UMTS Long Term Evolution (LTE) - Technology Introduction
Application Note

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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 - 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 related testing aspects.

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LTE Technology Introduction

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1 Introduction

Most of the UMTS networks worldwide have been already 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+** is a significant enhancement in 3GPP Release 7, 8, 9 and even 10. 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 Release 7 features of HSPA+ are downlink MIMO (Multiple Input Multiple Output), higher order modulation for uplink (16QAM) and downlink (64QAM), improvements of layer 2 protocols, and continuous packet connectivity. Generally spoken these features can be categorized in data-rate or capacity enhancement features versus web-browsing and power saving features. With higher Release 8, 9 and 10 capabilities like the combination of 64QAM and MIMO, up to four carrier operations for the downlink (w/o MIMO), and two carriers operation for the uplink are now possible. This increases downlink and uplink data rates up to theoretical peaks of 168 Mbps and 23 Mbps, respectively. In addition the support of circuit-switched services over HSPA (CS over HSPA) has been a focus for the standardization body in terms of improving HSPA+ functionality in Release 8. For further details and more information on HSPA+ please take a look at [Ref. 12].

However to ensure the competitiveness of UMTS for the next decade and beyond, concepts for **UMTS Long Term Evolution** (LTE) have been first time introduced in 3GPP Release 8. Objectives are higher data rates, lower latency on the user plane and control plane and a 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). Based on promising field trials, proving the concept of LTE as described in the following sections, real life LTE deployments significantly increased from the start of the first commercial network in end 2009. As LTE offers also a migration path for 3GPP2 standardized technologies (CDMA2000®1xRTT and 1xEV-DO) it can be seen as the true mobile broadband technology.

This application note focuses on LTE/E-UTRA technology. In the following, the terms LTE, E-UTRA or E-UTRAN 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 device capabilities.
- **Chapter 8** summarizes voice and SMS delivery via LTE
- **Chapter 9** explains test requirements for LTE.
- **Chapters 10 - 13** provide additional information including literature references.

For detailed information on LTE enhancements coming with 3GPP Release 9 please take a look at [Ref. 14]. An introduction to LTE-Advanced (3GPP Release 10) is provided in [Ref. 15].

2 Requirements for UMTS Long Term Evolution

LTE is focusing on an 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 in 2004 and have been captured in [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.

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

Spectrum Efficiency: Downlink target is 3-4 times better than 3GPP Release 6. Uplink target is 2-3 times better than 3GPP Release 6. The following table summarizes the data rate and spectrum efficiency requirements set for LTE.

Downlink (20 MHz)			Uplink (20 MHz)		
Unit	Mbps	bps/Hz	Unit	Mbps	bps/Hz
Requirement	100	5.0	Requirement	50	2.5
2x2 MIMO	172.8	8.6	16QAM	57.6	2.9
4x4 MIMO	326.4	16.3	64QAM	86.4	4.3

Table 1: Data rate and spectrum efficiency requirements defined for LTE

Latency: User plane latency. The one-way transit time between a packet being available at the IP layer in either the device or radio access network and the availability of this packet at IP layer in the radio access network/device shall be less than 30 ms. Test in a lab environment show that the time can be less than that [see Figure 1].

Control plane latency. Also C-plane, that means the time it takes to transfer the device from a passive connection with the network (IDLE state) to an active connection (CONNECTED state) shall be further reduced, e.g. less than 100 ms to allow fast transition times.

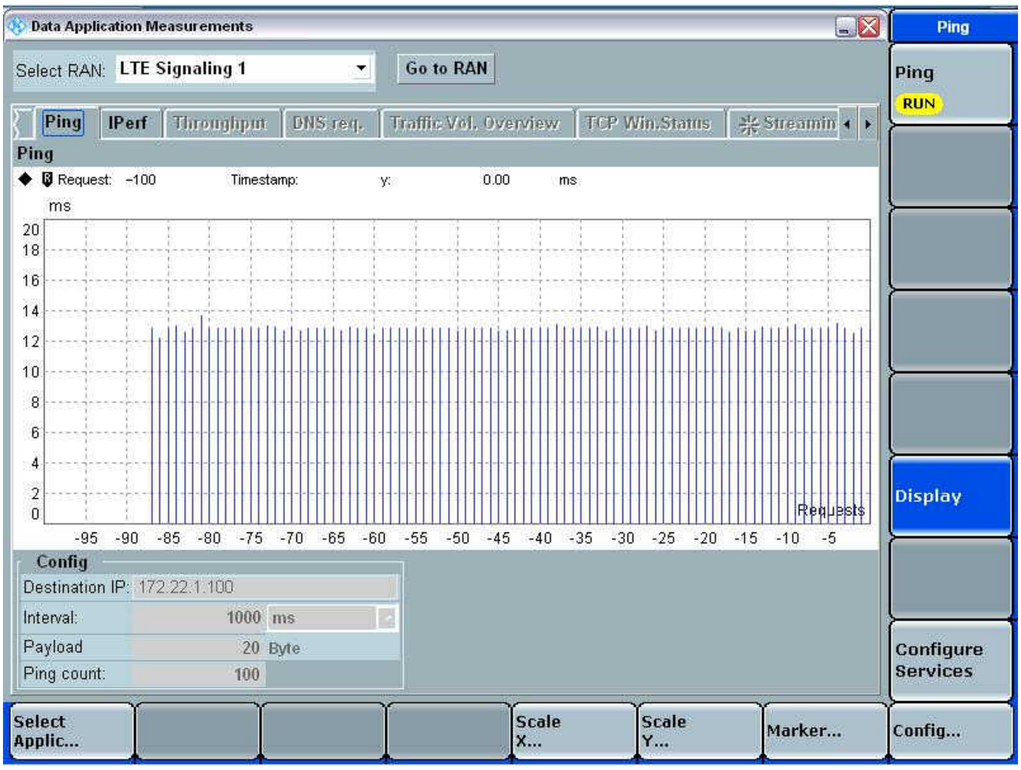


Figure 1: PING test (about 12 ms) using Data Application Unit (DAU) in R&S® CMW500 Wideband Radio Communication Tester while doing data end-to-end (E2E) testing for UMTS LTE (FDD)

Bandwidth: LTE supports a subset of bandwidths of 1.4, 3, 5, 10, 15 and 20 MHz.

