} \approx 0.6016 \text{ information bits/symbol.}$$

## 9.2.2 CQI Feedback Modes

CQI is reported with other uplink control information including Precoder Matrix Indicator (PMI) and Rank Indicator (RI) on PUSCH or PUCCH. The reporting of CQI, PMI, and RI in the time domain can be categorized into two classes:

• **Periodic reporting:** The UE reports CQI, PMI, and RI with reporting periods configured by the higher layer on the PUCCH. If the UE is scheduled in the uplink, the periodic reporting is carried on PUSCH.

• **Aperiodic reporting:** The UE reports CQI, PMI, and RI using the PUSCH upon receiving either a DCI format 0 or a random access response grant. Feedback via PUSCH can be used to provide large and more detailed reporting in a single reporting instance compared to the periodic feedback.

In cases where both periodic reporting on the PUCCH and the aperiodic reporting PUSCH happen to be on the same subframe, the UE will only transmit the aperiodic report over the PUSCH and ignore the periodic PUCCH report.

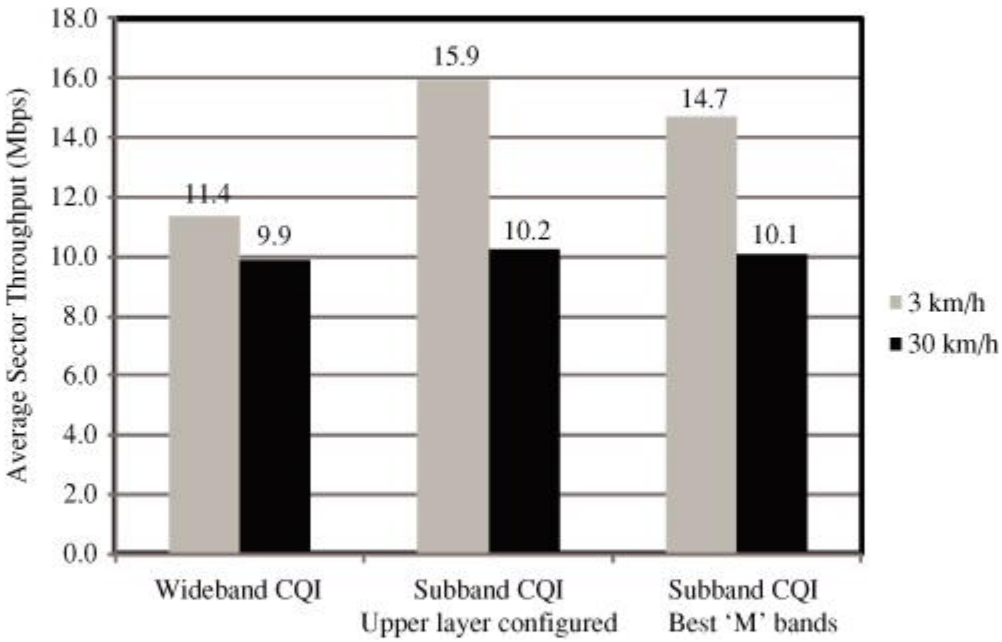
As we discussed previously, in the frequency domain the CQI reporting can be classified as subband CQI and wideband CQI. Both periodic and aperiodic reporting modes support wideband and subband CQI reporting. In the case of periodic CQI reporting mode when subband CQI is requested, the UE cycles through the different subbands from one reporting instance to the next. This allows for subband CQI reporting without requiring too much overhead in the uplink. The only problem with this is that it could take a while for the eNode-B to develop a complete picture in order to effectively utilize the CQI information for frequency selective scheduling. For aperiodic reporting, the UE can report the subband CQI across all the bands in one single report. This is possible since the available bandwidth on PUSCH is much larger than that of PUCCH. In LTE there are two distinct reporting mechanisms for subband CQI feedback when the aperiodic reporting mode is used:

• **Higher Layer Configured Subband Report:** In this case, the UE reports the subband CQI for each band in a single feedback report. The size of a band is specified by a higher layer message and is contingent on the system bandwidth.

• **UE Selected Subband Report:** In this case, the UE reports the subband CQI for the ‘M’ bands with the highest CQI values. The CQI for the rest of the bands is not reported. In this case, the value of *M* and the size of a band is given by a higher layer message and is also contingent on the system bandwidth.

Figure 9.1 shows the average per sector downlink throughput for the various wideband and subband CQI feedback modes. The results are typical of a 10MHz FDD system in a multicell deployment.

**Figure 9.1** The average downlink throughput per sector for various CQI feedback modes.




Each reporting class supports a number of different *reporting modes*, where each reporting mode is characterized by a specific CQI feedback type and a PMI feedback type, which are listed in Table 9.4 and Table 9.5 for periodic reporting and aperiodic reporting, respectively. There are seven *transmission modes* in the downlink, as described in Section 7.2.2, and each of them supports a specific subset of the reporting modes, the details of which are shown in Table 9.6. In the remainder of this subsection, details about different CQI feedback modes are described.

**Table 9.4** CQI and PMI Feedback Types for Periodic PUCCH Reporting Modes

| PUCCH CQI Feedback Type | PMI Feedback Type | |
|---|---|---|
| | No PMI | Single PMI |
| Wideband (Wideband CQI) | Mode 1-0 | Mode 1-1 |
| UE Selected (Subband CQI) | Mode 2-0 | Mode 2-1 |

**Table 9.5** CQI and PMI Feedback Types for Aperiodic PUSCH Reporting Modes

| PUSCH CQI Feedback Type | PMI Feedback Type | | |
|---|---|---|---|
| | No PMI | Single PMI | Multiple PMI |
| Wideband (Wideband CQI) | | | Mode 1-2 |
| UE Selected (Subband CQI) | Mode 2-0 | | Mode 2-2 |
| Higher Layer-Configured (Subband CQI) | Mode 3-0 | Mode 3-1 | |

**Table 9.6** The Supporting CQI Reporting Modes for Different Transmission Modes

| Transmission Mode | Periodic Reporting Mode | Aperiodic Reporting Mode |
|---|---|---|
| 1. Single-antenna port, port 0 | Modes 1-0, 2-0 | Modes 2-0, 3-0 |
| 2. Transmit diversity | Modes 1-0, 2-0 | Modes 2-0, 3-0 |
| 3. Open-loop spatial multiplexing | Modes 1-0, 2-0 | Modes 2-0, 3-0 |
| 4. Closed-loop spatial multiplexing | Modes 1-1, 2-1 | Modes 1-2, 2-2, 3-1 |
| 5. Multiuser MIMO | Modes 1-1, 2-1 | Mode 3-1 |
| 6. Closed-loop Rank = 1 precoding | Modes 1-1, 2-1 | Modes 1-2, 2-2, 3-1 |
| 7. Single-antenna port, port 5 | Modes 1-0, 2-0 | Modes 2-0, 3-0 |

**Periodic CQI Reporting**

First, we describe periodic CQI reporting, where a UE is semi-statically configured by higher layers to periodically feed back CQI on the PUCCH in one of the reporting modes given in Table 9.4. Note that mode 1-0 and 2-0 do not report PMI and they are used for OL MIMO modes and single-antenna port transmission. Mode 1-1 and mode 2-1 report a single PMI for CL MIMO modes, i.e., only the wideband PMI is reported. The periodic CQI feedback is useful for scheduling and adaptive modulation and coding, and can also be used to check or change semi-static parameters such as the MIMO mode or transmission mode.

Considering the reporting for CQI/PMI and RI, there are four different reporting types supported for each of these reporting modes as given in Table 9.7:

• Type 1 report supports CQI feedback for the UE selected subbands.
• Type 2 report supports wideband CQI and PMI feedback.
• Type 3 report supports RI feedback.
• Type 4 report supports wideband CQI.

