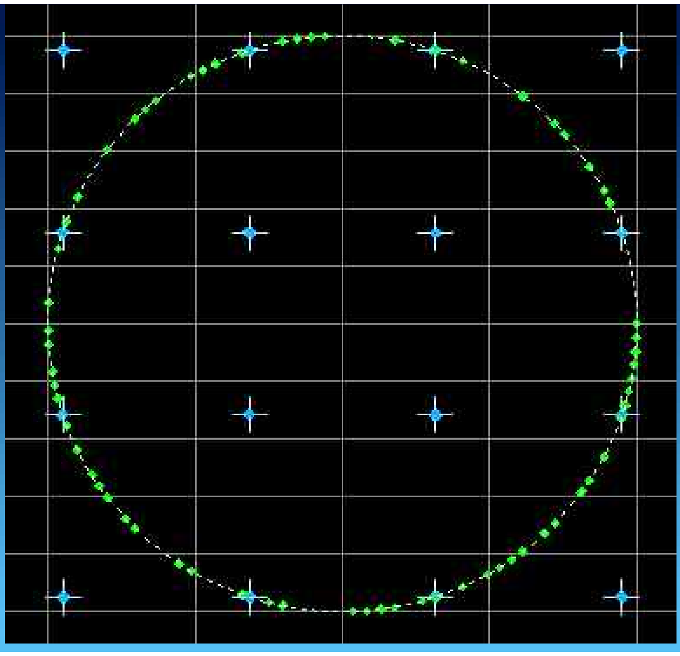


Rohde & Schwarz Products: FSQ, FSG, FSV, FSQ-K100, FSV-K100, FSQ-K101, FSV-K101, FSQ-K102, SMU200A, SMU-K55, SMU-K255, SMATE200A, SMATE-K55, SMJ100A, SMJ-K55, SMJ-K255, WinIQSIM2, AFQ100A/B, AFQ-K255, AMU200A, AMU-K55, AMU-K255, CMW500, TS8980

UMTS Long Term Evolution (LTE) Technology Introduction

Application Note 1MA111

Even with the introduction of HSPA, evolution of UMTS has not reached its end. To ensure the competitiveness of UMTS for the next 10 years and beyond, UMTS Long Term Evolution (LTE) has been introduced in 3GPP release 8. LTE, which is also known as Evolved UTRA and Evolved UTRAN, provides new physical layer concepts and protocol architecture for UMTS. This application note introduces LTE FDD and TDD technology and testing aspects.

ROHDE & SCHWARZ

Contents

The following abbreviations are used in this application note for R&S test equipment:

- The Vector Signal Generator R&S® SMU200A is referred to as the SMU200A.
- The Vector Signal Generator R&S® SMATE200A is referred to as the SMATE200A.
- The Vector Signal Generator R&S® SMJ100A is referred to as the SMJ100A.
- SMU200A, SMATE200A, and SMJ100A in general is referred to as the SMx.
- The IQ Modulation Generators R&S® AFQ100A/B are referred to as the AFQ100A/B.
- The Baseband Signal Generator and Fading Simulator R&S® AMU200A is referred to as the AMU200A.
- The Signal Analyzer R&S® FSQ is referred to as FSQ.
- The Signal Analyzer R&S® FSG is referred to as FSG.
- The Signal Analyzer R&S® FSV is referred to as FSV.
- The Wideband Radio Communication Tester R&S® CMW500 is referred to as the CMW500.
- The RF test system R&S® TS8980 is referred to as the TS8980.

1 Introduction

Currently, UMTS networks worldwide are being upgraded to High Speed Packet Access (HSPA) in order to increase data rate and capacity for packet data. HSPA refers to the combination of High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA). While HSDPA was introduced as a 3GPP release 5 feature, HSUPA is an important feature of 3GPP release 6.

However, even with the introduction of HSPA, evolution of UMTS has not reached its end. **HSPA+** will bring significant enhancements in 3GPP release 7 and 8. Objective is to enhance performance of HSPA based radio networks in terms of spectrum efficiency, peak data rate and latency, and exploit the full potential of WCDMA based 5 MHz operation. Important features of HSPA+ are downlink MIMO (Multiple Input Multiple Output), higher order modulation for uplink and downlink, improvements of layer 2 protocols, and continuous packet connectivity.

In order to ensure the competitiveness of UMTS for the next 10 years and beyond, concepts for **UMTS Long Term Evolution** (LTE) have been introduced in 3GPP release 8. Objective is a high-data-rate, low-latency and packet-optimized radio access technology. LTE is also referred to as E-UTRA (Evolved UMTS Terrestrial Radio Access) or E-UTRAN (Evolved UMTS Terrestrial Radio Access Network).

This application note focuses on LTE/E-UTRA technology. In the following, the terms LTE or E-UTRA are used interchangeably.

LTE has ambitious requirements for data rate, capacity, spectrum efficiency, and latency. In order to fulfill these requirements, LTE is based on new technical principles. LTE uses new multiple access schemes on the air interface: OFDMA (Orthogonal Frequency Division Multiple Access) in downlink and SC-FDMA (Single Carrier Frequency Division Multiple Access) in uplink. Furthermore, MIMO antenna schemes form an essential part of LTE. In order to simplify protocol architecture, LTE brings some major changes to the existing UMTS protocol concepts. Impact on the overall network architecture including the core network is referred to as 3GPP System Architecture Evolution (SAE).

LTE includes an FDD (Frequency Division Duplex) mode of operation and a TDD (Time Division Duplex) mode of operation. LTE TDD which is also referred to as TD-LTE provides the long term evolution path for TD-SCDMA based networks. This application note gives an introduction to LTE technology, including both FDD and TDD modes of operation.

Chapter 2 outlines requirements for LTE.

Chapter 3 describes the downlink transmission scheme for LTE.

Chapter 4 describes the uplink transmission scheme for LTE.

Chapter 5 outlines LTE MIMO concepts.

Chapter 6 focuses on LTE protocol architecture.

Chapter 7 introduces LTE UE capabilities.

Chapter 8 explains test requirements for LTE.

Chapters 9-12 provide additional information including literature references.

2 Requirements for UMTS Long Term Evolution

LTE is focusing on optimum support of Packet Switched (PS) Services. Main requirements for the design of an LTE system were identified in the beginning of the standardization work on LTE and have been captured in 3GPP TR 25.913 [Ref. 1]. They can be summarized as follows:

- **Data Rate:** Peak data rates target 100 Mbps (downlink) and 50 Mbps (uplink) for 20 MHz spectrum allocation, assuming 2 receive antennas and 1 transmit antenna at the terminal. *Note: These requirement values are exceeded by the LTE specification, see chapter 7.*

- **Throughput:** Target for downlink average user throughput per MHz is 3-4 times better than release 6. Target for uplink average user throughput per MHz is 2-3 times better than release 6.

- **Spectrum Efficiency**: Downlink target is 3-4 times better than release 6. Uplink target is 2-3 times better than release 6.

- **Latency**: The one-way transit time between a packet being available at the IP layer in either the UE or radio access network and the availability of this packet at IP layer in the radio access network/UE shall be less than 5 ms. Also C-plane latency shall be reduced, e.g. to allow fast transition times of less than 100 ms from camped state to active state.

- **Bandwidth:** Scaleable bandwidths of 5, 10, 15, 20 MHz shall be supported. Also bandwidths smaller than 5 MHz shall be supported for more flexibility, i.e. 1.4 MHz and 3 MHz.

- **Interworking**: Interworking with existing UTRAN/GERAN systems and non-3GPP systems shall be ensured. Multimode terminals shall support handover to and from UTRAN and GERAN as well as inter-RAT measurements. Interruption time for handover between E-UTRAN and UTRAN/GERAN shall be less than 300 ms for real time services and less than 500 ms for non real time services.

- **Multimedia Broadcast Multicast Services** (MBMS): MBMS shall be further enhanced and is then referred to as E-MBMS. *Note: E-MBMS specification has been largely moved to 3GPP release 9.*

- **Costs:** Reduced CAPEX and OPEX including backhaul shall be achieved. Cost effective migration from release 6 UTRA radio interface and architecture shall be possible. Reasonable system and terminal complexity, cost and power consumption shall be ensured. All the interfaces specified shall be open for multi-vendor equipment interoperability.

- **Mobility**: The system should be optimized for low mobile speed (0-15 km/h), but higher mobile speeds shall be supported as well including high speed train environment as special case.

- **Spectrum allocation**: Operation in paired (Frequency Division Duplex / FDD mode) and unpaired spectrum (Time Division Duplex / TDD mode) is possible.

- **Co-existence**: Co-existence in the same geographical area and co-location with GERAN/UTRAN shall be ensured. Also, co-existence between operators in adjacent bands as well as cross-border co-existence is a requirement.

- **Quality of Service**: End-to-end Quality of Service (QoS) shall be supported. VoIP should be supported with at least as good radio and backhaul efficiency and latency as voice traffic over the UMTS circuit switched networks

- **Network synchronization**: Time synchronization of different network sites shall not be mandated.

3 LTE Downlink Transmission Scheme

OFDMA

The downlink transmission scheme for E-UTRA FDD and TDD modes is based on conventional OFDM. In an OFDM system, the available spectrum is divided into multiple carriers, called subcarriers. Each of these subcarriers is independently modulated by a low rate data stream.
OFDM is used as well in WLAN, WiMAX and broadcast technologies like DVB. OFDM has several benefits including its robustness against multipath fading and its efficient receiver architecture.

Figure 1 shows a representation of an OFDM signal taken from [Ref. 2]. In this figure, a signal with 5 MHz bandwidth is shown, but the principle is of course the same for the other E-UTRA bandwidths. Data symbols are independently modulated and transmitted over a high number of closely spaced orthogonal subcarriers. In E-UTRA, downlink modulation schemes QPSK, 16QAM, and 64QAM are available.

In the time domain, a guard interval may be added to each symbol to combat inter-OFDM-symbol-interference due to channel delay spread. In E-

UTRA, the guard interval is a **cyclic prefix** which is inserted prior to each OFDM symbol.

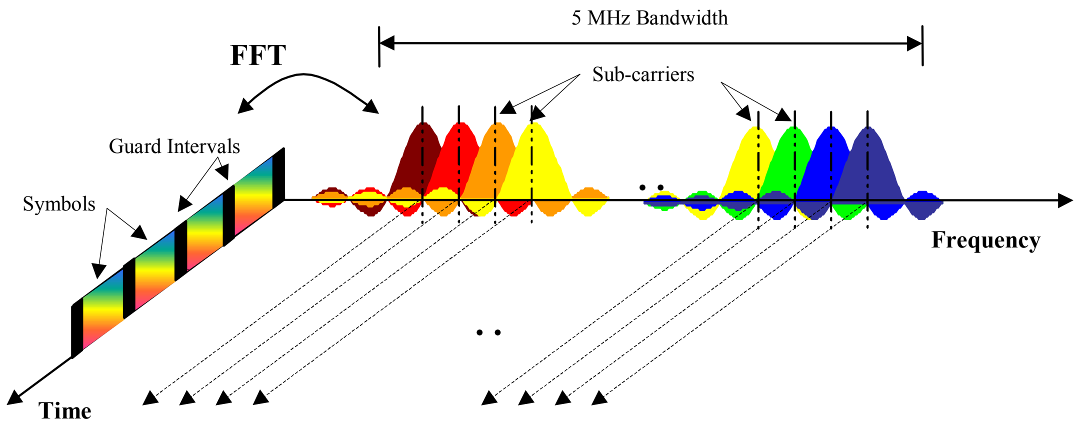


Figure 1 Frequency-time representation of an OFDM Signal [Ref. 2]

In practice, the OFDM signal can be generated using IFFT (Inverse Fast Fourier Transform) digital signal processing. The IFFT converts a number N of complex data symbols used as frequency domain bins into the time domain signal. Such an *N*-point IFFT is illustrated in *Figure 2*, where $a(mN+n)$ refers to the n^{th} subcarrier modulated data symbol, during the time period $mT_u < t \leq (m+1)T_u$.

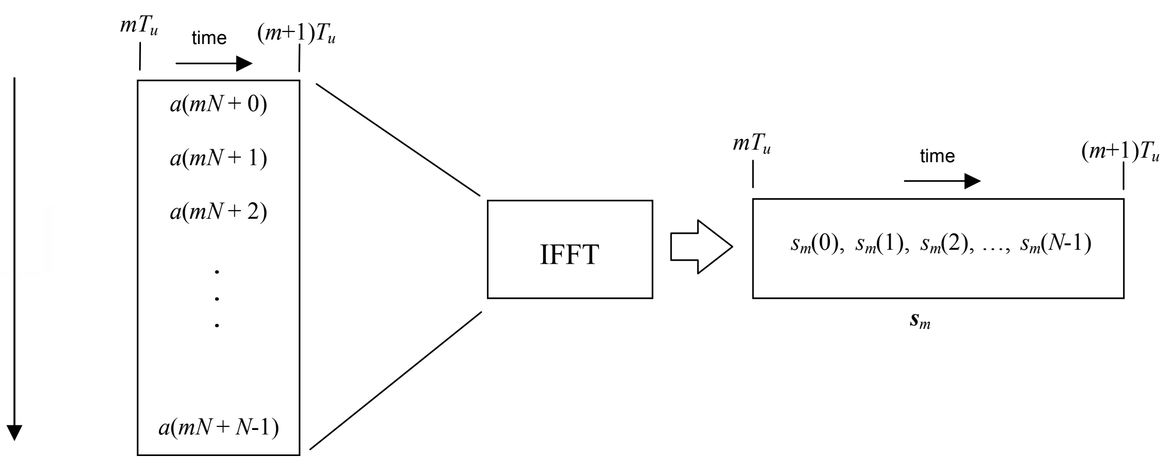


Figure 2 OFDM useful symbol generation using an IFFT [[Ref. 2]

The vector $\boldsymbol{s}_m$ is defined as the useful OFDM symbol. It is the time superposition of the N narrowband modulated subcarriers. Therefore, from a parallel stream of N sources of data, each one independently modulated, a waveform composed of N orthogonal subcarriers is obtained, with each subcarrier having the shape of a frequency *sinc* function (see *Figure 1*).

Figure 3 illustrates the mapping from a serial stream of QAM symbols to *N* parallel streams, used as frequency domain bins for the IFFT. The *N*-point time domain blocks obtained from the IFFT are then serialized to create a time domain signal. Not shown in *Figure 3* is the process of cyclic prefix insertion.

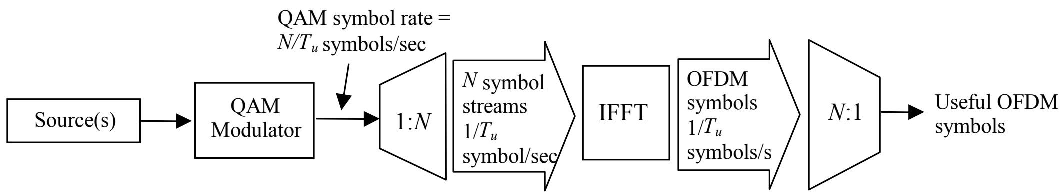


Figure 3 OFDM Signal Generation Chain [Ref. 2]

In contrast to an OFDM transmission scheme, **OFDMA** allows the access of multiple users on the available bandwidth. Each user is assigned a specific time-frequency resource. As a fundamental principle of E-UTRA, the data channels are shared channels, i.e. for each transmission time interval of 1 ms, a new scheduling decision is taken regarding which users are assigned to which time/frequency resources during this transmission time interval.

OFDMA parametrization

Two frame structure types are defined for E-UTRA: frame structure type 1 for FDD mode, and frame structure type 2 for TDD mode. The E-UTRA frame structures are defined in [Ref. 3].
For the frame structure type 1, the 10 ms radio frame is divided into 20 equally sized slots of 0.5 ms. A subframe consists of two consecutive slots, so one radio frame contains ten subframes. This is illustrated in Figure 4 (T_s is expressing the basic time unit corresponding to 30.72 MHz).

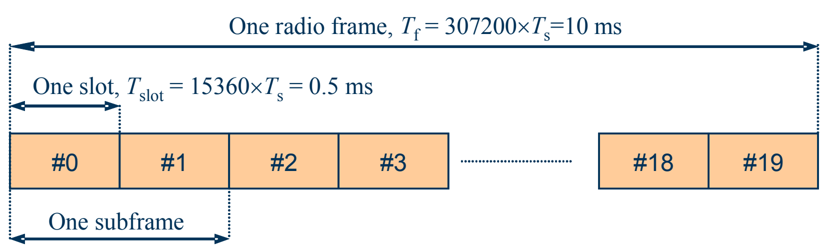


Figure 4 Frame structure type 1 [Ref. 3]

For the frame structure type 2, the 10 ms radio frame consists of two half-frames of length 5 ms each. Each half-frame is divided into five subframes of each 1 ms, as shown in *Figure 5* below. All subframes which are not special subframes are defined as two slots of length 0.5 ms in each subframe. The special subframes consist of the three fields DwPTS (Downlink Pilot Timeslot), GP (Guard Period), and UpPTS (Uplink Pilot Timeslot). These fields are already known from TD-SCDMA and are maintained in LTE TDD. DwPTS, GP and UpPTS have configurable individual lengths and a total length of 1ms.

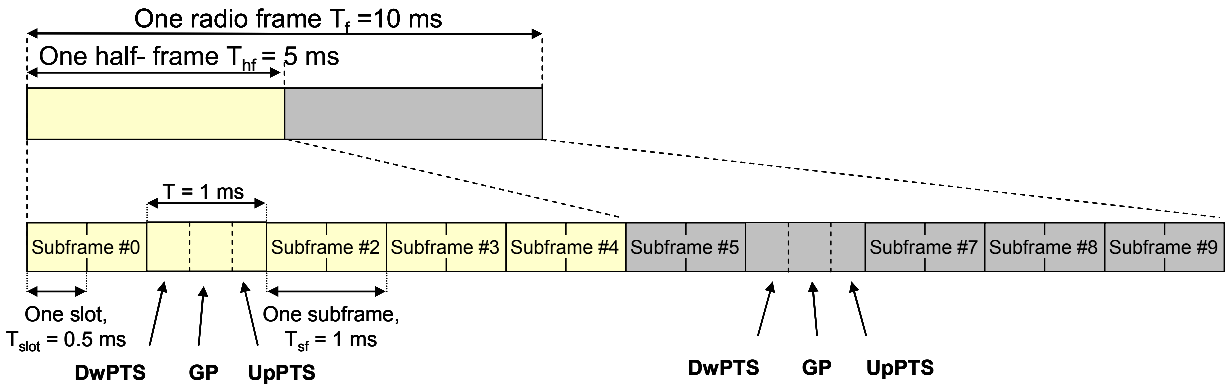


Figure 5 Frame structure type 2 (for 5 ms switch-point periodicity) [Ref. 3]

Seven uplink-downlink configurations with either 5 ms or 10 ms downlink-to-uplink switch-point periodicity are supported. In case of 5 ms switch-point periodicity, the special subframe exists in both half-frames. In case of 10 ms switch-point periodicity the special subframe exists in the first half frame only. Subframes 0 and 5 and DwPTS are always reserved for downlink transmission. UpPTS and the subframe immediately following the special subframe are always reserved for uplink transmission. Table 1 shows the supported uplink-downlink configurations, where “D” denotes a subframe reserved for downlink transmission, “U” denotes a subframe reserved for uplink transmission, and “S” denotes the special subframe.

Uplink-downlink configuration	Downlink-to-Uplink Switch-point periodicity	Subframe number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

Table 2 Uplink-Downlink configurations for LTE TDD [Ref. 3]

Figure 6 shows the structure of the downlink resource grid for both FDD and TDD.