Interworking: Interworking with existing UTRAN/GERAN systems and non-3GPP specified systems was 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 Enhanced-MBMS (E-MBMS). *Note: Physical layer aspects for E-MBMS have been taken into account already in 3GPP Release 8, where the support by higher layers has been largely moved to 3GPP Release 9.*

Costs: Reduced CAPEX and OPEX including backhaul shall be achieved. Cost effective migration from 3GPP 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. Voice over Internet Protocol (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

3.1 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 2 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 is added to each symbol to combat inter-symbol-interference (ISI) due to channels delay spread. The delay spread is the time between the symbol arriving on the first multi-path signal and the last multi-path signal component, typically several µs dependent on the environment (i.e. indoor, rural, suburban, city center). The guard interval has to be selected in that way, that it is greater than the maximum expected delay spread. In E-UTRA, the guard interval is a **cyclic prefix** which is inserted prior to each OFDM symbol.

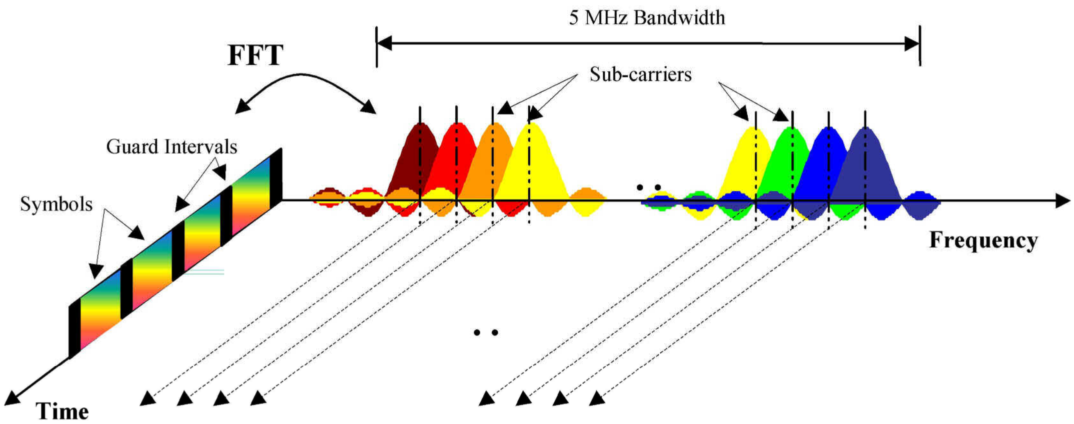


Figure 2: Frequency-time representation of an OFDM Signal [Ref. 2]

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 3 where $a(mN+n)$ refers to the n^{th} subcarrier modulated data symbol, during the time period $mT_u < t \leq (m+1)T_u$.

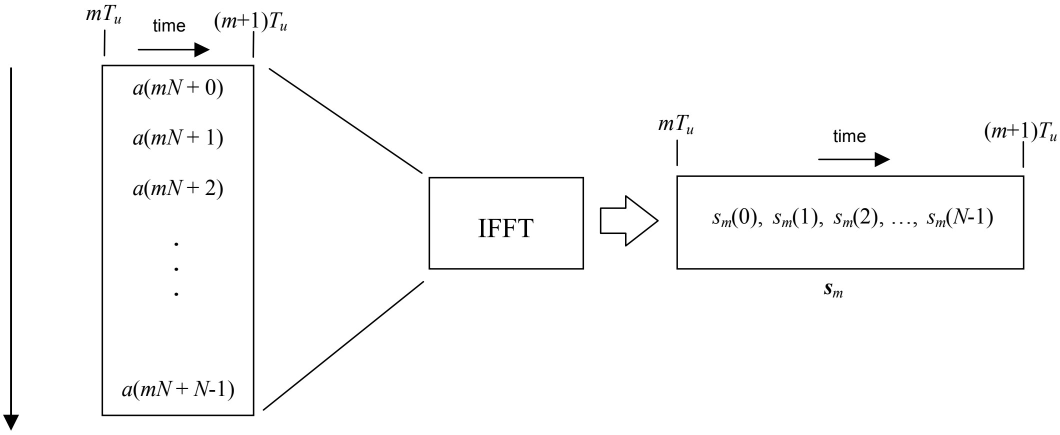


Figure 3: OFDM useful symbol generation using an IFFT [Ref. 2]

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 2).

Figure 4 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. The process of cyclic prefix insertion is not shown in Figure 4.

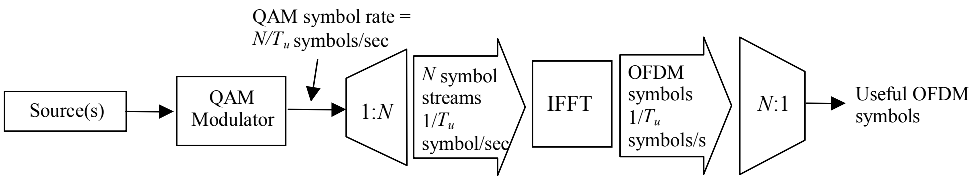


Figure 4: OFDM Signal Generation Chain [Ref. 2]

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 (TTI) of 1 ms, a new scheduling decision is taken regarding which users are assigned to which time/frequency resources during this TTI.

3.2 OFDMA parameterization

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 5.

