

# LTE MAC Scheduler & Radio Resource Scheduling

## Abstract

3GPP's Long Term Evolution (LTE) technology uses an air interface based on OFDMA and SC-FDMA to deliver the flexibility and increased spectral efficiency required by a new generation of high-speed, all-IP mobile networks. The LTE air interface supports deployment flexibility with both TDD and FDD modes and a range of channel bandwidths upto 20MHz. Adaptive modulation and coding together with advanced, multi-antenna mechanisms increase the spectral efficiency. The air interface supports wideband, high-speed operation in line with LTE's packet-switched architecture.

Efficient utilisation of the air interface is central to LTE system performance and user Quality of Experience. The base station is responsible for controlling the air interface between the network and users. This paper considers the benefits and challenges facing the LTE MAC Scheduler in utilising such a flexible and complex air interface.

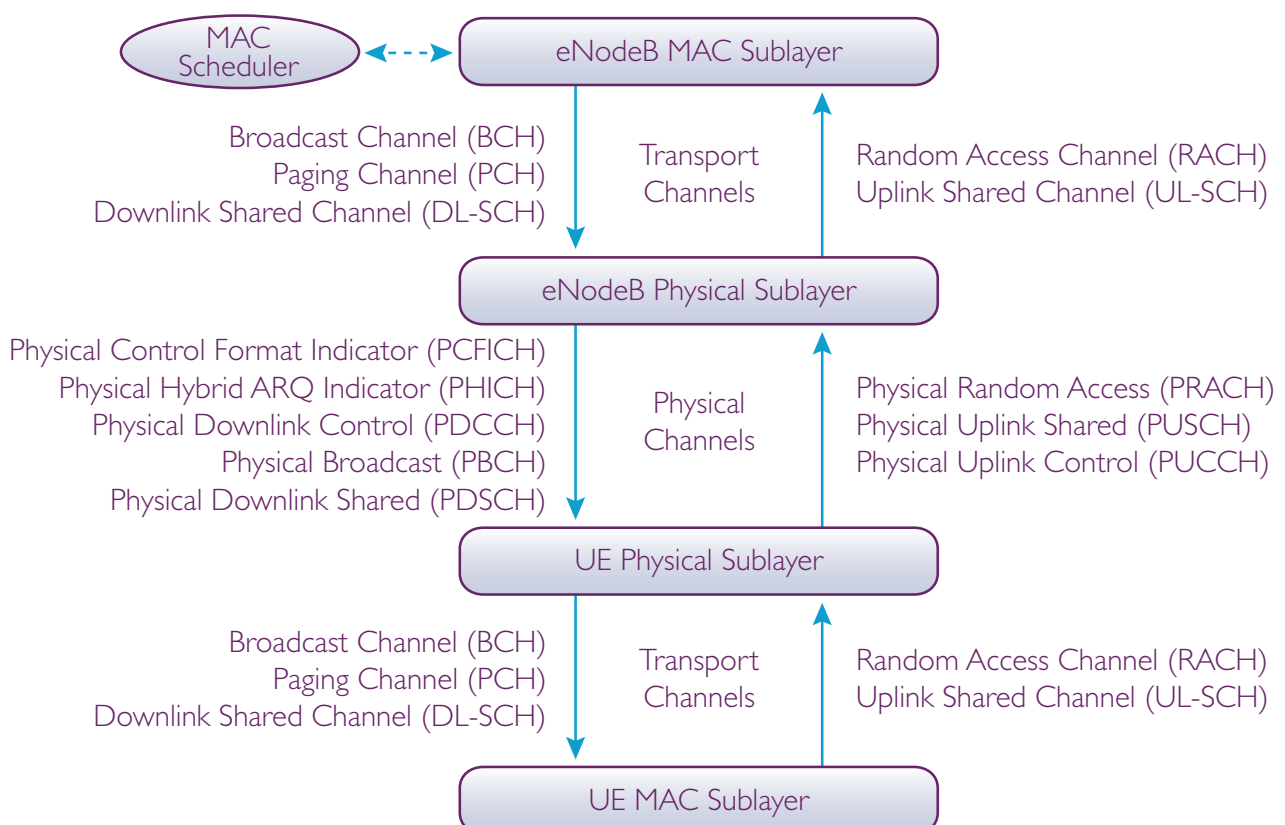


Figure 1: LTE Transport & Physical Channels

## Introduction

Long Term Evolution (LTE) is the evolution of the existing 3G mobile network towards a higher capacity, lower latency and more efficient radio access and core network. It will provide the additional capacity and lower cost-per-bit needed to sustain the exponential growth in mobile data witnessed over the last few years.