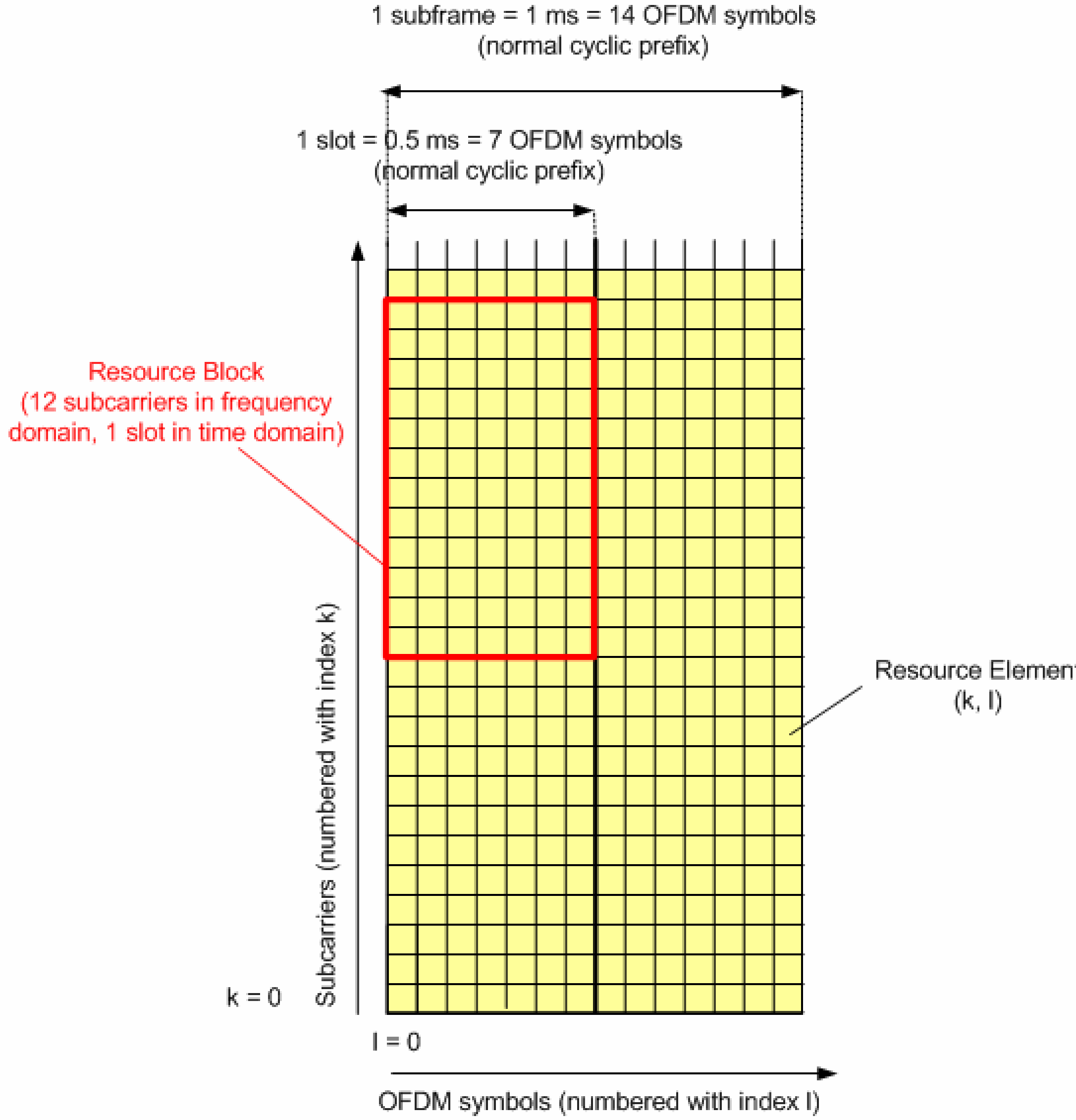


Figure 6 Downlink resource grid [Ref. 3]

The subcarriers in LTE have a constant spacing of Δf = 15 kHz. In the frequency domain, 12 subcarriers form one **resource block**. The resource block size is the same for all bandwidths. The number of resource blocks for the different LTE bandwidths is listed in *Table 3*.

Table 3 Number of resource blocks for different LTE bandwidths (FDD and TDD) [Ref. 4]

Channel bandwidth [MHz]	1.4	3	5	10	15	20
Number of resource blocks	6	15	25	50	75	100

To each OFDM symbol, a cyclic prefix (CP) is appended as guard time, compare *Figure 1*. One downlink slot consists of 6 or 7 OFDM symbols, depending on whether extended or normal cyclic prefix is configured, respectively. The extended cyclic prefix is able to cover larger cell sizes with higher delay spread of the radio channel. The cyclic prefix lengths in samples and µs are summarized in *Table 4*.

Table 4 Downlink frame structure parametrization (FDD and TDD) [Ref. 3]

Configuration	Resource block size N_{sc}^{RB}	Number of symbols $N_{\mathrm{symb}}^{\mathrm{DL}}$	Cyclic Prefix length in samples	Cyclic Prefix length in µs
Normal cyclic prefix Δf=15 kHz	12	7	160 for first symbol 144 for other symbols	5.2 µs for first symbol 4.7 µs for other symbols
Ext. cyclic prefix Δf=15 kHz	12	6	512	16.7 µs

Downlink data transmission

Data is allocated to the UEs in terms of resource blocks, i.e. one UE can be allocated integer multiples of one resource block in the frequency domain. These resource blocks do not have to be adjacent to each other. In the time domain, the scheduling decision can be modified every transmission time interval of 1 ms. The scheduling decision is done in the base station (eNodeB). The scheduling algorithm has to take into account the radio link quality situation of different users, the overall interference situation, Quality of Service requirements, service priorities, etc. Figure 1 shows an example for allocating downlink user data to different users (UE 1 – 6).

The user data is carried on the Physical Downlink Shared Channel (**PDSCH**).

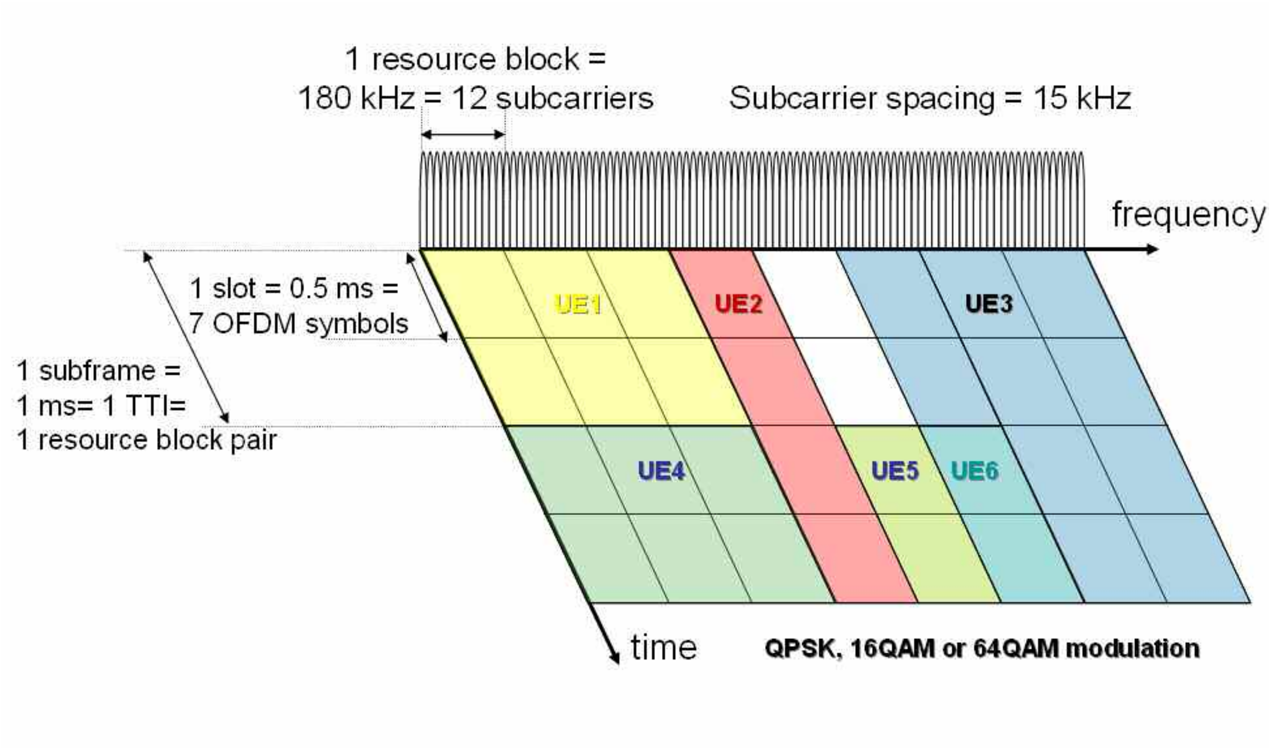


Figure 7 OFDMA time-frequency multiplexing (example for normal cyclic prefix)

Downlink control channels

The Physical Downlink Control Channel (**PDCCH**) serves a variety of purposes. Primarily, it is used to convey the scheduling decisions to individual UEs, i.e. scheduling assignments for uplink and downlink.

The PDCCH is located in the first OFDM symbols of a subframe. For frame structure type 2, PDCCH can also be mapped onto the first two OFDM symbols of DwPTS field.

An additional Physical Control Format Indicator Channel (**PCFICH**) carried on specific resource elements in the first OFDM symbol of the subframe is used to indicate the number of OFDM symbols for the PDCCH (1, 2, 3, or 4 symbols are possible). PCFICH is needed because the load on PDCCH can vary, depending on the number of users in a cell and the signaling formats conveyed on PDCCH.

The information carried on PDCCH is referred to as **downlink control information (DCI)**. Depending on the purpose of the control message, different formats of DCI are defined. As an example, the contents of DCI format 1 are shown in *Table 5*. DCI format 1 is used for the assignment of a downlink shared channel resource when no spatial multiplexing is used (i.e. the scheduling information is provided for one code word only). The information provided contains everything what is necessary for the UE to be able to identify the resources where to receive the PDSCH in that subframe and how to decode it. Besides the resource block assignment, this also includes information on the modulation and coding scheme and on the hybrid ARQ protocol.

The Cyclic Redundancy Check (CRC) of the DCI is scrambled with the UE identity that is used to address the scheduled message to the UE.

Table 5 Contents of DCI format 1 carried on PDCCH [Ref. 5]

Information type	Number of bits on PDCCH	Purpose
Resource allocation header	1	Indicates whether resource allocation type 0 or 1 is used
Resource block assignment	Depending on resource allocation type	Indicates resource blocks to be assigned to the UE
Modulation and coding scheme	5	Indicates modulation scheme and, together with the number of allocated physical resource blocks, the transport block size
HARQ process number	3 (TDD), 4 (FDD)	Identifies the HARQ process the packet is associated with
New data indicator	1	Indicates whether the packet is a new transmission or a retransmission
Redundancy version	2	Identifies the redundancy version used for coding the packet
TPC command for PUCCH	2	Transmit power control (TPC) command for adapting the transmit power on the Physical Uplink Control Channel (PUCCH)
Downlink assignment index (TDD only)	2	number of downlink subframes for uplink ACK/NACK bundling

In order to save signaling resources on PDCCH, more DCI formats to schedule one code word are defined which are optimized for specific use cases and transmission modes, for example scheduling of paging channel, random access response, and system information blocks. DCI formats 2 and 2A provide downlink shared channel assignments in case of closed loop or open loop spatial multiplexing, respectively. In these cases, scheduling information is provided for two code words within one control message. Additionally there is DCI format 0 to convey uplink scheduling grants, and DCI formats 3 and 3a to convey transmit power control (TPC) commands for the uplink.

There is different ways to signal the resource allocation within DCI, in order to trade off between signaling overhead and flexibility. For example, DCI format 1 may use resource allocation types 0 or 1 as described in the following. An additional resource allocation type 2 method is specified for other DCI formats.

In **resource allocation type 0**, a bit map indicates the resource block groups that are allocated to a UE. A **resource block group (RGB)** consists of a set of consecutive physical resource blocks (1…4 depending on system bandwidth). The allocated resource block groups do not have to be adjacent to each other. *Figure 8* illustrates the definition of resource block groups for the 20MHz bandwidth case.

In **resource allocation type 1**, a bitmap indicates physical resource blocks inside a selected **resource block group subset**. The information field for the resource block assignment on PDCCH is therefore split up into 3 parts: one part indicates the selected resource block group subset. 1 bit indicates whether an offset shall be applied when interpreting the bitmap towards the resource blocks. The third part contains the bitmap that indicates to the UE specific physical resource blocks inside the resource block group subset. These resource blocks do not have to be adjacent to each other. *Figure 8* for the 20 MHz case shows the definition of p=4 resource block group subsets and which resource block groups are part of each subset.

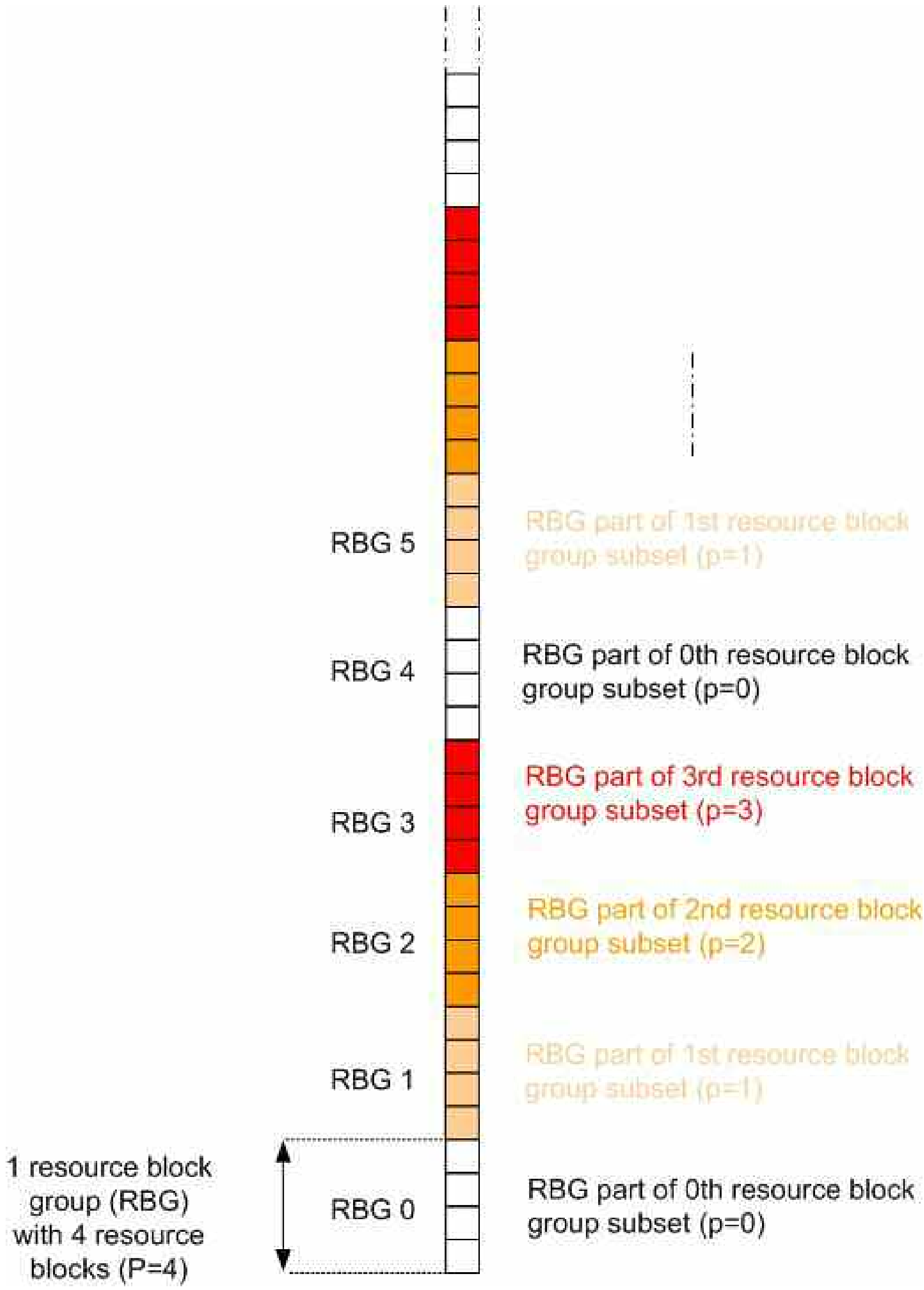


Figure 8 Resource block groups for resource allocation type 0/1 (example: 20 MHz bandwidth, 1 resource block group contains P=4 resource blocks)

In **resource allocation type 2**, physical resource blocks are not directly allocated. Instead, virtual resource blocks are allocated which are then mapped onto physical resource blocks. The information field for the resource block assignment carried on PDCCH contains a resource indication value (RIV) from which a starting virtual resource block and a length in terms of contiguously allocated virtual resource blocks can be derived. Both **localized and distributed virtual resource block assignment** is possible which are differentiated by a one-bit-flag within the DCI.

In the localized case, there is a one-to-one mapping between virtual and physical resource blocks.

Example: Let's assume a 10 MHz signal, i.e. 50 resource blocks are available. A UE shall be assigned an allocation of 10 resource blocks (L_{CRBs}=10), starting from resource block 15 (RB_{start}=15) in the frequency domain. According to the formula in [Ref. 6], a value of RIV=465 would then be signaled to the UE within DCI on PDCCH, and the UE could unambiguously derive the starting resource block and the number of allocated resource blocks from RIV again. For the given bandwidth of 10 MHz, 11 bits are available for signaling the RIV within the DCI. Signaling L_{CRBs} and RB_{start} explicitly would require 12 bits for the 10 MHz case. By focusing on the realistic combinations of L_{CRBs} and RB_{start} using RIV, 1 bit can therefore be saved and signaling is more efficient.

In the distributed case of resource allocation type 2, the virtual resource block numbers are mapped to physical resource block numbers according to the rule specified in [Ref. 3], and inter-slot hopping is applied: The first part of a virtual resource block pair is mapped to one physical resource block, the other part of the virtual resource block pair is mapped to a physical resource block which is a pre-defined gap distance away (which causes the inter-slot hopping). By doing so, frequency diversity is achieved. This mechanism is especially interesting for small resource blocks allocations, because these inherently provide less frequency diversity.

Besides PCFICH and PDCCH, additional downlink control channels are the Physical Hybrid ARQ Indicator channel (PHICH) and the Physical Broadcast Channel (PBCH). PHICH is used to convey ACK/NACKs for the packets received in uplink, see the section on uplink HARQ below. PBCH carries the Master Information Block, see the section on cell search below. *Table 6* shows a summary of downlink control channels.

Table 6 Downlink control channels

Downlink control channel	**Purpose**	**Modulation scheme**
Physical Downlink Control Channel (PDCCH)	Carries downlink control information (DCI), e.g. downlink or uplink scheduling assignments	QPSK
Physical Control Format Indicator Channel (PCFICH)	Indicates format of PDCCH (whether it occupies 1, 2, 3, or 4 symbols)	QPSK
Physical Hybrid ARQ Indicator Channel (PHICH)	Carries ACK/NACKs for uplink data packets	BPSK
Physical Broadcast Channel (PBCH)	Carries Master Information Block	QPSK

Downlink reference signal structure and cell search

The downlink reference signal structure is important for channel estimation. *Figure 9* shows the principle of the downlink reference signal structure for 1 antenna, 2 antenna, and 4 antenna transmission. Specific pre-defined resource elements (indicated by R_{0-3} in *Figure 9*) in the time-frequency domain are carrying the cell-specific reference signal sequence.