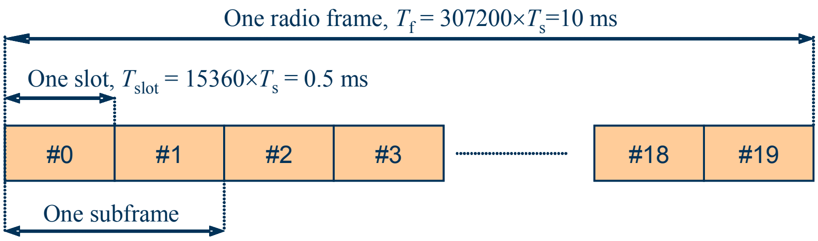


Figure 5: Frame structure type 1 [Ref. 3]

T_s (sampling time) is expressing the basic time unit for LTE, corresponding to a sampling frequency of 30.72 MHz. This sampling frequency is given due to the defined subcarrier spacing for LTE with Δf = 15 kHz and the maximum FFT size to generate the OFDM symbols of 2048[1]. Selecting these parameters ensures also simplified implementation of multi-standard devices, as this sampling frequency is a multiple of the chiprate defined for WCDMA (30.72 MHz / 8 = 3.84 Mcps) and CDMA2000®1xRTT (30.72 MHz / 25 = 1.2288 Mcps).

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 6 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.

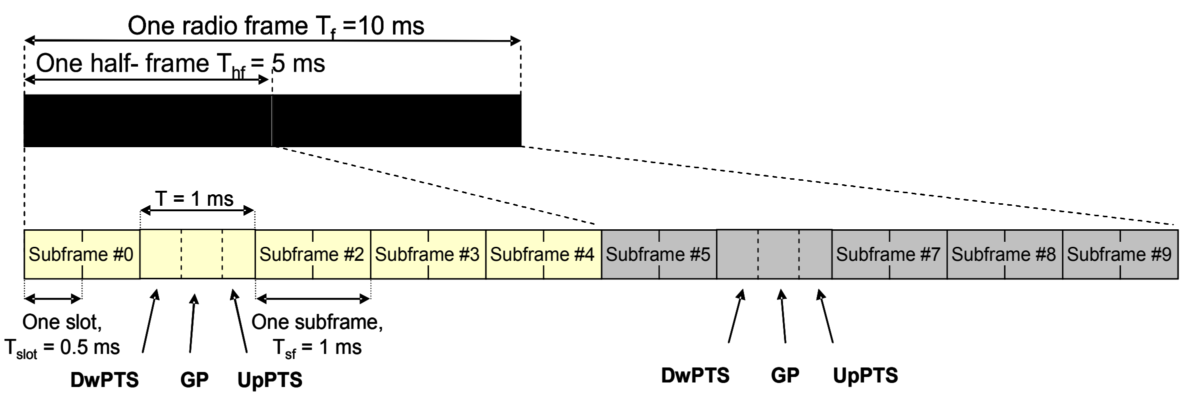


Figure 6: Frame structure type 2 (for 5 ms switch-point periodicity) [Ref. 3]

[1] f_S = 15 kHz * 2048 = 30.72 MHz = 1/T_S

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 2 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	10 ms	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]

There is always a special subframe when switching from DL to UL, which provides a guard period. Reason being is that all transmission in the UL from all the different UEs must arrive at the same time at the base station receiver. When switching from UL to DL only the base station is transmitting so there is no guard period needed. Beside UL-DL configuration there are also 9 special subframe configurations. These configurations are listed in [Ref. 3] and the length of the DwPTS, Guard Period (GP) and UpPTS is given in numbers of OFDM symbols. As it can be seen there are different lengths for GP, which is necessary to support different cell size, up to 100 km.

<table>
<tr><th rowspan="3">Special subframe config.</th><th colspan="4">Normal cyclic prefix in downlink</th><th colspan="4">Extended cyclic prefix in downlink</th></tr>
<tr><th rowspan="2">DwPTS</th><th rowspan="2">Guard Period</th><th colspan="2">UpPTS</th><th rowspan="2">DwPTS</th><th rowspan="2">Guard Period</th><th colspan="2">UpPTS</th></tr>
<tr><th>Normal cyclic prefix</th><th>Extended cyclic prefix</th><th>Normal cyclic prefix in uplink</th><th>Extended cyclic prefix in uplink</th></tr>
<tr><td>0</td><td>3</td><td>10</td><td rowspan="5">1</td><td rowspan="5">1</td><td>3</td><td>8</td><td rowspan="4">1</td><td rowspan="4">1</td></tr>
<tr><td>1</td><td>9</td><td>4</td><td>8</td><td>3</td></tr>
<tr><td>2</td><td>10</td><td>3</td><td>9</td><td>2</td></tr>
<tr><td>3</td><td>11</td><td>2</td><td>10</td><td>1</td></tr>
<tr><td>4</td><td>12</td><td>1</td><td>3</td><td>7</td><td rowspan="3">2</td><td rowspan="3">2</td></tr>
<tr><td>5</td><td>3</td><td>9</td><td rowspan="4">2</td><td rowspan="4">2</td><td>8</td><td>2</td></tr>
<tr><td>6</td><td>9</td><td>3</td><td>9</td><td>1</td></tr>
<tr><td>7</td><td>10</td><td>2</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>8</td><td>11</td><td>1</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Table 3: Special Subframe configurations in TD-LTE

It can be also extracted that downlink and uplink in TD-LTE can utilize different cyclic prefixes, which is different from LTE FDD. Figure 7 shows the structure of the downlink resource grid for both FDD and TDD.

