



LTE

The UMTS Long Term Evolution

FROM THEORY TO PRACTICE

Edited by: Stefania Sesia • Issam Toufik • Matthew Baker

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LTE – The UMTS Long Term Evolution

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From Theory to Practice

Second Edition

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Dedication

*To my family.
Stefania Sesia*

*To my parents for their sacrifices and unconditional love. To my brother and sisters for their love and
continual support. To my friends for being what they are.
Issam Toufik*

*To the glory of God, who 'so loved the world that He gave His only Son, that whoever believes in Him
shall not perish but have eternal life'. — The Bible.
Matthew Baker*

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waited for an uplink resource grant that would not be forthcoming. To avoid this, the `retxBSR` timer is restarted whenever an uplink grant message is received; if no uplink grant is received before the timer expires, the UE transmits another BSR.

If a UE does not have enough allocated UL-SCH resources to send a BSR when a trigger for a Regular BSR occurs, the UE sends a Scheduling Request (SR) on the Physical Uplink Control Channel (PUCCH – see Section 16.3.7) if possible; otherwise, the random access procedure (see Section 4.4.2.3) is used to request an allocation of uplink resources for sending a BSR. However, if a periodic or padding BSR is triggered when the UE does not have UL-SCH resources for a new transmission, the SR is not triggered.

Thus LTE provides suitable signalling to ensure that the eNodeB has sufficient information about the data waiting in each UE's uplink transmission buffer to allocate corresponding uplink transmission resources in a timely manner.

4.4.2.3 Random Access Procedure

The random access procedure is used when a UE is not allocated with uplink radio resources but has data to transmit, or when the UE is not time-synchronized in the uplink direction. Control of the random access procedure is an important part of the MAC layer functionality in LTE. The details are explained in Chapter 17.

4.4.2.4 Uplink Timing Alignment

Uplink timing alignment maintenance is controlled by the MAC layer and is important for ensuring that a UE's uplink transmissions arrive in the eNodeB without overlapping with the transmissions from other UEs. The details of the uplink timing advance mechanism used to maintain timing alignment are explained in Section 18.2.

The timing advance mechanism utilizes MAC Control Elements (see Section 4.4.2.7) to update the uplink transmission timing. However, maintaining the uplink synchronization in this way during periods when no data is transferred wastes radio resources and adversely impacts the UE battery life. Therefore, when a UE is inactive for a certain period of time the UE is allowed to lose uplink synchronization even in `RRC_CONNECTED` state. The random access procedure is then used to regain uplink synchronization when the data transfer resumes in either uplink or downlink.

4.4.2.5 Discontinuous Reception (DRX)

DRX functionality can be configured for an '`RRC_CONNECTED`' UE¹⁸ so that it does not always need to monitor the downlink channels. A DRX cycle consists of an 'On Duration' during which the UE should monitor the PDCCH and a 'DRX period' during which a UE can skip reception of downlink channels for battery saving purposes.

The parameterization of the DRX cycle involves a trade-off between battery saving and latency. On the one hand, a long DRX period is beneficial for lengthening the UE's battery life. For example, in the case of a web browsing service, it is usually a waste of resources for a UE continuously to receive downlink channels while the user is reading a downloaded

¹⁸Different DRX functionality applies to UEs which are in '`RRC_IDLE`'. These RRC states are discussed in Chapter 3.

web page. On the other hand, a shorter DRX period is better for faster response when data transfer is resumed – for example when a user requests another web page.

To meet these conflicting requirements, two DRX cycles – a short cycle and a long cycle – can be configured for each UE, with the aim of providing a similar degree of power saving for the UE in RRC_CONNECTED as in RRC_IDLE. The transition between the short DRX cycle, the long DRX cycle and continuous reception is controlled either by a timer or by explicit commands from the eNodeB. In some sense, the short DRX cycle can be considered as a confirmation period in case a late packet arrives, before the UE enters the long DRX cycle – if data arrives at the eNodeB while the UE is in the short DRX cycle, the data is scheduled for transmission at the next wake-up time and the UE then resumes continuous reception. On the other hand, if no data arrives at the eNodeB during the short DRX cycle, the UE enters the long DRX cycle, assuming that the packet activity is finished for the time being.

Figure 4.19 shows an example of DRX operation. The UE checks for scheduling messages (indicated by its C-RNTI on the PDCCH) during the ‘On Duration’ period of either the long DRX cycle or the short DRX cycle depending on the currently active cycle. When a scheduling message is received during an ‘On Duration’, the UE starts a ‘DRX Inactivity Timer’ and monitors the PDCCH in every subframe while the DRX Inactivity Timer is running. During this period, the UE can be regarded as being in a continuous reception mode. Whenever a scheduling message is received while the DRX Inactivity Timer is running, the UE restarts the DRX Inactivity Timer, and when it expires the UE moves into a short DRX cycle and starts a ‘DRX Short Cycle Timer’. The short DRX cycle may also be initiated by means of a MAC Control Element (see Section 4.4.2.7). When the ‘DRX Short Cycle Timer’ expires, the UE moves into a long DRX cycle.