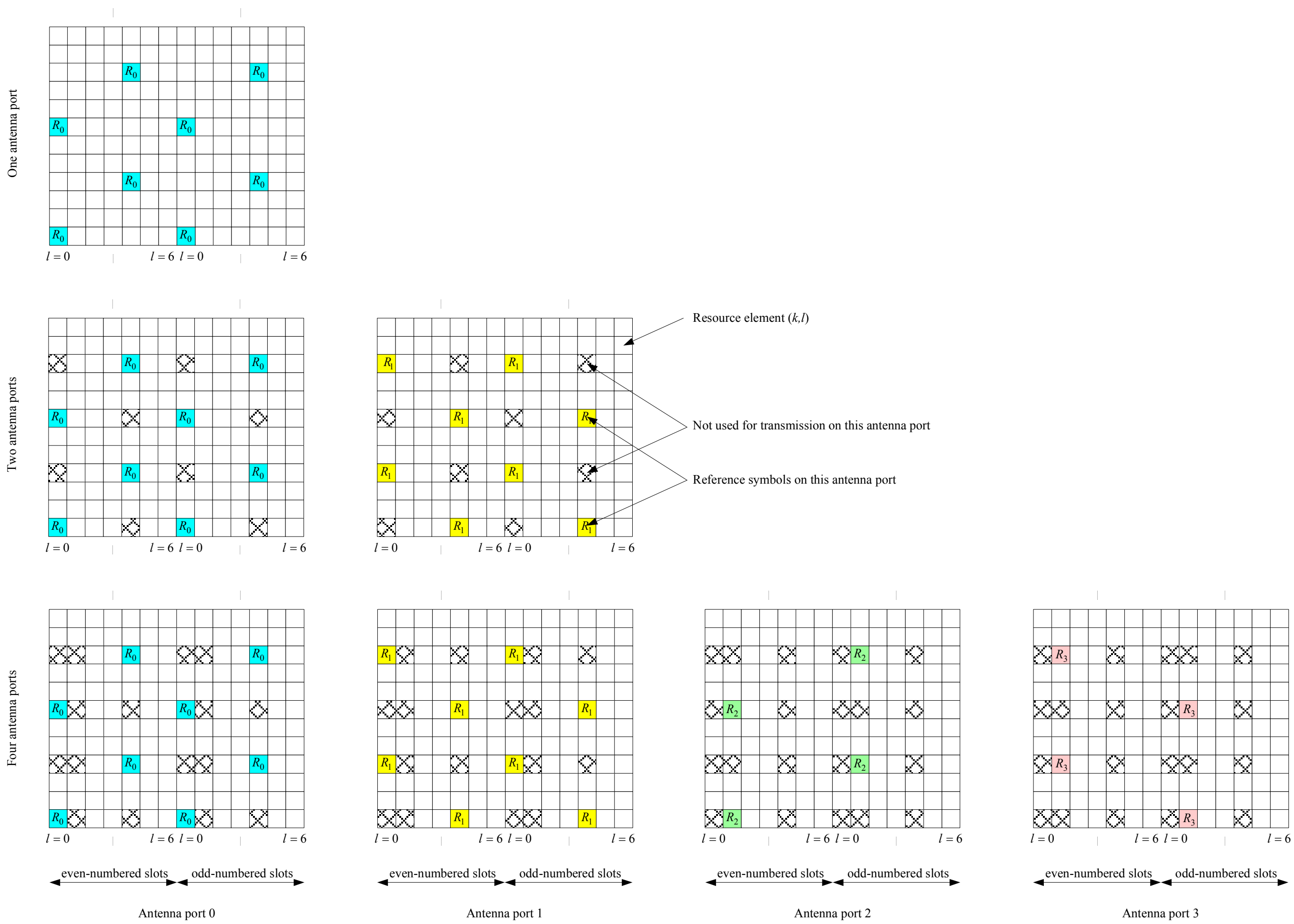


Figure 9 Downlink reference signal structure (normal cyclic prefix) [Ref. 3]

The reference signal sequence is derived from a pseudo-random sequence and results in a QPSK type constellation. Cell-specific frequency shifts are applied when mapping the reference signal sequence to the subcarriers.

During cell search, different types of information need to be identified by the UE: symbol and radio frame timing, frequency, cell identification, overall transmission bandwidth, antenna configuration, cyclic prefix length.

The first step of cell search in LTE is based on specific synchronization signals. LTE uses a hierarchical cell search scheme similar to WCDMA. Thus, a primary **synchronization signal** and a **secondary synchronization signal** are defined. The synchronization signals are transmitted twice per 10 ms on predefined slots, see *Figure 10* for FDD and Figure 11 for TDD. In the frequency domain, they are transmitted on 62 subcarriers within 72 reserved subcarriers around DC subcarrier.

The 504 available physical layer cell identities are grouped into 168 physical layer cell identity groups, each group containing 3 unique identities (0, 1, or 2). The secondary synchronization signal carries the physical layer cell identity group, and the primary synchronization signal carries the physical layer identity 0, 1, or 2.

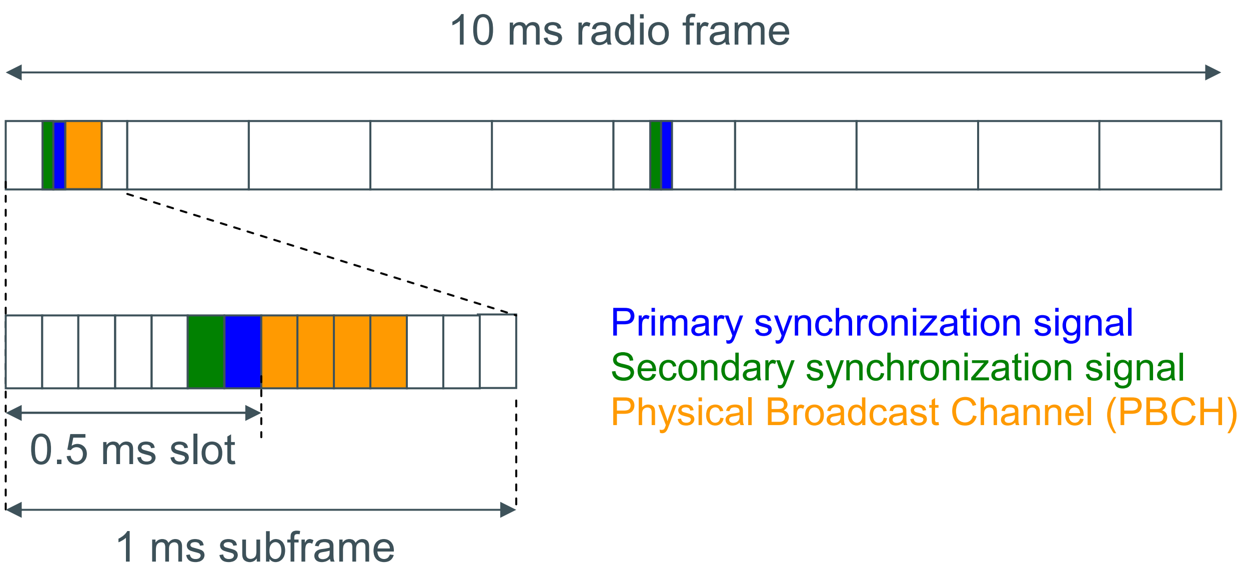


Figure 10 Primary/secondary synchronization signal and PBCH structure (frame structure type 1 / FDD, normal cyclic prefix)

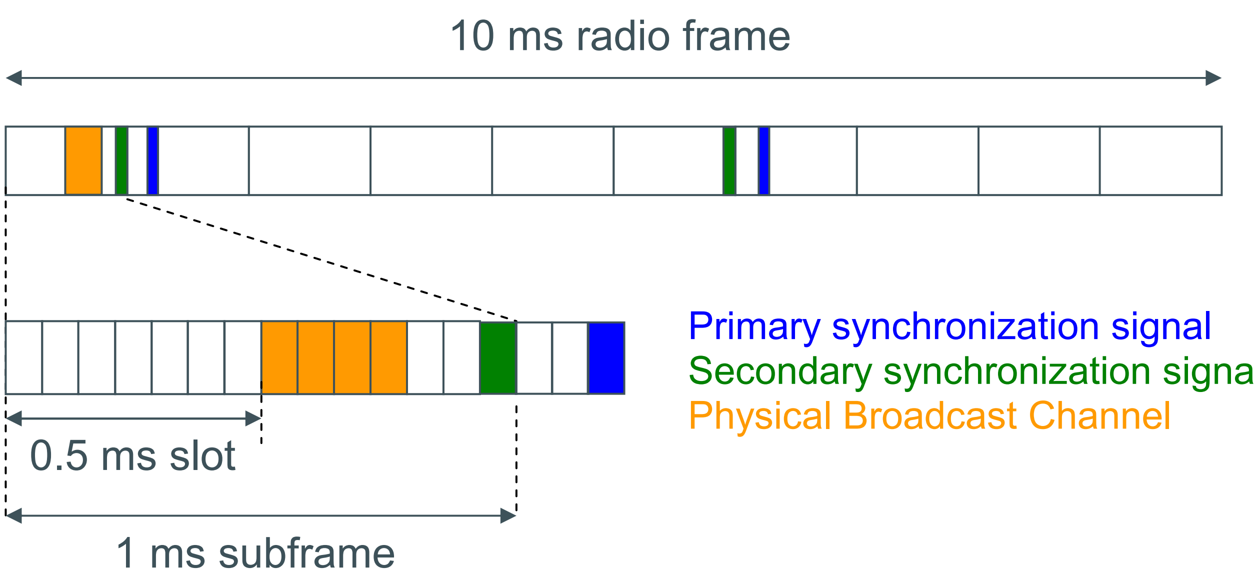


Figure 11 *Primary/secondary synchronization signal and PBCH structure (frame structure type 2 / TDD, normal cyclic prefix)*

As additional help during cell search, a Primary Broadcast Channel (**PBCH)** is available which carries the Master Information Block with basic physical layer information, e.g. system bandwidth, number of transmit antennas, and system frame number. It is transmitted within specific symbols of the first subframe on the 72 subcarriers centered around DC subcarrier. PBCH has 40 ms transmission time interval.

In order to enable the UE to support this cell search concept, it was agreed to have a minimum UE bandwidth reception capability of 20 MHz.

Downlink Hybrid ARQ (Automatic Repeat Request)

Downlink Hybrid ARQ is also known from HSDPA. It is a retransmission protocol. The UE can request retransmissions of data packets that were incorrectly received on PDSCH. ACK/NACK information is transmitted in uplink, either on Physical Uplink Control Channel (PUCCH) or multiplexed within uplink data transmission on Physical Uplink Shared Channel (PUSCH). 8 HARQ processes can be used.

The ACK/NACK transmission in FDD mode refers to the downlink packet that was received four subframes before. In TDD mode, the uplink ACK/NACK timing depends on the uplink/downlink configuration. For TDD, the use of a single ACK/NACK response for multiple PDSCH transmissions is possible (so-called ACK/NACK bundling).

4 LTE Uplink Transmission Scheme

SC-FDMA

During the study item phase of LTE, alternatives for the optimum uplink transmission scheme were investigated. While OFDMA is seen optimum to fulfil the LTE requirements in downlink, OFDMA properties are less favourable for the uplink. This is mainly due to weaker peak-to-average power ratio (PAPR) properties of an OFDMA signal, resulting in worse uplink coverage.

Thus, the LTE uplink transmission scheme for FDD and TDD mode is based on **SC-FDMA** (Single Carrier Frequency Division Multiple Access) with cyclic prefix. SC-FDMA signals have better PAPR properties compared to an OFDMA signal. This was one of the main reasons for selecting SC-FDMA as LTE uplink access scheme. The PAPR characteristics are important for cost-effective design of UE power amplifiers. Still, SC-FDMA signal processing has some similarities with OFDMA signal processing, so parametrization of downlink and uplink can be harmonized.

There are different possibilities how to generate an SC-FDMA signal. DFT-spread-OFDM (DFT-s-OFDM) has been selected for E-UTRA. The principle is illustrated in *Figure 12*.

For **DFT-s-OFDM**, a size-M DFT is first applied to a block of M modulation symbols. QPSK, 16QAM and 64 QAM are used as uplink E-UTRA modulation schemes, the latter being optional for the UE. The DFT transforms the modulation symbols into the frequency domain. The result is mapped onto the available subcarriers. In E-UTRA uplink, only localized transmission on consecutive subcarriers is allowed. An N-point IFFT where N>M is then performed as in OFDM, followed by addition of the cyclic prefix and parallel to serial conversion.

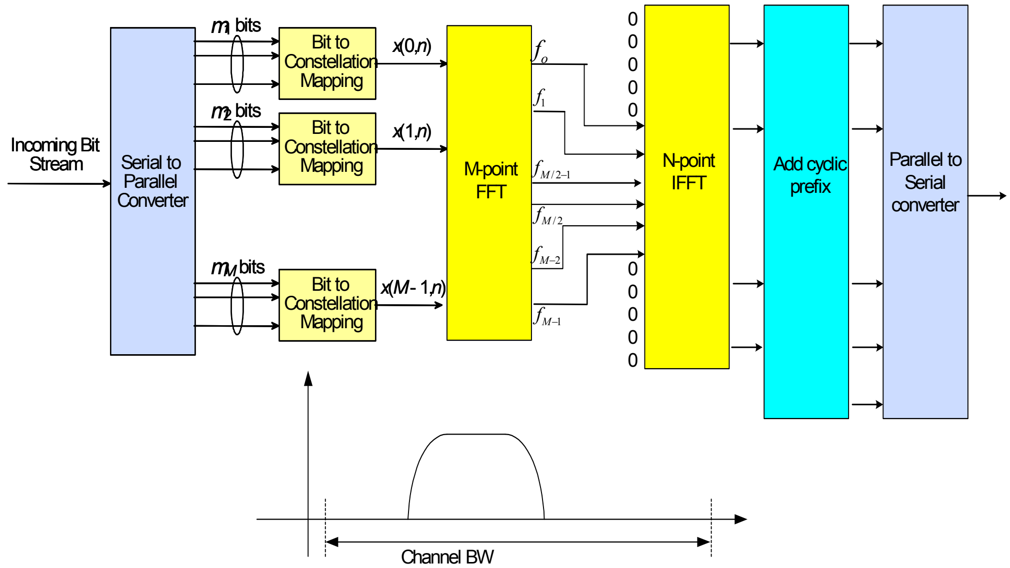


Figure 12 Block Diagram of DFT-s-OFDM (Localized transmission)

The DFT processing is therefore the fundamental difference between SC-FDMA and OFDMA signal generation. This is indicated by the term "DFT-spread-OFDM". In an SC-FDMA signal, each subcarrier used for transmission contains information of all transmitted modulation symbols, since the input data stream has been spread by the DFT transform over the available subcarriers. In contrast to this, each subcarrier of an OFDMA signal only carries information related to specific modulation symbols.

SC-FDMA parametrization

The LTE uplink structure is similar to the downlink. In frame structure type 1, an uplink radio frame consists of 20 slots of 0.5 ms each, and one subframe consists of two slots. The slot structure is shown in Figure 13. Frame structure type 2 consists also of ten subframes, but one or two of them are special subframes. They include DwPTS, GP and UpPTS fields, see *Figure 5*.

Each slot carries 7 SC-FDMA symbols in case of normal cyclic prefix configuration, and 6 SC-FDMA symbols in case of extended cyclic prefix configuration. SC-FDMA symbol number 3 (i.e. the 4th symbol in a slot) carries the reference signal for channel demodulation.

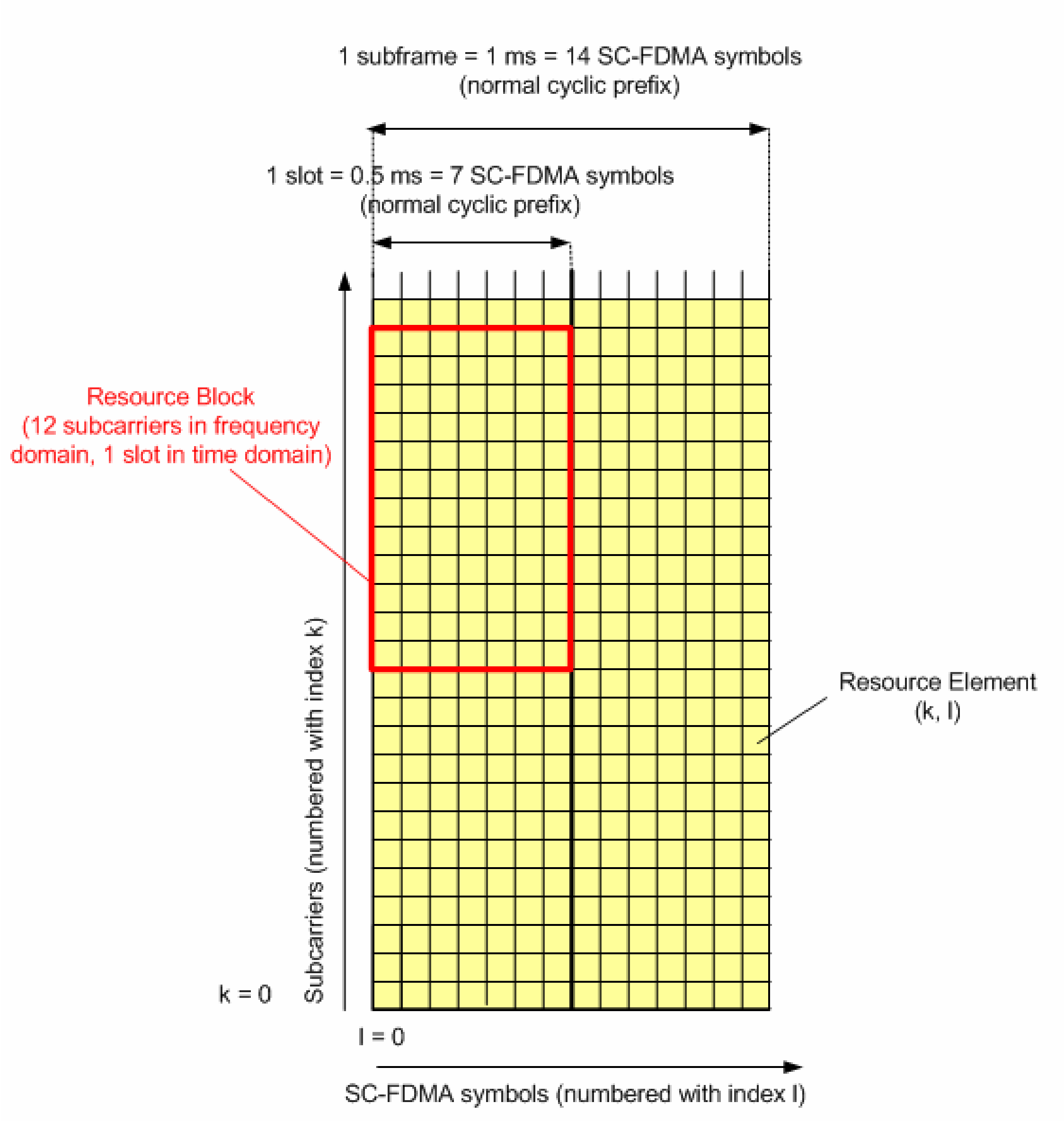


Figure 13 Uplink resource grid [Ref. 3]

Table 7 shows the configuration parameters in an overview table.