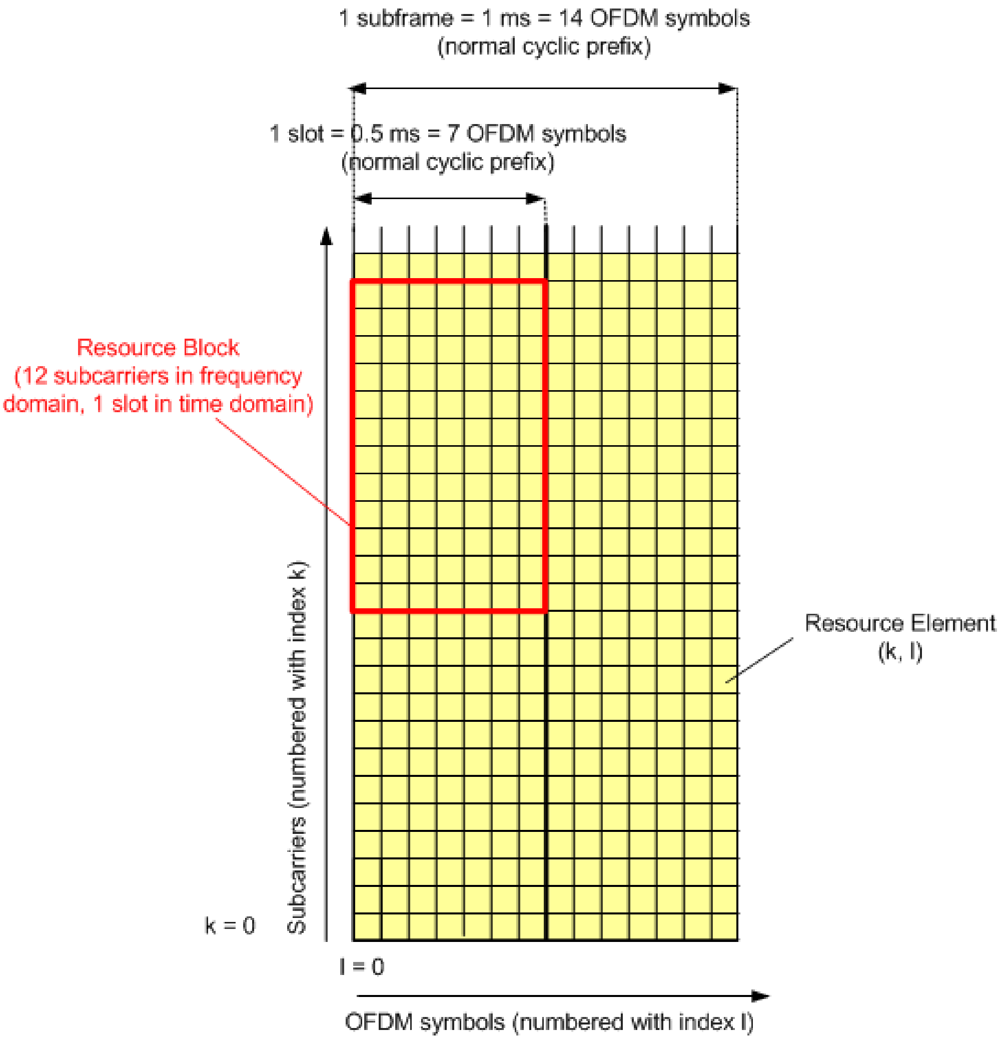


Figure 7: Downlink Resource grid [Ref. 3]

In the frequency domain, 12 subcarriers form one **Resource Block** (RB). With a subcarrier spacing of 15 kHz a RB occupies a bandwidth of 180 kHz. The number of resource blocks, corresponding to the available transmission bandwidth, is listed for the six different LTE bandwidths in Table 4.

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

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

To each OFDM symbol, a cyclic prefix (CP) is appended as guard time, compare Figure 2. 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, but reduces the number of available symbols. The cyclic prefix lengths in samples and µs are summarized in Table 5.

Configuration	Resource block size N_{symb}^{RB}	Number of Symbols N_{symb}^{DL}	Cyclic prefix length in samples	Cyclic prefix length in µs
Normal cyclic prefix Δf=15kHz	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=15kHz	12	6	512	16.7 µs

Table 5: Downlink frame structure parameterization (FDD and TDD) [Ref. 3]

With a sampling frequency of 30.72 MHz 307200 samples are available per radio frame (10 ms) and thus 15360 per time slot (0.5 ms). Due to the maximum FFT size each OFDM symbol consists of 2048 samples. With usage of normal cyclic prefix seven OFDM symbols are available or 7*2048 = 14336 samples per time slot. The remaining 1024 samples are the basis for cyclic prefix. It has been decided that the first OFDM symbol uses a cyclic prefix length of 160 samples, where the remaining six OFDM symbols using a cyclic prefix length of 144 samples. Multiplying the samples with the sampling time T_S, results in the cyclic prefix length in µs.

Please note that for E-MBMS another cyclic prefix of 33.3 µs is defined for a different subcarrier spacing of Δf = 7.5 kHz in order to have a much larger cell size.

3.3 Downlink data transmission

Data is allocated to a device (User Equipment, UE) 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. All scheduling decisions for downlink and uplink are done in the base station (enhanced NodeB, eNodeB or eNB). 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. and is a vendor-specific implementation. Figure 8 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**). The PDSCH(s) is the only channel that can be QPSK, 16QAM or 64QAM modulated.

