Table 9.6 RBG size for Type 0 resource allocation.

Downlink bandwidth $N_{\mathrm{RB}}^{\mathrm{DL}}$	RBG size (P)
$0 \leq 10$	1
11–26	2
27–63	3
64–110	4

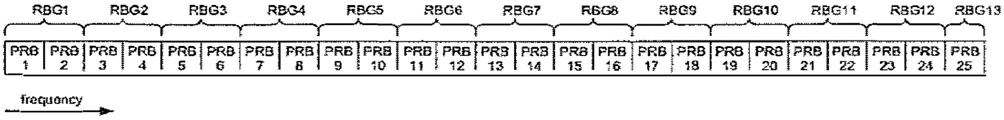

Figure 9.10 PRB addressed by a bitmap Type 0, each bit addressing a complete RBG.

smaller than for Type 0, since some bits are used to indicate the subset of the RBG which is addressed, and a shift in the position of the bitmap. The total number of bits (including these additional flags) is the same as for Type 0. An example for the case of $N_{\mathrm{RB}}^{\mathrm{DL}} = 25$, $N_{\mathrm{RBG}} = 11$ and $P = 2$ is shown in Figure 9.11. One bit is used for subset selection and another bit to indicate the shift.

The motivation for providing this method of resource allocation is flexibility in spreading the resources across the frequency domain to exploit frequency diversity.

Resource allocation Type 2. In resource allocations of Type 2, the resource allocation information indicates to a scheduled UE either:

- a set of contiguously allocated PRBs, or
- a distributed allocation comprising multiple non-consecutive PRBs (see Section 9.2.2.1).

The distinction between the two allocation methods is made by a 1-bit flag in the resource allocation message. PRB allocations may vary from a single PRB up to a maximum number of PRBs spanning the system bandwidth. A Type 2 resource allocation field consists of a Resource Indication Value (RIV) corresponding to a starting resource block ($\mathrm{RB}_{\mathrm{START}}$) and a length in terms of contiguously-allocated resource blocks (L_{CRBs}). The resource indication value is defined by

$$\text{if} \quad (L_{\mathrm{CRBs}} - 1) \leq \lfloor N_{\mathrm{RB}}^{\mathrm{DL}}/2 \rfloor \quad \text{then} \quad \mathrm{RIV} = N_{\mathrm{RB}}^{\mathrm{DL}}(L_{\mathrm{CRBs}} - 1) + \mathrm{RB}_{\mathrm{START}}$$

else

$$\mathrm{RIV} = N_{\mathrm{RB}}^{\mathrm{DL}}(N_{\mathrm{RB}}^{\mathrm{DL}} - L_{\mathrm{CRBs}} + 1) + (N_{\mathrm{RB}}^{\mathrm{DL}} - 1 - \mathrm{RB}_{\mathrm{START}})$$

An example of a method for reversing the mapping to derive the resource allocation from the RIV can be found in [2].

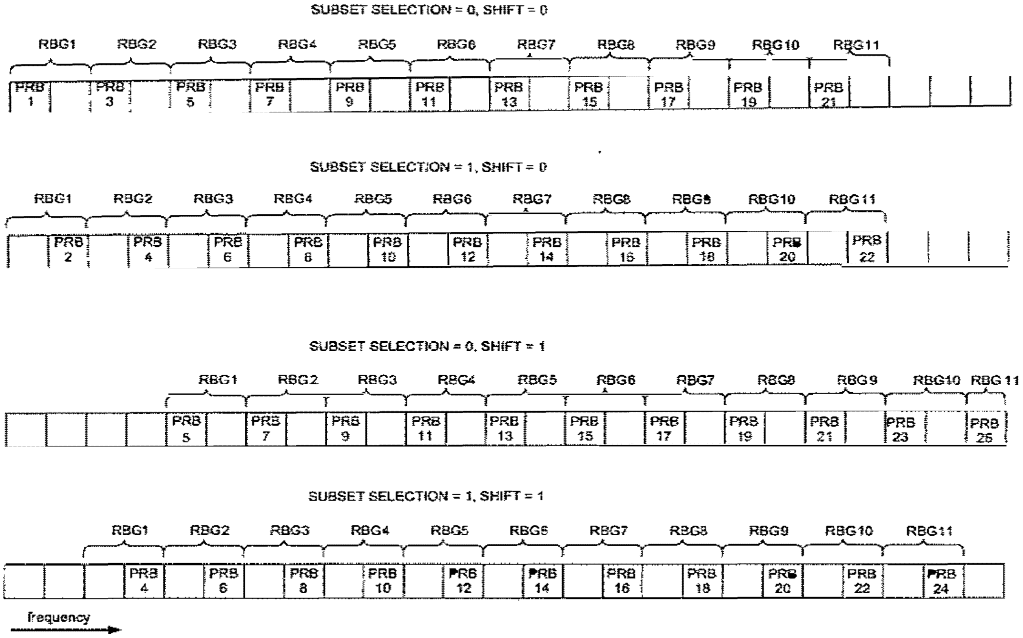

Figure 9.11 PRBs addressed by a bitmap Type 1, each bit addressing a subset of a RBG, depending on a subset selection and shift value.

9.3.3.2 PDCCH Transmission and Blind Decoding

The previous discussion has covered the structure and possible contents of an individual PDCCH message, and transmission by an eNodeB of multiple PDCCHs in a subframe. This section addresses the question of how these transmissions are organized so that a UE can locate the PDCCHs intended for it, while at the same time making efficient use of the resources allocated for PDCCH transmission.

A simple approach, at least for the eNodeB, would be to allow the eNodeB to place any PDCCH anywhere in the PDCCH resources (or CCEs) indicated by the PCFICH. In this case the UE would need to check all possible PDCCH locations, PDCCH formats and DCI formats, and act on those messages with correct CRCs (taking into account that the CRC is scrambled with a UE identity). Carrying out such a 'blind decoding' of all the possible combinations would require the UE to make many PDCCH decoding attempts in every subframe. For small system bandwidths the computational load would be reasonable, but for large system bandwidths, with a large number of possible PDCCH locations, it would become a significant burden, leading to excessive power consumption in the UE receiver. For example, blind decoding of 100 possible CCE locations for PDCCH Format 0 would be equivalent to continuously receiving a data rate of around 4 Mbps.

The alternative approach adopted for LTE is to define for each UE a limited set of CCE locations where a PDCCH may be placed. Such a constraint may lead to some limitations as to which UEs can be sent PDCCHs within the same subframe, which would thus restrict the UEs to which the eNodeB could grant resources. Therefore it is important for good system performance that the set of possible PDCCH locations available for each UE is not too small.

The set of CCE locations in which the UE may find its PDCCHs can be considered as a 'search space'. In LTE the search space is a different size for each PDCCH format. Moreover, separate *dedicated* and *common* search spaces are defined, where a dedicated search space is configured for each UE individually, while all UEs are informed of the extent of the common search space. Note that the dedicated and common search spaces may overlap for a given UE. The sizes of the common and dedicated search spaces are listed in Table 9.7.

Table 9.7 Search spaces for PDCCH formats.

PDCCH format	Number of CCEs (n)	Number of candidates in common search space	Number of candidates in dedicated search space
0	1	—	6
1	2	—	6
2	4	4	2
3	8	2	2

With such small search spaces it is quite possible in a given subframe that the eNodeB cannot find CCE resources to send PDCCHs to all the UEs that it would like to, because having assigned some CCE locations the remaining ones are not in the search space of a particular UE. To minimize the possibility of such blocking persisting into the next subframe, a UE-specific hopping sequence is applied to the starting positions of the dedicated search spaces.

In order to keep under control the computational load arising from the total number of blind decoding attempts, the UE is not required to search for all the defined DCI formats simultaneously. Typically, in the dedicated search space, the UE will always search for Formats 0 and 1A, which are both the same size and are distinguished by a flag in the message. In addition, a UE may be required to receive a further format (i.e. 1, 1B or 2, depending on the PDSCH transmission mode configured by the eNodeB).

In the common search space the UE will search for Formats 1A and 1C. In addition the UE may be configured to search for Format 3 or 3A, which have the same size as formats 0 and 1A, and may be distinguished by having the CRC scrambled by a different (common) identity, rather than a UE-specific one.

Considering the above, the UE would be required to carry out a maximum of 44 blind decodings in any subframe. This does not include checking the same message with different CRC values, which requires only a small additional computational complexity.

It is also worth noting that the PDCCH structure is adapted to avoid situations where a PDCCH CRC 'pass' might occur for multiple positions in the configured search-spaces due to repetition in the channel coding (for example, if a PDCCH was mapped to a high number of CCEs with a low code rate, then the CRC could pass for an overlapping smaller set of CCEs as well if the channel coding repetition was aligned). Such situations are avoided by adding a padding bit to any PDCCH messages having a size which could result in this problem occurring.

9.3.4 Scheduling Process from a Control Channel Viewpoint

To summarize the operation of the downlink control channels, a typical sequence of steps carried out by the eNodeB could be envisaged as follows:

1. Determine which UEs should be granted resources in the uplink, based on information such as channel quality measurements, scheduling requests and buffer status reports. Also decide on which resources should be granted.
2. Determine which UEs should be scheduled for packet transmission in the downlink, based on information such as channel quality indicator reports, and in the case of MIMO, rank indication and preferred precoding matrix.
3. Identify any common control channel messages which are required (e.g. power control commands using DCI Format 3).
4. For each message decide on the PDCCH format (i.e. 1, 2, 4 or 8 CCEs), and any power offset to be applied, in order to reach the intended UE(s) with sufficient reliability, while minimizing PDCCH overhead.
5. Determine how much PDCCH resource (in terms of CCEs) will be required, how many OFDM symbols would be needed for these PDCCHs and therefore what should be signalled on PCFICH.
6. Map each PDCCH to a CCE location within the appropriate search space.
7. If any PDCCHs cannot be mapped to a CCE location because all locations in the relevant search space have already been assigned, either:
    - continue to next step (step 8) accepting that one or more PDCCHs will not be transmitted, and not all DL-SCH and/or UL-SCH resources will be used, with a likely loss in throughput, or:
    - allocate one more OFDM symbol to support the required PDCCHs and possibly revisit step 1 and/or 2 and change UE selection and resource allocation (e.g. to fully use uplink and downlink resources).
8. Allocate the necessary resources to PCFICH and PHICH.
9. Allocate resources to PDCCHs.
10. Check that total power level per OFDM symbol does not exceed maximum allowed, and adjust if necessary.
11. Transmit downlink control channels.

Whatever approach the eNodeB implementer follows, the potentially high complexity of the scheduling process is clear, particularly bearing in mind that a cell may easily contain many hundreds of active UEs.

References[5]

[1] 3GPP Technical Specification 36.321, 'Multiplexing and Channel Coding (FDD) (Release 8)', www.3gpp.org.

[2] NEC, 'R1-072119: DL Unicast Resource Allocation Signalling', www.3gpp.org, 3GPP TSG RAN WG1, meeting 49, Kobe, Japan, May 2007.

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[5] All web sites confirmed 18th December 2008.

17

Uplink Physical Channel Structure

Robert Love and Vijay Nangia

17.1 Introduction

The LTE Single-Carrier Frequency Division Multiple Access (SC-FDMA) uplink provides separate physical channels for the transmission of data and control signalling, the latter being predominantly to support the downlink data transmissions. The detailed structure of these channels, as explained in this chapter, is designed to make efficient use of the available frequency-domain resources, and to support effective multiplexing between data and control signalling.