Table 7 Uplink frame structure parametrization (FDD and TDD) [Ref. 3]

Configuration	**Number of symbols** $N_{\mathrm{symb}}^{\mathrm{UL}}$	**Cyclic Prefix length in samples**	**Cyclic Prefix length in µs**
Normal cyclic prefix Δf=15 kHz	7	160 for first symbol 144 for other symbols	5.2 µs for first symbol 4.7 µs for other symbols
Extended cyclic prefix Δf=15 kHz	6	512	16.7 µs

Uplink data transmission

Scheduling of uplink resources is done by eNodeB. The eNodeB assigns certain time/frequency resources to the UEs and informs UEs about transmission formats to use. The scheduling decisions may be based on QoS parameters, UE buffer status, uplink channel quality measurements, UE capabilities, UE measurement gaps, etc.

In uplink, data is allocated in multiples of one resource block. Uplink resource block size in the frequency domain is 12 subcarriers, i.e. the same as in downlink. However, not all integer multiples are allowed in order to simplify the DFT design in uplink signal processing. Only factors 2,3, and 5 are allowed. Unlike in the downlink, UEs are always assigned contiguous resources in the LTE uplink.

The uplink transmission time interval is 1 ms (same as downlink).

User data is carried on the Physical Uplink Shared Channel (**PUSCH**).

By use of **uplink frequency hopping** on PUSCH, frequency diversity effects can be exploited and interference can be averaged.

The UE derives the uplink resource allocation as well as frequency hopping information from the uplink scheduling grant that was received four subframes before. DCI (Downlink Control Information) format 0 is used on PDCCH to convey the uplink scheduling grant, see *Table 8*.

Table 8 Contents of DCI format 0 carried on PDCCH [Ref. 5]

Information type	**Number of bits on PDCCH**	**Purpose**
Flag for format 0 / format 1A differentiation	1	Indicates DCI format to UE
Hopping flag	1	Indicates whether uplink frequency hopping is used or not
Resource block assignment and hopping resource allocation	Depending on resource allocation type	Indicates whether to use type 1 or type 2 frequency hopping and index of starting resource block of uplink resource allocation as well as number of contiguously allocated resource blocks
Modulation and coding scheme and redundancy version	5	Indicates modulation scheme and, together with the number of allocated physical resource blocks, the transport block size Indicates redundancy version to use
New data indicator	1	Indicates whether a new transmission shall be sent

TPC command for scheduled PUSCH	2	Transmit power control (TPC) command for adapting the transmit power on the Physical Uplink Shared Channel (PUSCH)
Cyclic shift for demodulation reference signal	3	Indicates the cyclic shift to use for deriving the uplink demodulation reference signal from the base sequence
Uplink index (TDD only)	2	Indicates the uplink subframe where the scheduling grant has to be applied
CQI request	1	Requests the UE to send a channel quality indication (CQI)

LTE supports both **intra- and inter-subframe frequency hopping**. It is configured per cell by higher layers whether both intra- and inter-subframe hopping or only inter-subframe hopping is supported. In intra-subframe hopping (=inter-slot hopping), the UE hops to another frequency allocation from one slot to another within one subframe. In inter-subframe hopping, the frequency resource allocation changes from one subframe to another.

The uplink scheduling grant in DCI format 0 contains a 1 bit flag for switching hopping on or off. Also, the UE is being told whether to use type 1 or type 2 frequency hopping, and receives the index of the first resource block of the uplink allocation.

Type 1 hopping refers to the use of an explicit offset in the 2nd slot resource allocation. *Figure 14* and *Figure 15* show two different examples. Both examples use intra- / inter-subframe hopping, based on type 1 hopping scheme, but with a different offset applied. Two subframes of a 10 MHz signal are shown. The offset between the slots is different in both figures. It is adjustable and indicated to the UE also within the resource block assignment / hopping resource allocation field in DCI format 0.

Type 2 hopping refers to the use of a pre-defined hopping pattern [Ref. 3]. The bandwidth available for PUSCH is sub-divided into sub-bands (e.g. 4 sub-bands with 5 resource blocks each in the 5 MHz case), and the hopping is performed between sub-bands (from one slot or subframe to another, depending on whether intra- or inter-subframe are configured, respectively). Additionally, mirroring can be applied according to a mirroring function, which means that the resource block allocation starts from the other direction of the sub-band where they are located in. Note that in case of type 2 hopping, the resource allocation for the UE cannot be larger than the sub-band configured.

The UE will first determine the allocated resource blocks after applying all the frequency hopping rules. Then, the data is being mapped onto these resources, first in subcarrier order, then in symbol order.

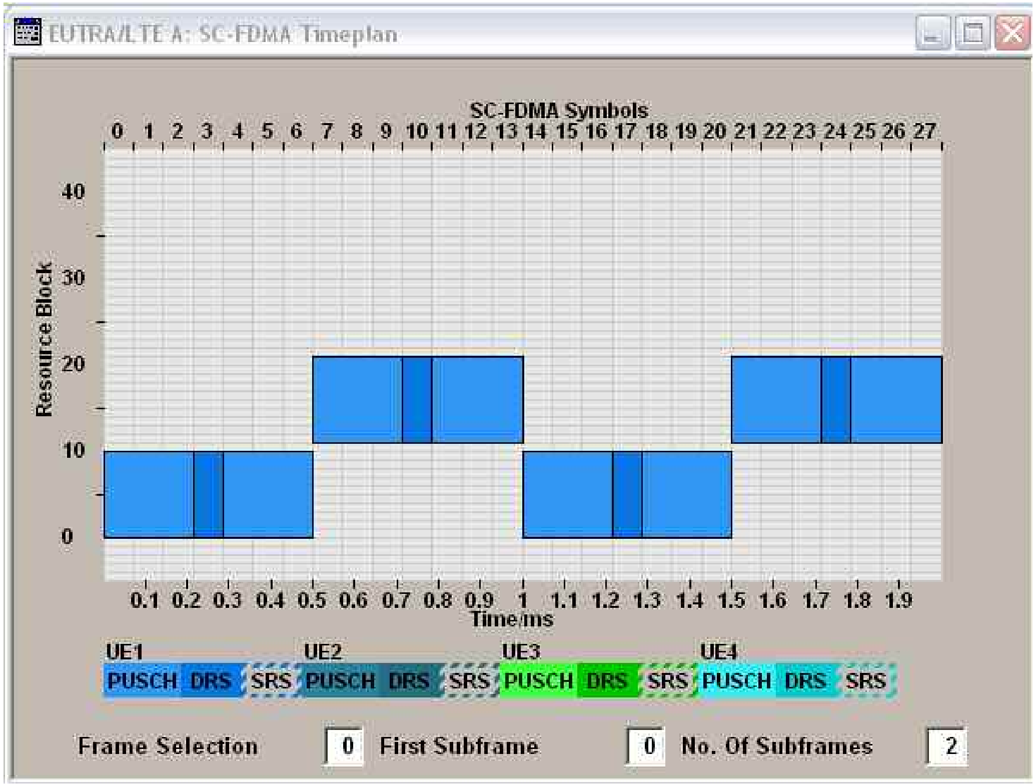


Figure 14 Intra- and inter-subframe hopping, type 1 (DRS = Demodulation Reference Signal)

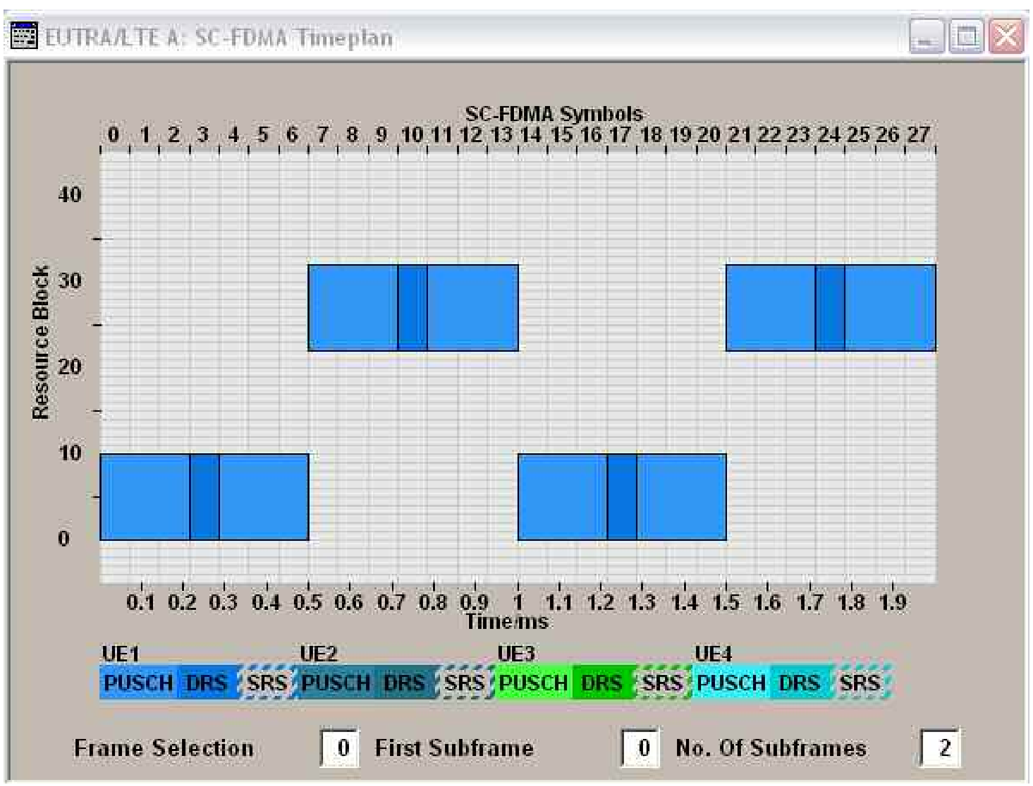


Figure 15 Another example for intra- and inter-subframe hopping, type 1, based on a different offset

Uplink control channel PUCCH

The Physical Uplink Control Channel (**PUCCH**) carries uplink control information (UCI), i.e. ACK/NACK information related to data packets received in the downlink, channel quality indication (CQI) reports, precoding matrix information (PMI) and rank indication (RI) for MIMO, and scheduling requests (SR). The PUCCH is transmitted on a reserved frequency region in the uplink which is configured by higher layers. PUCCH resource blocks are located at both edges of the uplink bandwidth, and inter-slot hopping is used on PUCCH. *Figure 16* shows an example for a PUCCH resource allocation. One resource block is reserved at the edge of the bandwidth, and inter-slot hopping is applied.

For TDD, PUCCH is not transmitted in special subframes.

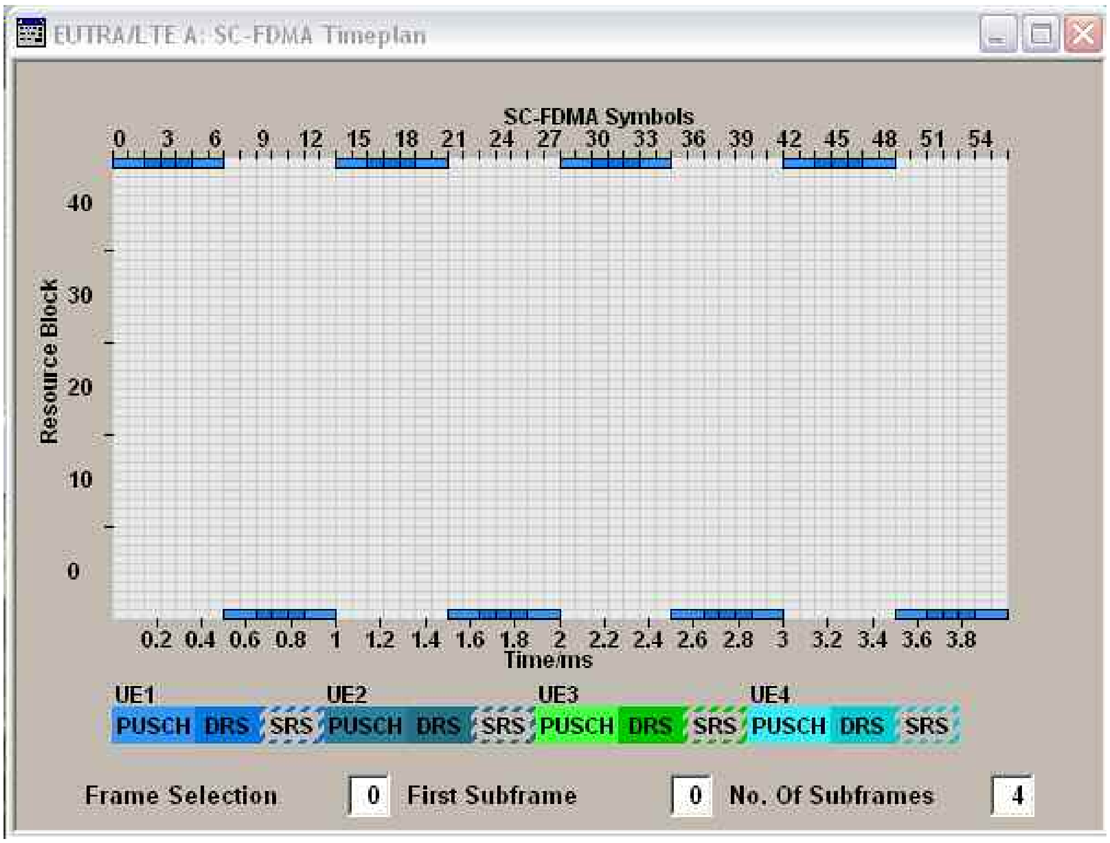


Figure 16 Example for PUCCH resource allocation (format 1a)

Note that a UE only uses PUCCH when it does not have any data to transmit on PUSCH. If a UE has data to transmit on PUSCH, it would multiplex the control information with data on PUSCH.

According to the different types of information that PUCCH can carry, different PUCCH formats are specified, see *Table 9*.

Table 9 PUCCH formats and contents

PUCCH format	Contents	Modulation scheme	Number of bits per subframe, M_{bit}
1	Scheduling Request (SR)	N/A	N/A (information is carried by presence or absence of transmission)
1a	ACK/NACK, ACK/NACK+SR	BPSK	1
1b	ACK/NACK, ACK/NACK+SR	QPSK	2
2	CQI/PMI or RI (any CP), (CQI/PMI or RI)+ACK/NACK (ext. CP only)	QPSK	20
2a	(CQI/PMI or RI)+ACK/NACK (normal CP only)	QPSK+BPSK	21
2b	(CQI/PMI or RI)+ACK/NACK (normal CP only)	QPSK+QPSK	22

When a UE has ACK/NACK to send in response to a downlink PDSCH transmission, it will derive the exact PUCCH resource to use from the PDCCH transmission (i.e. the number of the first control channel element used for the transmission of the corresponding downlink resource assignment). When a UE has a scheduling request or CQI to send, higher layers will configure the exact PUCCH resource.

PUCCH formats 1, 1a, and 1b are based on cyclic shifts from a Zadoff-Chu type of sequence [Ref. 3], i.e. the modulated data symbol is multiplied with the cyclically shifted sequence. The cyclic shift varies between symbols and slots. Higher layers may configure a limitation that not all cyclic shifts are available in a cell. Additionally, a spreading with an orthogonal sequence is applied. PUCCH formats 1, 1a, and 1b carry three reference symbols per slot in case of normal cyclic prefix (located on SC-FDMA symbol numbers 2, 3, 4).

For PUCCH formats 1a and 1b, when both ACK/NACK and SR are transmitted in the same subframe, the UE shall transmit ACK/NACK on its assigned ACK/NACK resource for negative SR transmission and transmit ACK/NACK on its assigned SR resource for positive SR transmission.

In PUCCH formats 2, 2a, and 2b, the bits for transmission are first scrambled and QPSK modulated. The resulting symbols are then multiplied with a cyclically shifted Zadoff-Chu type of sequence where again the cyclic shift varies between symbols and slots [Ref. 3]. PUCCH formats 2, 2a, and 2b carry two reference symbols per slot in case of normal cyclic prefix (located on SC-FDMA symbol numbers 1, 5).

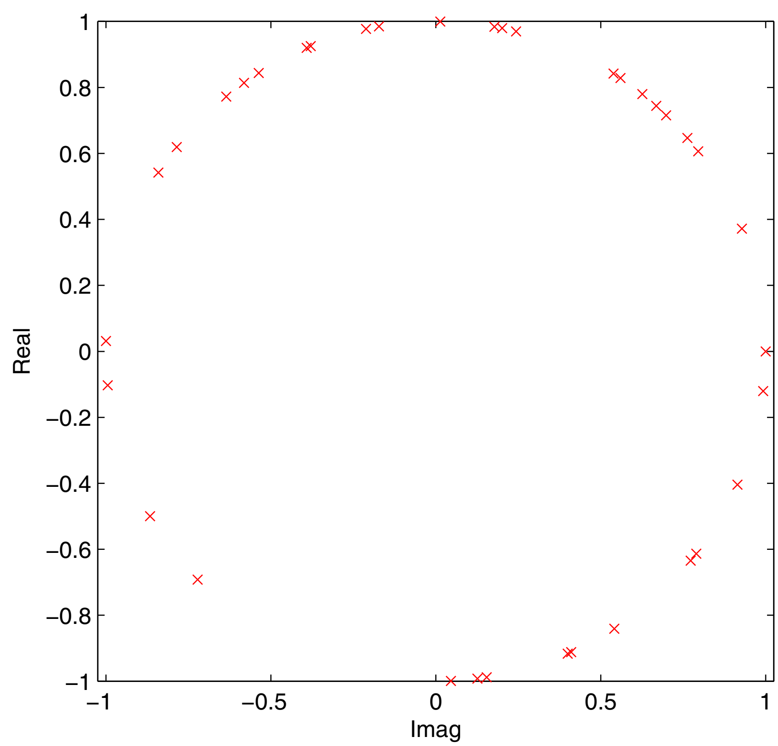
A resource block can either be configured to support a mix of PUCCH formats 2/2a/2b and 1/1a/1b, or to support formats 2/2a/2b exclusively.

Uplink reference signal structure

There is two types of uplink reference signals:

- the **demodulation reference signal** is used for channel estimation in the eNodeB receiver in order to demodulate control and data channels. It is located on the 4th symbol in each slot (for normal cyclic prefix) and spans the same bandwidth as the allocated uplink data.
- the **sounding reference signal** provides uplink channel quality information as a basis for scheduling decisions in the base station. The UE sends a sounding reference signal in different parts of the bandwidths where no uplink data transmission is available. The sounding reference signal is transmitted in the last symbol of the subframe. The configuration of the sounding signal, e.g. bandwidth, duration and periodicity, are given by higher layers.

Both uplink reference signals are derived from so-called Zadoff-Chu sequence types [Ref. 3]. This sequence type has the property that cyclic shifted versions of the same sequence are orthogonal to each other. Reference signals for different UEs are derived by different cyclic shifts from the same base sequence. Figure 17 shows the complex values of two example reference signals which were generated by two different cyclic shifts of the same sequence.