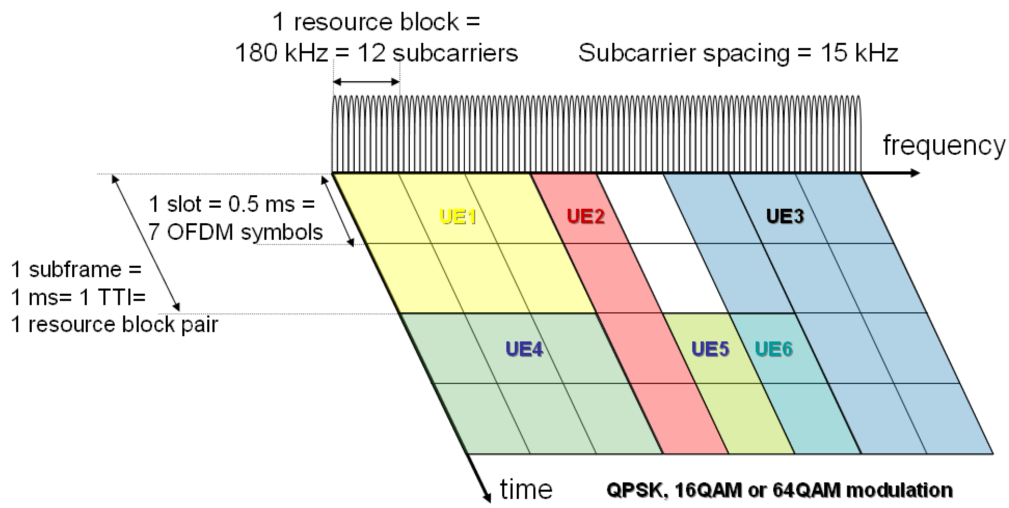


Figure 8: OFDMA time-frequency multiplexing (example for normal cyclic prefix)

3.4 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 downlink and uplink.

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 each subframe is used to indicate the number of OFDM symbols used 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 number of symbols that are used to carry the PDCCH are also dependent on the configured bandwidth, so for example for a 1.4 MHz the minimum number of symbols is always two, at maximum 4 whereas for a 10 MHz channel the minimum is only one symbol, but the maximum is three OFDM symbols. Figure 9 visualizes this with the help of the OFDMA time plan available on all Rohde & Schwarz signal generator products, in this particular case using the R&S®SMU200A Vector Signal Generator.

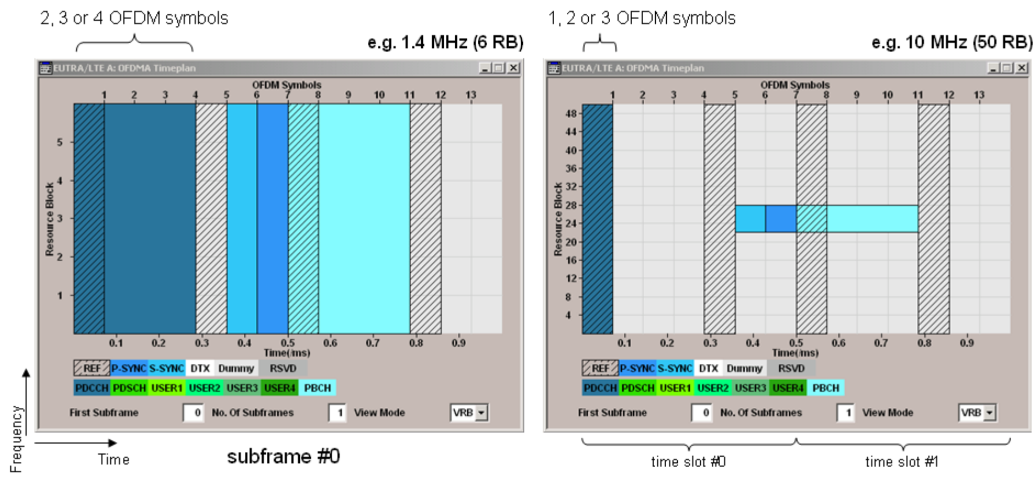


Figure 9: Number of OFDM symbols used for PDCCH are depending on bandwidth

The information carried on PDCCH is referred to as **downlink control information (DCI)**. Depending on their purpose different formats of DCI are defined. Table 6 shows the DCI formats and there purposes as they are defined in 3GPP Release 8.

DCI Format	Content and Tasks	Allocation Type used
0	Scheduling of PUSCH	2
1	Scheduling of one PDSCH codeword	0, 1
1A	Compact scheduling of one PDSCH codeword and random access procedure initiated by a PDCCH order	2
1B	Compact scheduling of one PDSCH code word with pre-coding	2
1C	Very compact scheduling of one PDSCH codeword, RACH response and dynamic BCCH scheduling	2
1D	Compact scheduling of one PDSCH codeword with precoding and power offset information	2
2	Scheduling PDSCH to UE's configured in closed-loop spatial multiplexing mode	0, 1
2A	Scheduling PDSCH to UE's configured in open loop spatial multiplexing mode	0 ,1
3	Transmission of TPC commands for PUCCH and PUSCH with 2-bit power adjustments	-
3A	Transmission of TPC commands for PUCCH and PUSCH with single bit power adjustments	-

Table 6: DCI formats carried on PDCCH as defined in 3GPP Release 8

As an example, the contents of DCI format 1 are shown in Table 7. 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.

Information type	Number of bits on PDCCH	Purpose
Resource allocation header	1	Indicates which resource allocation type is used, so whether it is resource allocation type 0 or 1
Resource block assignment	Depending on resource allocation type	Indicates the number of resource blocks to be assigned to the device
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 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

Table 7: Contents of DCI format 1 carried on PDCCH [Ref. 5]

How does a UE know that a DCI format is intended for it? The Cyclic Redundancy Check (CRC) of the DCI format will be scrambled with the UE's identity. This identity is assigned by the network to the device during the random access procedure. The UE does monitor the beginning of each subframe for its identity, based on a defined time schedule, coming from higher layers.

There are other, pre-reserved identities to serve different purposes for example inform about scheduling of system and paging information or to provide a response on an attempt to access the network.

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. In LTE the complexity of the radio channel is adopted while using different transmission modes. Table 8 gives an overview of the transmission modes and related DCI formats as defined in 3GPP Release 8.