LTE also introduces multiple antenna techniques to the uplink, including closed-loop antenna selection and Spatial Division Multiple Access (SDMA) or Multi-User Multiple-Input Multiple-Output (MU-MIMO). The physical layer transmissions of the LTE uplink are comprised of three physical channels and two signals:

- PRACH – Physical Random Access CHannel (see Chapter 19);
- PUSCH – Physical Uplink Shared CHannel (see Section 17.2);
- PUCCH – Physical Uplink Control CHannel (see Section 17.3);
- DM RS – DeModulation Reference Signal (see Section 16.5);
- SRS – Sounding Reference Signal (see Section 16.6).

The uplink physical channels, and their relationship to the higher-layer channels, are summarized in Figure 17.1.

LTE – The UMTS Long Term Evolution: from Theory to Practice Stefania Sesia, Issam Toufik and Matthew Baker

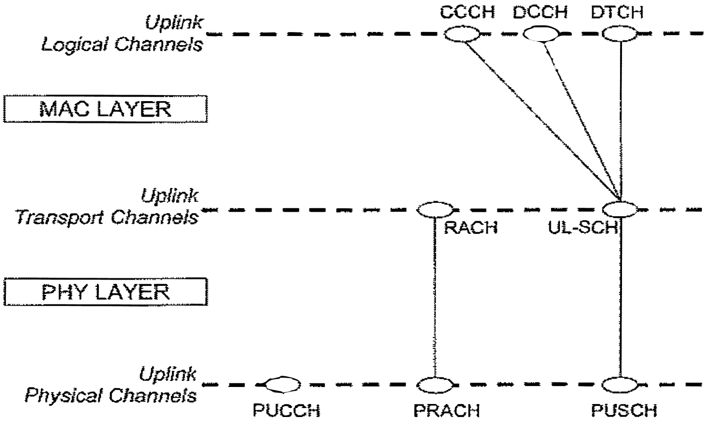

Figure 17.1 Summary of uplink physical channels and mapping to higher layers.

17.2 Uplink Shared Data Channel Structure

The Physical Uplink Shared CHannel (PUSCH), which carries data from the Uplink Shared Channel (UL-SCH) transport channel, uses DFT-Spread OFDM (DFT-S-OFDM), as described in Chapter 15. The transmit processing chain is shown in Figure 17.2. As explained in Chapter 10, the information bits are first channel-coded with a turbo code of mother code rate $r = 1/3$, which is adapted to a suitable final code rate by a rate-matching process. This is followed by symbol-level channel interleaving which follows a simple 'time-first' mapping [1] – in other words, adjacent data symbols end up being mapped first to adjacent SC-FDMA symbols in the time domain, and then across the subcarriers (see [2], Section 5.2.2.8). The coded and interleaved bits are then scrambled by a length-31 Gold code (as in Section 6.3) prior to modulation mapping, DFT-spreading, subcarrier mapping[1] and OFDM modulation. The signal is frequency-shifted by half a subcarrier prior to transmission, to avoid the distortion caused by the d.c. subcarrier being concentrated in one RB, as described in Section 15.3.3. The modulations supported are QPSK, 16QAM and 64QAM (the latter being only for the highest category of User Equipment (UE)).

The baseband SC-FDMA transmit signal for SC-FDMA symbol ℓ is thus of the form (see [3], Section 5.6),

$$s_\ell(t) = \sum_{k=-\lfloor N_{\mathrm{RB}}^{\mathrm{UL}} N_{\mathrm{sc}}^{\mathrm{RB}}/2 \rfloor}^{k=-\lceil N_{\mathrm{RB}}^{\mathrm{UL}} N_{\mathrm{sc}}^{\mathrm{RB}}/2 \rceil - 1} a_{k^-,\ell} \exp[j2\pi(k + 1/2)\Delta f(t - N_{\mathrm{CP},\ell} T_s)] \qquad (17.1)$$

for $0 \leq t < (N_{\mathrm{CP},\ell} + N)T_s$, where $N_{\mathrm{CP},\ell}$ is the number of samples of the Cyclic Prefix (CP) in SC-FDMA symbol ℓ (see Section 15.3), $N = 2048$ is the Inverse Fast Fourier

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[1] Only localized mapping (i.e. to contiguous blocks of subcarriers) is supported for PUSCH and PUCCH transmissions in LTE.

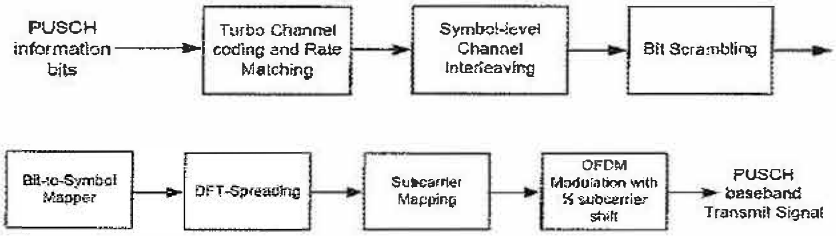

Figure 17.2 Uplink physical data channel processing.

Transform (IFFT) size, $\Delta f = 15$ kHz is the subcarrier spacing, $T_s = 1/(N \cdot \Delta f)$ is the sampling interval, $N_{\mathrm{RB}}^{\mathrm{UL}}$ is the uplink system bandwidth in RBs, $N_{\mathrm{sc}}^{\mathrm{RB}} = 12$ is the number of subcarriers per resource block, $k^{(-)} = k + \lfloor N_{\mathrm{RB}}^{\mathrm{UL}} N_{\mathrm{sc}}^{\mathrm{RB}}/2 \rfloor$ and $a_{k,\ell}$ is the content of subcarrier k on symbol ℓ. For PUSCH data SC-FDMA symbols, $a_{k,\ell}$ is obtained by DFT-spreading the data QAM symbols, $[d_{0,\ell}, d_{1,\ell}, \ldots, d_{M_{\mathrm{SC}}^{\mathrm{PUSCH}}-1,\ell}]$ to be transmitted on data SC-FDMA symbol ℓ (see [3], Section 5.3.3),

$$a_{k,\ell} = \frac{1}{\sqrt{M_{\mathrm{sc}}^{\mathrm{PUSCH}}}} \sum_{i=0}^{M_{\mathrm{sc}}^{\mathrm{PUSCH}}-1} d_{i,\ell} e^{-j2\pi ik/M_{\mathrm{sc}}^{\mathrm{PUSCH}}} \tag{17.2}$$

for $k = 0, 1, 2, \ldots, M_{\mathrm{sc}}^{\mathrm{PUSCH}} - 1$, where $M_{\mathrm{sc}}^{\mathrm{PUSCH}} = M_{\mathrm{RB}}^{\mathrm{PUSCH}} \cdot N_{\mathrm{sc}}^{\mathrm{RB}}$ and $M_{\mathrm{RB}}^{\mathrm{PUSCH}}$ is the allocated PUSCH bandwidth in RBs.

As explained in Section 4.4.1, a Hybrid Automatic Repeat reQuest (HARQ) scheme is used, which in the uplink is synchronous, using N-channel stop and wait. This means that retransmissions occur in specific periodically-occurring subframes (HARQ channels). Further details of the HARQ operation are given in Section 10.3.2.5.

17.2.1 Scheduling Supported in LTE SC-FDMA Uplink

In the LTE uplink, both frequency-selective scheduling and non-frequency-selective scheduling are supported. The former is based on the eNodeB exploiting available channel knowledge to schedule a UE to transmit using specific Resource Blocks (RBs) in the frequency domain where the channel response is good. The latter does not make use of frequency-specific channel knowledge, but rather aims to benefit from frequency diversity during the transmission of each transport block. The possible techniques supported in LTE are discussed in more detail below. Intermediate approaches are also possible.

17.2.1.1 Frequency-Selective Scheduling

With frequency-selective scheduling, the same localized[2] allocation of transmission resources is typically used in both slots of a subframe – there is no frequency hopping during a subframe. The frequency-domain RB allocation and the Modulation and Coding Scheme (MCS) are chosen based on the location and quality of an above-average gain in the uplink

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[2] Localized means that allocated RBs are consecutive in the frequency domain.

channel response [4]. In order to enable frequency-selective scheduling, timely channel quality information is needed at the eNodeB. One method for obtaining such information in LTE is by uplink channel sounding using the SRS described in Section 16.6. The performance of frequency-selective scheduling using the SRS depends on the sounding bandwidth and the quality of the channel estimate, the latter being a function of the transmission power spectral density used for the SRS. With a large sounding bandwidth, link quality can be evaluated on a larger number of RBs. However, this is likely to lead to the SRS being transmitted at a lower power density, due to the limited total UE transmit power, and this reduces the accuracy of the estimate for each RB within the sounding bandwidth. Conversely, sounding a smaller bandwidth can improve channel estimation on the sounded RBs but results in missing channel information for certain parts of the channel bandwidth, thus risking exclusion of the best quality RBs. As an example, experiments performed in reference [5] show that at least for a bandwidth of 5 MHz, frequency-selective scheduling based on full-band sounding outperforms narrower bandwidth sounding.

17.2.1.2 Frequency-Diverse or Non-Selective Scheduling

There are cases when no, or limited, frequency-specific channel quality information is available, for example because of SRS overhead constraints or high Doppler conditions. In such cases, it is preferable to exploit the frequency diversity of LTE's wideband channel.

In LTE, frequency hopping of a localized transmission is used to provide frequency-diversity. Two hopping modes are supported – hopping only between subframes (inter-subframe hopping), or hopping both between and within subframes (inter- and intra-subframe hopping). These modes are illustrated in Figure 17.3. Cell-specific broadcast signalling is used to configure the hopping mode (see [6], Section 8.4).

In case of intra-subframe hopping, a frequency hop occurs at the slot boundary in the middle of a subframe; this provides frequency diversity within a codeword (i.e. within a single transmission of transport block). On the other hand, inter-subframe hopping provides frequency diversity between HARQ retransmissions of a transport block, as the frequency allocation hops every allocated subframe.

Two methods are defined for the frequency hopping allocation (see [6], Section 8.4): either a pre-determined pseudo-random frequency hopping pattern (see reference [3], Section 5.3.4), or an explicit hopping offset signalled in the UL resource grant on the PDCCH. For uplink system bandwidths less than 50 RBs, the size of the hopping offset (modulo the system bandwidth) is approximately half the number of RBs available for PUSCH transmissions (i.e. $\lfloor N_{\mathrm{RB}}^{\mathrm{PUSCH}}/2\rfloor$), while for uplink system bandwidths of 50 RBs or more, the possible hopping offsets are $\lfloor N_{\mathrm{RB}}^{\mathrm{PUSCH}}/2\rfloor$, and $\pm\lfloor N_{\mathrm{RB}}^{\mathrm{PUSCH}}/4\rfloor$ (see [6], Section 8.4).

Signalling the frequency hop via the uplink resource grant can be used for frequency semi-selective scheduling [7], in which the frequency resource is assigned selectively for the first slot of a subframe and frequency diversity is also achieved by hopping to a different frequency in the second slot. In some scenarios this may yield intermediate performance between that of fully frequency-selective and fully non-selective scheduling; this may be seen as one way to reduce the sounding overhead typically needed for fully frequency-selective scheduling.