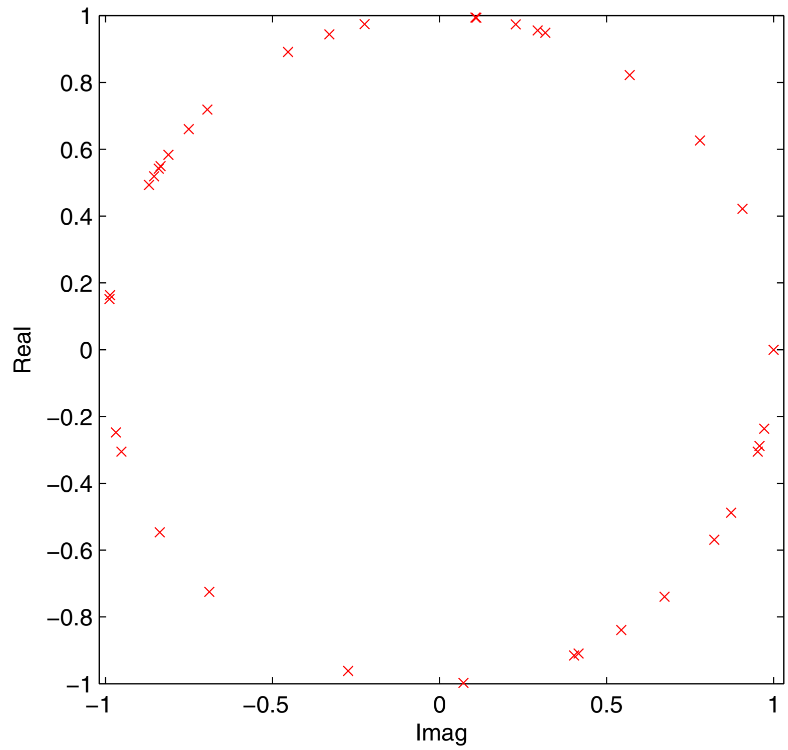


Figure 17 *Uplink reference signal sequences for an allocation of three resource blocks, generated by different cyclic shifts of the same base sequence*

The available base sequences are divided into groups identified by a sequence group number u. Within a group, the available sequences are numbered with index v. The sequence group number u and the number within the group v may vary in time. This is called group hopping, and sequence hopping, respectively.

Group hopping is switched on or off by higher layers. The sequence group number u to use in a certain timeslot is controlled by a pre-defined pattern.

Sequence hopping only applies for uplink resource allocations of more than five resource blocks. In case it is enabled (by higher layers), the base sequence number v within the group u is updated every slot.

Random access

The random access procedure is used to request initial access, as part of handover, or to re-establish uplink synchronization. 3GPP defines a contention based and a non-contention based random access procedure.

The structure of the contention based procedure used e.g. for initial access is shown in *Figure 18*.

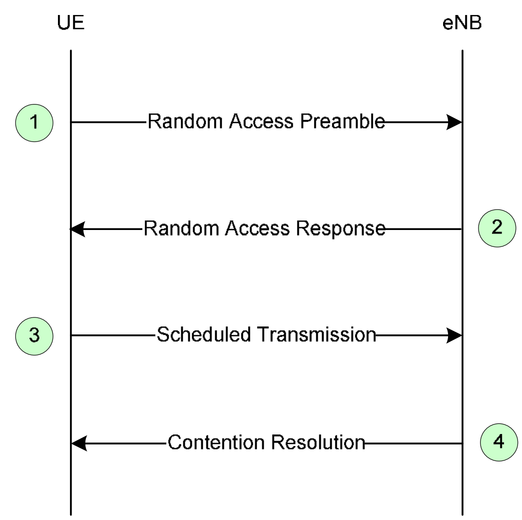


Figure 18 Random access procedure (contention based) [Ref. 7]

The transmission of the random access preamble is restricted to certain time and frequency resources. In the frequency domain, the random access preamble occupies a bandwidth of six resource blocks. Different PRACH configurations are defined which indicate system and subframe numbers with PRACH opportunities, as well as possible preamble formats. The PRACH configuration is provided by higher layers.

The random access preamble is defined as shown in *Figure 19*. The preamble consists of a sequence with length T_{SEQ} and a cyclic prefix with length T_{CP}. For frame structure type 1, four different preamble formats are defined with different T_{SEQ} and T_{CP} values, e.g. reflecting different cell sizes. An additional 5th preamble format is defined for frame structure type 2.

Figure 19 Random access preamble [Ref. 3]

Per cell, there are 64 random access preambles. They are generated from Zadoff-Chu type of sequences [Ref. 3].

In step 1 in *Figure 18*, the preamble is sent. The time-frequency resource where the preamble is sent is associated with an identifier (the Random Access Radio Network Temporary Identifier (RA-RNTI)).

In step 2, a random access response is generated in Medium Access Control (MAC) layer of eNodeB and sent on downlink shared channel. It is addressed to the UE via the RA-RNTI and contains a timing advance value, an uplink grant, and a temporary C-RNTI. Note that eNodeB may generate multiple random access responses for different UEs which can be concatenated inside one MAC protocol data unit (PDU). The preamble identifier is contained in the MAC sub-header of each random access response, so that the UE can find out whether there exists a random access response for the used preamble.

In step 3, UE will for initial access send an RRC CONNECTION REQUEST message on the uplink common control channel (CCCH), based on the uplink grant received in step 2.

In step 4, contention resolution is done, by mirroring back in a MAC PDU the uplink CCCH service data unit (SDU) received in step 3. The message is sent on downlink shared channel and addressed to the UE via the temporary C-RNTI. When the received message matches the one sent in step 3, the contention resolution is considered successful.

Uplink Hybrid ARQ (Automatic Repeat Request)

Hybrid ARQ retransmission protocol is also used in LTE uplink. The eNodeB has the capability to request retransmissions of incorrectly received data packets. ACK/NACK information in downlink is sent on Physical Hybrid ARQ Indicator Channel (**PHICH**). After a PUSCH transmission the UE will therefore monitor the corresponding PHICH resource four subframes later (for FDD). For TDD the PHICH subframe to monitor is derived from the uplink/downlink configuration and from PUSCH subframe number.

The PHICH resource is determined from lowest index physical resource block of the uplink resource allocation and the uplink demodulation reference symbol cyclic shift associated with the PUSCH transmission, both indicated in the PDCCH with DCI format 0 granting the PUSCH transmission.

A PHICH group consists of multiple PHICHs that are mapped to the same set of resource elements, and that are separated through different orthogonal sequences. The UE derives the PHICH group number and the PHICH to use inside that group from the information on the lowest resource block number in the PUSCH allocation, and the cyclic shift of the demodulation reference signal.

The UE can derive the redundancy version to use on PUSCH from the uplink scheduling grant in DCI format 0, see *Table 8*.

8 HARQ processes are supported in the uplink for FDD, while for TDD the number of HARQ processes depends on the uplink-downlink configuration.

5 LTE MIMO Concepts

Multiple Input Multiple Output (MIMO) systems form an essential part of LTE in order to achieve the ambitious requirements for throughput and spectral efficiency. MIMO refers to the use of multiple antennas at transmitter and receiver side. For the LTE downlink, a 2x2 configuration for MIMO is assumed as baseline configuration, i.e. two transmit antennas at the base station and two receive antennas at the terminal side. Configurations with four transmit or receive antennas are also foreseen and reflected in specifications.

Different gains can be achieved depending on the MIMO mode that is used. In the following, a general description of spatial multiplexing and transmit diversity is provided. Afterwards, LTE-specific MIMO features are highlighted.

Spatial Multiplexing

Spatial multiplexing allows to transmit different streams of data simultaneously on the same resource block(s) by exploiting the spatial dimension of the radio channel. These data streams can belong to one single user (single user MIMO / SU-MIMO) or to different users (multi user MIMO / MU-MIMO). While SU-MIMO increases the data rate of one user, MU-MIMO allows to increase the overall capacity. Spatial multiplexing is only possible if the mobile radio channel allows it.

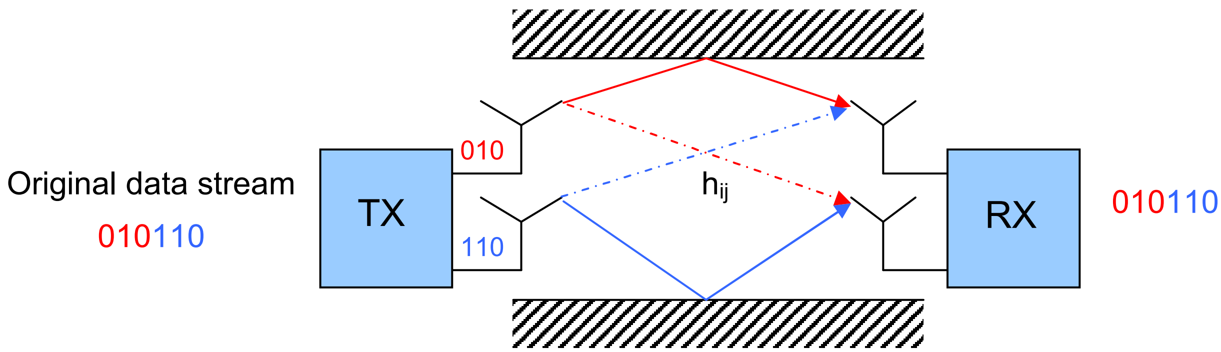


Figure 20 Spatial multiplexing (simplified)

Figure 20 shows a simplified illustration of spatial multiplexing. In this example, each transmit antenna transmits a different data stream. This is the basic case for spatial multiplexing.

Each receive antenna may receive the data streams from all transmit antennas. The channel (for a specific delay) can thus be described by the following channel matrix **H**:

$$H = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1Nt} \\ h_{21} & h_{22} & & h_{2Nt} \\ \vdots & \vdots & \ddots & \vdots \\ h_{Nr1} & h_{Nr2} & \cdots & h_{NrNt} \end{bmatrix}$$

In this general description, N_t is the number of transmit antennas, N_r is the number of receive antennas, resulting in a 2x2 matrix for the baseline LTE scenario. The coefficients h_{ij} of this matrix are called channel coefficients from transmit antenna j to receive antenna i, thus describing all possible paths between transmitter and receiver side.

The number of data streams that can be transmitted in parallel over the MIMO channel is given by min $\{N_t, N_r\}$ and is limited by the rank of the matrix **H**. The transmission quality degrades significantly in case the singular values of matrix **H** are not sufficiently strong. This can happen in case the two antennas are not sufficiently de-correlated, for example in an environment with little scattering or when antennas are too closely spaced. The rank of the channel matrix **H** is therefore an important criterion to determine whether spatial multiplexing can be done with good performance.

Note that *Figure 20* only shows an example. In practical MIMO implementations, the data streams are often weighted and added, so that each antenna actually transmits a combination of the streams, see below for more details regarding LTE.

Transmit Diversity

Instead of increasing data rate or capacity, MIMO can be used to exploit diversity and increase the robustness of data transmission. Transmit diversity schemes are already known from WCDMA release 99 and will also be part of LTE. Each transmit antenna transmits essentially the same stream of data, so the receiver gets replicas of the same signal. This increases the signal to noise ratio at the receiver side and thus the robustness of data transmission especially in fading scenarios. Typically an additional antenna-specific coding is applied to the signals before transmission to increase the diversity effect. Often, space-time coding is used according to Alamouti [Ref. 8].

Switching between the two MIMO modes transmit diversity and spatial multiplexing is possible depending on channel conditions.

Downlink MIMO modes in LTE

Different downlink MIMO modes are envisaged in LTE which can be adjusted according to channel condition, traffic requirements, and UE capability. The following transmission modes are possible in LTE:

- Single-Antenna transmission, no MIMO
- Transmit diversity
- Open-loop spatial multiplexing, no UE feedback required
- Closed-loop spatial multiplexing, UE feedback required
- Multi-user MIMO (more than one UE is assigned to the same resource block)
- Closed-loop precoding for rank=1 (i.e. no spatial multiplexing, but precoding is used)
- Beamforming

Figure 21 gives an overview of LTE downlink baseband signal generation including the steps relevant for MIMO transmission (layer mapper and precoding).

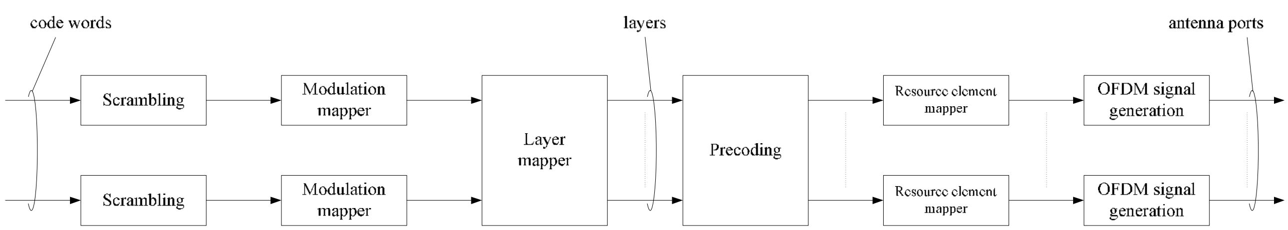


Figure 21 Overview of downlink baseband signal generation [Ref. 3]

In LTE spatial multiplexing, up to two code words can be mapped onto different spatial layers. One code word represents an output from the channel coder. The number of spatial layers available for transmission is equal to the rank of the matrix **H**. The mapping of code words onto layers is specified in [Ref. 3].

Precoding on transmitter side is used to support spatial multiplexing. This is achieved by multiplying the signal with a precoding matrix **W** before transmission. The optimum precoding matrix **W** is selected from a predefined "codebook" which is known at eNodeB and UE side. The codebook for the 2 transmit antenna case in LTE is shown in *Table 10*.The optimum pre-coding matrix is the one which offers maximum capacity.

Table 10 Precoding codebook for 2 transmit antenna case

Codebook index	Number of layers υ	
	1	2
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	-

The codebook in *Table 10* defines entries for the case of one or two spatial layers. In case of only one spatial layer, obviously spatial multiplexing is not possible, but there are still gains from precoding. For closed-loop spatial multiplexing and $\upsilon = 2$, the codebook index 0 is not used. For the 4 transmit antenna case, a correspondingly bigger codebook is defined [Ref. 3].

The UE estimates the radio channel and selects the optimum precoding matrix. This feedback is provided to the eNodeB. Depending on the available bandwidth, this information is made available per resource block or group of resource blocks, since the optimum precoding matrix may vary between resource blocks. The network may configure a subset of the codebook that the UE is able to select from.

In case of UEs with high velocity, the quality of the feedback may deteriorate. Thus, an **open loop spatial multiplexing mode** is also supported which is based on predefined settings for spatial multiplexing and precoding. In case of four antenna ports, different precoders are assigned cyclically to the resource elements.

The eNodeB will select the optimum MIMO mode and precoding configuration. The information is conveyed to the UE as part of the downlink control information (DCI) on PDCCH. DCI format 2 provides a downlink assignment of two code words including precoding information. DCI format 2a is used in case of open loop spatial multiplexing. DCI format 1b provides a downlink assignment of 1 code word including precoding information. DCI format 1d is used for multi-user spatial multiplexing with precoding and power offset information.

In case of **transmit diversity** mode, only one code word can be transmitted. Each antenna transmits the same information stream, but with different coding. LTE employs Space Frequency Block Coding (SFBC) which is derived from [Ref. 8] as transmit diversity scheme. A special precoding matrix is applied at transmitter side in the precoding stage in *Figure 21*. At a certain point in time, the antenna ports transmit the same data symbols, but with different coding and on different subcarriers. *Figure 22* shows an example for the 2 transmit antenna case, where the transmit diversity specific precoding is applied to an entity of two data symbols d(0) and d(1).

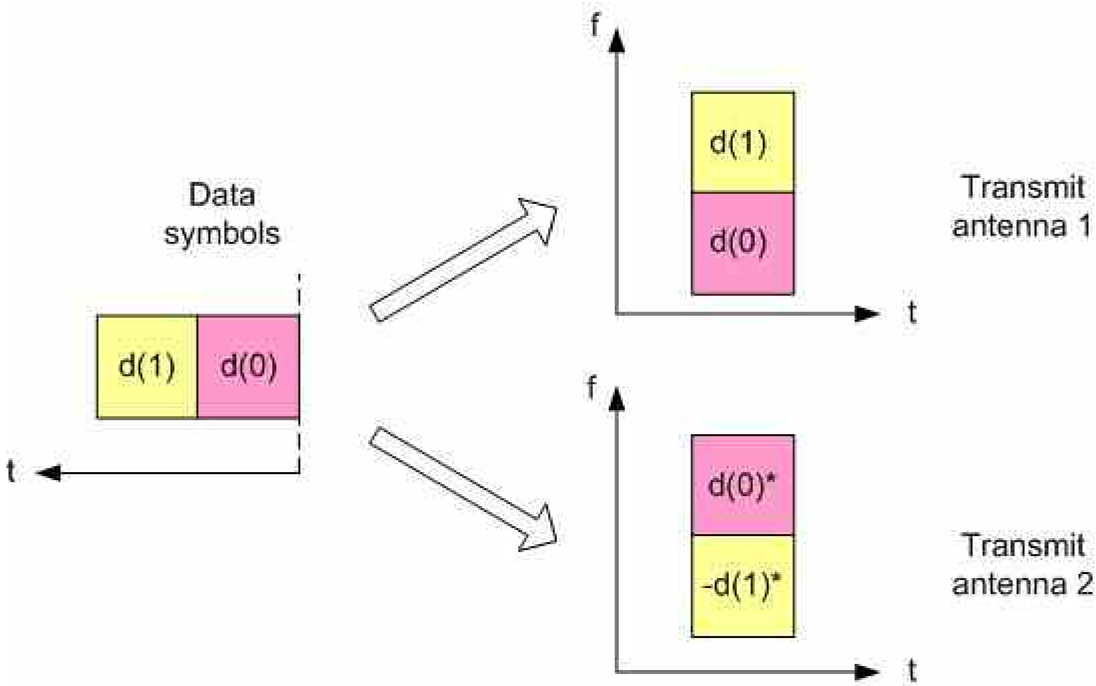


Figure 22 Transmit diversity (SFBC) principle

Cyclic Delay Diversity (CDD)

Cyclic delay diversity is an additional type of diversity which can be used in conjunction with spatial multiplexing in LTE. An antenna-specific delay is applied to the signals transmitted from each antenna port. This effectively introduces artificial multipath to the signal as seen by the receiver. By doing so, the frequency diversity of the radio channel is increased. As a special method of delay diversity, cyclic delay diversity applies a cyclic shift to the signals transmitted from each antenna port.

Reporting of UE feedback

In order for MIMO schemes to work properly, each UE has to report information about the mobile radio channel to the base station. A lot of different reporting modes and formats are available which are selected according to MIMO mode of operation and network choice.

The reporting may consist of the following elements:

- **CQI (channel quality indicator)** is an indication of the downlink mobile radio channel quality as experienced by this UE. Essentially, the UE is proposing to the eNodeB an optimum modulation scheme and coding rate to use for a given radio link quality, so that the resulting transport block error rate would not exceed 10%. 16 combinations of modulation scheme and coding rate are specified as possible CQI values. The UE may report different types of CQI. A so-called **"wideband CQI"** refers to the complete system bandwidth. Alternatively, the UE may evaluate a "**sub-band CQI**" value per sub-band of a certain number of resource blocks which is configured by higher layers. The full set of sub-bands would cover the entire system bandwidth. In case of spatial multiplexing, a CQI per code word needs to be reported.

- PMI (precoding matrix indicator) is an indication of the optimum precoding matrix to be used in the base station for a given radio condition. The PMI value refers to the codebook table, see e.g. *Table 10*. The network configures the number of resource blocks that are represented by a PMI report. Thus to cover the full bandwidth, multiple PMI reports may be needed. PMI reports are needed for closed loop spatial multiplexing, multi-user MIMO and closed-loop rank 1 precoding MIMO modes.
- RI (rank indication) is the number of useful transmission layers when spatial multiplexing is used. In case of transmit diversity, rank is equal to 1.

The reporting may be periodic or aperiodic and is configured by the radio network. Aperiodic reporting is triggered by a CQI request contained in the uplink scheduling grant, see *Table 8*. The UE would sent the report on PUSCH. In case of periodic reporting, PUCCH is used in case no PUSCH is available.