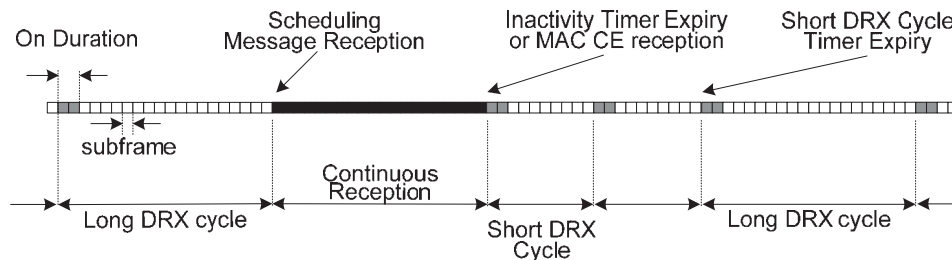


Figure 4.19: The two-level DRX procedure.

In addition to this DRX behaviour, a ‘HARQ RTT (Round Trip Time) timer’ is defined per downlink HARQ process with the aim of allowing the UE to sleep during the HARQ RTT. When decoding of a downlink TB for one HARQ process fails, the UE can assume that the next retransmission of the TB will occur after at least ‘HARQ RTT’ subframes. While the HARQ RTT timer is running, the UE does not need to monitor the PDCCH (provided that there is no other reason to be monitoring it). At the expiry of the HARQ RTT timer, if received data for a downlink HARQ process is not correctly decoded, the UE starts a ‘DRX Retransmission Timer’ for that HARQ process. While the timer is running, the UE

monitors the PDCCH for HARQ retransmissions. The length of the DRX Retransmission Timer is related to the degree of flexibility desired for the eNodeB's scheduler. For optimal UE battery consumption, it is desirable that eNodeB schedules a HARQ retransmission as soon as the HARQ RTT timer expires. However, this requires that eNodeB always reserve some radio resources for this, and therefore the DRX Retransmission timer can be used to relax this scheduling limitation while limiting the amount of time for which the UE has to monitor the PDCCH. The HARQ RTT is illustrated in Section 10.3.2.5.

4.4.2.6 Multiplexing and Logical Channel Prioritization

Unlike the downlink, where the multiplexing and logical channel prioritization is left to the eNodeB implementation, for the uplink the process by which a UE creates a MAC PDU to transmit using the allocated radio resources is fully standardized; this is designed to ensure that the UE satisfies the QoS of each configured radio bearer in a way which is optimal and consistent between different UE implementations. Based on the uplink transmission resource grant message signalled on the PDCCH, the UE has to decide on the amount of data for each logical channel to be included in the new MAC PDU, and, if necessary, also to allocate space for a MAC Control Element.

One simple way to meet this purpose is to serve radio bearers in order of their priority. Following this principle, the data from the logical channel of the highest priority is the first to be included into the MAC PDU, followed by data from the logical channel of the next highest priority, continuing until the MAC PDU size allocated by the eNodeB is completely filled or there is no more data to transmit.

Although this kind of priority-based multiplexing is simple and favours the highest priorities, it sometimes leads to starvation of low-priority bearers. Starvation occurs when the logical channels of the lower priority cannot transmit any data because the data from higher priority logical channels always takes up all the allocated radio resources.

To avoid starvation, while still serving the logical channels according to their priorities, in LTE a Prioritized Bit Rate (PBR) is configured by the eNodeB for each logical channel. The PBR is the data rate provided to one logical channel before allocating any resource to a lower-priority logical channel.

In order to take into account both the PBR and the priority, each logical channel is served in decreasing order of priority, but the amount of data from each logical channel included into the MAC PDU is initially limited to the amount corresponding to the configured PBR. Only when all logical channels have been served up to their PBR, then if there is still room left in the MAC PDU, each logical channel is served again in decreasing order of priority. In this second round, each logical channel is served only if all logical channels of higher priority have no more data for transmission.

In most cases, a MAC Control Element has higher priority than any other logical channel because it controls the operation of a MAC entity. Thus, when a MAC PDU is composed and there is a MAC Control Element to send, the MAC Control Element is generally included first and the remaining space is used to include data from logical channels. However, since the padding BSR is used to fill up remaining space in a MAC PDU, it is included into a MAC PDU after other logical channels. Among the various types of MAC Control Element (see Section 4.4.2.7) and logical channel, the 'C-RNTI' MAC Control Element and CCCH (CCCH) have the highest priority because they are used for either contention resolution or

cyclic shift index is then used to shift the PHICH allocations in the downlink so that each UE receives its ACK or NACK on a different PHICH. This mapping of the PHICH allocations is illustrated in Figure 9.9.