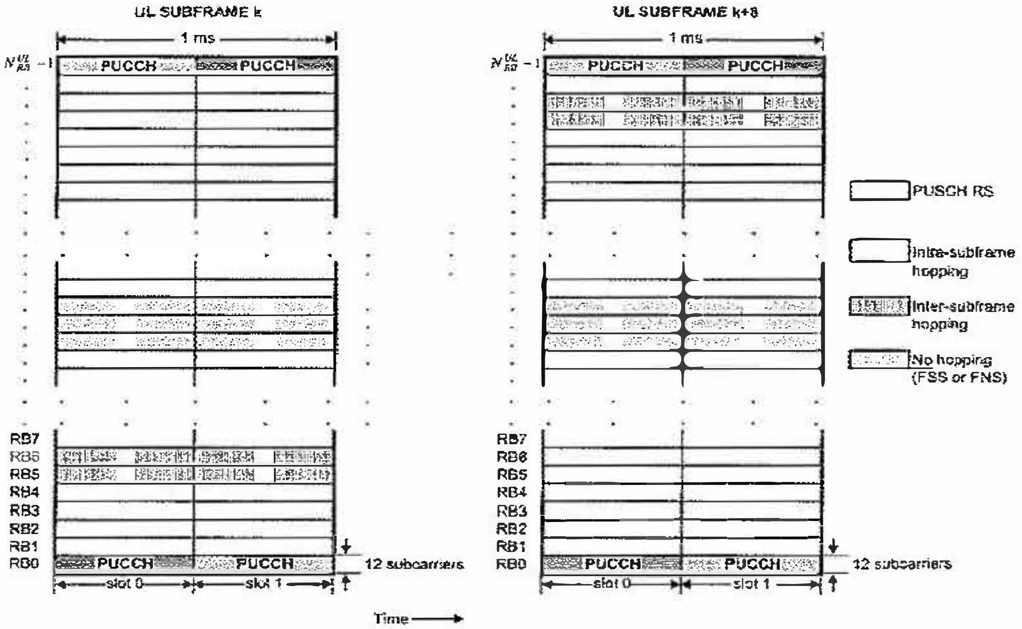


Figure 17.3 Uplink physical data channel processing.

17.3 Uplink Control Channel Design

In general, uplink control signalling in mobile communications systems can be divided into two categories:

- **Data-associated control signalling.** Control signalling which is always transmitted together with uplink data, and is used in the processing of that data. Examples include transport format indications, 'new data' indicators, and MIMO parameters.

- **Data non-associated control signalling.** Control signalling not associated with uplink data, transmitted independently of any uplink data packet. Examples include HARQ Acknowledgments (ACK/NACK) for downlink data packets, Channel Quality Indicators (CQIs), and MIMO feedback (such as Rank Indicator (RI) or Precoding Matrix Indicator (PMI)) for downlink transmissions. Scheduling Requests (SRs) for uplink transmissions also fall into this category.

In LTE, the low signalling latency afforded by the short subframe duration of 1 ms, together with the orthogonal nature of the uplink multiple access scheme which necessitates centralized resource allocation, make it appropriate for the eNodeB to be in full control of the uplink transmission parameters. Consequently uplink data-associated control signalling is not necessary in LTE, as the relevant information is already known to the eNodeB. Therefore only data non-associated control signalling is supported in the LTE uplink.

When simultaneous uplink PUSCH data and control signalling is scheduled for a UE, the control signalling is multiplexed together with the data prior to the DFT spreading, in order to preserve the single-carrier low-Cubic Metric (CM) property of the uplink transmission. The uplink control channel, PUCCH, is used by a UE to transmit any necessary control signalling only in subframes in which the UE has not been allocated any RBs for PUSCH transmission.

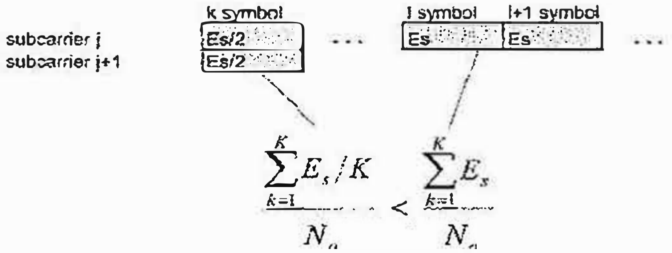
In the design of the PUCCH, special consideration was given to maintaining a low CM [8].

17.3.1 Physical Uplink Control Channel (PUCCH) Structure

The control signalling on the PUCCH is transmitted in a frequency region on the edges of the system bandwidth.

In order to minimize the resources needed for transmission of control signalling, the PUCCH in LTE is designed to exploit frequency diversity: each PUCCH transmission in one subframe is comprised of a single (0.5 ms) RB at or near one edge of the system bandwidth, followed (in the second slot of the subframe) by a second RB at or near the opposite edge of the system bandwidth, as shown in Figure 17.5; together, the two RBs are referred to as a *PUCCH region*. This design can achieve a frequency diversity benefit of approximately 2 dB compared to transmission in the same RB throughout the subframe.

At the same time, the narrow bandwidth of the PUCCH in each slot (only a single resource block) maximizes the power per subcarrier for a given total transmission power (see Figure 17.4), and therefore helps to fulfil stringent coverage requirements.



$$\frac{\sum_{k=1}^{K} E_s/K}{N_o} < \frac{\sum_{k=1}^{K} E_s}{N_o}$$

Figure 17.4 The link budget of a two-slot narrowband transmission exceeds that of a one-slot wider-band transmission, given equal coding gain.

Positioning the control regions at the edges of the system bandwidth has a number of advantages, including the following:

- The frequency diversity achieved through frequency hopping is maximized by allowing hopping from one edge of the band to the other.
- Out-Of-Band (OOB) emissions are smaller if a UE is only transmitting on a single RB per slot compared to multiple RBs. The PUCCH regions can therefore serve as a kind of guard band between the wider-bandwidth PUSCH transmissions of adjacent carriers, and therefore can improve coexistence [9].

Table 17.1 Typical numbers of PUCCH regions.

Bandwidth (MHz)	Number of 0.5 ms RBs subframe	Number of PUCCH regions
1.4	2	1
3	4	2
5	8	4
10	16	8
20	32	16

- Using control regions on the band edges maximizes the achievable PUSCH data rate, as the entire central portion of the band can be allocated to a single UE. If the control regions were in the central portion of a carrier, a UE bandwidth allocation would be limited to one side of the control region in order to maintain the single-carrier nature of the signal, thus limiting the maximum data achievable rate.
- Control regions on the band edges impose fewer constraints on the uplink data scheduling, both with and without inter-/intra-subframe frequency hopping.

The number of resource blocks (in each slot) that can be used for PUCCH transmission within the cell is $N_{\text{RB}}^{\text{PUCCH}}$ (parameter 'pusch-HoppingOffset'). This is indicated to the UEs in the cell through broadcast signalling. Note that the number of PUCCH RBs per slot is the same as the number of PUCCH regions per subframe. Some typical expected numbers of PUCCH regions for different LTE bandwidths are shown in Table 17.1.

Figures 17.5 and 17.6 show respectively examples of even and odd numbers of PUCCH regions being configured in a cell. In the case of an even number of PUCCH regions (Figure 17.5), both RBs of each RB-pair (e.g. RB-pair 2 and RB-pair $N_{\text{RB}}^{\text{UL}} - 3$) are used for PUCCH transmission. However, for the case of an odd number of PUCCH regions (Figure 17.6), one RB of an RB-pair in each slot is not used for PUCCH (e.g. one RB of RB-pair 2 and RB-pair $N_{\text{RB}}^{\text{UL}} - 3$ is unused). In order to exploit the unused RBs in each slot in the case of an odd number of PUCCH regions, the eNodeB may schedule a UE with an intra-subframe frequency hopping (i.e. mirror hopping) PUSCH allocation in the unused RBs.

Alternatively, a UE can be assigned a localized allocation which includes the unused RB-pair, (e.g. RB-pair 2 or RB-pair $N_{\text{RB}}^{\text{UL}} - 3$). In this case, the UE will transmit PUSCH data on both RBs of the RB-pair, assuming that neither of the RBs are used for PUCCH by any UE in the subframe. Thus, the eNodeB scheduler can appropriately schedule PUSCH transmission (mirror hopping or localized) on the PUCCH RBs when they are under-utilized. The eNodeB may also choose to schedule low-power PUSCH transmission (e.g. from UEs close to the eNodeB) in the outer RBs of the configured PUCCH region, while the inner PUCCH region is used for PUCCH signalling. This can provide further reduction in OOB emissions which is necessary in some frequency bands, by moving higher-power PUCCH transmission (e.g. those from cell-edge UEs) slightly away from the edge of the band.

17.3.1.1 Multiplexing of UEs within a PUCCH Region

Control signalling from multiple UEs can be multiplexed into a single PUCCH region using orthogonal Code Division Multiplexing (CDM). In some scenarios this can have benefits

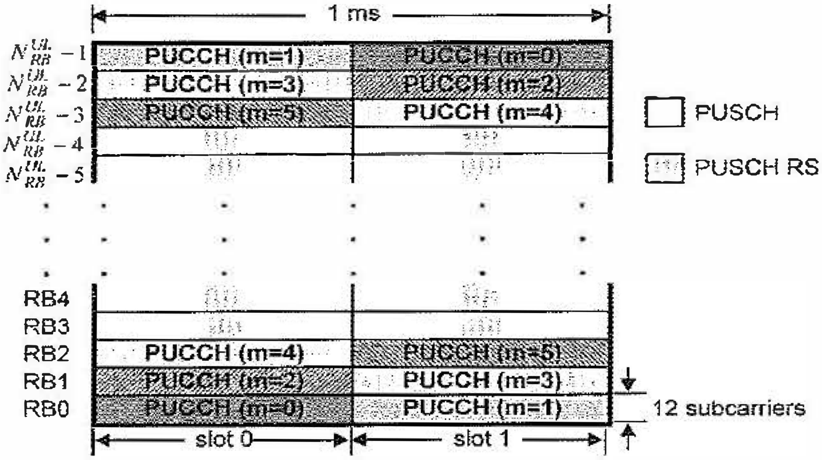


Figure 17.5 PUCCH uplink control structure with an even number of 'PUCCH Control Regions' ($N_{\mathrm{RB}}^{\mathrm{PUCCH}} = 6$). Reproduced by permission of © 3GPP.