**Table 9.7** PUCCH Report Type Payload Size Per Reporting Mode

| PUCCH Report Type | Mode State | PUCCH Reporting Modes Mode 1-1 (bits/BP) | Mode 2-1 (bits/BP) | Mode 1-0 (bits/BP) | Mode 2-0 (bits/BP) |
|---|---|---|---|---|---|
| 1. Subband CQI | RI= 1 | NA | 4+L | NA | 4+L |
| | RI > 1 | NA | 7+L | NA | 4+L |
| 2. Wideband CQI/PMI | 2 TX Antennas RI= 1 | 6 | 6 | NA | NA |
| | 4 TX Antennas RI= 1 | 8 | 8 | NA | NA |
| | 2 TX Antenna RI > 1 | 8 | 8 | NA | NA |
| | 4 TX Antennas RI > 1 | 11 | 11 | NA | NA |
| 3. RI | 2-layer spatial multiplexing | 1 | 1 | 1 | 1 |
| | 4-layer spatial multiplexing | 2 | 2 | 2 | 2 |
| 4. Wideband CQI | RI= 1 | NA | NA | 4 | 4 |

Periodic reporting supports both UE-selected subband reporting and wideband reporting. In the following, we will first describe these two reporting types, and then describe the reporting period for each type.

*UE-Selected Subband CQI*

For the UE-selected subband CQI, a CQI report describes the channel quality in a particular part of the bandwidth. For this reporting type, two concepts are important to understand the feedback scheme:

• **Subband:** The system bandwidth, given by $N_{RB}^{DL}$, is divided into *N* subbands, where $\lfloor N_{RB}^{DL}/k \rfloor$ subbands are of size *k* and one is of size $N_{RB}^{DL} - k \cdot \lfloor N_{RB}^{DL}/k \rfloor$. The CQI report is for one of these subbands.

• **Bandwidth part:** A bandwidth part (BP) *j* consists of $N_J$ consecutive subbands, and a total of *J* BPs span the system bandwidth $N_{RB}^{DL}$. If $J = 1$, then $N_J = \lceil N_{RB}^{DL}/k \rceil$. If $J > 1$, then $N_J = \lceil N_{RB}^{DL}/k/J \rceil$ or $N_J = \lceil N_{RB}^{DL}/k/J \rceil - 1$, depending on the values of $N_{RB}^{DL}$, *k*, and *J*.

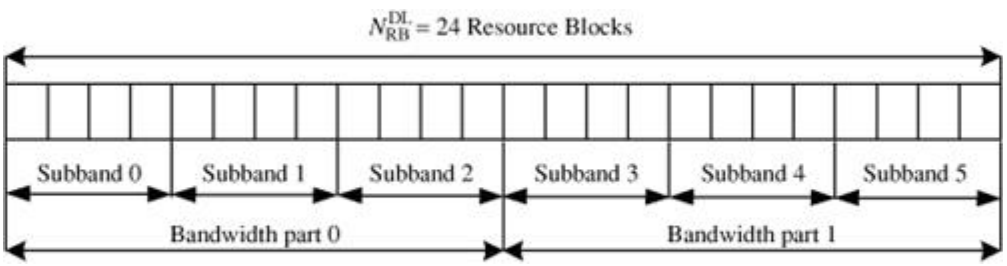
The subband size *k* and the number of BPs *J* are given in Table 9.8 for different bandwidths. An example of $N_{RB}^{DL} = 24$ is shown in Figure 9.2, with $k = 4$ and $J = 2$. The UE selects the single subband with the best CQI out of $N_J$ subbands of the *j*-th BP and feeds back the corresponding CQI together with an *L*-bit label where $L = \lceil \log_2 \lceil N_{RB}^{DL}/k/J \rceil \rceil$. From Table 9.8, we see that the value of *L* is 1 or 2.

The value of $j$ (the BP index) is determined by $j = \text{mod}(N_{SF}, J)$, where $N_{SF}$ is a counter that a UE increments after each subband report transmission, so it does not need to be fed back to the eNode-B. Therefore, the UE-selected subband reporting only selects to report CQI for a subband from a certain BP but not from the whole bandwidth, which reduces the feedback overhead.

**Table 9.8** Subband Size ($k$) and Bandwidth Parts ($J$) vs. Downlink System Bandwidth in Periodic Reporting

| System Bandwidth $N_{RB}^{DL}$ | Subband Size ($k$) | Bandwidth Parts ($J$) |
|---|---|---|
| 6–7 | NA | NA |
| 8–10 | 4 | 1 |
| 11–26 | 4 | 2 |
| 27–63 | 6 | 3 |
| 64–110 | 8 | 4 |

**Figure 9.2** The structure of subbands and bandwidth parts.




The number of CQI feedback bits for type 1 subband CQI reporting is shown in Table 9.7. For mode 2-0, the feedback consists of a 4-bit CQI and an $L$-bit subband label. For OL spatial multiplexing, the preferred subband selection and CQI calculation are conditioned on the last reported RI; for other transmission modes, they are calculated conditioned on RI = 1. For mode 2-1, the feedback consists of an $L$-bit subband label and a 4-bit or 7-bit CQI, where the 4-bit CQI is for single-codeword CL spatial multiplexing and the 7-bit CQI is for two-codeword CL spatial multiplexing, with 4 bits for codeword 0 and 3 bits for the spatial differential value for codeword 1. The 3-bit spatial differential CQI value for codeword 1 is defined by:

(9.5)

$$\text{Codeword 1 offset level} = \text{CQI index for codeword 0} - \text{CQI index for codeword 1.}$$

The mapping from the 3-bit spatial differential value to the offset level is shown in Table 9.9. For CL spatial multiplexing, the subband selection and CQI values are calculated conditioned on the last reported wideband PMI and RI; for other transmission modes, they are calculated conditioned on the last reported PMI and RI = 1.

**Table 9.9** Mapping Spatial Differential CQI Value to Offset Level

| Subband Differential CQI Value | Offset Level |
|---|---|
| 0 | 0 |
| 1 | 1 |
| 2 | 2 |
| 3 | $\geq 3$ |
| 4 | $\leq -4$ |
| 5 | $-3$ |
| 6 | $-2$ |
| 7 | $-1$ |

*Wideband CQI*

For wideband CQI, a CQI report describes the channel quality over the set *S* of all the subbands. Different reporting modes with wideband CQI are described as follows:

• For single-antenna port and transmit diversity, as well as OL spatial multiplexing, i.e., for mode 1-0 and 2-0, a single 4-bit CQI is reported.

• The reporting is similar for mode 1-1 and 2-1. The feedback consists of a 4-bit (for single-codeword spatial multiplexing) or 7-bit CQI (for two-codeword spatial multiplexing) and a single PMI. The single PMI is selected assuming transmission on set *S* subbands and conditioned on the last reported periodic RI. The wideband CQI value is calculated assuming the use of the selected PMI in all subbands.

Based on these rules, together with the PMI feedback that will be discussed in Section 9.3, we are able to determine the payload size for each reporting mode in Table 9.7. For example, the payload size for reporting type 2 is 8 bits (RI = 1) or 11 bits (RI > 1) for mode 1-1 and 2-1, which consists of a 4-bit PMI and a 4-bit or 7-bit CQI.

*Reporting Period*

The reporting periods for the CQI feedback depend on the reporting type:

• The period $N_p$ of the subband CQI reporting is selected from the set {2, 5, 10, 20, 40, 80, 160, OFF} for the FDD mode and from the set {1, 5, 10, 20, 40, 80, 160, OFF} for the TDD mode. The value of $N_p$ is configured by higher-layer signaling.

• The wideband CQI/PMI reporting period is $N_p$ if it is not configured with subband CQI reporting; otherwise, the wideband CQI/PMI reporting period is $H \cdot N_p$. The integer $H$ is defined as $H = J \cdot K + 1$, where $J$ is the number of bandwidth parts and $K$ is selected from the set {1, 2, 3, 4}. In this case, between every two consecutive wideband CQI/PMI reports, the remaining $J \cdot K$ reporting instances are used for subband CQI reports on $K$ full cycles of BPs.