Uplink MIMO

Uplink MIMO schemes for LTE will differ from downlink MIMO schemes to take into account terminal complexity issues. For the uplink, MU-MIMO can be used. Multiple user terminals may transmit simultaneously on the same resource block. This is also referred to as spatial division multiple access (SDMA). The scheme requires only one transmit antenna at UE side which is a big advantage. The UEs sharing the same resource block have to apply mutually orthogonal pilot patterns.

To exploit the benefit of two or more transmit antennas but still keep the UE cost low, transmit antenna selection can be used. In this case, the UE has two transmit antennas but only one transmit chain and amplifier. A switch will then choose the antenna that provides the best channel to the eNodeB. This decision is made according to feedback provided by the eNodeB. The CRC parity bits of the DCI format 0 are scrambled with an antenna selection mask indicating UE antenna port 0 or 1. The support of transmit antenna selection is a UE capability.

6 LTE Protocol Architecture

System Architecture Evolution (SAE)

3GPP SAE is addressing the evolution of the overall system architecture including core network. Objective is to develop a framework for an evolution of the 3GPP system to a higher-data-rate, lower-latency, packet-optimized system that supports multiple radio access technologies. The focus of this work is on the PS domain with the assumption that voice services are supported in this domain. Clear requirement is the support of heterogeneous access networks in terms of mobility and service continuity.

E-UTRAN

An overall E-UTRAN description can be found in [Ref. 7]. The network architecture is illustrated in Figure 23.

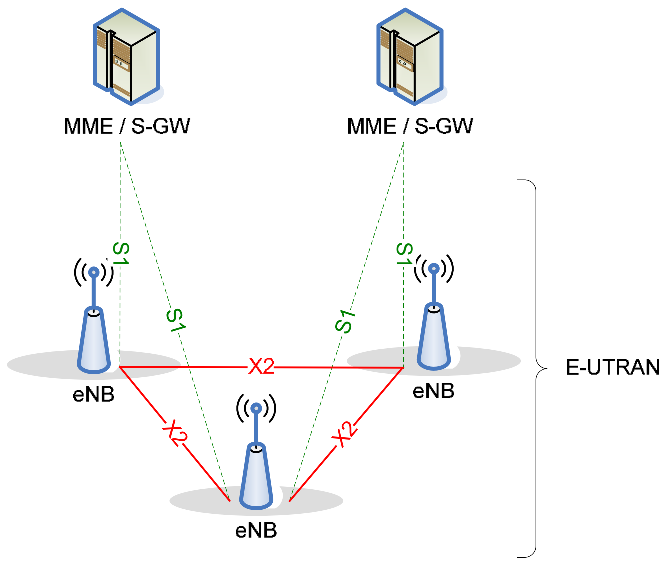


Figure 23 Overall network architecture [Ref. 7]

The E-UTRAN consists of eNodeBs (eNBs), providing the E-UTRA user plane (PDPC/RLC/MAC/PHY) and control plane (RRC) protocol terminations towards the UE. The eNBs are interconnected with each other by means of the X2 interface. The eNBs are also connected by means of the S1 interface to the EPC (Evolved Packet Core), more specifically to the MME (Mobility Management Entity) and to the S-GW (Serving Gateway). NAS protocols are terminated in MME.

The following figure illustrates the functional split between eNodeB and Evolved Packet Core.

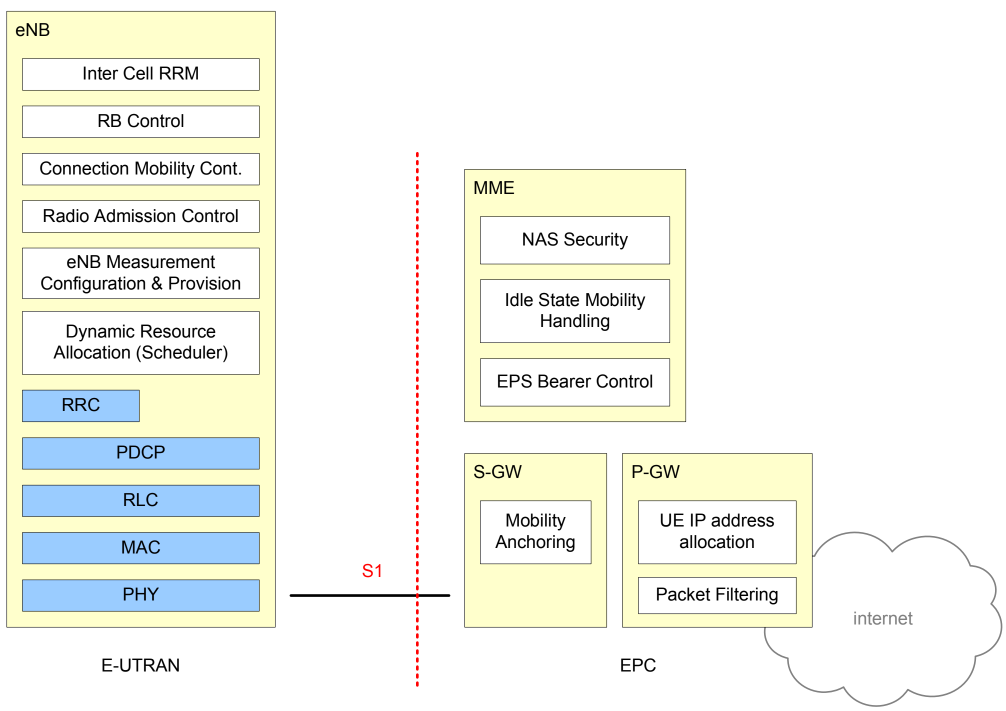


Figure 24 Functional split between E-UTRAN and EPC [Ref. 7]

The base station functionality has increased significantly in E-UTRAN, e.g. compared to WCDMA release 99. The base station hosts functions for radio bearer control, admission control, mobility control, uplink and downlink scheduling as well as measurement configuration.

The LTE user plane protocol stack is shown in *Figure 25*.

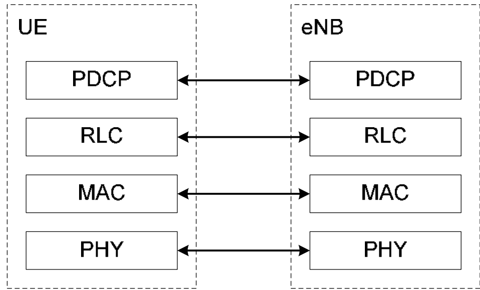


Figure 25 User plane protocol stack [Ref. 7]

The LTE control plane protocol stack is shown in *Figure 26*.

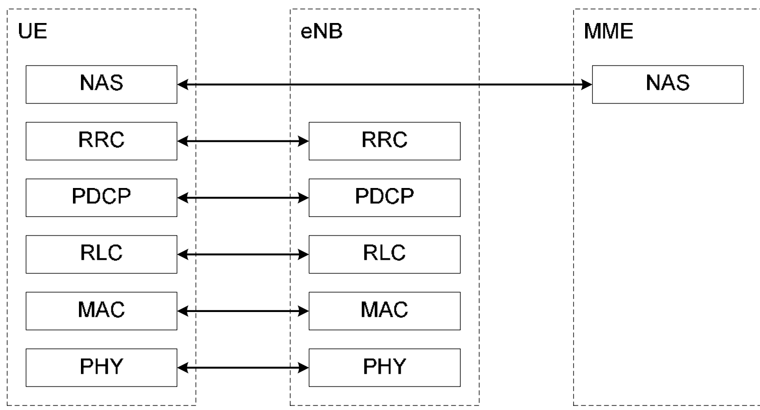


Figure 26 Control plane protocol stack [Ref. 7]

Layer 3 procedures

Radio Resource Control (RRC) protocol is responsible for handling layer 3 procedures over the air interface, including e.g. the following:

- Broadcast of system information
- RRC connection control, i.e. paging, establishing / reconfiguring / releasing RRC connections, assignment of UE identies
- Initial security activation for ciphering and integrity protection
- Mobility control, also for inter-RAT handovers
- Quality of Service control
- Measurement configuration control

RRC is also responsible for lower layer configuration.

In the early deployment phase, LTE coverage will certainly be restricted to city and hot spot areas. In order to provide seamless service continuity, ensuring mobility between LTE and legacy technologies is therefore very important. These technologies include GSM/GPRS, WCDMA/HSPA, and CDMA2000 based technologies.

Figure 27 and *Figure 28* illustrate the mobility support between these technologies and LTE and indicate the procedures used to move between them. As a basic mechanism to prepare and execute the handovers, radio related information can be exchanged in transparent containers between the technologies.

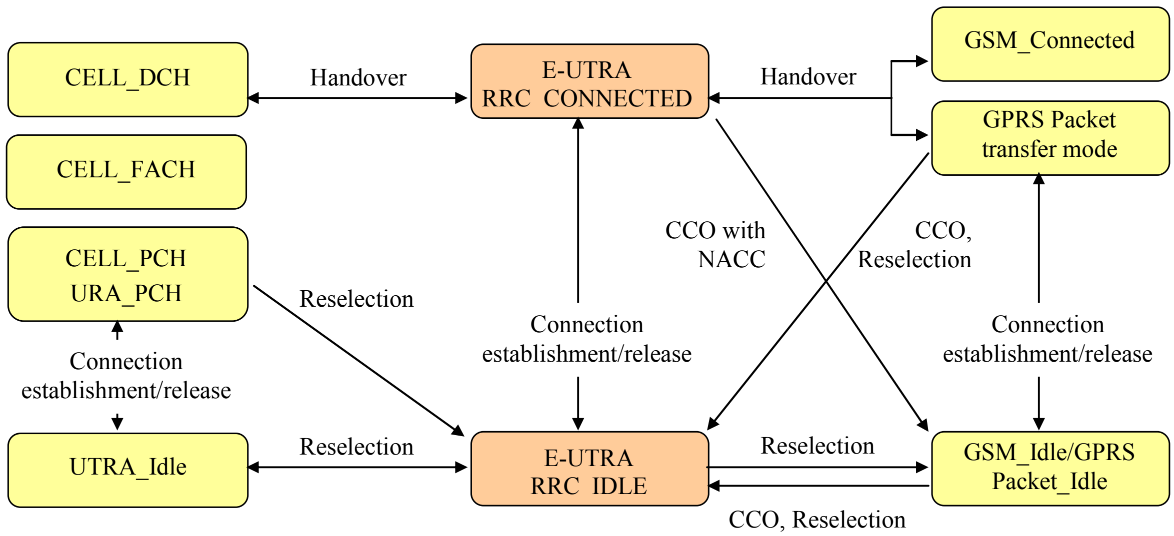


Figure 27 E-UTRA states and inter RAT mobility procedures [Ref. 9], CCO = Cell Change Order

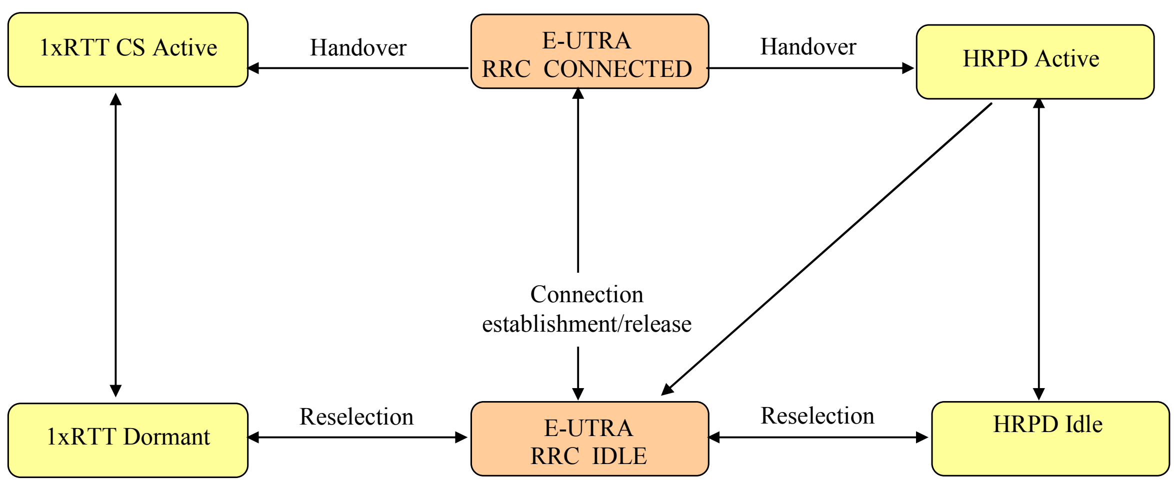


Figure 28 Mobility procedures between E-UTRA and CDMA2000 [Ref. 9], HRPD = High Rate Packet Data

RRC is responsible for configuring the lower layers. For example, *Table 11* lists physical layer elements that are configured by RRC messages. This shows that the physical layer parametrization can be optimized by RRC for specific applications and scenarios.

Table 11 Physical layer parameters configured by RRC (list not exhaustive)

Physical Layer Element	Configuration options by RRC
PDSCH	Power configuration, reference signal power
PHICH	Duration (short/long), parameter to derive number of PHICH groups
MIMO	Transmission mode, restriction of precoding codebook
CQI reporting	PUCCH resource, format, periodicity
Scheduling request	Resource and periodicity
PUSCH	Hopping mode (inter-subframe or intra- / inter-subframe), available sub-bands, power offsets for ACK/NACK, RI, CQI
PUCCH	Available resources, enabling simultaneous transmission of ACK/NACK and CQI
PRACH	Time/frequency resource configuration, available preambles, preamble configuration parameters, power ramping step size, initial target power, maximum number of preamble transmissions, response window size, contention resolution timer
Uplink demodulation reference signal	Group assignment, enabling of group hopping, enabling of group + sequence hopping
Uplink sounding reference signal	bandwidth configuration, subframe configuration, duration, periodicity, frequency domain position, cyclic shift, hopping information, simultaneous transmission of ACK/NACK and SRS
Uplink power control	UE specific power setting parameters, step size for PUCCH and PUSCH, accumulation enabled, index of TPC command for a given UE within DCI format 3/3a
TDD-specific parameters	DL/UL subframe configuration, special subframe configuration

Layer 2 structure

Figure 29 and *Figure 30* show the downlink and uplink structure of layer 2. The service access points between the physical layer and the MAC sublayer provide the transport channels. The service access points between the MAC sublayer and the RLC sublayer provide the logical channels. Radio bearers are defined on top of PDCP layer. Multiplexing of several logical channels on the same transport channel is possible.

E-UTRAN provides ARQ and HARQ functionalities. The ARQ functionality provides error correction by retransmissions in acknowledged mode at layer 2. The HARQ functionality ensures delivery between peer entities at layer 1. The HARQ is an N-channel stop-and-wait protocol with asynchronous downlink retransmissions and synchronous uplink retransmissions. ARQ retransmissions are based on RLC status reports and HARQ/ARQ interaction.

Security functions ciphering and integrity protection are located in PDCP protocol.

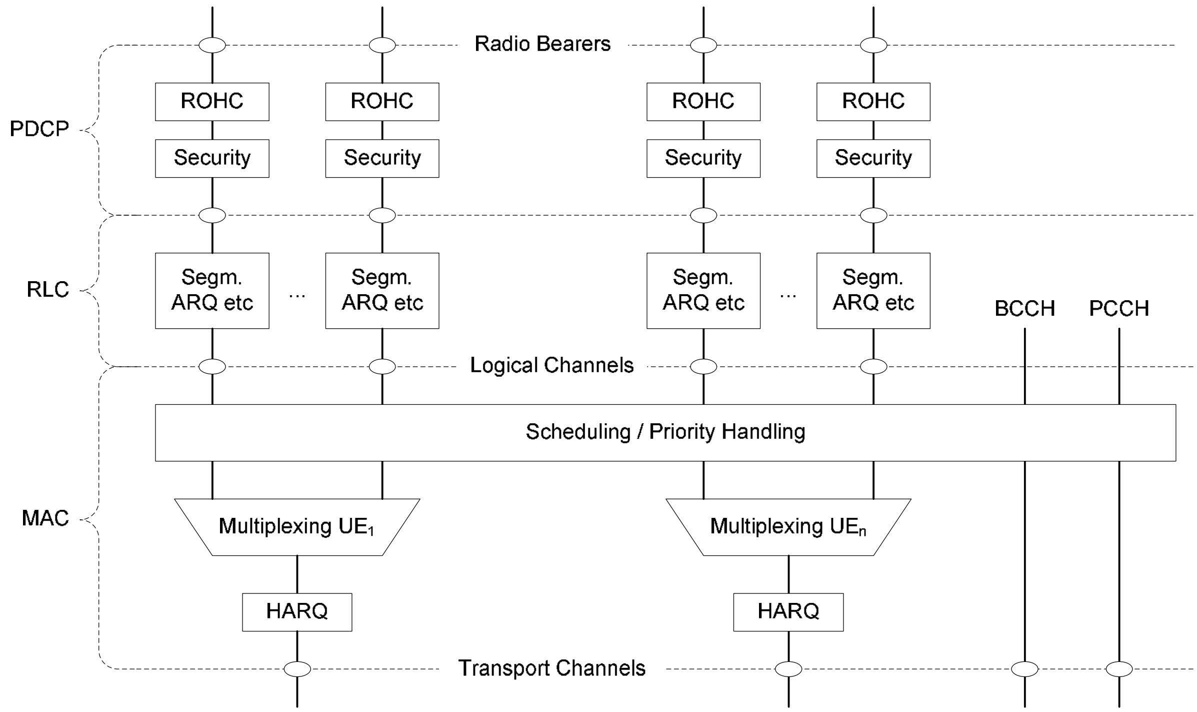


Figure 29 Downlink layer 2 structure [Ref. 7]

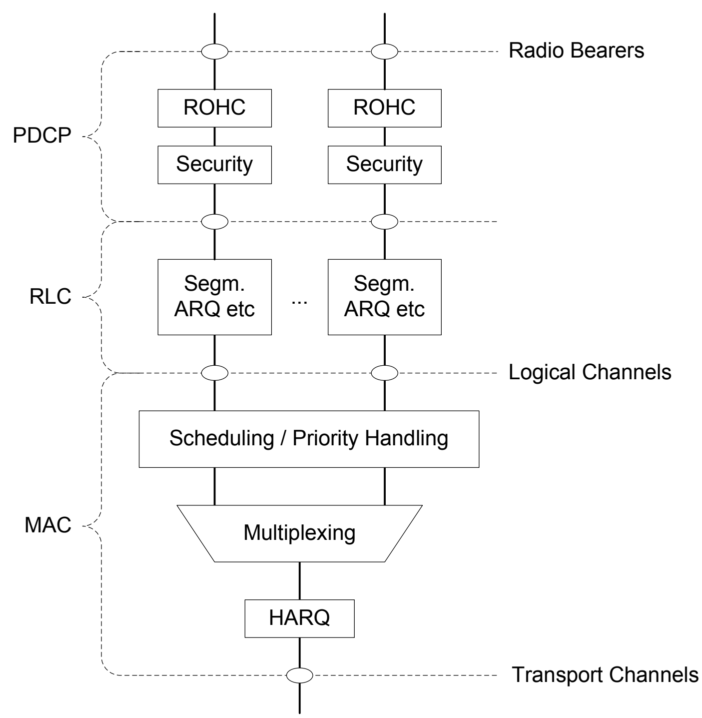


Figure 30 Uplink layer 2 structure [Ref. 7]

Transport channels

In order to reduce complexity of the LTE protocol architecture, the number of transport channels has been reduced. This is mainly due to the focus on shared channel operation, i.e. no dedicated channels are used any more. Downlink transport channels are:

- Broadcast Channel (BCH)
- Downlink Shared Channel (DL-SCH)
- Paging Channel (PCH)

Uplink transport channels are:

- Uplink Shared Channel (UL-SCH)
- Random Access Channel (RACH)

Logical channels

Logical channels can be classified in control and traffic channels.