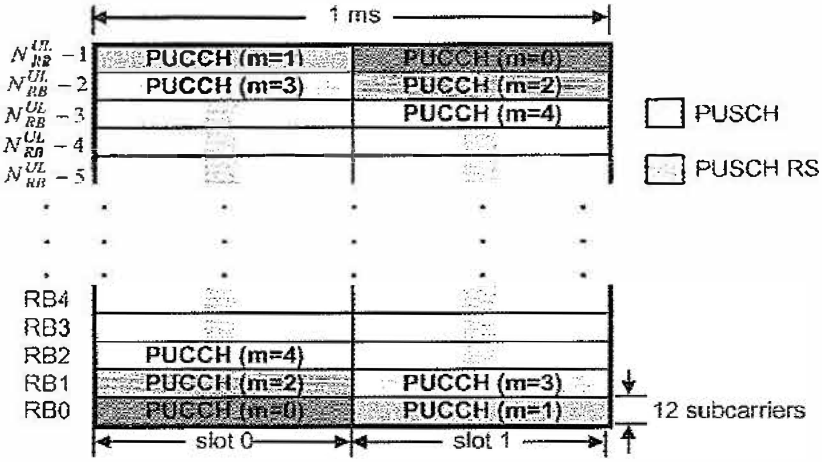


Figure 17.6 Example of odd number of PUCCH control RBs or regions ($N_{\mathrm{RB}}^{\mathrm{PUCCH}} = 5$).

over a pure FDM approach, as it reduces the need to limit the power differentials between the PUCCH transmissions of different UEs. One technique to provide orthogonality between UEs is by using cyclic time shifts of a sequence with suitable properties, as explained in Section 16.2.2. In a given SC-FDMA symbol, different cyclic time shifts of a waveform (e.g. a Zadoff–Chu (ZC) sequence as explained in Section 7.2.1) are modulated with a UE-specific QAM symbol carrying the necessary control signalling information, with the supported number of cyclic time shifts determining the number of UEs which can be multiplexed per

SC-FDMA symbol. As the PUCCH RB spans 12 subcarriers, and assuming the channel is approximately constant over the RB (i.e. a single-tap channel), the LTE PUCCH supports up to 12 cyclic shifts per PUCCH RB.

For control information transmissions with a small number of control signalling bits, such as 1- or 2-bit positive/negative acknowledgments (ACK/NACK), orthogonality is achieved between UEs by a combination of cyclic time shifts within an SC-FDMA symbol and SC-FDMA symbol time-domain spreading with orthogonal spreading codes, i.e. modulating the SC-FDMA symbols by elements of an orthogonal spreading code [10]. CDM of multiple UEs is used rather than Time Domain Multiplexing (TDM) because CDM enables the time duration of the transmission to be longer, which increases the total transmitted energy per signalling message in the case of a power-limited UE.

Thus, the LTE PUCCH control structure uses frequency-domain code multiplexing (different cyclic time shifts of a base sequence) and/or time-domain code multiplexing (different orthogonal block spreading codes), thereby providing an efficient, orthogonal control channel which supports small payloads (up to 22 coded bits) from multiple UEs simultaneously, together with and good operational capability at low SNR.

17.3.1.2 Control Signalling Information Carried on PUCCH

The control signalling information carried on the PUCCH can consist of:

- Scheduling Requests (SRs) (see Section 4.4.2.2).
- HARQ ACK/NACK in response to downlink data packets on (PDSCH). One ACK/NACK bit is transmitted in case of single codeword downlink transmission while two ACK/NACK bits are used in case of two codeword downlink transmission.
- CQI, which for the purposes of control signalling categorization, is taken to include the MIMO-related feedback consisting of RIs and PMI. 20 bits per subframe are used for the CQI.

The amount of control information which a UE can transmit in a subframe depends on the number of SC-FDMA symbols available for transmission of control signalling data (i.e. excluding SC-FDMA symbols used for reference signal transmission for coherent detection of the PUCCH). The PUCCH supports seven different formats depending on the information to be signalled. The mapping between the PUCCH format and the Uplink Control Information (UCI) supported in LTE is shown in Table 17.2 (see [6] Section 10.1, [3] Table 5.4-1).

The physical mapping of the PUCCH formats to the PUCCH regions is shown in Figure 17.7.

It can be seen that the PUCCH CQI formats 2/2a/2b are mapped and transmitted on the band-edge RBs (e.g. PUCCH region $m = 0, 1$) followed by a mixed PUCCH RB (if present, e.g. region $m = 2$) of CQI format 2/2a/2b and SR/HARQ ACK/NACK format 1/1a/1b, and then by PUCCH SR/HARQ ACK/NACK format 1/1a/1b (e.g. region $m = 4, 5$). The number of PUCCH RBs available for use by CQI format 2/2a/2b, N_{RB}^{2}, is indicated to the UEs in the cell by broadcast signalling.

Table 17.2 Supported uplink control information formats on PUCCH.

PUCCH Format	Uplink Control Information (UCI)
Format 1	Scheduling request (SR) (unmodulated waveform)
Format 1a	1-bit HARQ ACK/NACK with/without SR
Format 1b	2-bit HARQ ACK/NACK with/without SR
Format 2	CQI (20 coded bits)
Format 2	CQI and 1- or 2-bit HARQ ACK/NACK (20 bits) for extended CP only
Format 2a	CQI and 1-bit HARQ ACK/NACK (20 + 1 coded bits)
Format 2b	CQI and 2-bit HARQ ACK/NACK (20 + 2 coded bits)

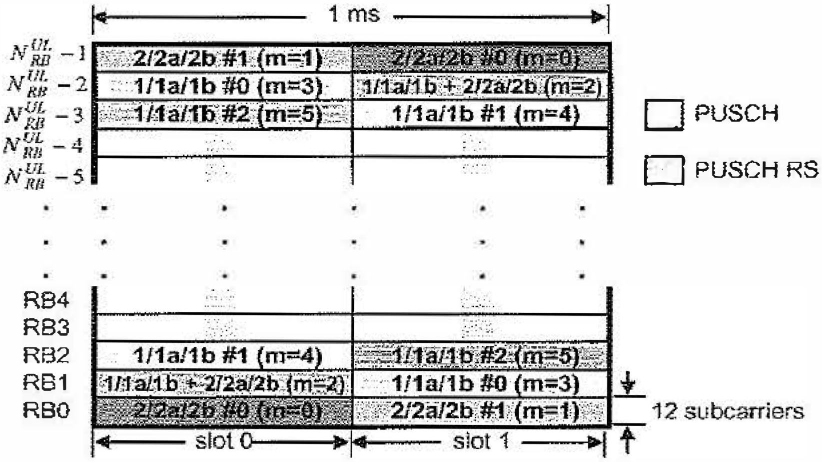


Figure 17.7 Physical mapping of PUCCH formats to PUCCH RBs or regions.

17.3.2 Channel Quality Indicator Transmission on PUCCH (Format 2)

The PUCCH CQI channel structure (Format 2) for one slot with normal CP is shown in Figure 17.8. SC-FDMA symbols 1 and 5 are used for DM RS transmissions in the case of the normal CP (while in the case of the extended CP only one RS is transmitted, on SC-FDMA symbol 3).

The number of RS symbols per slot results from a trade-off between channel estimation accuracy and the supportable code rate for the control signalling bits. For a small number of control information bits with a low SNR operating point (for a typical 1% target error rate), improving the channel estimation accuracy by using more RS symbols (e.g. 3) is more beneficial than being able to use a lower channel code rate. However, with larger numbers of control information bits the required SNR operating point increases, and the higher code rate resulting from a larger overhead of RS symbols becomes more critical, thus favouring fewer RS symbols. In view of these factors, two RS symbols per slot (in case of normal CP) was

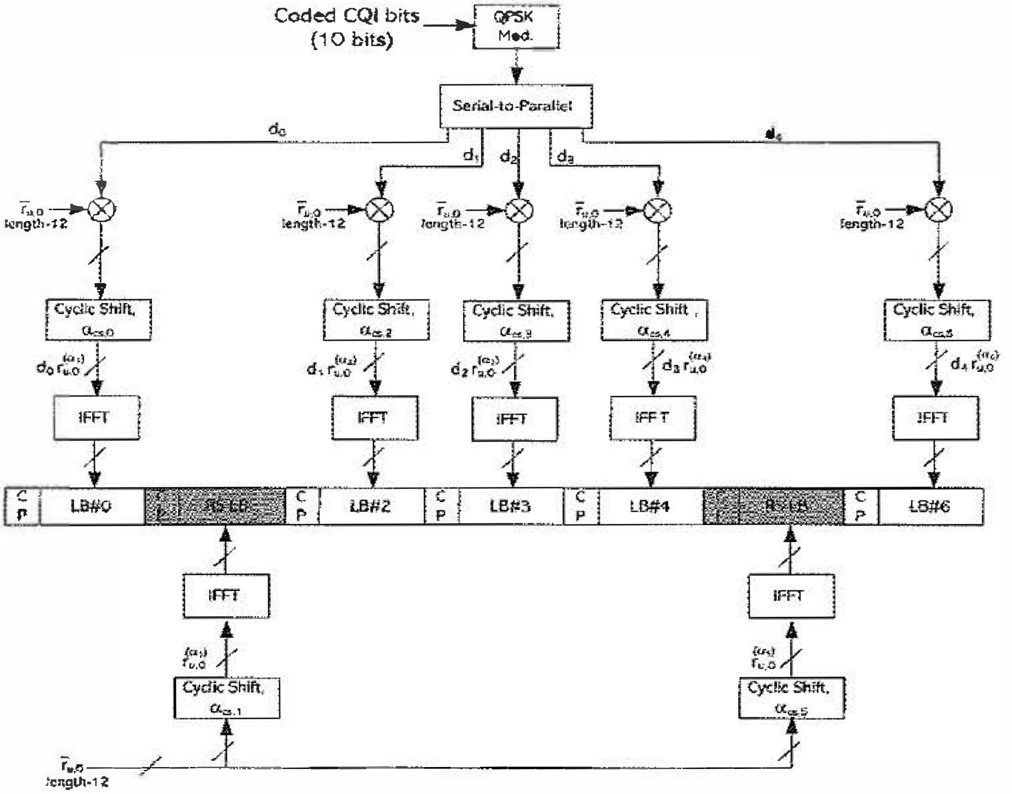


Figure 17.8 CQI channel structure for PUCCH format 2/2a/2b with normal CP for one slot.

considered to provide the best trade-off in terms of performance and RS overhead, given the payload sizes required.

10 CQI information bits are channel coded with a rate 1/2 punctured (20, k) Reed–Muller code (see reference [2], Section 5.2.3.3) to give 20 coded bits, which are then scrambled (in a similar way to PUSCH data with a length-31 Gold sequence) prior to QPSK constellation mapping. One QPSK modulated symbol is transmitted on each of the 10 SC-FDMA symbols in the subframe by modulating a cyclic time shift of the base RS sequence of length-12 prior to OFDM modulation. The 12 equally-spaced cyclic time shifts allow 12 different UEs to be orthogonally multiplexed on the same CQI PUCCH RB.

The DM RS signal sequence (on the 2nd and 6th SC-FDMA symbols for the normal CP, or the 4th symbol for the extended CP) is similar to the frequency domain CQI signal sequence but without the CQI data modulation.

In order to provide inter-cell interference randomization, cell-specific symbol-level cyclic time shift hopping is used, as described in Section 16.4. For example, the PUCCH cyclic time shift index on SC-FDMA symbol l in even slots n_s is obtained by adding (modulo-12) a pseudo-random cell-specific PUCCH cyclic shift offset to the assigned cyclic time shift $n_{\mathrm{RS}}^{\mathrm{PUCCH}}$. Intra-cell interference randomization is achieved by cyclic time shift remapping in the second slot as explained in Section 16.4.