• For the RI reporting, if RI and wideband CQI/PMI are configured, the reporting interval of the RI reporting is $N_p \cdot M_{RI}$, where $M_{RI}$ is configured by higher-layer signaling and is selected from the set {1, 2, 4, 8, 16, 32, OFF}; if RI is configured with both wideband CQI/PMI and subband CQI reporting, the reporting interval of the RI reporting is $H \cdot N_p \cdot M_{RI}$. In case of a collision between RI and wideband CQI/PMI or subband CQI reporting, the wideband CQI/PMI or subband CQI is dropped.

Therefore, the report period is the longest for RI while shortest for subband CQI.

**Aperiodic CQI Reporting**

If a UE receives either a DCI format 0 or a random access response grant in subframe $n$, and if the respective CQI request field is set to 1 and is not reserved, the UE shall perform aperiodic CQI, PMI, and RI reporting using the PUSCH channel in subframe $n + k$. The value of $k$ is specified as follows:

• For FDD, $k = 4$.

• For TDD UL/DL configuration 1–6, $k$ is given in Table 9.10.

**Table 9.10** The Values of $k$ for TDD Configuration 0–6

| TDD UL/DL Configuration | DL Subframe Number $n$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 0 | 4 | 6 | | | | 4 | 6 | | | |
| 1 | | 6 | | | 4 | | 6 | | | 4 |
| 2 | | | | 4 | | | | | 4 | |
| 3 | 4 | | | | | | | | 4 | 4 |
| 4 | | | | | | | | | 4 | 4 |
| 5 | | | | | | | | | 4 | |
| 6 | 7 | 7 | | | | 7 | 7 | | | 5 |

• For TDD UL/DL configuration 0:

– If the Most Significant Bit (MSB) of the UL index is set to 1 and the Least Significant Bit (LSB) is set to 0 or 1, *k* is given in Table 9.10.

– If the MSB of the UL index is set to 0 and the LSB is set to 1, *k* is equal to 7.

As shown in Table 9.5, there are three different aperiodic CQI feedback types: wideband feedback, higher layer-configured subband feedback, and UE-selected subband feedback, and five reporting modes. Modes 2-0 and 3-0 are for single-antenna-port transmission and OL MIMO modes, while Mode 3-1 with single PMI and Modes 1-2 and 2-2 with multiple PMI are for CL MIMO modes.

*Wideband Feedback*

For wideband feedback, a UE selects a preferred precoding matrix for each subband, assuming transmission only in that subband. Then each UE reports one wideband CQI value for each codeword, assuming the use of the selected precoding matrix in each subband, and it also reports the selected PMI for each subband, i.e., multiple PMIs are reported.

*Higher Layer-Configured Subband Feedback*

There are two different reporting modes with higher layer-configured subband feedback: Mode 3-0 (without PMI) and Mode 3-1 (with single PMI). The supported subband size *k* is the same as that for the periodic reporting, as in Table 9.8. As a separate CQI is reported for each subband, this reporting type provides the finest frequency granularity but also has the highest overhead.

• For Mode 3-0, a UE reports one subband CQI for each subband, together with a wideband CQI. Both the wideband and subband CQI represent channel quality for the first codeword, even when RI > 1. No PMI is reported for this mode.

• For Mode 3-1, a single precoding matrix is selected, assuming transmission over the whole system bandwidth. A UE reports one subband CQI value per codeword for each subband, together with a wideband CQI value per codeword, assuming the use of the single precoding matrix in all subbands. A 4-bit wideband CQI is reported for each of codeword 0 and codeword 1. The selected precoding matrix is also reported.

The subband CQI values for each codeword are encoded differentially with respect to their respective wideband CQI using 2 bits defined by:

(9.6)

subband differential CQI offset level = subband CQI index − wideband CQI index.

The mapping from the 2-bit differential value to the offset level is show in Table 9.11.

**Table 9.11** Mapping Subband Differential CQI Value to Offset Level

| Subband Differential CQI Value | Offset Level for Mode 3-0 and 3-1 | Offset Level for Mode 2-0 and 2-2 |
|---|---|---|
| 0 | 0 | $\leq 1$ |
| 1 | 1 | 2 |
| 2 | $\geq 2$ | 3 |
| 3 | $\leq -2$ | $\geq 4$ |

*UE-Selected Subband Feedback*

For UE-selected subband feedback, there are two different reporting modes: Mode 2-0 (without PMI) and Mode 2-2 (with multiple PMI).

• For Mode 2-0, the UE selects a set of *M* preferred subbands of size *k*, where the values of *M* and *k* are given in Table 9.12 for different system bandwidths. The UE will report one CQI value reflecting transmission only over the *M* selected subbands. This is called the *best-M method*. Additionally, the UE will also report a wideband CQI value.

**Table 9.12** Subband Size (*k*) and Number of Subbands (*M*) vs. Downlink System Bandwidth in Aperiodic Reporting

| System Bandwidth $N_{RB}^{DL}$ | Subband Size ($k$) | M |
|---|---|---|
| 6–7 | NA | NA |
| 8–10 | 2 | 1 |
| 11–26 | 2 | 3 |
| 27–63 | 3 | 5 |
| 64–110 | 4 | 6 |

• For Mode 2-2, the UE first jointly selects the set of *M* preferred subbands of size *k* and a preferred single precoding matrix. Then it will report one CQI value per codeword reflecting transmission only over the selected *M* preferred subbands, together with the selected single precoding matrix. The UE will also select a precoding matrix assuming transmission over the whole system bandwidth. Then it reports a wideband CQI per codeword together with the selected single PMI for the whole system bandwidth.

The CQI value for the $M$ selected subbands for each codeword is encoded differentially using 2 bits relative to its respective wideband CQI, with the mapping from the 2-bit differential value to the offset level shown in Table 9.11. For all UE-selected feedback modes, the UE shall report the position of the $M$ selected subbands using a combinatorial index $r$ defined as:

(9.7)

$$r = \sum_{i=0}^{M-1} \left\langle \begin{array}{c} N - s_i \\ M - i \end{array} \right\rangle,$$

where the set $\{s_i\}_{i=0}^{M-1}$ $(1 \le s_i \le N,\ s_i < s_{i+1})$ contains the $M$ sorted subband indices and

(9.8)

$$\left\langle \begin{array}{c} x \\ y \end{array} \right\rangle = \begin{cases} \binom{x}{k} & x \ge y \\ 0 & x < y \end{cases}$$

is the extended binomial coefficient, resulting in unique label $r \in \left\{0, \ldots, \binom{N}{M} - 1\right\}$. So the number of bits to denote the positions of the $M$ selected subbands is $L = \left\lceil \log_2 \binom{N}{M} \right\rceil$.

## 9.3 PRECODER FOR CLOSED-LOOP MIMO OPERATIONS

MIMO transmission is a key technique in LTE and can provide a significant throughput gain, especially with the spatial multiplexing mode. The amount of feedback required to provide the full CSI to the eNode-B is large, particularly in multicarrier systems. In order to mitigate the feedback issue, limited feedback mechanisms are used in LTE as indicated in Chapter 5. The UE chooses the optimum rank and precoder for downlink transmission based on a predefined set of precoders, also known as a codebook. In this case, instead of indicating the full precoding matrix, the UE only needs to indicate the index of the precoding matrix from the codebook. RI is reported by the UE to indicate the number of layers, i.e., the number of data streams used in spatial multiplexing. For CL MIMO modes, i.e., the transmission modes 4, 5, and 6, the preferred precoding matrix in the predefined codebook needs to be reported, which is provided by the PMI. In this section, we describe the feedback of PMI and RI.

### 9.3.1 Precoder Estimation for Multicarrier Systems

The precoder estimation at the UE can be done based on a few different metrics. The most common metric is the capacity-based one. The precoder is chosen to maximize the MIMO capacity of the effective channel, which includes the radio channel and the precoder. This metric is suitable for the receivers based on maximum likelihood detection. For a simpler receiver, such as the one based on Minimum Mean Square Error (MMSE), this approach is not optimal, as the rate achieved by MMSE receivers is not given by the MIMO capacity equation. For MMSE receivers, the optimal precoder is chosen such that the post-MMSE SINR across both streams is optimized in order to achieve maximum sum rate throughput across both streams.