As part of the move from 3G to LTE, the air interface has been redesigned to use OFDMA and SC-FDMA in the downlink and uplink respectively. This new air interface has several advantages over the WCDMA air interface used by 3G mobile networks, including the ability to support data-orientated, wideband operation.

OFDM facilitates the use of adaptive modulation and coding with higher-order modulations and advanced, multi-antenna mechanisms for increased spectral efficiency, squeezing more performance out of valuable and limited spectrum resources.

User-plane and control-plane traffic is passed over the LTE air interface using Data and Signalling Radio Bearers (DRB & SRB)<sup>1</sup>. Each connected User Equipment (UE) supports three SRBs and up to eight DRBs. Each DRB has its own Quality of Service (QoS) configuration in order to support different types of service, e.g. one bearer for mobile broadband access plus a second for a conversational video call. QoS is examined in more detail in a separate white paper by Roke Manor: "LTE MAC Scheduler & Radio Bearer QoS".

Air interface related processing is performed by the MAC and Physical layers in the LTE base station (eNodeB) and UE. The MAC sublayers in the eNodeB and UE are responsible for multiplexing the contents of broadcast channels, SRBs and DRBs onto the Transport Channels presented by the Physical layers, as shown in Figure 1. The Physical layers in the eNodeB and UE map the Transport Channels to the associated Physical Channels, which are combined to form the downlink (OFDMA) and uplink (SC-FDMA) channels of the air interface.

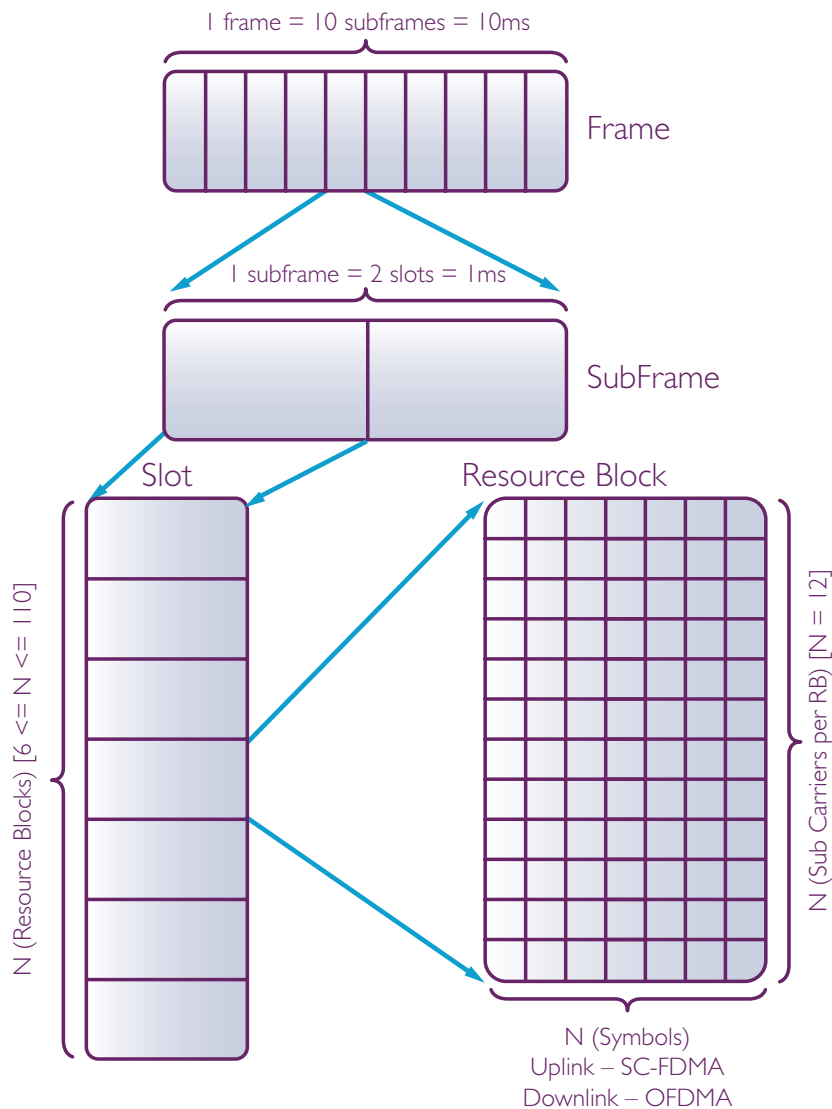


Figure 2: LTE Frame Structure

1. The terms DRB and SRB are used for referring to radio bearers to avoid confusion with the RB acronym used for Resource Blocks.