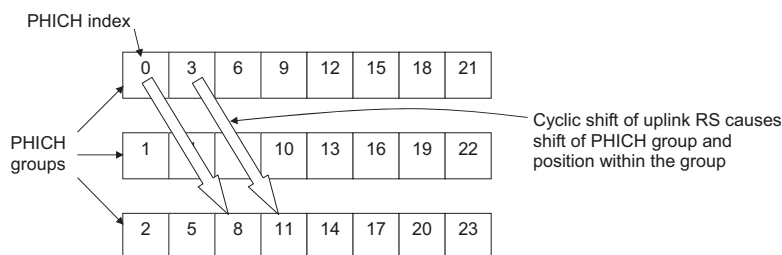


Figure 9.9: Indexing of PHICHs within PHICH groups, and shifting in the case of cyclic shifting of the uplink demodulation reference signals.

The PHICH indexing for the case of uplink MIMO in Release 10 is explained in Section 29.4.1. The use of the PHICH in the case of aggregation of multiple carriers in Release 10 is explained in Section 28.3.1.3.

The PHICHs are transmitted on the same set of antenna ports as the PBCH, and transmit diversity is applied if more than one antenna port is used.

9.3.5 Physical Downlink Control CHannel (PDCCH)

Each PDCCH carries a message known as Downlink Control Information (DCI), which includes resource assignments and other control information for a UE or group of UEs. In general, several PDCCHs can be transmitted in a subframe.

Each PDCCH is transmitted using one or more *Control Channel Elements* (CCEs), where each CCE corresponds to nine REGs. Four QPSK symbols are mapped to each REG.

Four PDCCH formats are supported, as listed in Table 9.1.

Table 9.1: PDCCH formats.

PDCCH format	Number of CCEs (n)	Number of REGs	Number of PDCCH bits
0	1	9	72
1	2	18	144
2	4	36	288
3	8	72	576

CCEs are numbered and used consecutively, and, to simplify the decoding process, a PDCCH with a format consisting of n CCEs may only start with a CCE with a number equal to a multiple of n .

The number of CCEs aggregated for transmission of a particular PDCCH is known as the ‘aggregation level’ and is determined by the eNodeB according to the channel conditions. For example, if the PDCCH is intended for a UE with a good downlink channel (e.g. close to the eNodeB), then one CCE is likely to be sufficient. However, for a UE with a poor channel (e.g. near the cell border) then eight CCEs may be required in order to achieve sufficient robustness. In addition, the power level of a PDCCH may be adjusted to match the channel conditions.

9.3.5.1 Formats for Downlink Control Information (DCI)

The required content of the control channel messages depends on the system deployment and UE configuration. For example, if the infrastructure does not support MIMO, or if a UE is configured in a transmission mode which does not involve MIMO, there is no need to signal the parameters that are only required for MIMO transmissions. In order to minimize the signalling overhead, it is therefore desirable that several different message formats are available, each containing the minimum payload required for a particular scenario. On the other hand, to avoid too much complexity in implementation and testing, it is desirable not to specify too many formats. The set of DCI message formats in Table 9.2 is specified in LTE; Format 2B was added in Release 9, and Formats 2C and 4 were added in Release 10. Additional formats may be defined in future.

Table 9.2: Supported DCI formats.

DCI format	Purpose	Applicable PDSCH transmission mode(s)
0	PUSCH grants	All
1	PDSCH assignments with a single codeword	1,2,7
1A	PDSCH assignments using a compact format	All
1B	PDSCH assignments for rank-1 transmission	6
1C	PDSCH assignments using a very compact format	n/a
1D	PDSCH assignments for multi-user MIMO	5
2	PDSCH assignments for closed-loop MIMO operation	4
2A	PDSCH assignments for open-loop MIMO operation	3
2B	PDSCH assignments for dual-layer beamforming	8
2C	PDSCH assignments for up to 8-layer spatial multiplexing	9
3	Transmit Power Control (TPC) commands for multiple users for PUCCH and PUSCH with 2-bit power adjustments	n/a
3A	Transmit Power Control (TPC) commands for multiple users for PUCCH and PUSCH with 1-bit power adjustments	n/a
4	PUSCH grants for up to 4-layer spatial multiplexing	All (if configured for PUSCH transmission mode 2)

The information content of the different DCI message formats is listed below for Frequency Division Duplex (FDD) operation. Some small differences exist for Time Division Duplex (TDD), and these are outlined afterwards.