In a CL MIMO system, the interference is dynamic in nature, as the precoders used at interfering cells change from one TTI to the next. Thus, choosing a precoder based on the instantaneous interference seen by a UE can lead to suboptimal performance, since the spatial characteristics of the interference can change from the time the precoder was chosen to the time the precoder was applied. It has been shown that in such cases it is better to choose the precoder based on long-term characteristics of the interference such as the interference variance at each receive antenna.

For the *l*-th subcarrier, the achievable rate for an MMSE receiver is

(9.9)

$$R_l = \sum_{k=1}^{M} \log_2(1 + \mathrm{SINR}_k) = -\sum_{k=1}^{M} \log_2\left(\left(\mathbf{I}_M + \frac{\rho}{M}\mathbf{F}^H\mathbf{H}^H\mathbf{H}\mathbf{F}\right)^{-1}_{k,k}\right),$$

where $M$ = 1 to 4, depending on the number of layers, and **H** and **F** are the channel matrix and precoding matrix, respectively. For a multicarrier system, the sum capacity over a subband with $N$ subcarriers is

(9.10)

$$R_{\mathrm{sum}} = \sum_{l=1}^{N} R_l.$$

The precoder is chosen to maximize $R_{sum}$ for a given subband (subband PMI) or the entire bandwidth (wideband PMI). For the MU-MIMO mode, the rank-1 precoder of the SU-MIMO mode is applied. The eNode-B schedules two UEs with orthogonal precoders and similar CQI level on the same radio resource. The two rank-1 precoders are used together to create a rank-2 precoding matrix for the two streams for two different UEs.

## 9.3.2 Precoding Matrix Index (PMI) and Rank Indication (RI) Feedback

The RI report is determined from the supported set of RI values for the corresponding eNode-B and the UE antenna configuration. The value of RI can be 1 or 2 for two-antenna ports and from 1 to 4 for four-antenna ports. The mapping between RI bits and the channel rank is shown in Table 9.13. UEs need to report RI for both CL and OL MIMO modes. For the CL spatial multiplexing, the RI report, together with the PMI, informs the eNode-B to select the suitable precoder; for OL MIMO, the RI report supports selection between transmit diversity (RI = 1) and OL spatial multiplexing (RI > 1). Only wideband RI reporting is supported, i.e., only a single RI is reported for the whole bandwidth, as subband RI reporting provides little performance gain. In addition, as the channel rank normally changes slowly, the reporting period for RI is longer than CQI in periodic reporting.

**Table 9.13** RI Mapping

| RI Bits | Channel Rank |
|---|---|
| 0 | 1 |
| 1 | 2 |
| 0, 0 | 1 |
| 0, 1 | 2 |
| 1, 0 | 3 |
| 1, 1 | 4 |

PMI reports the channel-dependent precoding matrix for CL MIMO modes. The codebooks for two-antenna and four-antenna ports are described in Table 7.8 and 7.9 in Section 7.2.2, respectively.

• **For two-antenna ports:** When RI = 1, a PMI value of $n \in \{0, 1, 2, 3\}$ corresponds to the codebook index $n$ given in Table 7.8 with $v = 1$; when RI = 2, a PMI value of $n \in \{0, 1\}$ corresponds to the codebook index $n+1$ given in Table 7.8 with $v = 2$.

• **For four-antenna ports:** A PMI value of $n \in \{0, 1, ..., 15\}$ corresponds to the codebook index $n$ given in Table 7.9 with $v$ = RI.

Accordingly, the number of feedback bits for PMI reporting can be determined and is shown in Table 9.14.

**Table 9.14** Number of Feedback Bits for PMI

| Two-Antenna Ports | Four-Antenna Ports |
|---|---|
| 2 (RI = 1)<br>1 (RI = 2) | 4 |

Although the codebooks are given in Tables 7.8 and 7.9, each UE can be restricted to report PMI within a subset of the predefined precoder codebook when specified by higher layer signaling. A bitmap is used to specify all possible precoder codebook subsets from which the UE can assume the eNode-B may be using. The codebook subset restriction is supported for OL and CL spatial multiplexing, multiuser MIMO, and closed-loop rank = 1 precoding, with the number of bits given in Table 9.15 for different transmission modes. In the case of OL spatial multiplexing, these precoders are used for the four-antenna case, as discussed in Section 7.2.2. A bit value of zero in the bitmap indicates that the PMI reporting is not allowed to correspond to the precoder associated with the bit. The association of bits to precoders for different MIMO modes is given as follows:

• **Open-loop spatial multiplexing**

– **Two-antenna ports:** There are 2 bits in the bitmap. The bit $a_0$ is associated with the precoder for the open-loop transmit diversity; the bit $a_1$ is associated with the precoder in Table 7.8 with index 0 and $v = 2$, i.e., the normalized identity matrix.

– **Four-antenna ports:** There are 4 bits in the bitmap. The bit $a_0$ is associated with the open-loop transmit diversity precoder for four-antenna ports; bit $a_{v-1}$, $v = 2, 3, 4$ is associated with the precoders in Table 7.9 corresponding to $v$ layers and codebook indices 12, 13, 14, and 15, and these precoders for each $v$ will be applied cyclically to the $v$ vectors on the PDSCH.

• **Closed-loop spatial multiplexing**

– **Two-antenna ports:** There are 6 bits associated with the 6 precoders in Table 7.8 except the precoder with index 0 and $v = 2$.

– **Four-antenna ports:** There are 64 bits associated with all the precoders in Table 7.9.

• **Multiuser MIMO and closed-loop Rank = 1 precoding**

– **Two-antenna ports:** There are 4 bits associated with the precoders in Table 7.8 for $v = 1$.

– **Four-antenna ports:** There are 16 bits associated with the precoders in Table 7.9 for $v = 1$.

**Table 9.15** Number of Bits in Codebook Subset Restriction Bitmap

| Transmission Mode | Number of Bits $A_c$ | |
|---|---|---|
| | Two-Antenna Ports | Four-Antenna Ports |
| Open-loop spatial multiplexing | 2 | 4 |
| Closed-loop spatial multiplexing | 6 | 64 |
| Multiuser MIMO | 4 | 16 |
| Closed-loop rank = 1 precoding | 4 | 16 |

Therefore, each reported PMI value corresponds to a codebook index given in Table 7.8 or Table 7.9 for two-antenna ports and four-antenna ports, respectively, with the subset restriction discussed above. In aperiodic reporting modes, PMI can be either wideband or subband, while only wideband PMI reporting is supported in periodic reporting modes.

The eNode-B can override the PMI reported by UEs. The actual precoding matrix used may be different from the PMI reported from the UE, and the eNode-B needs to send precoding information on PDCCH, which either indicates the actual PMI or informs the UE that the reported PMI is applied. This information field is called Transmit Precoding Matrix Indication (TPMI), which is contained in DCI format 2 for CL spatial multiplexing with 3 bits for two transmit antennas and 6 bits for four transmit antennas. If the TPMI indicates a precoding matrix, this matrix is used on all frequency resources allocated. The eNode-B may also decide to perform transmit diversity and indicate this in the TPMI. For OL spatial multiplexing, there is also a TPMI field contained in DCI format 2A, which indicates whether the transmit diversity or OL spatial multiplexing is used.

## 9.4 UPLINK CHANNEL SOUNDING

Channel sounding is mainly used for uplink channel quality measurement at the eNode-B. The Sounding Reference Symbol (SRS) is transmitted by the UE in the uplink for the eNode-B to estimate the channel state information, which includes the MIMO channel of the desired signal, SINR, noise, interference level, etc. The SRS can also be used for uplink timing estimation and uplink power control. The signal sequence and resource mapping of the SRS were discussed in Section 8.4.

The SRS transmission is always in the last SC-FDMA symbol in the configured subframe, on which PUSCH data transmission is not allowed. The eNode-B can either request an individual SRS transmission from a UE or configure a UE to periodically transmit SRS. The periodicity may take any value of 2, 5, 10, 20, 40, 80, 160, and 320 ms.