Transmission Mode (TM)	DCI format	Transmission scheme of PDSCH corresponding to PDCCH
Mode 1	DCI format 1A	Single-antenna port, port 0 (SISO)
	DCI format 1	Single-antenna port, port 0 (SISO)

Mode 2	DCI format 1A	Transmit diversity (TxD)
	DCI format 1	Transmit diversity (TxD)
Mode 3	DCI format 1A	Transmit diversity (TxD)
	DCI format 2A	Large delay CDD or Transmit diversity (TxD)
Mode 4	DCI format 1A	Transmit diversity (TxD)
	DCI format 2	Closed-loop spatial multiplexing or TxD
Mode 5	DCI format 1A	Transmit diversity (TxD)
	DCI format 1D	Multi-user MIMO (MU-MIMO)
Mode 6	DCI format 1A	Transmit diversity (TxD)
	DCI format 1B	Closed-loop spatial multiplexing using a single transmission layer
Mode 7	DCI format 1A	If the number of PBCH antenna ports is one, Single-antenna port, port 0 is used otherwise TxD
	DCI format 1	Single-antenna port; port 5

Table 8: LTE transmission modes as of 3GPP Release 8

DCI formats 2 and 2A provide downlink shared channel assignments in case of closed loop spatial multiplexing (TM4) or open loop spatial multiplexing (TM3), respectively. Closed-loop spatial multiplexing means, that the UE provides feedback on the MIMO transmission where it does not for open-loop spatial multiplexing. See section 5 for further details. For DCI formats 2/2A, scheduling information are 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 to different devices within one message. These two formats are used to power control devices that are semi-persistent scheduled, for example while doing a VoIP call.

3.4.1 Resource Allocation Types in LTE

As mentioned above there are different ways to signal the resource allocation within DCI, in order to tradeoff 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 method is specified with resource allocation type 2. All three different resource allocation types can be utilized in the downlink, depending on the format (see Table 6). In the uplink only resource allocation type 2 is used.

As a trade of between signaling overhead and efficiency not individual resource blocks are allocated to the device while using resource allocation types 0 and 1. They work rather with so called resource block groups (RBG). A resource block group consists out of a number of resource blocks. This number depends on the system bandwidth and is between 1 RB (i.e. 1.4 MHz) and 4 RB (i.e. 20 MHz). In case of 20 MHz / 100 RB there are 25 RBG available, each one consist of 4 RB.

For **resource allocation type 0**, a bit map indicates now, which resource block group(s) are allocated to a UE. For the 20 MHz case this bitmap is 25 bits long. A ‘1’ indicates this RBG is assigned to the device, a ‘0’ does not. The allocated resource block groups do not have to be adjacent to each other.

Figure 10 illustrates an example for 10 MHz / 50 RB, where the bitmap is 17 bit due to the RBG size of 3 RB. One group only consists of 2 RB in this particular case. As shown only the first RBG, two in the middle of the spectrum and the very last RBG is allocated to the device. The bitmap itself will be converted into decimal and is signaled as so called **Resource Indication Value** (RIV) within the DCI format to the device.

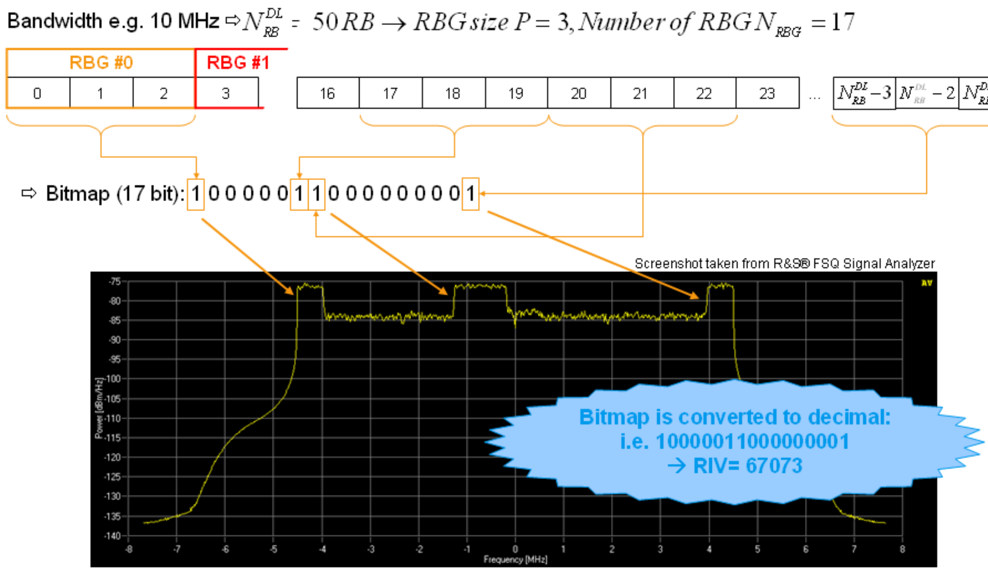


Figure 10: Resource Allocation Type 0

Also **resource allocation type 1**, works with RBG. But first the RBG are organized into so called **resource block group subset**, each one consisting now out of a number of RBG. The used bitmap indicates a RB within a RBG within the selected RBG subset. Therefore the information for the resource block assignment coded in the bitmap with the DCI format is 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 the resource blocks inside the resource block group subset. These resource blocks do not have to be adjacent to each other. Also this bitmap is converted from binary into decimal and signaled as RIV within the DCI format to the UE.

Figure 11 shows the effect, if the same RIV is signaled with the DCI, but resource allocation type 0 or 1 are used, respectively. The difference is only one bit within DCI format 1. It can be easily seen that the device scheduled in this case has to look at different parts of the spectrum to find the RB assigned to it, demodulate and decode its data. The purpose of these two different allocation types is to achieve an efficient and effective frequency-selective scheduling, either on a RBG level or on a RB level.