Format 0. DCI Format 0 is used for the transmission of resource grants for the PUSCH. The following information is transmitted:

- Flag to differentiate between Format 0 and Format 1A;
- Resource assignment and frequency hopping flag;
- Modulation and Coding Scheme (MCS);
- New Data Indicator (NDI);
- HARQ information and Redundancy Version (RV);
- Power control command for scheduled PUSCH;
- Cyclic shift for uplink Demodulation RS;
- Request for transmission of an aperiodic CQI report (see Sections 10.2.1 and 28.3.2.3).

Format 1. DCI Format 1 is used for the transmission of resource assignments for single codeword PDSCH transmissions (transmission modes 1, 2 and 7 (see Section 9.2.2.1)). The following information is transmitted:

- Resource allocation type (see Section 9.3.5.4);
- RB assignment;
- MCS;
- HARQ information and RV;
- Power control command for Physical Uplink Control CHannel (PUCCH).

Format 1A. DCI Format 1A is used for compact signalling of resource assignments for single codeword PDSCH transmissions for any PDSCH transmission mode. It is also used to allocate a dedicated preamble signature to a UE to trigger contention-free random access (see Section 17.3.2); in this case the PDCCH message is known as a *PDCCH order*. The following information is transmitted:

- Flag to differentiate between Format 0 and Format 1A;
- Flag to indicate that the distributed mapping mode (see Section 9.2.2.1) is used for the PDSCH transmission (otherwise the allocation is a contiguous set of physical RBs);
- RB assignment;
- MCS;
- HARQ information and RV;
- Power control command for PUCCH.

Format 1B. DCI Format 1B is used for compact signalling of resource assignments for PDSCH transmissions using closed-loop precoding with rank-1 transmission (transmission mode 6). The information transmitted is the same as in Format 1A, but with the addition of an indicator of the precoding vector applied for the PDSCH transmission.

Format 1C. DCI Format 1C is used for very compact transmission of PDSCH assignments. When format 1C is used, the PDSCH transmission is constrained to using QPSK modulation. This is used, for example, for signalling paging messages and some broadcast system information messages (see Section 9.2.2.2), and for notifying UEs of a change of MBMS control information on the Multicast Control Channel (MCCH – see Section 13.6.3.2). The following information is transmitted:

- RB assignment;
- Coding scheme.

The RV is not signalled explicitly, but is deduced from the SFN (see [1, Section 5.3.1]).

Format 1D. DCI Format 1D is used for compact signalling of resource assignments for PDSCH transmissions using multi-user MIMO (transmission mode 5). The information transmitted is the same as in Format 1B, but, instead of one of the bits of the precoding vector indicators, there is a single bit to indicate whether a power offset is applied to the data symbols. This is needed to show whether the transmission power is shared between two UEs.

Format 2. DCI Format 2 is used for the transmission of resource assignments for PDSCH for closed-loop MIMO operation (transmission mode 4). The following information is transmitted:

- Resource allocation type (see Section 9.3.5.4);
- RB assignment;
- Power control command for PUCCH;
- HARQ information and RV for each codeword;
- MCS for each codeword;
- A flag to indicate if the mapping from transport blocks to codewords is reversed;
- Number of spatial layers;
- Precoding information and indication of whether one or two codewords are transmitted on the PDSCH.

Format 2A. DCI Format 2A is used for the transmission of resource assignments for PDSCH for open-loop MIMO operation (transmission mode 3). The information transmitted is the same as for Format 2, except that if the eNodeB has two transmit antenna ports, there is no precoding information, and, for four antenna ports, two bits are used to indicate the transmission rank.

Format 2B. DCI Format 2B is introduced in Release 9 and is used for the transmission of resource assignments for PDSCH for dual-layer beamforming (transmission mode 8). The information transmitted is similar to Format 2A, except that no precoding information is included and the bit in Format 2A for indicating reversal of the transport block to codeword mapping is replaced in Format 2B by a bit indicating the scrambling code applied to the UE-specific RSs for the corresponding PDSCH transmission (see Section 8.2.3).

Format 2C. DCI Format 2C is introduced in Release 10 and is used for the transmission of resource assignments for PDSCH for closed-loop single-user or multi-user MIMO operation with up to 8 layers (transmission mode 9). The information transmitted is similar to Format 2B; full details are given in Section 29.3.2.

Formats 3 and 3A. DCI Formats 3 and 3A are used for the transmission of power control commands for PUCCH and PUSCH, with 2-bit or 1-bit power adjustments respectively. These DCI formats contain individual power control commands for a group of UEs.

Format 4. DCI Format 4 is introduced in Release 10 and is used for the transmission of resource grants for the PUSCH when the UE is configured in PUSCH transmission mode 2 for uplink single-user MIMO. The information transmitted is similar to Format 0, with the addition of MCS and NDI information for a second transport block, and precoding information; full details are given in Section 29.4.