A UE is semi-statically configured by higher layer signalling to report periodically different CQI, PMI, and RI types (see Section 10.2.1) on CQI PUCCH using a PUCCH *resource index* $n_{\mathrm{PUCCH}}^{(2)}$, which indicates both the PUCCH region and the cyclic time shift to be used. The PUCCH region m used for the PUCCH format 2/2a/2b transmission (see Figure 17.7), is given by (see [3], Section 5.4.3)

$$m = \left\lfloor \frac{n_{\mathrm{PUCCH}}^{(2)}}{12} \right\rfloor \tag{17.3}$$

and the assigned cyclic time shift, $n_{\mathrm{RS}}^{\mathrm{PUCCH}}$, is given by

$$n_{\mathrm{RS}}^{\mathrm{PUCCH}} = n_{\mathrm{PUCCH}}^{(2)} \bmod 12 \tag{17.4}$$

17.3.3 Multiplexing of CQI and HARQ ACK/NACK from a UE on PUCCH

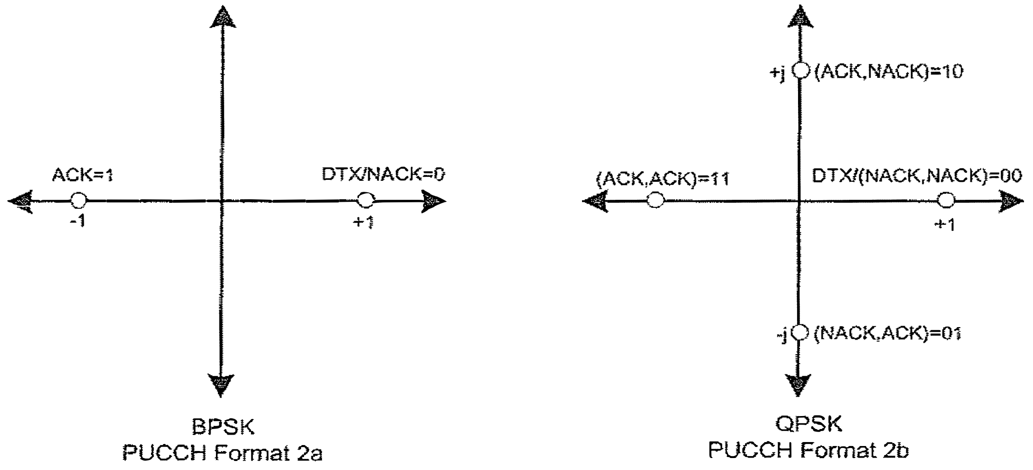
In LTE, the simultaneous transmission of HARQ ACK/NACK and CQI by a UE can be enabled by UE-specific higher layer signalling. In case simultaneous transmission is not enabled, and the UE needs to transmit HARQ ACK/NACK on the PUCCH in the same subframe in which a CQI report has been configured, the CQI is dropped and only HARQ ACK/NACK is transmitted using the transmission structure detailed in Section 17.3.4.

In subframes where the eNodeB scheduler allows for simultaneous transmission of CQI and HARQ ACK/NACK from a UE, the CQI and the 1- or 2-bit HARQ ACK/NACK information needs to be multiplexed in the same PUCCH RB, while maintaining the low CM single carrier property of the signal. The method used to achieve this is different for the case of normal CP and extended CP as described in the following sections.

17.3.3.1 Multiplexing of CQI and HARQ ACK/NACK – Normal CP (Format 2a/2b)

The transmission structure for CQI data is the same as described in Section 17.3.2. In order to transmit a 1- or 2-bit HARQ ACK/NACK together with CQI (Format 2a/2b), the HARQ ACK/NACK bits (which are not scrambled) are BPSK/QPSK modulated as shown in Figure 17.9, resulting in a single HARQ ACK/NACK modulation symbol, d_{HARQ}. A positive acknowledgement (ACK) is encoded as a binary '1' and a negative acknowledgement (NACK) is encoded as a binary '0' (see [2], Section 5.2.3.4).

The single HARQ ACK/NACK modulation symbol, d_{HARQ}, is then used to modulate the second RS symbol (SC-FDMA symbol 5) in each CQI slot – i.e. ACK/NACK is signalled using the RS. It can be seen from Figure 17.9 that the modulation mapping is such that a NACK (or NACK, NACK in the case of two downlink MIMO codewords) is mapped to +1, resulting in a default NACK in case neither ACK nor NACK is transmitted (so-called Discontinuous Transmission (DTX)), as happens if the UE fails to detect the downlink grant on the Physical Downlink Control CHannel (PDCCH). In other words, a DTX (no RS modulation) is interpreted as a NACK by the eNodeB, triggering a downlink retransmission.



BPSK
PUCCH Format 2a

QPSK
PUCCH Format 2b

Figure 17.9 Constellation mapping for HARQ ACK/NACK.

As the one of the RS in a CQI slot is modulated by the HARQ ACK/NACK modulation symbol, some different ACK/NACK and CQI detection schemes are possible. In low-Doppler environments with little channel variation over the 0.5 ms slot, coherent detection of ACK/NACK and CQI can be achieved by using only the first RS symbol in the slot as the phase reference. Alternatively, to improve the channel estimation quality for CQI detection, an estimate of the HARQ ACK/NACK symbol can be used to undo the modulation on the second RS in the slot so that both RS symbols can be used for channel estimation and demodulation of CQI. In high-Doppler environments in which significant channel variations occur over a slot, relying on a single RS symbol for coherent detection degrades performance of ACK/NACK and CQI. In such cases blind decoding or multiple hypothesis testing of the different ACK/NACK combinations can be used to decode the ACK/NACK and CQI, selecting the hypothesis that maximizes the correlation between the received signal and the estimated CQI information [11] (i.e. a Maximum Likelihood detection).

17.3.3.2 Multiplexing of CQI and HARQ ACK/NACK – Extended CP (Format 2)

In the case of the extended CP (with one RS symbol per slot), the 1- or 2-bit HARQ ACK/NACK is jointly encoded with the CQI resulting in a (20, $k_{\mathrm{CQI}} + k_{\mathrm{ACK/NACK}}$) Reed–Muller based block code. A 20-bit codeword is transmitted on the PUCCH using the CQI channel structure in Section 17.3.2. The joint coding of the ACK/NACK and CQI is performed as shown in Figure 17.10. The largest number of information bits supported by the block code is 13, corresponding to $k_{\mathrm{CQI}} = 11$ CQI bits and $k_{\mathrm{ACK/NACK}} = 2$ bits (for two-codeword transmission in the downlink).

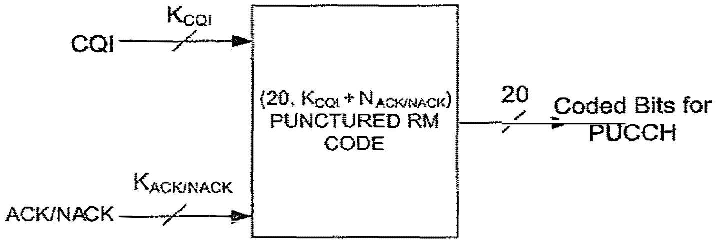


Figure 17.10 Joint coding of HARQ ACK/NACK and CQI for extended CP.

17.3.4 HARQ ACK/NACK Transmission on PUCCH (Format 1a/1b)

The PUCCH channel structure for HARQ ACK/NACK transmission with no CQI is shown in Figure 17.11 for one slot with normal CP. Three (two in case of extended CP) SC-FDMA symbols are used in the middle of the slot for RS transmission, with the remaining four SC-FDMA symbols being used for ACK/NACK transmission. Due to the small number of ACK/NACK bits, three RS symbols are used to improve the channel estimation accuracy for a lower SNR operating point than for the CQI structure in Section 17.3.2.

Both 1- and 2-bit acknowledgements are supported using BPSK and QPSK modulation respectively. The HARQ ACK/NACK bits (which are not scrambled) are BPSK/QPSK modulated according to the modulation mapping shown in Figure 17.9 (see [3], Table 5.4.1-1) resulting in a single HARQ ACK/NACK modulation symbol. A positive ACK is encoded as a binary '1' and a negative ACK (NACK) as a binary '0' (see [2], Section 5.2.3.4). The modulation mapping is the same as the mapping for 1- or 2-bit HARQ ACK/NACK when multiplexed with CQI for PUCCH formats 2a/2b.

As in the case of CQI transmission, the one BPSK/QPSK modulated symbol (which is phase-rotated by 90 degrees in the second slot) is transmitted on each SC-FDMA data symbol by modulating a cyclic time shift of the base RS sequence of length-12 (i.e. frequency-domain CDM) prior to OFDM modulation. In addition, as mentioned in Section 17.3.1.1, time-domain spreading with orthogonal (Walsh–Hadamard or DFT) spreading codes is used to code-division-multiplex UEs. Thus, a large number of UEs (data and RSs) can be multiplexed on the same PUCCH RB using frequency-domain and time-domain code multiplexing. The RSs from the different UEs are multiplexed in the same way as the data SC-FDMA symbols.

For the cyclic time shift multiplexing, the number of cyclic time shifts supported in an SC-FDMA symbol for PUCCH HARQ ACK/NACK RBs is configurable by a cell-specific higher-layer signalling parameter $\Delta_{\mathrm{shift}}^{\mathrm{PUCCH}} \in \{1, 2, 3\}$, indicating 12, 6, or 4 shifts respectively (see [3], Section 5.4.1). The value selected by the eNodeB for $\Delta_{\mathrm{shift}}^{\mathrm{PUCCH}}$ can be based on the expected delay spread in the cell.

For the time-domain spreading CDM, the number of supported spreading codes for ACK/NACK data is limited by the number of RS symbols, as the multiplexing capacity of RS is smaller than that of the data symbols due to smaller number of RS symbols. For example, in the case of six supportable cyclic time shifts and three (or two) orthogonal time spreading codes in case of normal (or extended) CP with three (or two) RS symbols, acknowledgments from 18 (or 12) different UEs can be multiplexed within one PUCCH RB. The length-2

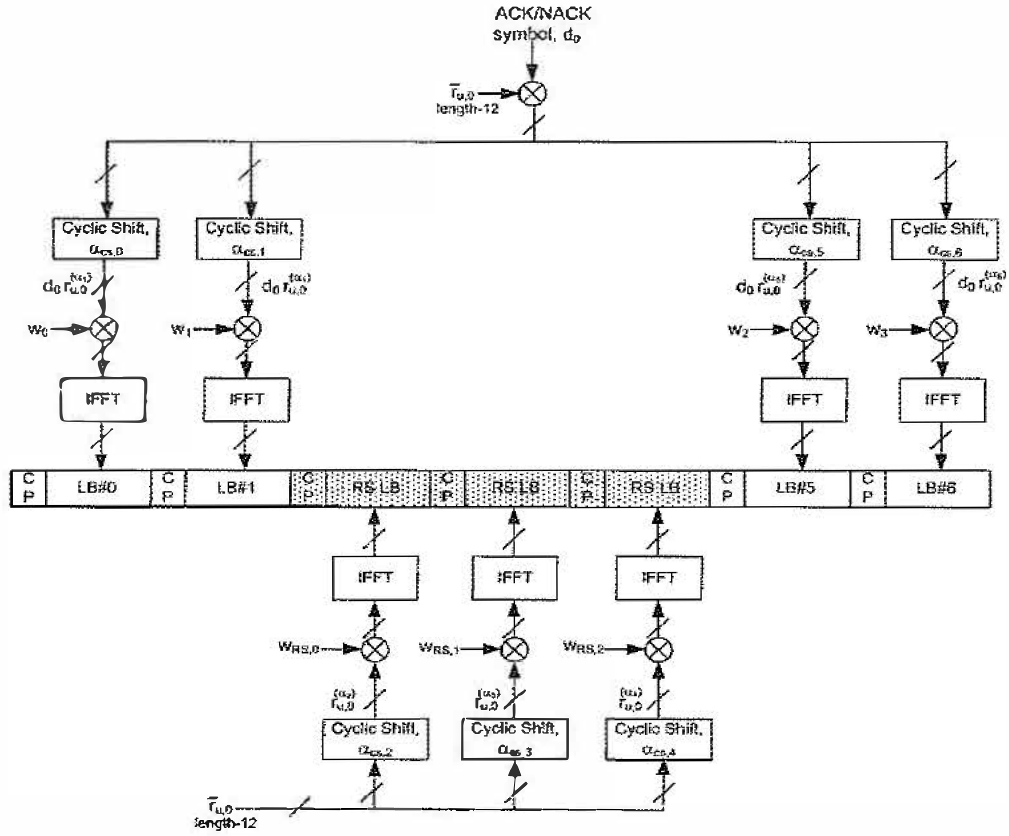


Figure 17.11 ACK/NACK structure – users are multiplexed using different cyclic shifts and time-domain spreading.

and length-4 orthogonal block spreading codes are based on Walsh–Hadamard codes, and the length-3 spreading codes are based on DFT codes as shown in Table 17.3. A subset of size-s orthogonal spreading codes of a particular length L ($s \leq L$) is used depending on the number of RS SC-FDMA symbols. For the normal CP with four data SC-FDMA symbols and three supportable orthogonal time spreading codes (due to there being three RS symbols), the indices 0, 1, 2 of the length-4 orthogonal spreading codes are used for the data time-domain block spreading.