Figure 11: Difference between Resource Allocation Type 0 (left) and Type 1 (right)

With **resource allocation type 2**, it comes to a differentiation between physical resource blocks, which we discussed so far and virtual resource blocks. The reason is that RB in resource allocation type 2 is not allocated directly. 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 again a RIV from which this time 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. DCI formats 1A, 1B, 1C, 1D and 0 are using resource allocation type 2. It depends on the purpose if *localized* or *distributed* mode is used.

In the *localized case*, there is a one-to-one mapping between virtual and physical resource blocks. An 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 rules 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 9 shows a summary of downlink control channels, their purpose and the used modulation scheme.

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/NACK for uplink data packets	BPSK
Physical Broadcast Channel (PBCH)	Carries Master Information Block	QPSK

Table 9: Downlink control channels

3.5 Downlink reference signal structure and cell search

The downlink reference signal structure is important for initial acquisition and cell search, coherent detection and demodulation at the UE and further basis for channel estimation and radio link quality measurements. Downlink reference signal provide further help to the device to distinguish between the different transmit antenna used at the eNodeB. *Figure 12* shows the mapping principle of the downlink reference signal structure for up to four transmit antennas. Specific pre-defined resource elements in the time-frequency domain are carrying the cell-specific reference signal sequence. In the frequency domain every six subcarrier carries a portion of the reference signal pattern, which repeats every fourth OFDM symbol.

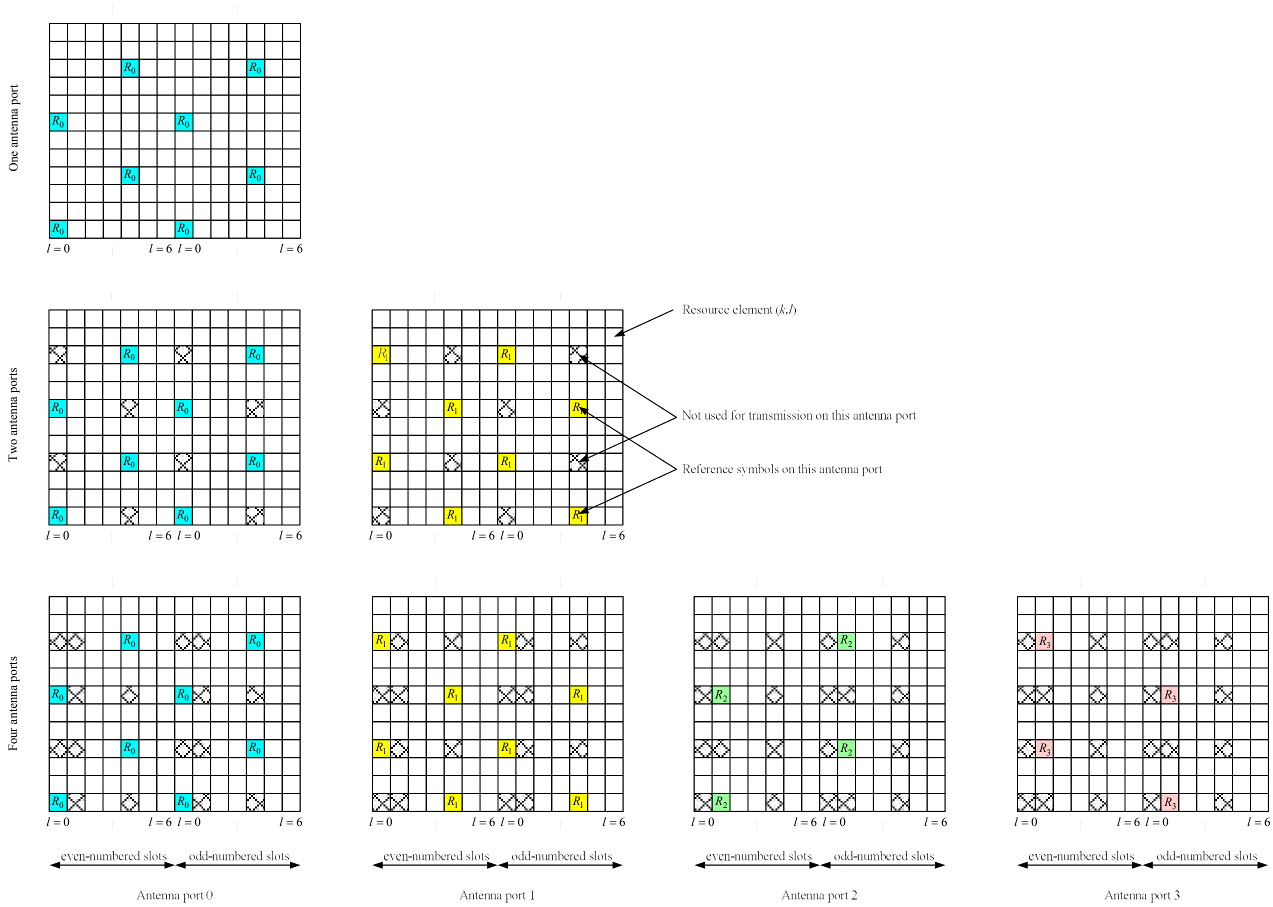


Figure 12: Downlink reference signal structure (normal cyclic prefix) **[Ref. 3]**

The **reference signal sequence** is derived from a pseudo-random sequence and results in a QPSK type constellation. Frequency shifts are applied when mapping the reference signal sequence to the subcarriers, means the mapping is cell-specific and distinguish the different cells.

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, and 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 13 for FDD and Figure 14 for TDD. In the frequency domain, they are transmitted on 62 subcarriers within 72 reserved subcarriers around the unused 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.