DCI Formats for TDD. In TDD operation, the DCI formats contain the same information as for FDD, but with some additions (see Section 23.4.3 for an explanation of the usage of these additions):

- Uplink index (in DCI Formats 0 and 4, uplink-downlink configuration 0 only);
- Downlink Assignment Index (DAI) (in DCI Formats 0, 1, 1A, 1B, 1D, 2, 2A 2B, 2C and 4, uplink-downlink configurations 1–6 only); see Section 23.4.3 for details of DAI usage.

DCI Format modifications in Release 10. In the case of aggregation of multiple carriers in Release 10, DCI Formats 0, 1, 1A, 1B, 1D, 2, 2A, 2B, 2C and 4 can be configured to include a carrier indicator for cross-carrier scheduling; this is explained in detail in Section 28.3.1.1. In DCI Formats 0 and 4, additional fields are included to request transmission of an aperiodic Sounding Reference Signal (SRS) (see Section 29.2.2) and to indicate whether the uplink PRB allocation is contiguous or multi-clustered (see Section 28.3.6.2 for details). In TDD operation, DCI Formats 2B and 2C may also be configured to include an additional field to request transmission of an aperiodic SRS.

9.3.5.2 PDCCH CRC Attachment

In order that the UE can identify whether it has received a PDCCH transmission correctly, error detection is provided by means of a 16-bit CRC appended to each PDCCH. Furthermore, it is necessary that the UE can identify which PDCCH(s) are intended for it. This could in theory be achieved by adding an identifier to the PDCCH payload; however, it turns out to be more efficient to scramble the CRC with the ‘UE identity’, which saves the additional payload but at the cost of a small increase in the probability of falsely detecting a PDCCH intended for another UE.

In addition, for UEs which support antenna selection for uplink transmissions (see Section 16.6), the requested antenna may be indicated using Format 0 by applying an antenna-specific mask to the CRC. This has the advantage that the same size of DCI message can be used, irrespective of whether antenna selection is used.

9.3.5.3 PDCCH Construction

In general, the number of bits required for resource assignment depends on the system bandwidth, and therefore the message sizes also vary with the system bandwidth. The numbers of payload bits for each DCI format (including information bits and CRC) are summarized in Table 9.3, for each of the supported values of system bandwidth. In addition, padding bits are added if necessary in the following cases:

- To ensure that Formats 0 and 1A are the same size, even in the case of different uplink and downlink bandwidths, in order to avoid additional complexity at the UE receiver;
- To ensure that Formats 3 and 3A are the same size as Formats 0 and 1A, likewise to avoid additional complexity at the UE receiver;
- To avoid potential ambiguity in identifying the correct PDCCH location as described in Section 9.3.5.5;
- To ensure that Format 1 has a different size from Formats 0/1A, so that these formats can be easily distinguished at the UE receiver;
- To ensure that Format 4 has a different size from Formats 1/2/2A/2B/2C, again so that this format can be easily distinguished.

In Release 10, some optional additional information bits may be configured in some of the DCI formats; these are not included in Table 9.3, but are explained below the table. Because their presence may affect the number of padding bits, any such additional bits do not necessarily increase the transmitted size of the DCI format by the same amount.

In order to provide robustness against transmission errors, the PDCCH information bits are coded as described in Section 10.3.3. The set of coded and rate-matched bits for each PDCCH are then scrambled with a cell-specific scrambling sequence; this reduces the possibility of confusion with PDCCH transmissions from neighbouring cells. The scrambled bits are mapped to blocks of four QPSK symbols (REGs). Interleaving is applied to these symbol blocks, to provide frequency diversity, followed by mapping to the available physical REs on the set of OFDM symbols indicated by the PCFICH. This mapping process excludes the REs reserved for RSs and the other control channels (PCFICH and PHICH).

The PDCCHs are transmitted on the same set of antenna ports as the PBCH, and transmit diversity is applied if more than one antenna port is used.

9.3.5.4 Resource Allocation

Conveying indications of physical layer resource allocation is one of the major functions of the PDCCHs. While the exact use of the PDCCHs depends on the algorithms implemented in the eNodeB, it is nevertheless possible to outline some general principles of typical operation.

In each subframe, PDCCHs indicate the frequency-domain resource allocations. As discussed in Section 9.2.2.1, resource allocations are normally localized, meaning that a Physical RB (PRB) in the first half of a subframe is paired with the PRB at the same frequency in the second half of the subframe. For simplicity, the explanation here is in terms of the first half subframe only.

The main design challenge for the signalling of frequency-domain resource allocations (in terms of a set of RBs) is to find a good compromise between flexibility and signalling overhead. The most flexible, and arguably the simplest, approach is to send each UE a

Table 9.3: DCI format payload sizes (in bits), without padding, for different FDD system bandwidths.