Similarly, for the extended CP case with four data SC-FDMA symbols but only two RS symbols, orthogonal spreading code indices 0 and 2 of length-4 are used for the data block spreading codes. For the length-4 orthogonal codes, the code sequences used are such that subsets of the code sequences result in the minimum inter-code interference in high Doppler conditions where generally the orthogonality between the code sequences breaks down [12]. Table 17.4 summarizes the time-domain orthogonal spreading code lengths (i.e. spreading

Table 17.3 Time-domain orthogonal spreading code sequences. Reproduced by permission of © 3GPP.

Orthogonal code sequence index	Length-2 Walsh–Hadamard	Length-3 DFT	Length-4 Walsh–Hadamard
0	$[+1 \quad +1]$	$[+1 \quad +1 \quad +1]$	$[+1 \quad +1 \quad +1 \quad +1]$
1	$[+1 \quad -1]$	$[1 \quad e^{j2\pi/3} \quad e^{j4\pi/3}]$	$[+1 \quad -1 \quad +1 \quad -1]$
2	N/A	$[1 \quad e^{j4\pi/3} \quad e^{j2\pi/3}]$	$[+1 \quad -1 \quad -1 \quad +1]$
3	N/A	N/A	$[+1 \quad +1 \quad -1 \quad -1]$

Table 17.4 Spreading factors for time-domain orthogonal spreading codes for data and RS for PUCCH formats 1/1a/1b for normal and extended CP.

	Normal CP		Extended CP	
	Data, $N_{\mathrm{SF}}^{\mathrm{PUCCH}}$	RS, $N_{\mathrm{RS}}^{\mathrm{PUCCH}}$	Data, $N_{\mathrm{SF}}^{\mathrm{PUCCH}}$	RS, $N_{\mathrm{RS}}^{\mathrm{PUCCH}}$
Spreading factor	4	3	4	2

factors) for data and RS. The number of supportable orthogonal spreading codes is equal to the number of RS SC-FDMA symbols, $N_{\mathrm{RS}}^{\mathrm{PUCCH}}$.

It should be noted that it is possible for the transmission of HARQ ACK/NACK and SRS to be configured in the same subframe. If this occurs, the eNodeB can also configure (by cell-specific broadcast signalling) the way in which these transmissions are to be handled by the UE. One option is for the ACK/NACK to take precedence over the SRS, such that the SRS is not transmitted and only HARQ ACK/NACK is transmitted in the relevant subframe, according to the PUCCH ACK/NACK structure in Figure 17.11. The alternative is for the eNodeB to configure the UEs to use a shortened PUCCH transmission in such subframes, whereby the last SC-FDMA symbol of the ACK/NACK (i.e. the last SC-FDMA symbol in the second slot of the subframe is not transmitted: this is shown in Figure 17.12).

This maintains the low CM single-carrier property of the transmitted signal, by ensuring that a UE never needs to transmit both HARQ ACK/NACK and SRS symbols simultaneously, even if both signals are configured in the same subframe. If the last symbol of the ACK/NACK is not transmitted in the second slot of the subframe, this is known as a *shortened* PUCCH format, as shown in Figure 17.13.[3] For the shortened PUCCH, the length of the time-domain orthogonal block spreading code is reduced by one (compared to the first slot shown in Figure 17.11). Hence, it uses the length-3 DFT basis spreading codes in Table 17.3 in place of the length-4 Walsh–Hadamard codes.

The frequency-domain HARQ ACK/NACK signal sequence on data SC-FDMA symbol *n* is defined in [3], Section 5.4.1.

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[3] Note that configuration of SRS in the same subframe as CQI or SR is not valid. Therefore the shortened PUCCH formats are only applicable for PUCCH formats 1a and 1b.

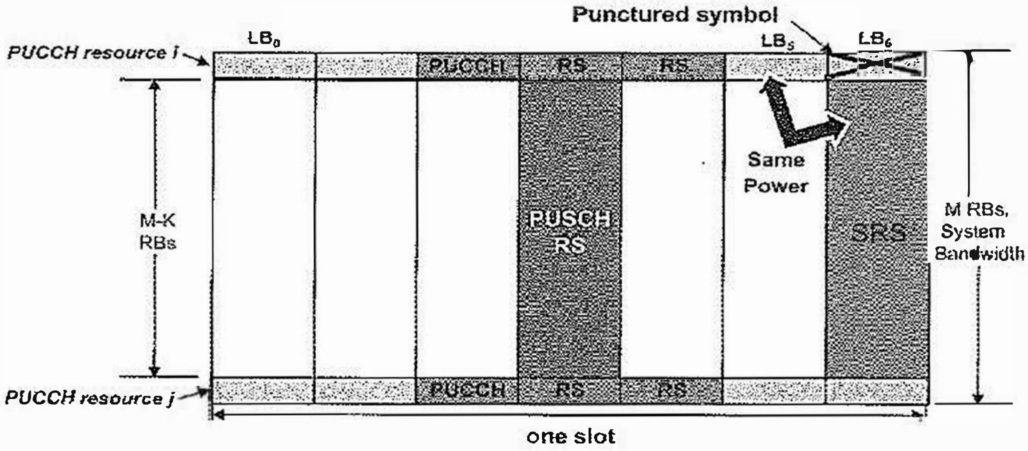

Figure 17.12 A UE may not simultaneously transmit on SRS and PUCCH or PUSCH, in order to avoid violating the single-carrier nature of the signal. Therefore, a PUCCH or PUSCH symbol may be punctured if SRS is transmitted.

The number of HARQ ACK/NACK resource indices $N^{(1)}_{\text{PUCCH, RB}}$ corresponding to cyclic-time-shift/orthogonal-code combinations that can be supported in a PUCCH RB is given by

$$N^{(1)}_{\text{PUCCH, RB}} = c \cdot P, \quad c = \begin{cases} 3 & \text{normal cyclic prefix} \\ 2 & \text{extended cyclic prefix} \end{cases} \tag{17.5}$$

where $P = 12/\Delta^{\text{PUCCH}}_{\text{shift}}$, and $\Delta^{\text{PUCCH}}_{\text{shift}} \in \{1, 2, 3\}$ is the number of equally spaced cyclic time shifts supported.

As in the case of CQI (see Section 17.3.2), cyclic time shift hopping (described in Section 16.4) is used to provide inter-cell interference randomization.

In the case of semi-persistently scheduled downlink data transmissions on the PDSCH (see Section 4.4.2.1) without a corresponding downlink grant on the control channel (PDCCH), the PUCCH ACK/NACK resource index $n^{(1)}_{\text{PUCCH}}$ to be used by a UE is semi-statically configured by higher layer signalling. This PUCCH ACK/NACK resource is used for ACK/NACK transmission corresponding to initial HARQ transmission. For dynamically-scheduled downlink data transmissions (including HARQ retransmissions for semi-persistent data) on PDSCH (indicated by downlink assignment signalling on the PDCCH), the PUCCH HARQ ACK/NACK resource index $n^{(1)}_{\text{PUCCH}}$ is implicitly determined based on the index of the first Control Channel Element (CCE, see Section 9.3) of the downlink control assignment.

The PUCCH region m used for the HARQ ACK/NACK with format 1/1a/1b transmission for the case with no mixed PUCCH region (shown in Figure 17.7), is given by [3], Section 5.4.3

$$m = \left\lfloor \frac{n^{(1)}_{\text{PUCCH}}}{N^{(1)}_{\text{PUCCH, RB}}} \right\rfloor + N^{(2)}_{\text{RB}} \tag{17.6}$$

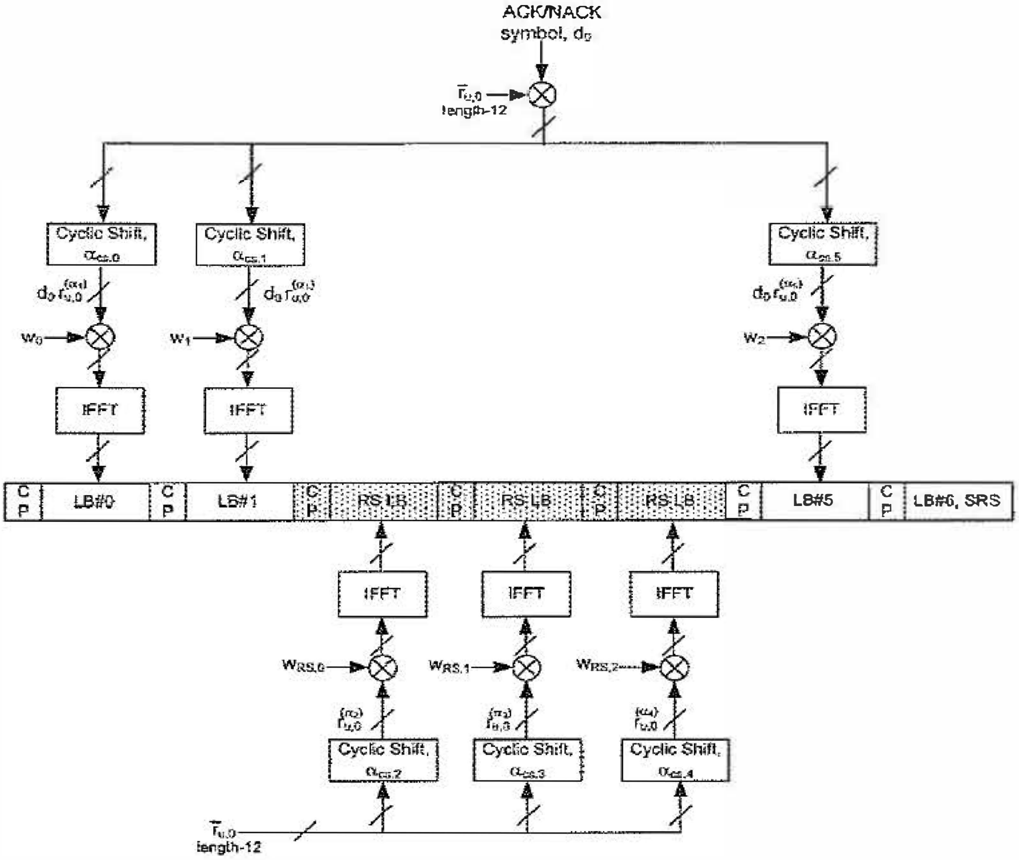

Figure 17.13 Shortened PUCCH ACK/NACK Structure when simultaneous SRS and ACK/NACK is enabled in the cell.

where $N_{\mathrm{RB}}^{(2)}$ is the number of RBs that are available for PUCCH formats 2/2a/2b and is a cell-specific broadcast parameter (see [3], Section 5.4).