The UE-specific SRS parameters include the starting physical resource block assignment, duration of SRS transmission, SRS periodicity and SRS subframe offset, SRS bandwidth, frequency hopping bandwidth, and cyclic shift. These parameters are semi-statically configured by higher layers. A UE shall not transmit SRS in the following scenarios:

• If SRS and PUCCH format 2/2a/2b transmissions happen to coincide in the same subframe

• Whenever SRS and ACK/NAK and/or positive SR transmissions happen to coincide in the same subframe unless the parameter *Simultaneous-AN-and-SRS* is TRUE

If the UE is equipped with two transmit antennas, then it alternates between two-antennas every time the SRS is transmitted. This allows the eNode-B to select the transmit antenna if the closed-loop antenna selection is enabled.

## 9.5 BUFFER STATUS REPORTING IN UPLINK

A Buffer Status Report (BSR) is sent from the UE to the serving eNode-B to provide information about the amount of pending data in the uplink buffer of the UE. The buffer status, along with other information, such as priorities allocated to different logical channels, is useful for the uplink scheduling process to determine which UEs or logical channels should be granted radio resources at a given time.

A BSR is triggered if any of the following events occurs:

• Uplink data for a logical channel becomes available for transmission, and either the data belongs to a logical channel with higher priority than the priorities of the logical channels for which data is already available for transmission, or there is no data available for transmission for any of the logical channels. In this case, the BSR is referred to as “regular BSR.”

• Uplink resources are allocated and the number of padding bits is equal to or larger than the size of the BSR MAC control element, in which case the BSR is referred to as “padding BSR.”

• A serving cell change occurs, in which case the BSR is referred to as "regular BSR."

• The retransmission BSR timer expires and the UE has data available for transmission, in which case the BSR is referred to as "regular BSR."

• The periodic BSR timer expires, in which case the BSR is referred to as "periodic BSR."

The buffer status is reported on a per radio bearer[1] (logical channel) group basis, where a radio bearer group is defined as a group of radio bearers with similar QoS requirements and belong to the same QCI (QoS Class Identifier). There are two BSR formats used in the LTE uplink: short BSR that reports only one radio bearer group, and long BSR that reports multiple radio bearer groups. For regular and periodic BSR, if more than one radio bearer group has data available for transmission in the TTI where the BSR is transmitted, long BSR is reported; otherwise, short BSR is reported. For padding BSR:

• When the number of padding bits is equal to or larger than the size of the short BSR plus its subheader but smaller than the size of the long BSR plus its subheader, truncated BSR with the highest priority logical channel is reported if more than one logical channel group has buffered data; otherwise, short BSR is reported.

• If the number of padding bits is equal to or larger than the size of the long BSR plus its subheader, long BSR is reported.

When the BSR procedure determines that at least one BSR has been triggered, and then if the UE has been allocated uplink resources, a buffer status report is transmitted; if a regular BSR has been triggered and the UE has no allocated uplink resource, a scheduling request for a BSR transmission is triggered. A MAC PDU shall contain at most one MAC BSR control element, even when multiple events trigger. In this case, the regular BSR and the periodic BSR shall have precedence over the padding BSR. All triggered BSRs shall be cancelled in the following two scenarios:

• The uplink grant can accommodate all pending data available for transmission but is not sufficient to additionally accommodate the BSR MAC control element.

• A BSR is included in a MAC PDU for transmission.

## 9.6 SCHEDULING AND RESOURCE ALLOCATION

The main purpose of scheduling and resource allocation is to efficiently allocate the available radio resources to UEs to optimize a certain performance metric with QoS requirement constraints. Scheduling algorithms for LTE can be divided into two categories:

• **Channel-dependent scheduling:** The allocation of resource blocks to a UE is based on the channel condition, e.g., proportional fairness scheduler, max CI (Carrier to Interference) scheduler, etc.

• **Channel-independent scheduling:** The allocation of resource blocks to a UE is random and not based on channel condition, e.g., round-robin scheduler.

In a multicarrier system such as LTE, channel-dependent scheduling can be further divided into two categories:

• **Frequency diverse scheduling:** The UE selection is based on wideband CQI. However, the PRB allocation in the frequency domain is random. It can exploit time selectivity and frequency diversity of the channel.

• **Frequency selective scheduling:** The UE selection is based on both wideband and subband CQI, and the PRB allocation is based on the subband CQI. This can exploit both time and frequency selectivity of the channel.

In this section, we mainly focus on the frequency selective scheduling.

Dynamic channel-dependent scheduling is one of the key features to provide high spectrum efficiency in LTE. To better exploit the channel selectivity, the packet scheduler is located in the eNode-B, which allocates physical layer resources for both the DL-SCH and UL-SCH transport channels every TTI. Resource assignment consists of PRBs and MCS. Such scheduling depends heavily on the channel information available at the eNode-B, which is provided by the uplink CQI reporting for the downlink channel and by channel sounding for the uplink channel, as discussed in Section 9.2 and Section 9.4, respectively. The scheduler should also take account of the traffic volume and the QoS requirement of each UE and associated radio bearers. Due to the implementation of OFDMA/SC-FDMA, LTE is able to exploit the channel variation in both the time and frequency domain, which is a major advantage compared to HSPA, which is able to exploit channel variation only in the time domain.

The objective of channel-dependent scheduling, as discussed in Chapter 4, is to exploit multiuser diversity to improve the spectrum efficiency. Meanwhile, it should also consider such issues as fairness and QoS requirements. In addition, scheduling is tightly integrated with link adaptation and the H-ARQ process. The scheduling algorithm is not standardized and is eNode-B vendor specific. See [10–13] for the investigation of different scheduling schemes in LTE, and refer to Chapter 4 for related discussion. In this section, we focus on the signaling for both downlink and uplink scheduling. Dynamic scheduling is mainly applied on the data traffic, which is the focus in this section. The scheduling of VoIP services will be discussed in Section 9.7.

## 9.6.1 Signaling for Scheduling in Downlink and Uplink

For both downlink and uplink, the eNode-B scheduler dynamically controls which time-frequency resources are allocated to a certain UE. The resource assignments, including the assigned time/frequency resources and respective transmission formats, are conveyed through downlink control signaling. The minimum size of radio resource that can be allocated to a UE corresponds to two resource blocks, which is 1 ms duration in the time domain and 180kHz in the frequency domain. Both downlink and uplink employ orthogonal transmission, so each resource block is allocated to a single UE except in the MU-MIMO mode. Both localized and distributed resource allocations are supported in the downlink, while in the uplink UEs are always assigned contiguous resources, i.e., only localized allocation is supported. In addition, there is a strict constraint on the UE transmit power in the uplink, which is subject to the uplink power control that will be discussed in Section 9.10.

**Signaling for Downlink Scheduling**

The channel state information at the eNode-B for the downlink scheduling is obtained through CQI reporting from UEs, as discussed in Section 9.2. To enable frequency selective scheduling, subband CQI reporting is required. The eNode-B dynamically allocates resources to UEs at each TTI. A UE always monitors the PDCCH for possible allocations. For dynamically scheduled data traffic, the UE is configured by the higher layers to decode the PDCCH with CRC scrambled by the C-RNTI.[2] The UE shall decode the PDCCH and any corresponding PDSCH according to the respective combinations defined in Table 9.16. For example, when a UE configured in transmission mode 3 or 4 (OL and CL spatial multiplexing) receives a DCI format 1A assignment, it shall assume that the PDSCH transmission is associated with transport block 1 and that transport block 2 is disabled, and transmit diversity is applied. The DCI carries the downlink scheduling assignment and other information necessary to decode and demodulate data symbols. The transport channel processing of DCI was described in Section 7.3.