Control channels are:

- Broadcast Control Channel (BCCH)
- Paging Control Channel (PCCH)
- Common Control Channel (CCCH)
- Dedicated Control Channel (DCCH)

Traffic channels are:

- Dedicated Traffic Channel (DTCH)

Mapping between logical and transport channels in downlink and uplink is shown in the following figures.

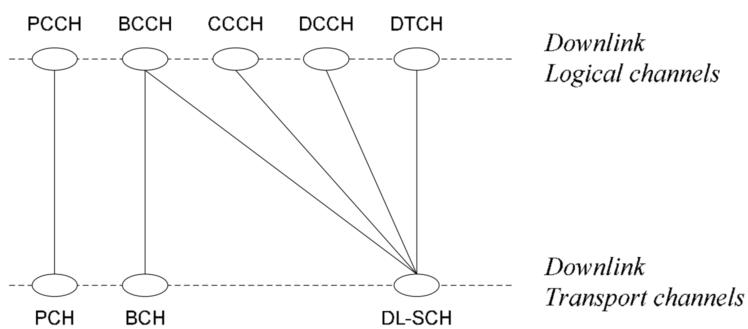


Figure 31 Mapping between DL logical and transport channels [Ref. 10]

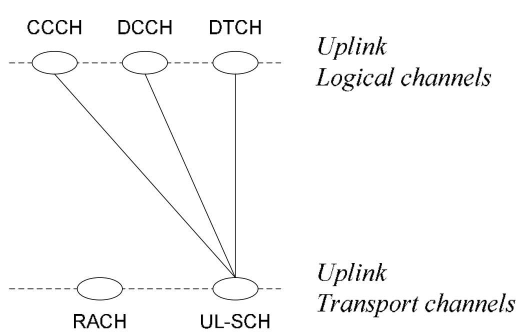


Figure 32 Mapping between UL logical and transport channels [Ref. 10]

Transport block structure (MAC Protocol Data Unit (PDU))

The structure of the MAC PDU has to take into account the LTE multiplexing options and the requirements of functions like scheduling, timing alignment, etc.

A MAC PDU for DL-SCH or UL-SCH consists of a MAC header, zero or more MAC Service Data Units (SDU), zero or more MAC control elements, and optionally padding, see *Figure 33*.

In case of MIMO spatial multiplexing, up to two transport blocks can be transmitted per transmission time interval per UE.

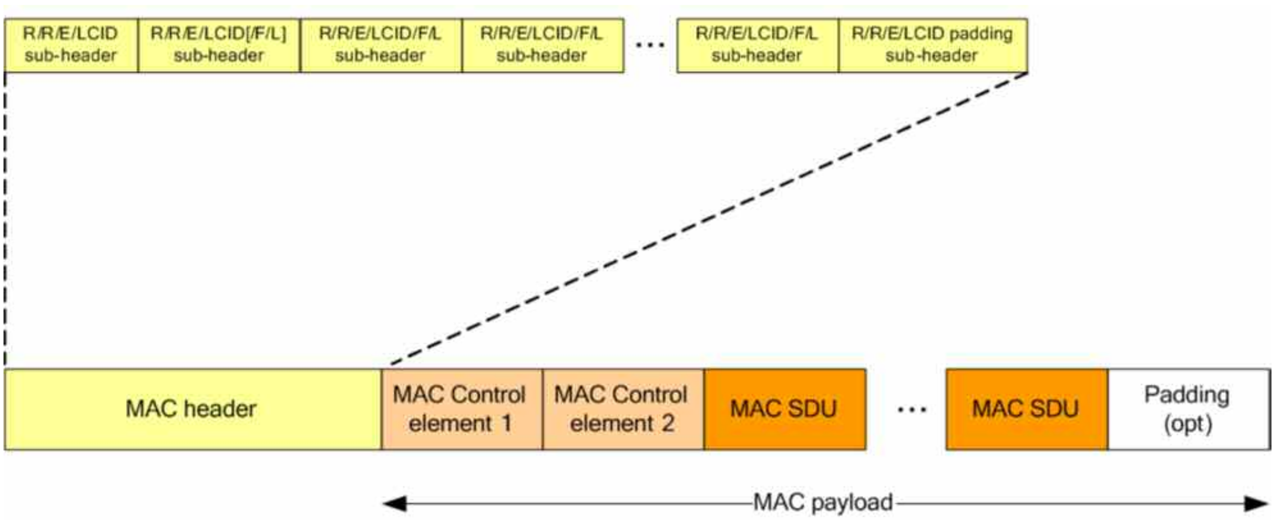


Figure 33 Structure of MAC PDU [Ref. 10]

The MAC header may consist of multiple sub-headers. Each sub-header corresponds to a MAC control element, a MAC SDU, or padding, and provides more information on the respective field in terms of contents and length. MAC SDUs can belong to different logical channels (indicated by the LCID / logical channel identifier field in the sub-header), so that multiplexing of logical channels is possible.

The following MAC control elements are specified which are identified by the LCID field in the MAC sub-header:

- Buffer status
- C-RNTI (Cell Radio Network Temporary Identifier)
- DRX command
- UE contention resolution identity: used during random access as a means to resolve contention, see description to *Figure 18*
- Timing advance: indicates the amount of timing adjustment in 0.5 µs that the UE has to apply in uplink
- Power headroom.

7 UE capabilities

Depending on the data rate and MIMO capabilities, different UE categories are defined [Ref. 11]. The categories for downlink and uplink are shown in *Table 12* and *Table 13*, respectively. Please note that the maximum data rates are to be understood as theoretical peak values and are not expected to be achieved in realistic network conditions.

Table 12 Downlink UE categories [Ref. 11]

UE Category	Maximum number of DL-SCH transport block bits received within a TTI	Maximum number of bits of a DL-SCH transport block received within a TTI	Total number of soft channel bits	Maximum number of supported layers for spatial multiplexing in DL	Maximum downlink data rate
Category 1	10296	10296	250368	1	10 Mbps
Category 2	51024	51024	1237248	2	51 Mbps
Category 3	102048	75376	1237248	2	102 Mbps
Category 4	150752	75376	1827072	2	151 Mbps
Category 5	302752	151376	3667200	4	303 Mbps

Table 13 Uplink UE categories [Ref. 11]

UE Category	Maximum number of bits of an UL-SCH transport block transmitted within a TTI	Support for 64QAM in UL	Maximum uplink data rate
Category 1	5160	No	5 Mbps
Category 2	25456	No	25 Mbps
Category 3	51024	No	51 Mbps
Category 4	51024	No	51 Mbps
Category 5	75376	Yes	75 Mbps

Additionally, different values of layer 2 buffer size are associated with each UE category.

Independent from the UE category, the following features are defined as UE capabilities in [Ref. 11]:

- Supported Robust Header Compression (ROHC) profiles
- Support of uplink transmit diversity
- Support of UE specific reference signals for FDD
- Need for measurement gaps
- Support of radio access technologies and radio frequency bands

8 LTE Testing

LTE RF testing

This section highlights aspects of testing base station and terminal transmitter and receiver parts and RF components for LTE.

First of all, LTE signal characteristics need to be investigated. While for LTE downlink, developers can leverage from OFDMA expertise gained with technologies like WiMAX and WLAN, this is not so straightforward for the uplink. SC-FDMA technology used in LTE uplink is not known from other standards yet. Thus, uplink signal characteristics need to be investigated with particular caution.

General settings

The following parameters primarily characterize the LTE signal:

- Frequency
- Bandwidth / number of resource blocks of the LTE signal
- FDD or TDD mode
- Antenna configuration
- Cyclic prefix length
- Allocation of user data and modulation/coding schemes
- Configuration of L1/2 control channels
- MIMO schemes and precoding

LTE signal generation

For generating an LTE signal, signal generators **SMU200A**, **SMJ100A** or **SMATE200A** are available. Software option SMx-K55 (*Digital Standard LTE/EUTRA*) provides LTE functionality on these signal generators. Alternatively, simulation software **WinIQSIM2** running on a PC can be used to generate waveforms for digitally modulated signals which can be uploaded on the above-mentioned signal generators. This requires software option SMU-K255 or SMJ-K255. WinIQSIM2 is also available for the IQ modulation generator **AFQ100A/B** with software option AFQ-K255. The **AMU200A** baseband signal generator and fading simulator supports LTE with software option AMU-K55 or AMU-K255.

Figure 34 shows the OFDMA time plan used to illustrate the resource allocation within the LTE downlink signal configured by the user. In the example in *Figure 34*, a 1 ms subframe of a 10 MHz LTE downlink signal is shown. The x-axis represents OFDM symbols, the y-axis represents resource blocks. In this example, all available 50 resource blocks are allocated with user data of two different users. The reference symbols are located in the first and fifth OFDM symbol of each slot, and the L1/L2 control channel PDCCH (together with PCFICH and PHICH) occupies the first two OFDM symbols. Note that these settings are configurable to create an LTE signal individually. Since the first subframe of a radio frame is shown, also the primary and secondary synchronization signals and the Physical Broadcast Channel PBCH can be seen.

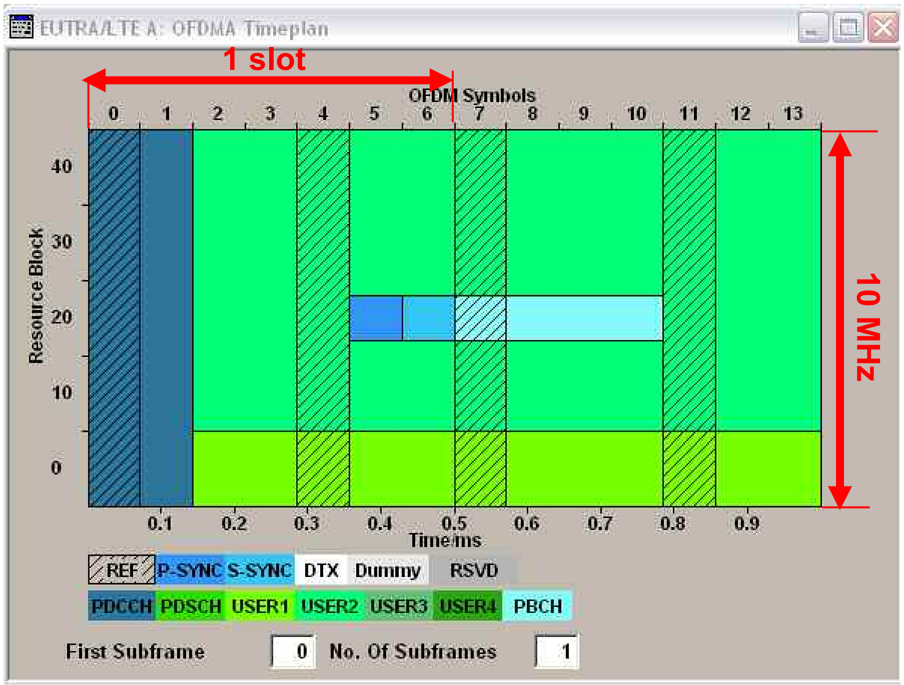


Figure 34 OFDMA time plan for LTE signal generation, 1 subframe

Another example of the OFDMA time plan is shown in *Figure 35*. Here, an excerpt of 10 subframes is shown, highlighting the repetition interval of the synchronization signals in subframes 0 and 5. In this example, the allocation with user data varies over time, e.g. to simulate an arbitrary scheduling scenario.

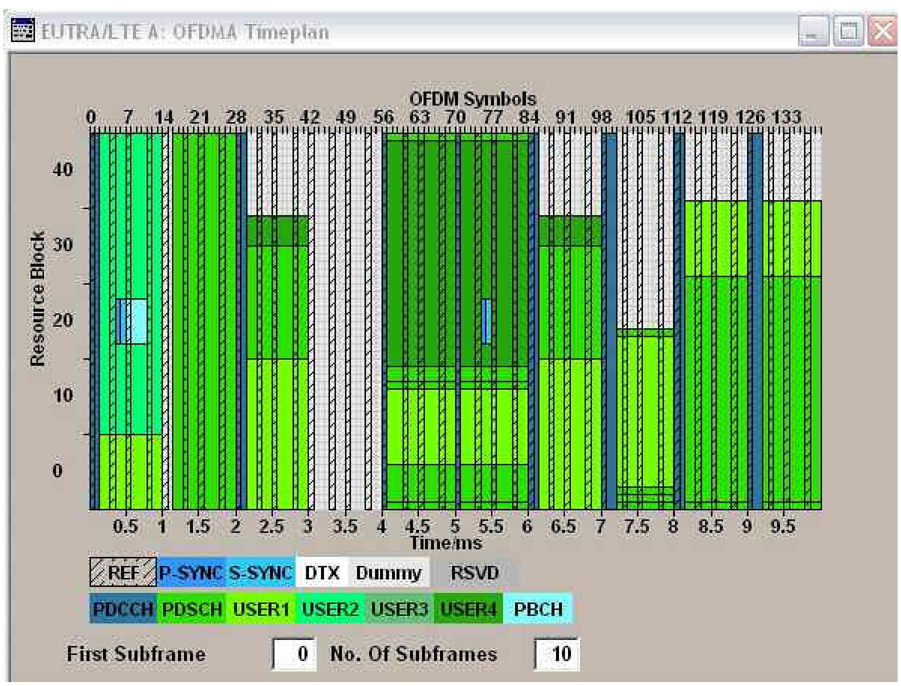


Figure 35 OFDMA time plan for LTE signal generation, 10 subframes

Besides first SISO tests, MIMO test setups are of high importance. Both signal generators **SMU200A** and **AMU200A** provide a comprehensive and easy-to-use 2x2 MIMO setup in one box. They provide the generation of the signals from two transmit antennas as well as fully 3GPP compliant propagation channel simulation. An example setup for 2x2 MIMO receiver tests is shown in Figure 36

Figure 36 *Downlink MIMO receiver test: Signal generator SMU200A provides LTE downlink signals from two transmit antennas including channel simulation*

Figure 37 shows the user interface of the **SMU200A** for this setup in more detail.

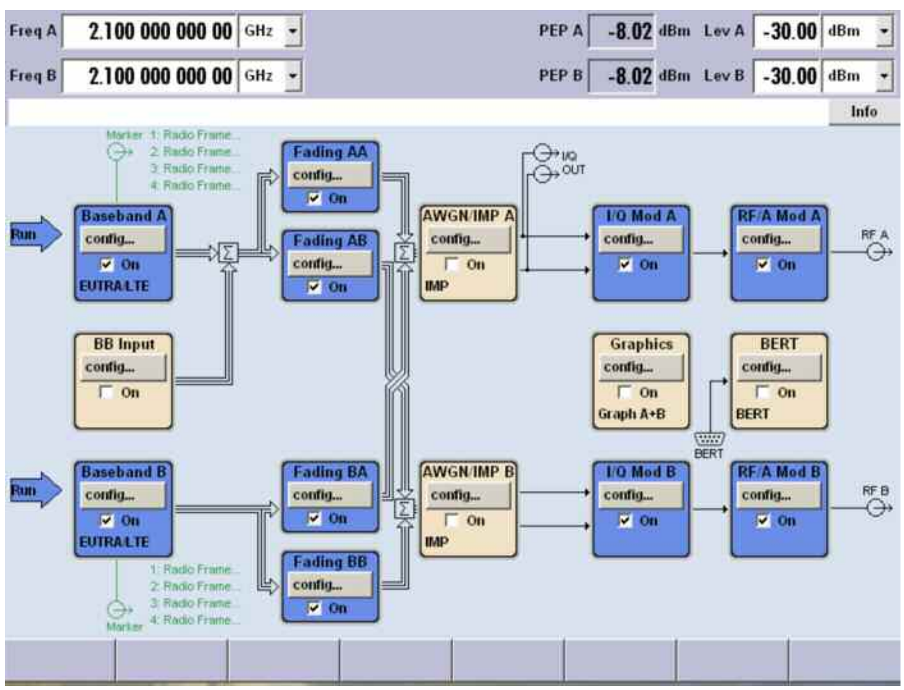


Figure 37 *User interface of the SMU200A signal generator for 2x2 MIMO tests: The signal flow is shown from the generation of the two baseband LTE signals on the left via the four fading channels to the two RF outputs on the right.*

The user can select the MIMO mode for the generation of the transmit antenna signals. Transmit diversity, cyclic delay diversity, and spatial multiplexing can be selected and configured. By use of a second signal generator, an extension to a 4x2 MIMO scenario is easily possible.

The MIMO fading capability is provided with software option SMU-K74 (*2x2 MIMO Fading*) for **SMU200A**, and with AMU-K74 for **AMU200A**, respectively. Four baseband fading simulators are providing the fading characteristics for the channels between each transmit and each receive antenna. Correlation properties can be set individually. For full flexibility, it is possible to specify the full $(N_t N_r)x(N_t N_r)$ correlation matrix according to the number of transmit antennas N_t and the number of receive antennas N_r for each multipath component. The faded signals are then summed up correctly before RF conversion and provided to the two RF outputs which can be connected to the dual antenna terminal.

LTE signal analysis

For analyzing the RF characteristics of an LTE signal, the high end spectrum and signal analyzers **FSQ** or **FSG** or the mid-range signal analyzer **FSV** can be used. Software options FSQ-K100 / FSV-K100 (*Application firmware 3GPP LTE/EUTRA downlink)* and FSQ-K101/ FSV-K101 (*Application firmware 3GPP LTE/EUTRA uplink*) are needed for LTE signal analysis.

Various measurement applications are offered: modulation quality, Error Vector Magnitude (EVM), constellation diagram, spectrum measurements, CCDF measurements, frequency error. For example, *Figure 38* shows the measurement of EVM versus carrier of an LTE downlink FDD signal. Alternatively, EVM can be measured versus symbol. The upper part of *Figure 38* shows the capture buffer over the selected time interval of 10 ms.

EVM analysis is of special interest for LTE. Due to the higher order modulation schemes up to 64QAM, stringent EVM requirements for the transmitter side apply in order to prevent a decrease in throughput.

Figure 38 Measurement of EVM versus carrier

CCDF and crest factor are important measurements for power amplifier design. *Figure 39* shows the CCDF measurement of an LTE downlink signal.

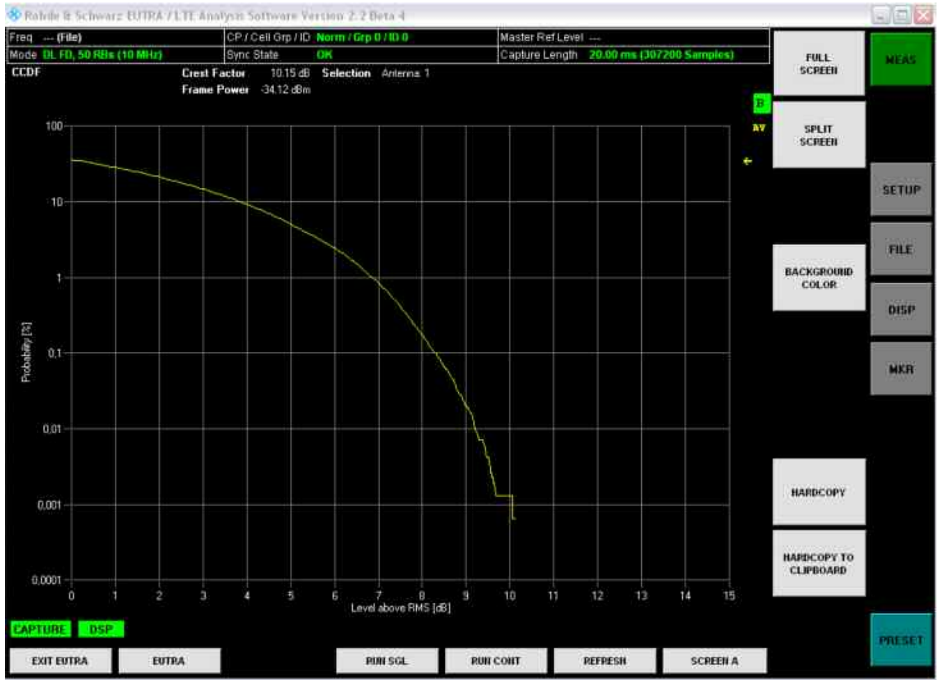


Figure 39 CCDF measurement

Figure 40 shows the constellation diagram of an LTE uplink signal where the user data is using 16QAM modulation. The constellation points on the circle represent the demodulation reference signal which is based on a Zadoff-Chu type of sequence.