The PUCCH resource index $n^{(1)}(n_s)$, corresponding to a combination of a cyclic time shift and orthogonal code ($n_{\mathrm{RS}}^{\mathrm{PUCCH}}$ and n_{oc}), within the PUCCH region m in even slots is given by

$$n^{(1)}(n_s) = n_{\mathrm{PUCCH}}^{(1)} \bmod N_{\mathrm{PUCCH,RB}}^{(1)} \quad \text{for } n_s \bmod 2 = 0 \tag{17.7}$$

The PUCCH resource index ($n_{\mathrm{RS}}^{\mathrm{PUCCH}}$, n_{oc}) allocation within a PUCCH RB format 1/1a/1b, is shown in Tables 17.5, 17.6, and 17.7, for $\Delta_{\mathrm{shift}}^{\mathrm{PUCCH}} \in \{1, 2, 3\}$ with 36, 18, and 12 resource indices respectively for the normal CP case [13]. For the extended CP, with two time-domain orthogonal spreading code sequences, only the first two columns of the orthogonal code

Table 17.5 PUCCH RB format 1/1a/1b resource index allocation, $\Delta_{\text{shift}}^{\text{PUCCH}} = 1$, 36 resource indices, normal CP.

Cyclic shift index, $n_{\text{RS}}^{\text{PUCCH}}$	Orthogonal code sequence index, n_{oc} $n_{\text{oc}} = 0$	$n_{\text{oc}} = 1$	$n_{\text{oc}} = 2$
0	0	12	24
1	1	13	25
2	2	14	26
3	3	15	27
4	4	16	28
5	5	17	29
6	6	18	30
7	7	19	31
8	8	20	32
9	9	21	33
10	10	22	34
11	11	23	35

Table 17.6 PUCCH RB format 1/1a/1b resource index allocation, $\Delta_{\text{shift}}^{\text{PUCCH}} = 2$, 18 resource indices, normal CP.

Cyclic shift index, $n_{\text{RS}}^{\text{PUCCH}}$	Orthogonal code sequence index, n_{oc} $n_{\text{oc}} = 0$	$n_{\text{oc}} = 1$	$n_{\text{oc}} = 2$
0	0		12
1		6	
2	1		13
3		7	
4	2		14
5		8	
6	3		15
7		9	
8	4		16
9		10	
10	5		17
11		11	

sequence index, $n_{\text{oc}} = 1, 2$ are used, resulting in 24, 12 and 8 resource indices for $\Delta_{\text{shift}}^{\text{PUCCH}} \in \{1, 2, 3\}$ respectively.

The PUCCH resources are first indexed in the cyclic time shift domain, followed by the orthogonal time spreading code domain.

The cyclic time shifts used on *adjacent* orthogonal codes can also be staggered, providing the opportunity to separate the channel estimates prior to de-spreading. As high Doppler breaks down the orthogonality between the spread blocks, offsetting the cyclic time shift

Table 17.7 PUCCH RB format 1/1a/1b resource index allocation, $\Delta_{\text{shift}}^{\text{PUCCH}} = 3$, 12 resource indices, normal CP.

	Orthogonal code sequence index, n_{oc}		
Cyclic shift index, $n_{\text{RS}}^{\text{PUCCH}}$	$n_{\text{oc}} = 0$	$n_{\text{oc}} = 1$	$n_{\text{oc}} = 2$
0	0		
1		4	
2			7
3	1		
4		5	
5			8
6	2		
7			
8			
9	3		
10		6	
11			9

values within each SC-FDMA symbol can restore orthogonality at moderate delay spreads. This can enhance the tracking of high Doppler channels [14].

In order to randomize intra-cell interference, PUCCH resource index remapping is used in the second slot [15]. Index remapping includes both cyclic shift remapping and orthogonal block spreading code remapping (similar to the case of CQI – see Section 17.3.2).

The PUCCH resource index remapping function in an odd slot is based on the PUCCH resource index in the even slot of the subframe, as defined in [3, Section 5.4.1].

17.3.5 Multiplexing of CQI and HARQ ACK/NACK in the Same PUCCH RB (Mixed PUCCH RB)

The multiplexing of CQI and HARQ ACK/NACK in different PUCCH RBs can in general simplify the system. However, in the case of small system bandwidths such as 1.4 MHz the control signalling overhead can become undesirably high with separate CQI and ACK/NACK RB allocations (two out of a total of six RBs for control signalling in 1.4 MHz system bandwidths). Therefore, multiplexing of CQI and ACK/NACK from different UEs in the same mixed PUCCH RB is supported in LTE to reduce the total control signalling overhead.

The ZC cyclic time shift structure facilitates the orthogonal multiplexing of CQI and ACK/NACK signals with different numbers of RS symbols. This is achieved by assigning different sets of adjacent cyclic time shifts to CQI and ACK/NACK signals [16] as shown in Table 17.8. As can be seen from this table, $N_{\text{cs}}^{(1)} \in \{0, 1, \ldots, 7\}$ cyclic time shifts are used for PUCCH ACK/NACK formats 1/1a/1b in the mixed PUCCH RB case, where $N_{\text{cs}}^{(1)}$ is a cell-specific broadcast parameter (see [3], Section 5.4) restricted to integer multiples of $\Delta_{\text{shift}}^{\text{PUCCH}}$. A guard cyclic time shift is used between the ACK/NACK and CQI cyclic shift resources to improve orthogonality and channel separation between UEs transmitting CQI and those transmitting ACK/NACK. To avoid mixing of the cyclic time shifts for ACK/NACK and

Table 17.8 Multiplexing of ACK/NACK (format 1/1a/1b) and CQI (format 2/2a/2b) from different UEs in the same (mixed) PUCCH RB by using different sets of cyclic time shifts.

Cyclic shift index	Cyclic shift index allocation
0	Format 1/1a/1b (HARQ ACK/NACK, SR) cyclic shifts
1	
2	
$\vdots$	
$N_{cs}^{(1)}$	
$N_{cs}^{(1)}+1$	Guard cyclic shift
$N_{cs}^{(1)}+2$	Format 2/2a/2b (CQI) cyclic shifts
$\vdots$	
10	
11	Guard cyclic shift

CQI, the cyclic time shift (i.e. the PUCCH resource index remapping function) for the odd slot of the subframe is not used; the same cyclic time shift as in the first slot of the subframe is used.

17.3.6 Scheduling Request (SR) Transmission on PUCCH (Format 1)

The structure of the SR PUCCH format 1 is the same as that of the ACK/NACK PUCCH format 1a/1b explained in Section 17.3.4, where a cyclic time shift of the base RS sequence is modulated with time-domain orthogonal block spreading. The SR uses simple On–Off keying, with the UE transmitting a SR with modulation symbol $d(0) = 1$ to request a PUSCH resource (positive SR transmission), and transmitting nothing when it does not request to be scheduled (negative SR).

Since the HARQ ACK/NACK structure is reused for the SR, different PUCCH resource indices (i.e. different cyclic time shift/orthogonal code combinations) in the same PUCCH region can be assigned for SR (Format 1) or HARQ ACK/NACK (Format 1a/1b) from different UEs. This results in orthogonal multiplexing of SR and HARQ ACK/NACK in the same PUCCH region. The PUCCH resource index to be used by a UE for SR transmission, $m_{\mathrm{PUCCH,SRI}}^{(1)}$, is configured by UE-specific higher-layer signalling.

In case a UE needs to transmit a positive SR in the same subframe as a scheduled CQI transmission, the CQI is dropped and only the SR is transmitted, in order to maintain the low CM of the transmit signal. Similarly, in the case of simultaneous SR and SRS configuration, the UE does not transmit SRS and transmits only SR (see [6], Section 8.2).

If an SR and ACK/NACK happen to coincide in the same subframe, the UE transmits the ACK/NACK on the assigned SR PUCCH resource for a positive SR and transmits ACK/NACK on its assigned ACK/NACK PUCCH resource in case of a negative SR (see [6], Section 8.3). The constellation mapping for simultaneous HARQ ACK/NACK and SR is shown in Figure 17.14.

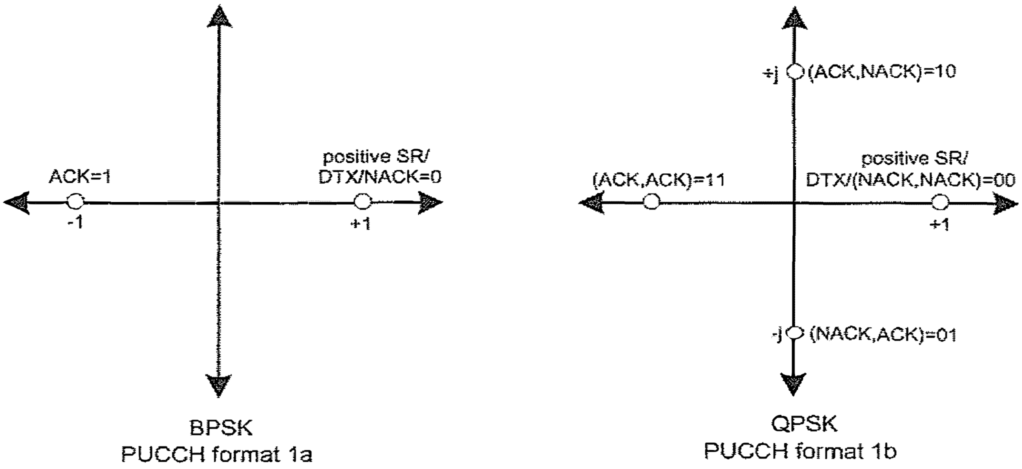

Figure 17.14 Constellation Mapping for ACK/NACK and SR for PUCCH format 1/1a/1b.

The modulation mapping is such that a NACK (or NACK, NACK in the case of two downlink MIMO codewords) is mapped to +1 resulting in a default NACK in case of DTX. This is similar to the case of multiplexing CQI and HARQ ACK/NACK for the normal CP case as described in Section 17.3.3.1.

17.4 Multiplexing of Control Signalling and UL-SCH Data on PUSCH

When control signalling is to be transmitted in a subframe in which the UE has been allocated transmission resources for the PUSCH, the control signalling is multiplexed together with the UL-SCH data prior to DFT-spreading, in order to preserve the low CM single-carrier property; the PUCCH is never transmitted in the same subframe as the PUSCH. The multiplexing of CQI/PMI, HARQ ACK/NACK, and RI with the PUSCH data symbols onto uplink resource elements is shown in Figure 17.15.

The number of resource elements used for each of CQI/PMI, ACK/NACK and RI is based on the MCS assigned for PUSCH and an offset parameter, $\Delta_{\text{offset}}^{\text{CQI}}$, $\Delta_{\text{offset}}^{\text{HARQ-ACK}}$, or $\Delta_{\text{offset}}^{\text{RI}}$, which is semi-statically configured by higher-layer signalling (see [2], Section 5.2.2.6). This allows different code rates to be used for the control signalling. PUSCH data and control information are never mapped to the same resource element. Control information is mapped in such a way that control is present in both slots of the subframe. Since the eNodeB has prior knowledge of uplink control signaling transmission, it can easily de-multiplex control and data packets.