	Bandwidth (PRBs)					
	6	15	25	50	75	100
Format 0	35	37	39	41	42	43
Format 1	35	38	43	47	49	55
Format 1A	36	38	40	42	43	44
Format 1B/1D (2 transmit antenna ports)	38	40	42	44	45	46
Format 1C	24	26	28	29	30	31
Format 2 (2 transmit antenna ports)	47	50	55	59	61	67
Format 2A (2 transmit antenna ports)	44	47	52	56	58	64
Format 2B (2 or 4 transmit antenna ports)	44	47	52	56	58	64
Format 2C	46	49	54	58	60	66
Format 4 (2 UE transmit antennas)	46	47	50	52	53	54
Format 1B/1D (4 transmit antenna ports)	40	42	44	46	47	48
Format 2 (4 transmit antenna ports)	50	53	58	62	64	70
Format 2A (4 transmit antenna ports)	46	49	54	58	60	66
Format 4 (4 UE transmit antennas)	49	50	53	55	56	57

Note that for Release 10 UEs:

- DCI Format 0 is extended by 1 bit for a multi-cluster resource allocation flag and may be further extended by 1 or 2 bits for aperiodic CQI request (see Section 28.3.2.3) and aperiodic SRS request (see Section 29.2.2), depending on configuration.
- DCI Format 1A may be extended by 1 bit for aperiodic SRS request, depending on configuration.
- In TDD operation, DCI Formats 2B and 2C may be extended by 1 bit for aperiodic SRS request, depending on configuration.
- DCI Format 4 always includes 2 bits for requesting aperiodic SRS (see Section 29.2.2), and 1 bit for aperiodic CQI request, but may be extended by an additional 1 bit for aperiodic CQI request in case of carrier aggregation (see Section 28.3.2.3).
- DCI Formats 0, 1, 1A, 1B, 1D, 2, 2A, 2B, 2C and 4 can be configured to be extended by 3 bits for a carrier indicator field (see Section 28.3.1.1).

bitmap in which each bit indicates a particular PRB. This would work well for small system bandwidths, but for large system bandwidths (i.e. up to 110 PRBs) the bitmap would need 110 bits, which would be a prohibitive overhead – particularly for small packets, where the PDCCH message could be larger than the data packet! One possible solution would be to send a combined resource allocation message to all UEs, but this was rejected on the grounds of the high power needed to reach all UEs reliably, including those at the cell edges. The approaches adopted in LTE Releases 8 and 9 are listed in Table 9.4, and further details are given below.

Resource allocation Type 0. In resource allocations of Type 0, a bitmap indicates the Resource Block Groups (RBGs) which are allocated to the scheduled UE, where an RBG is a set of consecutive PRBs. The RBG size (P) is a function of the system bandwidth as shown in Table 9.5. The total number of RBGs (N_{RBG}) for a downlink system bandwidth of

Table 9.4: Methods for indicating Resource Block (RB) allocation.

Method	UL/DL	Description	Number of bits required (see text for definitions)
Direct bitmap	DL	The bitmap comprises 1 bit per RB. This method is the only one applicable when the bandwidth is less than 10 resource blocks.	N_{RB}^{DL}
Bitmap: 'Type 0'	DL	The bitmap addresses Resource Block Groups (RBGs), where the group size (2, 3 or 4) depends on the system bandwidth.	$\lceil N_{RB}^{DL}/P \rceil$
Bitmap: 'Type 1'	DL	The bitmap addresses individual RBs in a subset of RBGs. The number of subsets (2, 3, or 4) depends on the system bandwidth. The number of bits is arranged to be the same as for Type 0, so the same DCI format can carry either type of allocation.	$\lceil N_{RB}^{DL}/P \rceil$
Contiguous allocations: 'Type 2'	DL or UL	Any possible arrangement of contiguous RB allocations can be signalled in terms of a starting position and number of RBs.	$\lceil \log_2(N_{RB}^{DL}(N_{RB}^{DL} + 1)) \rceil$ or $\lceil \log_2(N_{RB}^{UL}(N_{RB}^{UL} + 1)) \rceil$
Distributed allocations	DL	In the downlink, a limited set of resource allocations can be signalled where the RBs are scattered across the frequency domain and shared between two UEs. The number of bits is arranged to be the same as for contiguous allocations Type 2, so the same DCI format can carry either type of allocation.	$\lceil \log_2(N_{RB}^{DL}(N_{RB}^{DL} + 1)) \rceil$

N_{RB}^{DL} PRBs is given by $N_{RBG} = \lceil N_{RB}^{DL}/P \rceil$. An example for the case of $N_{RB}^{DL} = 25$, $N_{RBG} = 13$ and $P = 2$ is shown in Figure 9.10, where each bit in the bitmap indicates a pair of PRBs (i.e. two PRBs which are adjacent in frequency).

Table 9.5: RBG size for Type 0 resource allocation.