**Table 9.16** PDCCH and PDSCH Configured by C-RNTI

| UE DL Transmission Mode | DCI Format | Transmission Scheme of PDSCH |
|---|---|---|
| Mode 1 | DCI format 1A | Single-antenna port, port 0 |
| | DCI format 1 | Single-antenna port, port 0 |
| Mode 2 | DCI format 1A | Transmit diversity |
| | DCI format 1 | Transmit diversity |
| Mode 3 | DCI format 1A | Transmit diversity |
| | DCI format 2A | OL spatial multiplexing or transmit diversity |
| Mode 4 | DCI format 1A | Transmit diversity |
| | DCI format 2 | CL spatial multiplexing or transmit diversity |
| Mode 5 | DCI format 1A | Transmit diversity |
| | DCI format 1D | Multiuser MIMO |
| Mode 6 | DCI format 1A | Transmit diversity |
| | DCI format 1B | Closed-loop Rank = 1 precoding |
| Mode 7 | DCI format 1A | If the number of PBCH antenna ports is one, single-antenna port (port 0); otherwise, transmit diversity |
| | DCI format 1 | Single-antenna port, port 5 |

As shown in Section 6.3.3, in the downlink, while the two distributed allocation types (resource allocation type 0 and type 1) provide better performance with a high overhead, the localized allocation type (resource allocation type 2) provides a low overhead alternative at the cost of limited scheduling flexibility. The UE shall interpret the resource allocation field depending on the PDCCH DCI format detected. PDCCH DCI formats 1, 2, and 2A with type 0 and with type 1 resource allocation have the same format and are distinguished via the single bit resource allocation header field, where type 0 is indicated by 0 value and type 1 is indicated otherwise. PDCCH with DCI format 1A, 1B, 1C, and 1D have a type 2 resource allocation while PDCCH with DCI format 1, 2, and 2A have type 0 or type 1 resource allocation. The details of the resource assignment can be interpreted from DCI for different formats.

To determine the modulation order and transport block size, the UE shall first read the 5-bit “modulation and coding scheme” field ($I_{MCS}$) in the DCI, based on which a Transport Block Size (TBS) index can also be determined. The mapping between the MCS index $I_{MCS}$, the modulation order, and TBS index $I_{TBS}$ for PDSCH is shown in Table 9.17. The TBS can then be determined based on $I_{TBS}$ and the total number of allocated PRBs. Note that in Table 9.17 different MCS indices may be mapped to the same TBS, e.g., $I_{MCS} = 9, 10$ are mapped to $I_{TBS} = 9$, resulting in the same data rate. Such modulation overlap is adopted to improve the performance around the modulation switching points, as different combinations of modulation and coding with the same rate may provide different performance in different scenarios. For $29 \leq I_{MCS} \leq 31$, the TBS is determined from the previous scheduling grant for the same transport block using $0 \leq I_{MCS} \leq 28$.

**Table 9.17** Modulation and TBS Index for PDSCH

| MCS Index $I_{MCS}$ | Modulation Order | TBS Index $I_{TBS}$ |
|---|---|---|
| 0 | 2 | 0 |
| 1 | 2 | 1 |
| 2 | 2 | 2 |
| 3 | 2 | 3 |
| 4 | 2 | 4 |
| 5 | 2 | 5 |
| 6 | 2 | 6 |
| 7 | 2 | 7 |
| 8 | 2 | 8 |
| 9 | 2 | 9 |
| 10 | 4 | 9 |
| 11 | 4 | 10 |
| 12 | 4 | 11 |
| 13 | 4 | 12 |
| 14 | 4 | 13 |
| 15 | 4 | 14 |
| 16 | 4 | 15 |
| 17 | 6 | 15 |
| 18 | 6 | 16 |
| 19 | 6 | 17 |
| 20 | 6 | 18 |
| 21 | 6 | 19 |
| 22 | 6 | 20 |
| 23 | 6 | 21 |
| 24 | 6 | 22 |
| 25 | 6 | 23 |
| 26 | 6 | 24 |
| 27 | 6 | 25 |
| 28 | 6 | 26 |
| 29 | 2 | reserved |
| 30 | 4 | |
| 31 | 6 | |

**Signaling for Uplink Scheduling**

In the uplink, the channel state information is estimated at the eNode-B with the help of sounding reference signals, as discussed in Section 9.4. A UE always monitors the PDCCH in order to find possible allocation for uplink transmission. Only contiguous resource blocks can be allocated to a UE due to the SCFDMA nature of the UL transmission'. Frequency hopping can be applied to provide additional diversity. The UE obtains the uplink resource allocation as well as frequency hopping information from the uplink scheduling grant received four subframes earlier, i.e., if the UE detects a PDCCH with DCI format 0 in subframe $n$ intended for this UE, it will adjust the corresponding PUSCH transmission in subframe $n + 4$ accordingly.

To determine the modulation order, redundancy version, and transport block size for the PUSCH, the UE shall first read the 5-bit "modulation and coding scheme and redundancy version" field ($I_{MCS}$) in the DCI. The mapping between $I_{MCS}$, modulation order, and $I_{TBS}$ for the PUSCH is shown in Table 9.18. Note that $I_{MCS}$ also indicates the H-ARQ redundancy version. The redundancy version 1, 2, or 3 is indicated by $I_{MCS}$ = 29, 30, 31, respectively, in which case the modulation order is assumed to be the one indicated in the initial grant. Similar to the downlink, there is also modulation overlap around the switching points, e.g., $I_{MCS}$ = 10, 11 are both mapped to $I_{TBS}$ = 10. The transport block size can be determined from $I_{MCS}$ and $I_{TBS}$. For $20 \leq I_{MCS} \leq 31$, the transport block size is assumed to be as determined from DCI transport in the initial PDCCH for the same transport block using $0 \leq I_{MCS} \leq 28$.

**Table 9.18** Modulation, TBS Index, and Redundancy Version for PUSCH

| MCS Index $I_{MCS}$ | Modulation Order | TBS Index $I_{TBS}$ | Redundancy Version |
|---|---|---|---|
| 0 | 2 | 0 | 0 |
| 1 | 2 | 1 | 0 |
| 2 | 2 | 2 | 0 |
| 3 | 2 | 3 | 0 |
| 4 | 2 | 4 | 0 |
| 5 | 2 | 5 | 0 |
| 6 | 2 | 6 | 0 |
| 7 | 2 | 7 | 0 |
| 8 | 2 | 8 | 0 |
| 9 | 2 | 9 | 0 |
| 10 | 2 | 10 | 0 |
| 11 | 4 | 10 | 0 |
| 12 | 4 | 11 | 0 |
| 13 | 4 | 12 | 0 |
| 14 | 4 | 13 | 0 |
| 15 | 4 | 14 | 0 |
| 16 | 4 | 15 | 0 |
| 17 | 4 | 16 | 0 |
| 18 | 4 | 17 | 0 |
| 19 | 4 | 18 | 0 |
| 20 | 4 | 19 | 0 |
| 21 | 6 | 19 | 0 |
| 22 | 6 | 20 | 0 |
| 23 | 6 | 21 | 0 |
| 24 | 6 | 22 | 0 |
| 25 | 6 | 23 | 0 |
| 26 | 6 | 24 | 0 |
| 27 | 6 | 25 | 0 |
| 28 | 6 | 26 | 0 |
| 29 | reserved | reserved | 1 |
| 30 | reserved | reserved | 2 |
| 31 | reserved | reserved | 3 |

## 9.6.2 Multiuser MIMO Signaling

If MU-MIMO is used in the uplink, then it is transparent to the UE with the exception that two UEs should transmit orthogonal reference signals in order for the eNode-B to separate them. The uplink resource allocation is indicated on PDCCH using DCI format 0, which contains a 3-bit field to indicate the cyclic shift in the reference signal to be used by each UE.