The MAC Scheduler in the eNodeB is responsible for dynamically scheduling the LTE air interface in both the downlink and uplink directions. This scheduling activity needs to accommodate the broad range of air interface features whilst simultaneously optimising system capacity and delivering Quality of Experience (QoE) to users. This paper focuses on the role of the MAC Scheduler in allocating the radio resources of the LTE air interface.

## The LTE Air Interface

The LTE air interface is based on OFDM which has become an established technology for digital, wideband, wireless systems as demonstrated by WiMAX, WiFi and DVB-T. OFDM supports high data rates with low inter-symbol interference and consequently reduced implementation complexity, particularly on the receiver side. However, the reduced receiver complexity comes at the cost of increased Peak-to-Average Power Ratio, increased power amplifier linearity requirements and reduced power efficiency on the transmit side. Therefore, LTE uses OFDMA on the downlink to simplify the UE's receiver and SC-FDMA on the uplink to reduce the cost and power consumption associated with the UE's transmitter.

The LTE air interface is based around a frame structure, shown in Figure 2, and the concept of Subframes, Slots and Resource Blocks. The Transmission Time Interval (TTI) has been reduced to 1ms in LTE in order to support low-latency data transfer.

Each 10ms Frame is divided into ten 1ms Subframes, with each Subframe further divided into two 1ms Slots. A Slot consists of a number of OFDM symbols in the time-domain, where the number of symbols depends on the cyclic prefix in use. A single subcarrier in a single OFDM symbol is known as a Resource Element (RE).

Each Slot is divided in the frequency-domain into a number of Resource Blocks (RB), with the number of RBs depending on the channel bandwidth in use. A Resource Block Group (RBG) consists of multiple RBs in a single slot. Radio resource scheduling decisions in LTE are always made in units of RBs or RBGs.

In FDD mode, the frame structure is repeated for downlink and uplink. In TDD mode, the frame structure is shared between downlink and uplink, with some subframes being used for uplink data, and some for downlink data.

## MAC Scheduler

The MAC Scheduler is a key component of the eNodeB L2 radio protocol stack. It is responsible for scheduling the cell's radio resources used in the downlink and uplink whilst providing the required QoS for all active radio bearers.

The objective of radio resource scheduling is to allocate the available radio resources to specific UEs within the cell for the transmission and reception of Transport Blocks (TB). In the downlink, the eNodeB MAC sublayer builds a TB for a specific UE using data from one or more SRBs and/or DRBs. The UE MAC does the same in the uplink. For single antenna and diversity schemes, a single TB may be allocated to a UE per TTI. For MIMO schemes, multiple TBs may be allocated to a UE per TTI.

The MAC Scheduler runs every TTI (i.e. every subframe) and allocates the radio resources to be used in the downlink and uplink<sup>2</sup>. The radio resource scheduling function can split into:

- Shared Channel Scheduling. This involves the allocation of radio resources to be used by the downlink and uplink shared channels (PDSCH & PUSCH) for the transmission of user-plane and control-plane data.
- Control Channel Scheduling. This involves the scheduling of resources on the downlink control channel (PDCCH). The PDCCH is used for communicating downlink and uplink shared channel resource allocations, or grants, to the UEs in the cell.

The algorithms used in the MAC Scheduler to allocate radio resources have a significant effect on the performance of the individual base station and overall LTE radio access network. These algorithms are also largely implementation-specific and dependent on deployment and usage scenarios. Indoor femtocells/picocells will differ significantly from outdoor microcells/macrocels in terms of usage scenarios and RF environment.

The following sections look in more details at shared channel (downlink and uplink) and control channel scheduling.

### Shared Channel Scheduling

Shared channel scheduling can be divided into downlink (PDSCH) and uplink (PUSCH) functions, where each direction may be scheduled independently of the other. In each case, the aim of the shared channel scheduling algorithms is to allocate radio resources for the transmission of TBs within a TTI.

Before scheduling a UE, the eNodeB must consider whether data can be sent or received by that UE. A UE may be unable or prevented from receiving or transmitting in a particular TTI as a result of:

- Measurement gaps, where a UE temporarily 'disconnects' from the serving cell in order to measure the radio quality of a neighbouring cell.
- Discontinuous reception (DRX), where a UE powers down its radio interface for a period of time in order to conserve battery life.