As shown in Figure 17.15, CQI/PMI resources are placed at the beginning of the UL-SCH data resources and mapped sequentially to all SC-FDMA symbols on one subcarrier before continuing on the next subcarrier. The UL-SCH data is rate-matched (see Section 10.3.2.4)

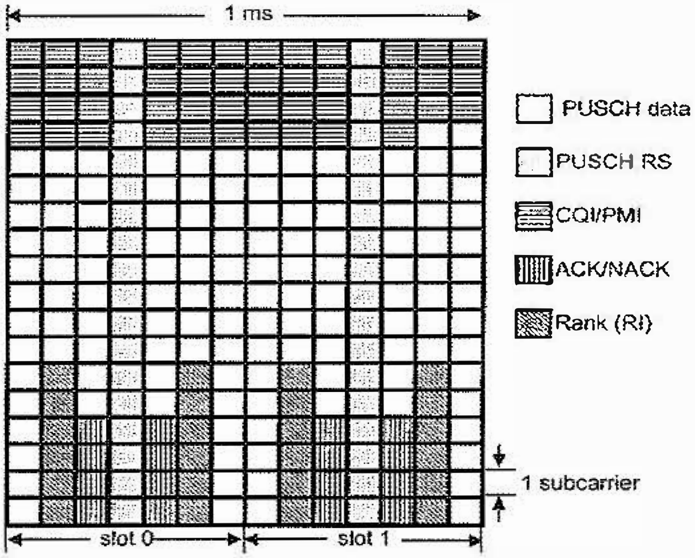

Figure 17.15 Multiplexing of control signalling with UL-SCH data.

around the CQI/PMI data. The same modulation order as UL-SCH data on PUSCH is used for CQI/PMI. For small CQI and/or PMI report sizes up to 11 bits, a (32, *k*) block code, similar to the one used for PUCCH, is used, with optional circular repetition of encoded data (see [2], Section 5.2.2.6.4); no CRC is applied. For large CQI reporting modes (> 11 bits), an 8-bit CRC is attached and channel coding and rate matching is performed using the tail-biting convolutional code as described in Chapter 10.

The HARQ ACK/NACK resources are mapped to SC-FDMA symbols, by puncturing the UL-SCH PUSCH data. Positions next to the RS are used, so as to benefit from the best possible channel estimation. The maximum amount of resource for HARQ ACK/NACK is 4 SC-FDMA symbols.

The coded RI symbols are placed next to the HARQ ACK/NACK symbol positions irrespective of whether ACK/NACK is actually present in a given subframe. The modulation of the 1- or 2-bit ACK/NACK or RI is such that the Euclidean distance of the modulation symbols carrying ACK/NACK and RI is maximized (see [2], Section 5.2.2.6). The outermost constellation points of the higher-order 16/64-QAM PUSCH modulations are used, resulting in increased transmit power for ACK/NACK/RI relative to the average PUSCH data power.

The coding of the RI and CQI/PMI are separate, with the UL-SCH data being rate-matched around the RI resource elements similarly to the case of CQI/PMI.

In the case of 1-bit ACK/NACK or RI, repetition coding is used. For the case of 2-bit ACK/NACK/RI, a (3, 2) simplex code is used with optional circular repetition of the encoded data (see [2], Section 5.2.2.6). The resulting code achieves the theoretical maximum values of the minimum Hamming distance of the output codewords in an efficient way. The (3, 2) simplex codeword mapping is shown in Table 17.9.

Table 17.9 (3, 2) Simplex code for 2-bit ACK/NACK and RI.

2-bit Information Bit Sequence	3-bit Output Codeword
00	000
01	011
10	101
11	110

In LTE, control signalling (using QPSK modulation) can also be scheduled to be transmitted on PUSCH without UL-SCH data. The control signalling (CQI/PMI, RI, and/or HARQ ACK/NACK) are multiplexed prior to DFT-spreading, in order to preserve the low CM single-carrier property. The multiplexing of HARQ ACK/NACK and RI with the CQI/PMI QPSK symbols onto uplink resource elements is similar to that shown in Figure 17.15. HARQ ACK/NACK is mapped to SC-FDMA symbols next to the RS, by puncturing the CQI data and RI symbols, irrespective of whether ACK/NACK is actually present in a given subframe. The number of resource elements used for each of ACK/NACK and RI is based on a reference MCS for CQI/PMI and offset parameters, $\Delta_{\text{offset}}^{\text{CQI}}$, $\Delta_{\text{offset}}^{\text{HARQ-ACK}}$, or $\Delta_{\text{offset}}^{\text{RI}}$. The reference CQI/PMI MCS is computed from the CQI payload size and resource allocation. The channel coding and rate matching of the control signalling without UL-SCH data is the same as that of multiplexing control with UL-SCH data as described above.

17.5 Multiple-Antenna Techniques

In the first version of LTE, simultaneous transmissions from multiple-transmit antennas of a single UE are not supported. Only a single power-amplifier is assumed to be available at the UE. However, LTE does support closed-loop antenna selection transmit diversity in the uplink from UEs which have multiple transmit antennas.

LTE is also designed to support uplink SDMA, or Virtual Multi-User MIMO (MU-MIMO), and this is discussed in more detail in Section 17.5.2.

17.5.1 Closed-Loop Switched Antenna Diversity

Uplink closed-loop antenna selection (for up to two transmit antennas) is supported as an optional UE capability in LTE (see [17], Section 4.3.4.1).

If a UE signals that it supports uplink antenna selection, the eNodeB may take this capability into consideration when configuring and scheduling the UE.[4]

If the eNodeB enables a UE's closed-loop antenna selection capability, the SRS transmissions then alternate between the transmit antennas in successive configured SRS transmission subframes, irrespective of whether frequency hopping is enabled or disabled, except when the UE is configured for a single one-shot SRS transmission (see [6], Section 8.2).

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[4] Alternatively, the eNodeB may permit the UE to use open-loop antenna selection, in which case the UE is free to determine which antenna to transmit from. This may be based on uplink-downlink channel reciprocity, for example in the case of TDD operation (see Section 23.5.2.5.

Table 17.10 UE transmit antenna selection CRC mask. Reproduced by permission of © 3GPP.

UE transmit antenna selection	Antenna selection mask $\langle x_{\mathrm{AS},0}, x_{\mathrm{AS},1}, \ldots, x_{\mathrm{AS},15} \rangle$
UE transmit antenna 0	⟨0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0⟩
UE transmit antenna 1	⟨0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1⟩

17.5.1.1 PUSCH UE Antenna Selection Indication

When closed-loop antenna selection is enabled, the eNodeB indicates which antenna should be used for the PUSCH by implicit coding in the uplink scheduling grant (Downlink Control Information (DCI) Format 0 – see Section 9.3): the 16 CRC parity bits are scrambled (modulo-2 addition) by an antenna selection mask [18], shown in Table 17.10 [19]. The antenna selection mask is applied in addition to the UE-ID masking which indicates for which UE the scheduling grant is intended. This implicit encoding avoids the use of an explicit antenna selection bit which would result in an increased overhead for UEs not supporting (or not configured) for transmit antenna selection.

It can be seen from Table 17.10 that the minimum Hamming distance between the antenna selection masks is only 1 rather than the maximum possible Hamming distance of 16. Since the CRC is masked by both the antenna selection indicator and the 16-bit UE-ID, the minimum Hamming distance between the correct UE-ID/antenna selection mask and the nearest erroneous UE-ID/antenna selection mask is 1 for any antenna selection mask. Out of the possible $2^{16} - 1$ incorrect masks, a vast majority ($2^{16} - 2$) result in the misidentification of the UE-ID, such that the performance is similar regardless of the Hamming distance between antenna selection masks. The primary advantage of using the mask ⟨0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1⟩ is the ease of implementation due to simpler half-space identification, as the eNodeB can allocate UE-IDs with a fixed Most Significant Bit (e.g. MSB set to '0', or equivalently UE IDs from 0 to $2^{15} - 1$). The UE-ID can be detected directly from the 15 least significant bits of the decoded mask without needing to use the transmitted antenna selection mask (bit 16).

The UE behaviour for adaptive/non-adaptive HARQ retransmissions when configured for antenna selection is as follows [18]:

- **Adaptive HARQ.** The antenna indicator (via CRC masking) is always sent in the UL grant to indicate which antenna to use. For example, for a high Doppler UE with adaptive HARQ, the eNodeB might instruct the UE to alternate between the transmit antennas, or alternatively select the primary antenna. In typical UE implementations, a transmit antenna gain imbalance of 3 to 6 dB between the secondary and primary antenna is not uncommon.

- **Non-adaptive HARQ.** The UE behaviour is unspecified as to which antenna to use. Thus, for low Doppler conditions, the UE could use the same antenna as that signalled in the UL grant, while at high Doppler the UE could hop between antennas or just select the primary antenna. For large numbers of retransmissions with non-adaptive HARQ, the antenna indicated on the UL grant may not be the best and it is better to let the UE select the antenna to use. If the eNodeB wishes to instruct the UE to use a specific antenna for the retransmissions, it can use adaptive HARQ.

17.5.2 Multi-User 'Virtual' MIMO or SDMA

Uplink MU-MIMO consists of multiple UEs transmitting on the same set of RBs, each using a single transmit antenna. From the point of view of an individual UE, such a mode of operation is hardly visible, being predominantly a matter for the eNodeB to handle in terms of scheduling and uplink reception.

However, in order to support uplink MU-MIMO, LTE specifically provides orthogonal DM RS using different cyclic time shifts (see Section 16.2.2) to enable the eNodeB to derive independent channel estimates for the uplink from each UE.

A cell can assign up to eight different cyclic time shifts using the 3-bit PUSCH cyclic time shift offset on the uplink scheduling grant. As a maximum of eight cyclic time shifts can be assigned, SDMA of up to eight UEs can be supported in a cell. SDMA between cells (i.e. uplink inter-cell cooperation) is supported in LTE by assigning the same base sequence-groups and/or RS hopping patterns to the different cells as explained in Section 16.3.

17.6 Summary

The main uplink physical channels are the PUSCH for data transmission and the PUCCH for control signalling.

The PUSCH supports resource allocation for both frequency-selective scheduling and frequency-diverse transmissions, the latter being by means of intra- and/or inter-subframe frequency hopping.

Control signalling (consisting of ACK/NACK, CQI/PMI and RI) is carried by the PUCCH when no PUSCH resources have been allocated. The PUCCH is deliberately mapped to resource blocks near the edge of the system bandwidth, in order to reduce out-of-band emissions caused by data transmissions on the inner RBs, as well as maximizing flexibility for PUSCH scheduling in the central part of the band. In all cases of multiplexing different kinds of control signalling, the single-carrier property of the uplink signal is preserved. The control signalling from multiple UEs is multiplexed via orthogonal coding by using cyclic time shift orthogonality and/or time-domain block spreading.

LTE also introduces multiple antenna techniques in the uplink, in particular through the support of closed-loop switched antenna diversity and SDMA. These techniques are also cost-effective for a UE implementation, as they neither assume simultaneous transmissions from multiple UE antennas.

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