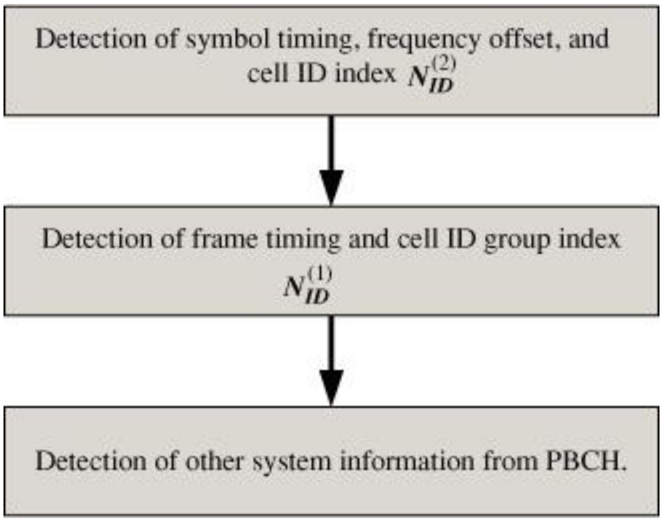
When MU-MIMO is used in the downlink, two rank-1 UEs are multiplexed on the same physical resource. Unlike SU-MIMO, in this case the power for each UE is reduced by 3 dB. This is indicated by the power offset field in DCI format 1D, which is used for MU-MIMO scheduling.

## 9.8 CELL SEARCH

When a UE powers on, it needs to acquire time and frequency synchronization with a cell and detect the physical-layer cell ID of that cell through the cell search procedure or synchronization procedure. Such synchronization is especially important for LTE, as the performance of LTE systems relies on the orthogonal intra-cell transmission in both uplink and downlink. During cell search, different types of information need to be identified by the UE, including symbol and frame timing, frequency, cell identification, transmission bandwidth, antenna configuration, and the cyclic prefix length.

LTE uses a hierarchical cell search scheme similar to WCDMA, demonstrated in Figure 9.4. As described in Section 7.6.2, a primary synchronization signal carrying the information about the physical-layer ID within the cell-ID group $(N_{ID}^{(2)} = 0, 1, 2)$ and a secondary synchronization signal carrying the physical-layer cell-ID group $(N_{ID}^{(1)} = 0, 1, \ldots, 167)$ are defined. The cell ID is then determined as $N_{ID}^{cell} = 3N_{ID}^{(1)} + N_{ID}^{(2)}$. Different from WCDMA, the cell search in LTE needs to consider different system bandwidths and different duplexing schemes, i.e., TDD and FDD. This is achieved by defining a common synchronization signal structure for all supported bandwidths, which occupies six resource blocks (72 subcarriers) centered around the DC subcarrier, corresponding to the most narrow bandwidth supported in LTE. In the time domain, there are two pairs of primary and secondary synchronization signals in each radio frame. The arrangement of the primary and secondary synchronization is done in a manner such that it is compatible with both the TDD and FDD frame structure.

**Figure 9.4** The cell search process.




In the first step of cell search, the UE detects the symbol timing and the cell ID index $N_{ID}^{(2)}$ from the primary synchronization signal. This can be achieved, e.g., through matched filtering between the received signal and the primary synchronization sequences. As there are three orthogonal sequences defined for the primary synchronization signal, the cell ID index $N_{ID}^{(2)}$ can be detected by identifying the received sequence. Frequency and Time synchronization can be performed based on the primary synchronization signal. OFDM symbol timing can be detected, but as there are two primary synchronization signals transmitted in each frame that are indistinguishable, frame timing cannot be detected.

In the next step, the UE detects the cell ID group index $N_{ID}^{(1)}$ and frame timing from the secondary synchronization signal. The index $N_{ID}^{(1)}$ is detected by identifying the shift in the m-sequence in the received signal. For detecting the frame timing, the pair of secondary synchronization signals in a radio frame has a different structure than primary synchronization signals: If the sequence pair of secondary synchronization signals $(\mathbf{d}_1, \mathbf{d}_2)$ is defined, then $(\mathbf{d}_2, \mathbf{d}_1)$ is not allowed. This property is used to resolve the 5-ms timing ambiguity in the first step, based on which the frame timing can be determined.

After the cell search, the UE can detect the broadcast channel to obtain other physical layer information, e.g., system bandwidth, number of transmit antennas, and system frame number. As discussed in Section 7.4, the system information is divided into Master Information Block (MIB) transmitted on the PBCH and System Information Blocks (SIB) transmitted on the PDSCH. At this stage, the UE detects MIB from the PBCH.

To maintain the uplink intra-cell orthogonality, uplink transmissions from different UEs should arrive at the eNode-B within a cyclic prefix. This is achieved through the timing advance procedure. The timing advance is obtained from the uplink received timing and sent by the eNode-B to the UE. The UE advances or delays its timing of transmissions to compensate for propagation delay and thus time-aligns its transmissions with other UEs. The timing advance command is on a per-need basis with a granularity in the step size of $0.52\mu s$ ($16 \times T_s$).

## 9.9 RANDOM ACCESS PROCEDURES

In LTE, there are two random access mechanisms:

• **Non-synchronized random access:** Non-synchronized random access is used when the UE uplink has not been time synchronized, or when the UE uplink loses synchronization. Its main purpose is to obtain synchronization of the uplink, notify the eNode-B that the UE has data to transmit, or transmit a small amount of control information and data packets.

• **Synchronized random access:** Synchronized random access is used when uplink synchronization is present. Its main purpose is to request resources for uplink data transmission from the eNode-B scheduler.

In this section, we focus on non-synchronized random access. The procedure of synchronized random access is similar except that it does not need the response of uplink timing information.

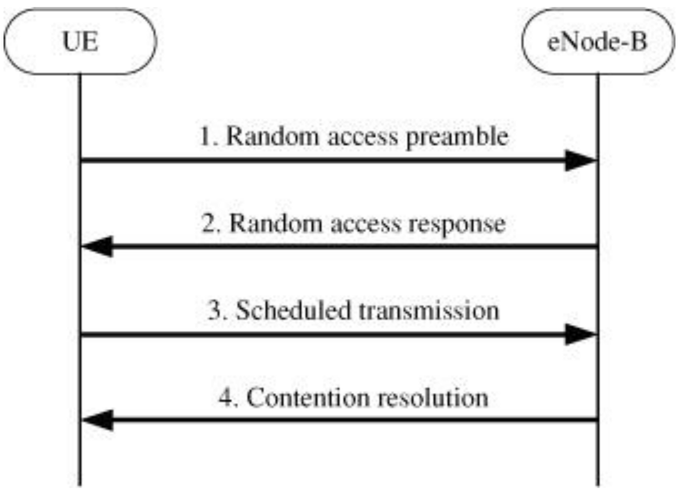
After the cell search procedure, the UE has obtained downlink synchronization. However, the uplink timing is not established due to the round-trip propagation delay. The non-synchronized access allows the eNode-B to estimate the UE transmission timing to within a fraction of the cyclic prefix and inform the UE about the timing correction. With uplink synchronization, the UE may request resources for uplink transmission. The eNode-B can also schedule data transmission in the resource blocks reserved for random access channel preamble transmission.

Prior to initiation of the non-synchronized random access procedure, each UE obtains the following information broadcast from eNode-B: random access channel parameters, including PRACH configuration; frequency position and preamble format; parameters for determining the root sequences, and their cyclic shifts in the preamble sequence set for the cell.

The non-synchronized random access procedure, which consists of four steps, is depicted in Figure 9.5 and described here:

1. First, multiple UEs transmit randomly selected random access code.
2. Second, eNode-B conducts a multiuser detection process and allocates resources to the detected UEs.
3. Third, each UE transmits detailed information using allocated resources.
4. Fourth, the eNode-B transmits the contention-resolution message on the DL-SCH. When the previous steps are finished successfully, eNode-B and each UE initiate data communication.

**Figure 9.5** The non-synchronized random access procedure.




## Step 1: Random Access Preamble Transmission

Based on the information obtained from eNode-B, the UE randomly selects a random access preamble, and transmits on the PRACH physical channel. The processing of random access channels and the random access preamble were discussed in Section 8.5. Open-loop power control is used to determine the initial transmit power level. Multiple UEs may transmit their random access preambles simultaneously through the same channel, and the eNode-B monitors the random access channel and conducts multiuser detection identifying each RACH transmission. The RACH signals from the different UEs are based on the Zadoff-Chu sequence with different cyclic shift resulting in a zero cross-correlation between them. This zero cross-correlation of the Zadoff-Chu sequence allows the eNode-B to simultaneously detect multiple UEs using a correlation-based detection process. The eNode-B also calculates the timing correction for the uplink transmission for each UE.