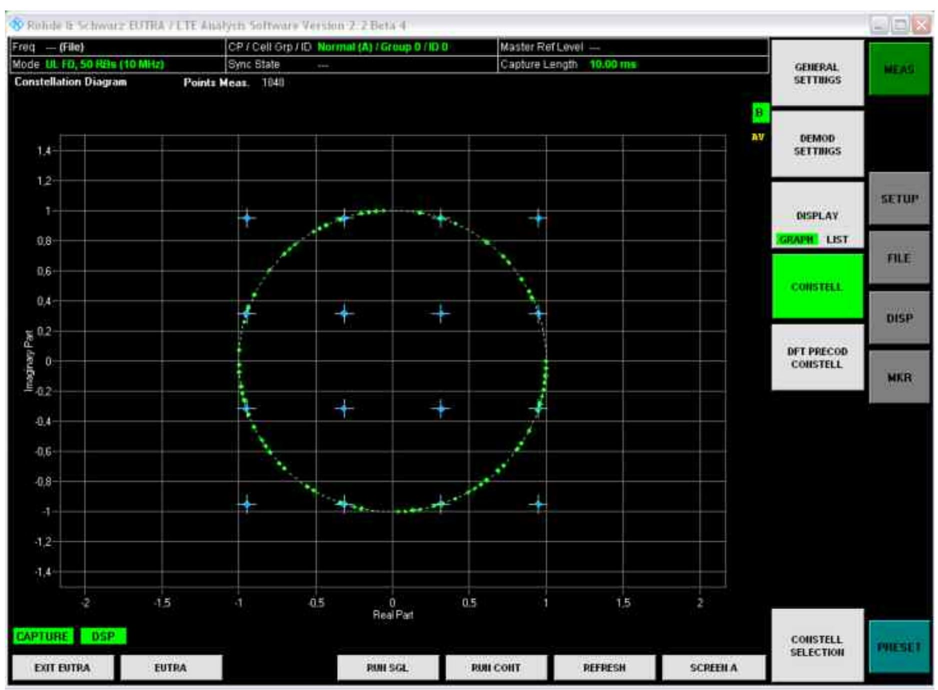


Figure 40 Uplink constellation diagram

Analysis of precoded LTE MIMO signals from two or four transmit antennas is possible when using two or four signal analyzers, respectively. Software option FSQ-K102 (*EUTRA/LTE Downlink, MIMO*) enables this functionality. By reverting the precoding applied to the MIMO signal, each transmitted stream can be analyzed separately.

Complex RF testing scenarios and advanced regression testing and automation needs are addressed by an RF test system. *Figure 41* shows the **TS8980 RF test system for R&D** which addresses early use cases for LTE RF terminal development. The system provides a clear upgrade path to a full RF conformance test system.

Figure 41 RF test system TS8980

LTE layer 1 and protocol test

LTE layer 1 has significant functionality. This includes layer 1 procedures like cell search, Hybrid ARQ retransmission protocol, scheduling, link adaptation, uplink timing control and power control. Furthermore, these procedures have stringent timing requirements. Therefore thorough testing of layer 1 procedures is needed to guarantee LTE performance.

LTE protocol stack testing is needed to verify signaling functionality like call setup and release, call reconfigurations, state handling, and mobility. Interworking with 2G and 3G systems such as GSM/EDGE, WCDMA/HSPA, and CDMA2000® 1xRTT/1x-EV-DO[1] is a requirement for LTE and needs to be tested carefully. A special focus is put on verification of throughput requirements in order to make sure that the terminal protocol stack and applications are capable of handling high data rates. Flexible test scenarios with individual parametrization possibilities are needed for R&D purposes already at a very early stage of LTE implementation.

The **CMW500 Wideband Radio Communication Tester** is a universal platform for all stages of LTE terminal testing from layer 1 up to protocol, and from early R&D up to conformance and manufacturing.

[1] CDMA2000® is a registered trademark of the Telecommunications Industry Association (TIA-USA).

Figure 42 CMW500 Wideband Radio Communication Tester

The **CMW500** supports all LTE frequency bands and all LTE bandwidths up to 20 MHz. Connection to the device under test is possible via RF interface or digital IQ interface. Protocol tests and verification of throughput under realistic propagation conditions is possible by connecting the **AMU200A** fading simulator to the **CMW500**.

By means of a virtual tester solution, host based protocol stack testing is supported as well. This is a purely software based test solution that does not require a layer 1 implementation at the UE side. Thus, the layer 2/3 protocol stack software of the device under test can be verified thoroughly before integration.

Powerful programming interfaces are available for both the virtual tester solution and the **CMW500**-hardware based solution. For R&D testing, highly flexible C/C++ based programming interfaces are available for creation of user-defined test scenarios. A comfortable tool chain allows easy execution, adaptation and analysis of scenarios. *Figure 43* shows the Message Composer for editing messages used by the test scenario in an intuitive graphical environment.

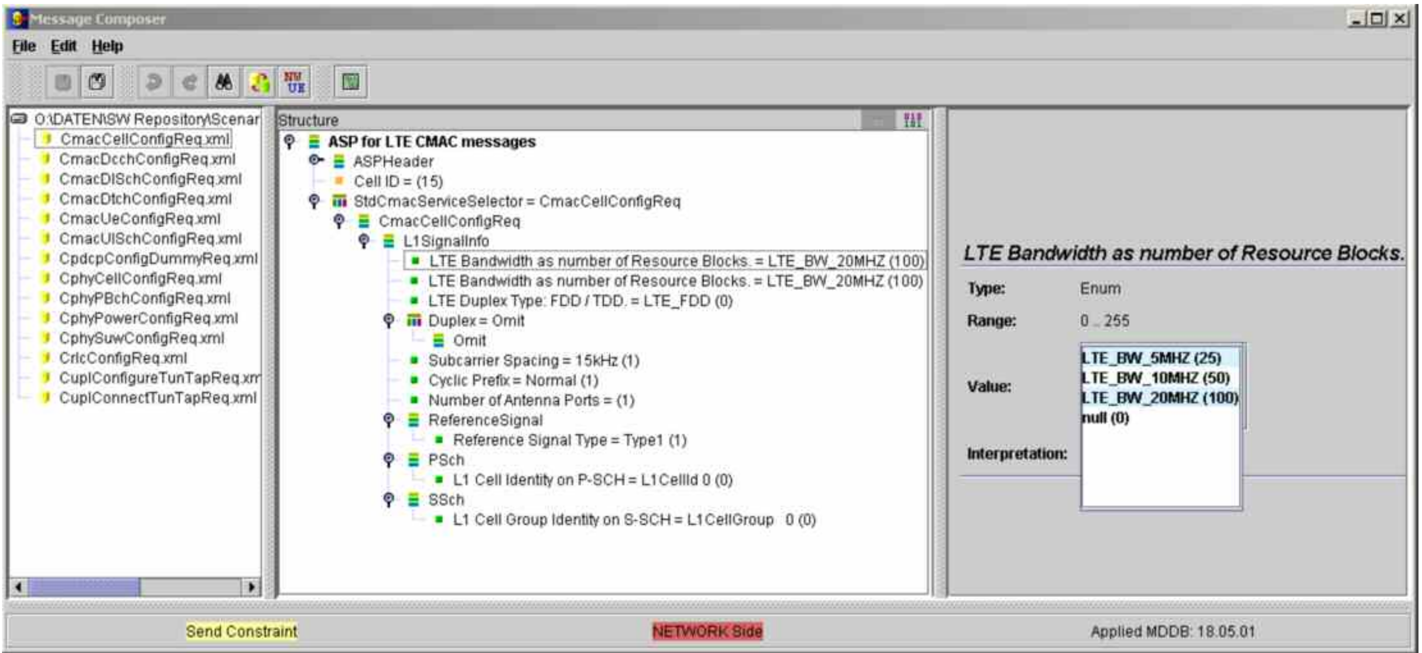


Figure 43 Message composer for editing messages used by a test scenario

For conformance testing, a TTCN-3 (Testing and Test Control Notation Version 3) based environment is used according to 3GPP specifications.

9 Abbreviations

3GPP	3rd Generation Partnership Project
ACK	Acknowledgement
ARQ	Automatic Repeat Request
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
CAPEX	Capital Expenditures
CCCH	Common Control Channel
CCDF	Complementary Cumulative Density Function
CCO	Cell Change Order
CDD	Cyclic Delay Diversity
CP	Cyclic Prefix
C-plane	Control Plane
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
C-RNTI	Cell Radio Network Temporary Identifier
CS	Circuit Switched
DCCH	Dedicated Control Channel
DCI	Downlink Control Information

DFT	Discrete Fourier Transform
DL	Downlink
DL-SCH	Downlink Shared Channel
DRS	Demodulation Reference Signal
DRX	Discontinuous Reception
DTCH	Dedicated Traffic Channel
DTX	Discontinuous Transmission
DVB	Digital Video Broadcast
DwPTS	Downlink Pilot Timeslot
eNB	E-UTRAN NodeB
EDGE	Enhanced Data Rates for GSM Evolution
EPC	Evolved Packet Core
E-UTRA	Evolved UMTS Terrestrial Radio Access
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
GERAN	GSM EDGE Radio Access Network
GP	Guard Period
GSM	Global System for Mobile communication
HARQ	Hybrid Automatic Repeat Request
HRPD	High Rate Packet Data
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
IFFT	Inverse Fast Fourier Transformation
IP	Internet Protocol
LCID	Logical channel identifier
LTE	Long Term Evolution
MAC	Medium Access Control
MBMS	Multimedia Broadcast Multicast Service
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MU-MIMO	Multi User MIMO
NACK	Negative Acknowledgement
NAS	Non Access Stratum
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditures

PAPR	Peak-to-Average Power Ratio
PBCH	Physical Broadcast Channel
PCCH	Paging Control Channel
PCFICH	Physical Control Format Indicator Channel
PCH	Paging Channel
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
PHICH	Physical Hybrid ARQ Indicator Channel
P-GW	PDN Gateway
PHY	Physical Layer
PMI	Precoding Matrix Indicator
PS	Packet Switched
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RACH	Random Access Channel
RAN	Radio Access Network
RA-RNTI	Random Access Radio Network Temporary Identifier
RAT	Radio Access Technology
RB	Radio Bearer
RF	Radio Frequency
RI	Rank Indicator
RIV	Resource Indication Value
RLC	Radio Link Control
ROHC	Robust Header Compression
RRC	Radio Resource Control
RRM	Radio Resource Management
RTT	Radio Transmission Technology
S1	Interface between eNB and EPC
SAE	System Architecture Evolution
SC-FDMA	Single Carrier – Frequency Division Multiple Access
SDMA	Spatial Division Multiple Access
SDU	Service Data Unit

SFBC	Space Frequency Block Coding
SISO	Single Input Single Output
S-GW	Serving Gateway
SR	Scheduling Request
SRS	Sounding Reference Signal
SU-MIMO	Single User MIMO
TDD	Time Division Duplex
TD-SCDMA	Time Division-Synchronous Code Division Multiple Access
TPC	Transmit Power Control
TS	Technical Specification
TTI	Transmission Time Interval
UCI	Uplink Control Information
UE	User Equipment
UL	Uplink
UL-SCH	Uplink Shared Channel
UMTS	Universal Mobile Telecommunications System
U-plane	User plane
UpPTS	Uplink Pilot Timeslot
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
VoIP	Voice over IP
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network
X2	Interface between eNBs

10 Additional Information

This application note is updated from time to time. Please visit the website **1MA111** to download the latest version.

Please send any comments or suggestions about this application note to **TM-Applications@rsd.rohde-schwarz.com**.

11 References

[Ref. 1] 3GPP TS 25.913; Requirements for E-UTRA and E-UTRAN (Release 7)

[Ref. 2] 3GPP TR 25.892; Feasibility Study for Orthogonal Frequency Division Multiplexing (OFDM) for UTRAN enhancement (Release 6)

[Ref. 3] 3GPP TS 36.211; Physical Channels and Modulation (Release 8)

[Ref. 4] 3GPP TS 36.101; User Equipment (UE) radio transmission and reception (Release 8)

[Ref. 5] 3GPP TS 36.212; Multiplexing and Channel Coding (Release 8)

[Ref. 6] 3GPP TS 36.213; Physical Layer Procedures (Release 8)

[Ref. 7] 3GPP TS 36.300; E-UTRA and E-UTRAN; Overall Description; Stage 2 (Release 8)

[Ref. 8] S.M. Alamouti (October 1998). "A simple transmit diversity technique for wireless communications", IEEE Journal on Selected Areas in Communications, Vol. 16., No. 8

[Ref. 9] 3GPP TS 36.331; Radio Resource Control (RRC) specification (Release 8)

[Ref. 10] 3GPP TS 36.321; Medium Access Control (MAC) protocol specification (Release 8)

[Ref. 11] 3GPP TS 36.306; User Equipment (UE) radio access capabilities (Release 8)

12 Ordering Information

Vector Signal Generator

R&S® SMU200A		1141.2005.02
R&S® SMU-B102	Frequency range 100 KHz to 2.2GHz for 1st RF Path	1141.8503.02
R&S® SMU-B103	Frequency range 100 KHz to 3GHz for 1st RF Path	1141.8603.02
R&S® SMU-B104	Frequency range 100 KHz to 4GHz for 1st RF Path	1141.8703.02
R&S® SMU-B106	Frequency range 100 KHz to 6 GHz for 1st RF Path	1141.8803.02
R&S® SMU-B202	Frequency range 100 KHz to 2.2 GHz for 2nd RF Path	1141.9400.02
R&S® SMU-B203	Frequency range 100 KHz to 3 GHz for 2nd RF Path	1141.9500.02
R&S® SMU-B9	Baseband Generator with digital modulation (realtime) and ARB (128 M Samples)	1161.0766.02
R&S® SMU-B10	Baseband Generator with digital modulation (realtime) and ARB (64MSamples)	1141.7007.02
R&S® SMU-B11	Baseband Generator with digital modulation (realtime) and ARB (16MSamples)	1159.8411.02
R&S® SMU-B13	Baseband Main Module	1141.8003.02
R&S® SMU-K55	Digital Standard 3GPP LTE/EUTRA	1408.7310.02
R&S® SMU-K255	Digital Standard 3GPP LTE/EUTRA for WinIQSIM2	1408.7362.02
R&S® SMU-B14	Fading simulator	1160.1800.02
R&S® SMU-B15	Fading simulator extension	1160.2288.02
R&S® SMU-K74	2x2 MIMO Fading	1408.7762.02
R&S® SMJ100A		1403.4507.02
R&S® SMJ-B103	Frequency range 100 kHz - 3 GHz	1403.8502.02
R&S® SMJ-B106	Frequency range 100 kHz - 6 GHz	1403.8702.02
R&S® SMJ-B9	Baseband generator with digital modulation (realtime) and ARB (128 M Samples)	1404.1501.02
R&S® SMJ-B10	Baseband Generator with digital modulation	1403.8902.02

	(realtime) and ARB (64MSamples)	
R&S® SMJ-B11	Baseband Generator with digital modulation (realtime) and ARB (16MSamples)	1403.9009.02
R&S® SMJ-B13	Baseband Main Module	1403.9109.02
R&S® SMJ-K55	Digital Standard 3GPP LTE/EUTRA	1409.2206.02
R&S® SMJ-K255	Digital standard 3GPP LTE/EUTRA for WinIQSIM2	1409.2258.02
R&S® SMATE200A		1400.7005.02
R&S® SMATE-B103	Frequency range 100 KHz to 3 GHz for 1st RF Path	1401.1000.02
R&S® SMATE-B106	Frequency range 100 KHz to 6 GHz for 1st RF Path	1401.1200.02
R&S® SMATE-B203	Frequency range 100 KHz to 3 GHz for 2nd RF Path	1401.1400.02
R&S® SMATE-B206	Frequency range 100 kHz - 6 GHz for 2nd RF path	1401.1600.02
R&S® SMATE-B9	Baseband Generator with digital modulation (real time) and ARB (128 M samples)	1404.7500.02
R&S® SMATE-B10	Baseband Generator with digital modulation (realtime) and ARB (64MSamples)	1401.2707.02
R&S® SMATE-B11	Baseband Generator with digital modulation (realtime) and ARB (16MSamples)	1401.2807.02
R&S® SMATE-B13	Baseband Main Module	1401.2907.02
R&S® SMATE-K55	Digital Standard 3GPP LTE/EUTRA	1404.7851.02
R&S® AMU200A	Baseband signal generator, base unit	1402.4090.02
R&S® AMU-B9	Baseband generator with digital modulation (realtime) and ARB (128 MSamples)	1402.8809.02
R&S® AMU-B10	Baseband generator with dig. modulation (realtime) and ARB (64 MSamples)	1402.5300.02
R&S® AMU-B11	Baseband generator with dig. modulation (realtime) and ARB (16 MSamples)	1402.5400.02
R&S® AMU-B13	Baseband main module	1402.5500.02
R&S® AMU-K55	Digital Standard LTE/EUTRA	1402.9405.02
R&S® AMU-K255	Digital Standard LTE/EUTRA for WInIQSIM2	1402.9457.02
R&S® AMU-B14	Fading Simulator	1402.5600.02
R&S® AMU-B15	Fading Simulator extension	1402.5700.02
R&S® AMU-K74	2x2 MIMO Fading	1402.9857.02
R&S® AFQ100A	IQ modulation generator base unit	1401.3003.02
R&S® AFQ-B10	Waveform memory 256 Msamples	1401.5106.02
R&S® AFQ-B11	Waveform memory 1Gsamples	1401.5206.02
R&S® AFQ-K255	Digital Standard LTE/EUTRA, WinIQSIM 2 required	1401.5906.02

Signal Analyzer

R&S® FSQ3	20 Hz to 3.6 GHz	1155.5001.03
R&S® FSQ8	20 Hz to 8 GHz	1155.5001.08

R&S® FSQ26	20 Hz to 26.5 GHz	1155.5001.26
R&S® FSQ40	20 Hz to 40 GHz	1155.5001.40
R&S® FSG8	9 kHz to 8 GHz	1309.0002.08
R&S® FSG13	9 kHz to 13.6 GHz	1309.0002.13
R&S® FSV3	9 kHz to 3.6 GHz	1307.9002.03
R&S® FSV7	9 kHz to 7 GHz	1307.9002.07
R&S® FSQ-K100	EUTRA/LTE Downlink / BS Analysis	1308.9006.02
R&S® FSV-K100	EUTRA/LTE Downlink / BS Analysis	1310.9051.02
R&S® FSQ-K101	EUTRA/LTE Uplink / UE Analysis	1308.9058.02
R&S® FSV-K101	EUTRA/LTE Uplink / UE Analysis	1310.9100.02
R&S® FSQ-K102	EUTRA/LTE Downlink, MIMO	1309.9000.02

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