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2. The MAC Scheduler schedules both the downlink and uplink every TTI in FDD mode. In TDD mode, the MAC Scheduler may need to schedule the downlink only, uplink only, both or neither, depending on the position in the frame and the cell configuration used.

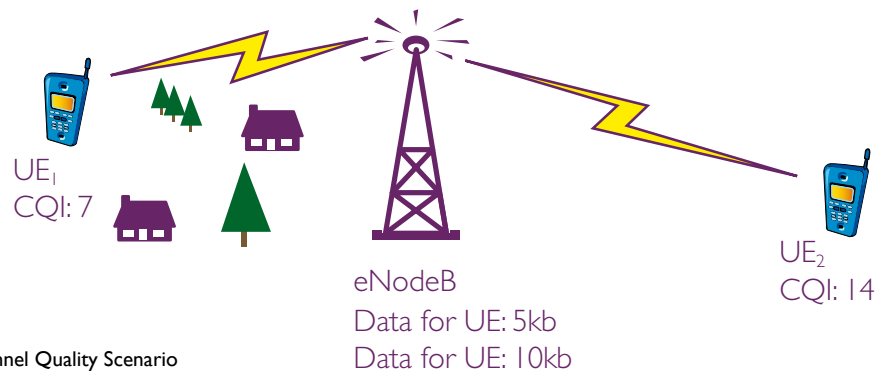


Figure 3: Downlink Channel Quality Scenario

- Half-duplex restrictions which prevent a UE from transmitting and receiving at the same time (only applicable to FDD).
- Timing synchronisation. Out-of-synch UEs may be able to receive downlink data correctly but cannot be allowed to transmit in the uplink due to the interference it would cause to other UEs within in the cell. NOTE: This also means that out-of-synch UEs cannot be sent data which requires the transmission of a HARQ Ack/Nak (on the uplink).

Having determined that a UE *can* be scheduled within a TTI, the MAC Scheduler then needs to decide whether a UE *should* be scheduled in that TTI. The following will influence the decision whether or not to schedule a UE:

- Semi Persistent Scheduling (SPS) allocations. SPS enables a UE to use a recurring allocation for receiving/transmitting data in pre-determined TTIs.
- HARQ retransmissions.
- Availability of data to send and QoS settings for individual DRBs.

In order to optimise the cell and system capacity, the eNodeB must optimise the spectral efficiency of shared channel transmissions to and from UEs. Link adaptation involves tailoring the modulation order (QPSK, 16-QAM, 64-QAM) and coding rate for each UE in the cell, depending on the downlink/uplink channel conditions. In LTE, Channel Quality Information (CQI) is collected by the eNodeB and used to determine the Modulation and Coding Scheme (MCS) for each UE in the cell. The mechanisms for determining the CQI differs between uplink and downlink directions, which are described later. MCS (i.e. spectral efficiency) may be used in QoS-aware scheduling algorithms such as Proportional Fair scheduling in determining which UEs to schedule and the size of the allocation and resulting TB.

The following sections cover the basics associated with downlink, uplink and control channel scheduling.

## Downlink Scheduling

The MAC Scheduler needs to allocate radio resources on the downlink shared channel (PDSCH) for the following:

- User-plane data from DRBs.
- L3/NAS control-plane data from SRBs, as well as L2 control signalling.
- Paging messages from the PCH transport channel.
- System Information Broadcasts (SIB).

Having prioritised what needs to be sent in the TTI, the MAC Scheduler allocates the radio resources to individual UEs in the form of downlink scheduling allocations. As mentioned earlier, scheduling is done in units of RBs or RBGs. The creation of each downlink scheduling allocation involves selecting how many RB[G]s to use, which RB[G]s to use and the MCS to be used.

The downlink MCS depends on the radio conditions experienced by the receiving UE. The MAC Scheduler receives CQI reports from all UEs in the cell based on their measurements of the downlink channel. The reported CQI is a number between 0 (worst) and 15 (best) indicating the most efficient MCS which would give a Block Error Rate (BLER) of 10% or less.

The example in Figure 3 shows two UEs, with UE1 reporting a CQI of 7 (16-QAM, 1.5bits/Hz) and UE2 reporting a CQI of 14 (64-QAM, 5.1bits/Hz). Therefore, transmissions to UE2 are approximately 3 times more spectrally efficient than transmissions to UE1. In terms of radio resources, 25 RBs are needed to send 5kb to UE1, whilst only 14 RBs are needed to send twice the amount of data (10kb) to UE2.