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

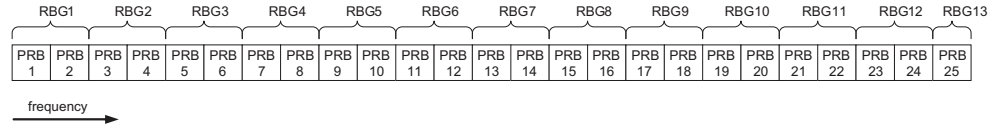


Figure 9.10: PRB addressed by a bitmap Type 0, each bit addressing a complete RBG.

Resource allocation Type 1. In resource allocations of Type 1, individual PRBs can be addressed (but only within a subset of the PRBs available). The bitmap used is slightly smaller than for Type 0, since some bits are used to indicate which subset of the RBG 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 $N_{RB}^{DL} = 25$, $N_{RBG} = 11$ and $P = 2$ is shown in Figure 9.11.

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

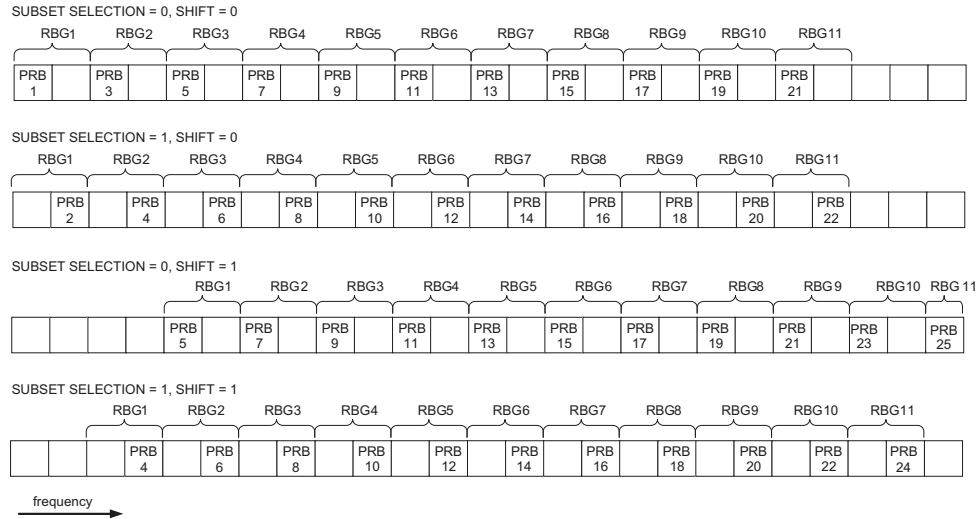


Figure 9.11: PRBs addressed by a bitmap Type 1, each bit addressing a subset of an RBG, depending on a subset selection and shift value.

Resource allocation Type 2. In resource allocations of Type 2, the resource allocation information indicates a contiguous set of PRBs, using either localized or distributed mapping (see Section 9.2.2.1) as indicated 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 RB (RB_{START}) and a length in terms of contiguously-allocated RBs (L_{CRBs}). The resource indication value is defined by

$$\begin{aligned} &\text{if } (L_{CRBs} - 1) \leq \lfloor N_{RB}^{DL}/2 \rfloor \text{ then } RIV = N_{RB}^{DL}(L_{CRBs} - 1) + RB_{START} \\ &\text{else } RIV = N_{RB}^{DL}(N_{RB}^{DL} - L_{CRBs} + 1) + (N_{RB}^{DL} - 1 - RB_{START}) \end{aligned}$$

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

Resource allocation in Release 10. In addition to the above methods, Release 10 supports a non-contiguous resource allocation method for the uplink, allowing two separate contiguous sets of PRBs to be assigned, as explained in detail in Section 28.3.6.2.

9.3.5.5 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 the 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 thus restricts the UEs to which the eNodeB can 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 *UE-specific* and *common* search spaces are defined; a UE-specific search space is configured for each UE individually, whereas all UEs are aware of the extent of the common search space. Note that the UE-specific and common search spaces may overlap for a given UE. The sizes of the common and UE-specific search spaces in Releases 8 and 9 are listed in Table 9.6.

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

Table 9.6: Search spaces for PDCCH formats in Releases 8 and 9.

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

Note: The search space sizes in Release 10 are discussed in Section 28.3.1.1.

particular UE. To minimize the possibility of such blocking persisting into the next subframe, a UE-specific hopping sequence (derived from the UE identity) is applied to the starting positions of the UE-specific search spaces from subframe to subframe.

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 UE-specific search space, the UE will always search for Formats 0 and 1A, which are 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, 1D, 2, 2A or 2B, depending on the PDSCH transmission mode configured by the eNodeB).