## Step 2: Random Access Response

If a random access attempt is detected, the eNode-B transmits the corresponding random access response on the DL-SCH, which contains the identity of the detected preamble, the timing correction for uplink transmission, a temporary identity for transmission in following steps, and an initial uplink resource grant. The random access response message can also include a backoff indicator to instruct the UE to back off for a period of time before retrying another random access attempt. The uplink scheduling grant for the following uplink transmission contains 20 bits, and the content is illustrated in Table 9.20. For the UE, once the random access preamble is transmitted, it will monitor the PDCCH for random access response identified by the Random Access Radio Network Temporary Identifier (RA-RNTI), as the time-frequency slot carrying the preamble is associated with an RA-RNTI. If the received random access response matches the transmitted preamble, the UE may stop monitoring.

**Table 9.20** The Content of Random Access Response Grant

| Information Type | Number of Bits | Purpose |
|---|---|---|
| Hopping flat | 1 | Indicates whether PUSCH frequency hopping is applied in the following step. |
| Fixed-size resource block assignment | 10 | Indicates the assigned radio resource for the following transmission. |
| Truncated modulation and coding scheme | 4 | Determines the modulation and coding scheme. |
| TPC command for scheduled PUSCH | 3 | Adjusts the transit power of PUSCH. |
| UL delay | 1 | Adjusts the uplink transmission timing. |
| CQI request | 1 | Used in non-contention-based random access procedure to determine whether an aperiodic CQI report is included in the corresponding PUSCH transmission. |

## Step 3: Scheduled Transmission

After step 2, the UE is uplink synchronized, and can transmit additional messages on scheduled UL-SCH. This step is to assist contention resolution. If the UEs that perform random access attempts in the same time-frequency resource use different preambles, different UEs can be identified by the eNode-B and there is no collision. However, it is possible that multiple UEs select the same preamble, which causes a collision. To resolve the contention for access, the UE that detects a random access preamble transmits a message containing a terminal identity. If the

UE is connected to a cell, Cell Radio Network Temporary Identifier (C-RNTI) will be used, which is a unique UE ID at the cell level; otherwise, a core network identifier is used. In step 3, the H-ARQ protocol is supported to improve the transmission reliability.

### Step 4: Contention Resolution

Contention resolution is the key feature of the random access channel. In this step, the eNode-B transmits the contention-resolution message on the DL-SCH, which contains the identity of the winning UE. The UE that observes a match between this identity and the identity transmitted in step 3 declares a success and completes its random access procedure. If this UE has not been assigned a C-RNTI, the temporary identity is then set as its C-RNTI. The H-ARQ protocol is supported in this step, and the UE with successful access will transmit an H-ARQ acknowledgment.

## 9.10 POWER CONTROL IN UPLINK

With SC-FDMA-based transmission in the LTE uplink, orthogonality between intra-cell transmission from multiple UEs is achieved, which removes the intra-cell interference and the near-far issue typical of CDMA-based systems such as W-CDMA/HSPA. This leaves inter-cell interference as the major cause of interference and performance degradation, especially for the cell-edge UEs. In LTE, the power control in the uplink is to control the interference caused by UEs to neighboring cells while maintaining the required SINR at the serving cell. In this section, we describe the power control scheme for the PUSCH transmission in the uplink.

Conventional power control in the uplink is to achieve the same SINR for different UEs at the base station, also known as full compensation, but it suffers low spectral efficiency as the common SINR is limited by the cell-edge UEs. LTE specifies Fractional Power Control (FPC) as the open-loop power control scheme, which allows for full or partial compensation of path loss and shadowing [7, 9, 14]. FPC allows the UEs with higher path loss, i.e., cell-edge UEs, to operate with lower SINR requirements so that they generate less interference to other cells, while having a minor impact on the cell-interior UEs so that they are able to transmit at higher data rates. Besides open-loop power control, there is also a closed-loop power control component, which is to further adjust the UE transmission power to optimize the system performance.

We first describe the FPC scheme, based on which the UE adjusts the transmission power according to:

(9.11)

$$P = \min\{P_{max}, 10 \log M + P_0 + \alpha \cdot PL\} \text{ [dBm]},$$

where $P_{max}$ is the maximum UE transmission power, $M$ is the number of assigned PRBs, $P_0$ is a parameter that controls the mean received SINR, $\alpha$ is the cell-specific path loss compensation factor, and $PL$ is the downlink path loss estimate calculated in the UE. Note that the transmit power increases with $M$, which is to to ensure the same power spectral density irrespective of the number of PRBs.

If we only consider path loss and assume $10 \log M + P_0 + \alpha \cdot PL \leq P_{max}$, then the received signal power at the eNode-B is

(9.12)

$$P_r = P - PL = 10 \log M + P_0 + (\alpha - 1) \cdot PL \text{ [dBm]}.$$

• If $\alpha = 1$, each UE has a constant received power, which corresponds to full compensation, or channel inversion.

• If $\alpha = 0$, each UE has the same transmission power that is independent of the path loss, i.e., no power control.

• For $0 < \alpha < 1$, it is the FPC, and different UEs will have different $P_r$, depending on their path loss to the serving base station.

We see that reducing the value of $\alpha$ mainly decreases the transmission power of celledge UEs, which have large PLs and are likely to cause a high level of interference to neighboring cells. Therefore, by adjusting the path loss compensation factor $\alpha$, we can reduce inter-cell interference and improve the spectrum efficiency.

Considering both open-loop and closed-loop components, the UE sets its total transmission power using the following formula:

(9.13)

$$P = \min\{P_{max}, 10 \log M + P_0(j) + \alpha(j) \cdot PL + \Delta_{MCS} + f(\Delta_i)\} \text{ [dBm]}.$$

There are three different PUSCH transmission types, corresponding to $j = 0, 1, 2$:

- For PUSCH (re)transmissions corresponding to a semi-persistent grant, $j = 0$.
- For PUSCH (re)transmissions corresponding to a dynamic scheduled grant, $j = 1$.
- For PUSCH (re)transmissions corresponding to the random access response grant, $j = 2$.

The parameters in (9.13) are described as follows:

- For $j = 0$ or 1, $P_0$ is composed of the sum of a cell-specific nominal component and a UE-specific component, provided by higher layers; for $j = 2$, $P_0$ is a cell-specific parameter signalled from higher layers.
- For $j = 0$ or 1, $\alpha(j)$ is a 3-bit cell-specific parameter, $\alpha(j) \in \{0, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1\}$; for $j = 2$, $\alpha(j) = 1$.
- $\Delta_{MCS}$ is a UE-specific parameter depending on the chosen modulation and coding scheme (MCS). A large value of $\Delta_{MCS}$ corresponds to higher coding rate and/or higher modulation order.
- $\Delta_i$ is a UE-specific closed-loop correction value included in the PDCCH, which is also referred to as a Transmit Power Control (TPC) command. This is to compensate the following effects including power amplifier error, path loss estimation error, and inter-cell interference level changes.
- The function $f(\cdot)$ is to perform closed-loop power control based on $\Delta_i$. It is UE specific. There are two types of closed-loop power control defined in LTE:

– **Accumulated:** The UE applies an offset based on $\Delta_i$ using the latest transmission power value as reference:

(9.14)

$$f(\Delta_i) = f(\Delta_{i-1}) + \Delta_{i-K}.$$

The value of $\Delta_i$ is $\Delta_i \in \{-1, 0, 1, 3\}$ [dB]. For the FDD mode, $K = 4$, and for the TDD mode, the value of $K$ depends on the UL/DL configuration [3].

– **Absolute:** The UE adjusts the transmission power with an absolute value based on $\Delta_i$:

(9.15)

$$f(\Delta_i) = \Delta_{i-K}.$$

For this case, the value of $\Delta_i$ is $\Delta_i \in \{-4, -1, 1, 4\}$ [dB]. For the FDD mode, $K = 4$, and for the TDD mode, the value of $K$ depends on the UL/DL configuration [3].

A similar power control scheme employing FPC is used for sounding reference signals.