CQI reports from UEs can take the following forms:

- Wideband CQI reports based on measurements across the entire downlink channel.
- Sub-band CQI reports based on measurements across subsets of the downlink channel.

In addition to the CQI value(s) reported by UEs, the eNodeB can use other information, such as HARQ retransmissions, to determine and refine the link adaptation and selected MCS.

With channel bandwidths up to 20MHz, the location of RB[G]s in the frequency domain can effect link adaptation and choice of MCS as individual UEs may experience better channel conditions for different frequencies within the downlink channel. Two approaches can be used to improve spectral efficiency and/or the probability of receiving a downlink transmission – frequency diversity and channel-aware scheduling.

Channel-aware scheduling refers to the allocation of radio resources to specific frequencies in the downlink channel corresponding to the best channel conditions for individual UEs. This relies on the eNodeB receiving sub-band CQI reports for individual UEs. The benefits of channel-aware

scheduling need to be balanced against the increased signalling needed for sub-band CQI reports. Channel-aware scheduling may not be appropriate for highly mobile users or other UEs experiencing rapidly changing channel conditions.

LTE supports a number of ways for allocating RB[G]s for downlink grants, as shown in Figure 4.

- Type 0 resource allocations use a bitmap of RBGs, where the RBG size is a function of the channel bandwidth. RBGs may be allocated from across the full channel bandwidth. Allocated RBGs are not required to be contiguous. Type 0 may be used for channel-aware or "manual" frequency diversity scheduling.
- Direct and Type 1 resource allocations use a bitmap of RBs. Type 1 is restricted to allocating RBs from a subset of RBGs (rather than the full channel bandwidth). Allocated RBs are not required to be contiguous. Type 1 may also be used for channel-aware and "manual" frequency diversity scheduling.
- Type 2 resource allocations support the contiguous or distributed allocation of RBs. The distributed allocation, as shown in Figure 4, provides good frequency diversity by scattering the allocated RBs in the frequency domain and changing the allocation in the second Slot of the Subframe.

different maximum data throughputs. In addition, some optional features may not be supported by all UEs in the cell, such as DRX or some kinds of sub-band CQI reporting.

## Uplink Scheduling

Within each uplink TTI, the eNodeB must evaluate which UEs require uplink resources, and if possible how much data each UE has/needs to send. Unlike in the downlink, this information is not directly available at the eNodeB. Instead, it is reported by UEs using one of the following:

- Scheduling Request (SR) which informs the eNodeB that the UE has an unspecified amount of data to send.
- Buffer Status Report (BSR) which informs the eNodeB that the amount of data the UE has to send is within a pre-defined range. The amount of data available is specified for logical channel groups rather than individual bearers. This can complicate the operation of a QoS-aware scheduler.

As with the downlink, the MAC Scheduler determines how many and which RB[G]s to allocate to a UE for an uplink grant and which MCS to use.

Unlike the downlink direction, where the UE receives pilot information for the full channel, UEs typically only transmit