In the common search space, the UE will typically search for Formats 1A and 1C. In addition, the UE may be configured to search for Formats 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, a Release 8/9 UE is required to carry out a maximum of 44 blind decodings in any subframe (12 in the common search space and 32 in the UE-specific search space). This does not include checking the same message with different CRC values, which requires only a small additional computational complexity. The number of blind decodings required for a Release 10 UE is discussed in Section 28.3.1.1.

Finally, the PDCCH structure is also adapted to avoid cases 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 thus aligned). Such cases are avoided by adding a padding bit to any PDCCH messages having a size which could result in this problem occurring.

9.3.6 PDCCH Scheduling Process

To summarize the arrangement of the PDCCH transmissions in a given subframe, a typical sequence of steps carried out by the eNodeB is depicted in Figure 9.12.

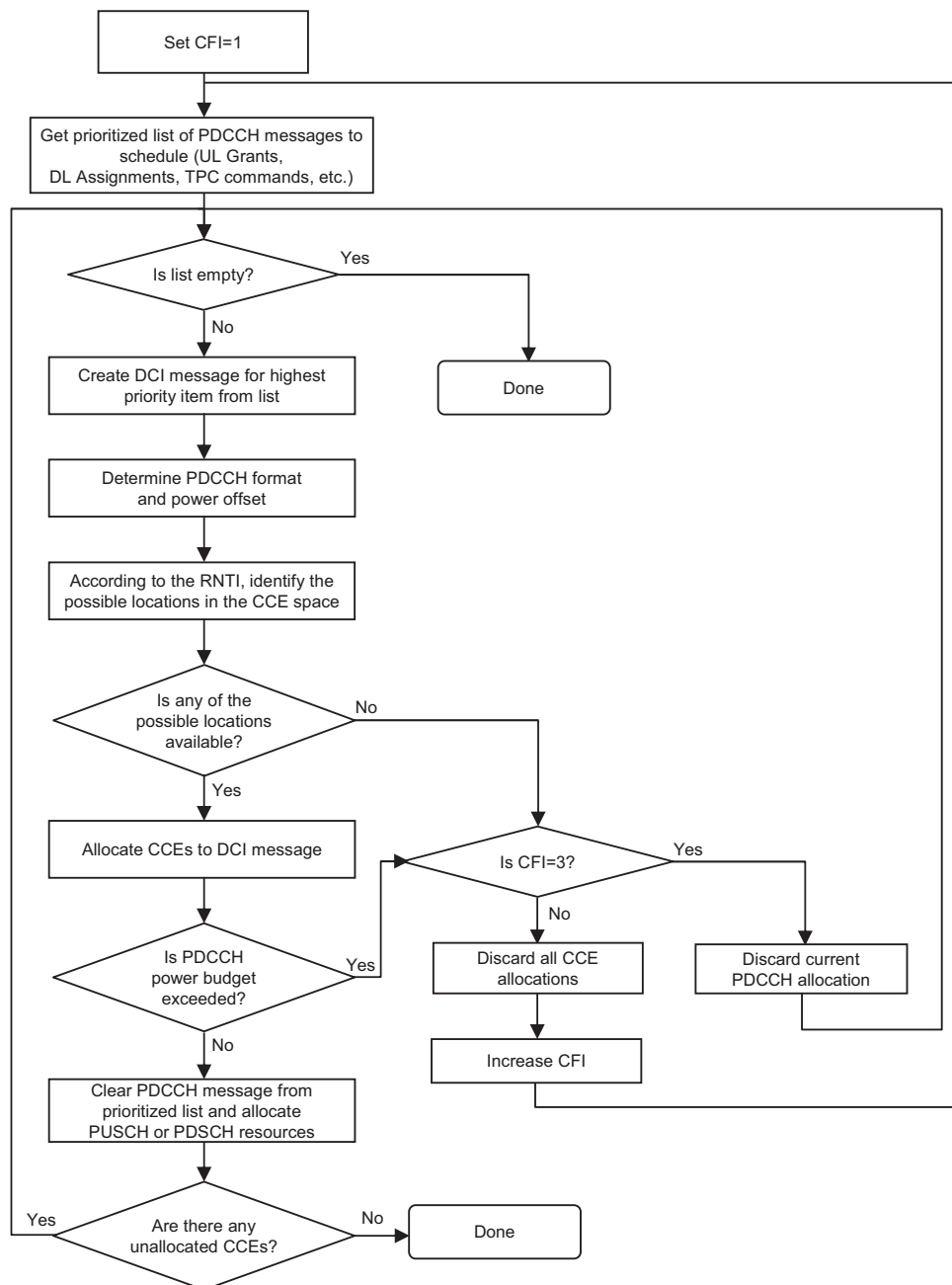


Figure 9.12: A typical sequence of PDCCH scheduling operations in a subframe.

References¹²

- [1] 3GPP Technical Specification 36.321, 'Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification', 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.

¹²All web sites confirmed 1st March 2011.