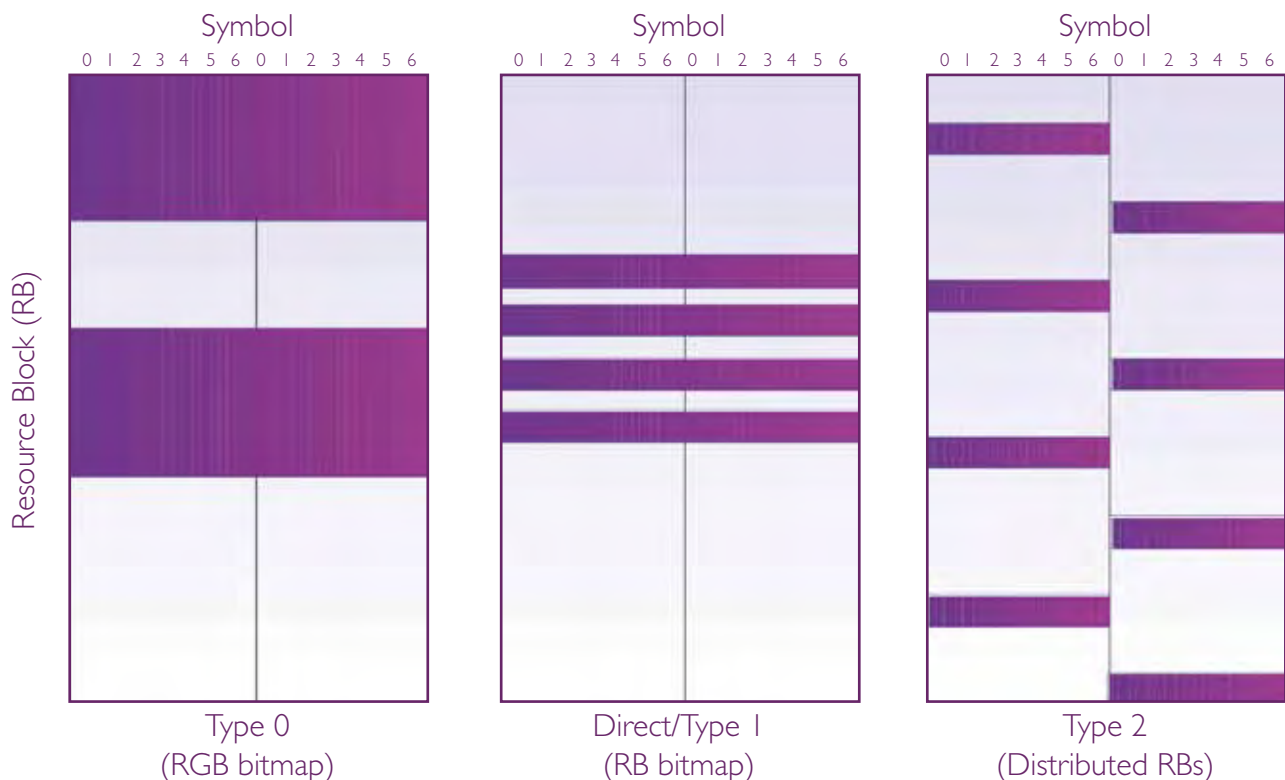


Figure 4: Downlink Resource Allocation

Channel-aware, frequency diversity scheduling and SPS can be used by the MAC Scheduler on a UE-by-UE basis in a cell. However, a trade-off is necessary in order to reduce the complexity of radio resource scheduling. This will depend on the deployment scenario, e.g. size of cell, mobility of users, channel bandwidth etc.

The UE's capabilities are also an important aspect which must be considered when allocating radio resources (for both the downlink and uplink). Different categories of UEs support

using a fraction of the available RBs. Measurements made by the eNodeB receiver therefore only provide partial channel information. A more complete view of the uplink channel quality for individual UEs can be gained by using the Sounding Reference Signal (SRS) feature. This involves configuring UEs within a cell to transmit a pre-defined sequence within certain RBs across the cell's bandwidth. This provides the eNodeB with accurate, wideband CQI for UEs within the cell at the expense of reassigning uplink radio resources for SRS use.

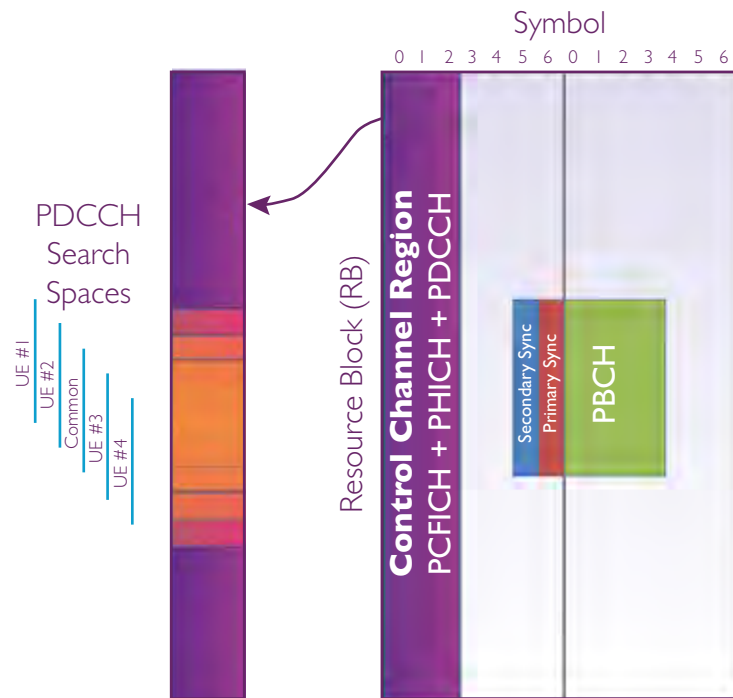


Figure 5 : Downlink Subframe & PDCCH Search Spaces

In narrow bandwidth cells, or in rare cases where a UE is allocated a high percentage of the RBs within a cell's bandwidth, the UE's Demodulation Reference Signal, which is transmitted in the middle symbol of each slot, can also be used to estimate a UE's uplink channel quality. For TDD implementations, the CQI reported by the UE for the downlink can also be used to provide an indication of the uplink channel quality if channel reciprocity is assumed.

Another technique, which utilises HARQ feedback to determine the correct MCS value, is to start with a low MCS and therefore low initial uplink throughput, then gradually increase the MCS until the target BLER is reached. Over time, the MCS would automatically be increased or decreased depending on whether an uplink transmission was received or not. While this technique uses signalling which is already present, and therefore adds no additional overhead to the system, the MCS takes a period of time to reach the optimal setting and reacts poorly to rapidly changing channel conditions.

Uplink channel-aware scheduling and frequency diversity can also be employed in the uplink to improve spectral efficiency and robustness. As with the downlink, uplink-channel aware scheduling requires detailed channel quality information for individual UEs which incurs a cost – the uplink radio resources used for SRS.

The use of SC-FDMA for the uplink means that there are additional constraints on the uplink air interface compared to the downlink direction. The most important of these is that the RBs allocated to a UE must be contiguous, meaning that uplink allocations are always provided to the UE as scheduling grants using Resource Allocation Type 2.

Frequency diversity can be employed in the uplink in one of two ways. First, a frequency hopping option is specified for the uplink with the frequency hop occurring at the end of

the first slot. Secondly, inter-TTI frequency hopping can be employed by randomising the allocation of RBs for each UE.

As with the downlink, SPS may be used to provide UEs with a recurring, pre-allocated uplink grant as an alternative to dynamically assigning radio resources each TTI. This is typically more applicable to Guaranteed Bit Rate (GBR) bearers which may be used for conversational voice or video calls.

The uplink is subtly different to the downlink in terms of HARQ retransmissions. In the downlink, HARQ retransmissions are asynchronous giving the MAC Scheduler some freedom in deciding when they should occur. However, in the uplink, HARQ retransmissions are synchronous meaning that the UE expects to retransmit the data exactly 8 TTIs (in the case of FDD) after the previous transmission. If the MAC Scheduler does not provide an uplink grant the UE will attempt to make a non-adaptive retransmission using the grant for the previous transmission. Obviously, this needs to be factored into any uplink radio resource scheduling.

## Control Channel Scheduling

In addition to scheduling the downlink and uplink shared channels (PDSCH & PUSCH), the MAC Scheduler also schedules the downlink control channel (PDCCH). The other control channels (e.g. PCFICH, PHICH) do not require scheduling.

The PDCCH is used to inform the UE of shared channel scheduling allocations for both the uplink and downlink, and is therefore a vital part of the scheduling process – if the allocation of shared channel resources cannot be communicated to the UE, the corresponding resources are unutilised. The PDCCH, PCFICH and PHICH channels are located in the Control Channel Region of the downlink subframe, as shown Figure 5. This region occupies the

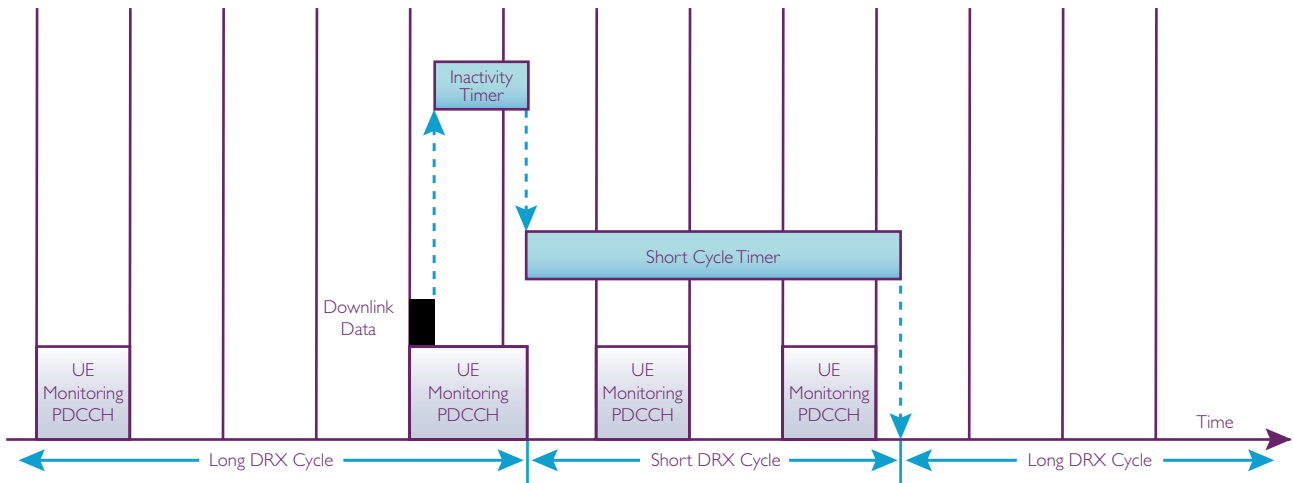


Figure 6: DRX

full downlink channel bandwidth. The number of symbols occupied by the Control Channel Region is dynamically configurable (1-3) on a per-TTI basis in order to optimise the use of downlink radio resources.

The downlink and uplink allocations to individual UEs are encoded as Downlink Control Information (DCI). These DCIs need to be scheduled onto the PDCCH.

The Control Channel Region consists of a number of Control Channel Elements (CCE), with a known number being assigned for use by the PDCCH. The number of CCEs which are needed to send a DCI message depends on the radio conditions experienced by a UE, with more CCEs being required for UEs at the cell edge to increase the robustness of the transmission.

Although the DCI messages are relatively small (anywhere from 8 to 51 bits, excluding the CRC), restrictions on the available coding rates mean that the PDCCH can become congested under certain circumstances. For example, when many users need to transmit small amounts of data (e.g. voice calls) the control channel could become saturated with scheduling assignments before the downlink/uplink shared channels are fully utilised. This problem is further compounded if many of the users are on the cell edge and require more PDCCH resources per scheduling assignment/DCI message.

However, it is not only the PDCCH capacity which can cause problems for the MAC Scheduler. A UE will use the information contained on the control channel to find the position of its downlink and/or uplink allocation for sending/receiving data. In order to avoid the UE decoding the entire control channel region, LTE introduces the concept of UE Search Spaces. A UE will only attempt to decode CCEs within a pre-calculated range referred to as the UE's own Search Space, which is determined by the Subframe/Slot number and the UE's C-RNTI. As shown in Figure 5, these Search Spaces can overlap. This can lead to a problem where the PDCCH may have space but a UE cannot be scheduled because the CCEs in its Search Space are fully occupied (by allocations for other UEs).

Scheduling the PDCCH is every bit as important as scheduling the downlink and uplink shared channels. Careful design of the MAC Scheduler is required to optimise PDCCH and shared channel utilisation. With sufficient computation, a near optimal solution can be found. However, the search for an optimal solution is always balanced against the need for the MAC Scheduler to run every TTI (1ms) with limited CPU resources.

## Additional Functionality

This section outlines a number of ways in which the MAC Scheduler can enhance performance and user QoE. Several of these features have been mentioned in the preceding sections.

- Semi Persistent Scheduling (SPS). The MAC Scheduler can allocate a recurring downlink/uplink allocation to a UE which is useful for GBR type bearers. Once setup, the recurring grants are not signalled on the PDCCH, thereby saving control channel resources.
- Discontinuous reception (DRX). LTE enables a UE to send and receive data in bursts and then power down its radio in the gaps in between. This can lead to significant power consumption savings in the UE and extended battery life. UEs are configured by the eNodeB to use DRX, which consists of a pattern of long and short cycles, as shown in Figure 6. As the name suggests, the long DRX cycle involves the UEs radio being powered down for longer. The UE will enter the short cycle if a scheduling allocation is received and will revert back to the long cycle on expiration of the short cycle timer.

Of course, accommodating SPS and DRX imposes constraints and complicates the task of radio resource scheduling further.

## Summary

The topic of scheduling data in an LTE system has been discussed and shown to be non trivial, especially when attempting to optimise system capacity whilst providing good user QoE. There are many factors which need to be considered, from the radio link quality across the system bandwidth to details such as the UE search space, all of which need to be accounted for by the radio resource scheduler when working alongside a QoS scheduler in an efficient LTE MAC Scheduler implementation.

Roke has been an active participant and contributor to the LTE design within the 3GPP RAN working groups since 2005. We have developed a range of resource scheduling algorithms and can provide expert support, enabling network equipment providers to accelerate the deployment of LTE eNodeB products with advanced MAC scheduling features.

For further information please contact  
Patrick Fuller  
Business Sector Consultant

**Roke Manor Research Ltd**  
Roke Manor, Romsey  
Hampshire, SO51 0ZN  
United Kingdom  
Part of the Chemring Group

T +44 (0)1794 833675  
F +44 (0)1794 833433  
patrick.fuller@roke.co.uk  
www.roke.co.uk

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