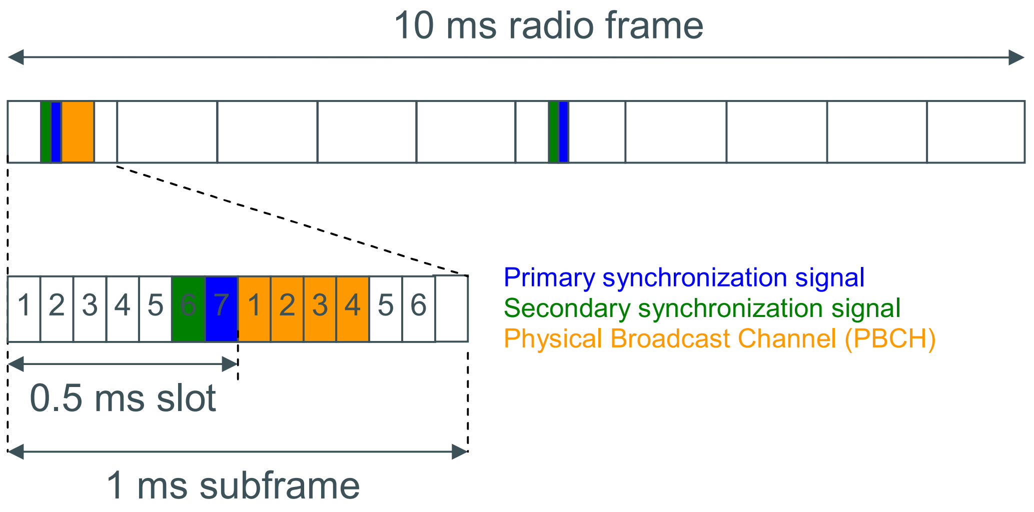


Figure 13: Primary/secondary synchronization signal and PBCH structure (frame structure type 1 / FDD, normal cyclic prefix)

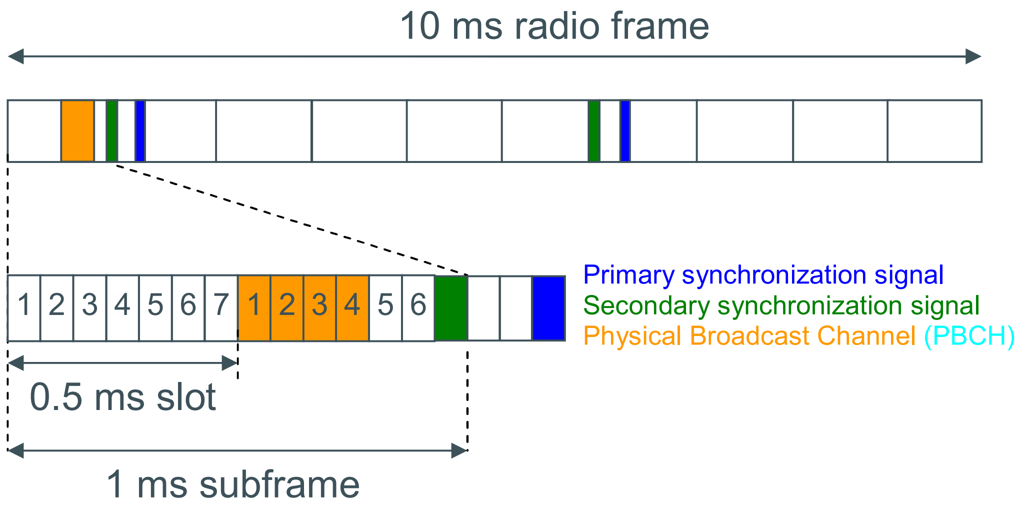


Figure 14: Primary/secondary synchronization signal and PBCH structure (frame structure type 2 / TDD, normal cyclic prefix)

As additional help during cell search, a Physical Broadcast Channel (**PBCH**) is available which carries the Master Information Block (MIB). The MIB provides basic physical layer information, e.g. system bandwidth, PHICH configuration, and system frame number. The number of used transmit antennas is provided indirectly using a specific CRC mask. The PBCH is transmitted on the first 4 OFDM in the second time slot of the first subframe on the 72 subcarriers centered around DC subcarrier. PBCH has 40 ms transmission time interval, means a device need to read four radio frames to get the whole content.

For further information and details on cell search and selection in UMTS LTE please refer to [Ref. 13].

3.6 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). In LTE FDD there are up to 8 HARQ processes in parallel. 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.

TDD UL/DL configuration	Number of HARQ processes for normal HARQ operation	Number of HARQ processes for subframe bundling operation
0	7	3
1	4	2
2	2	N/A
3	3	N/A
4	2	N/A
5	1	N/A
6	6	3

Table 10: Number of HARQ processes in TD-LTE (Downlink)

Two modes are supported by TD-LTE acknowledging or non-acknowledging data packets received in the downlink: ACK/NACK bundling and multiplexing. Which mode is used, is configured by higher layers. ACK/NACK bundling means, that ACK/NACK information for data packets received in different subframes is combined with logical AND operation.

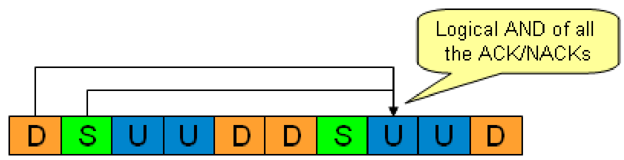


Figure 15: ACK/NACK bundling in TD-LTE

4 LTE Uplink Transmission Scheme

4.1 SC-FDMA

During the study item phase of LTE, alternatives for the optimum uplink transmission scheme were investigated. While OFDMA is seen optimum to fulfill the LTE requirements in downlink, OFDMA properties are less favorable 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 and challenges in power amplifier design for battery operated handset, as it requires very linear power amplifiers.

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 parameterization 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 16. For **DFT-s-OFDM**, a size-M DFT is first applied to a block of M modulation symbols. QPSK, 16QAM and 64QAM 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 number of subcarriers. For LTE Release 8 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.

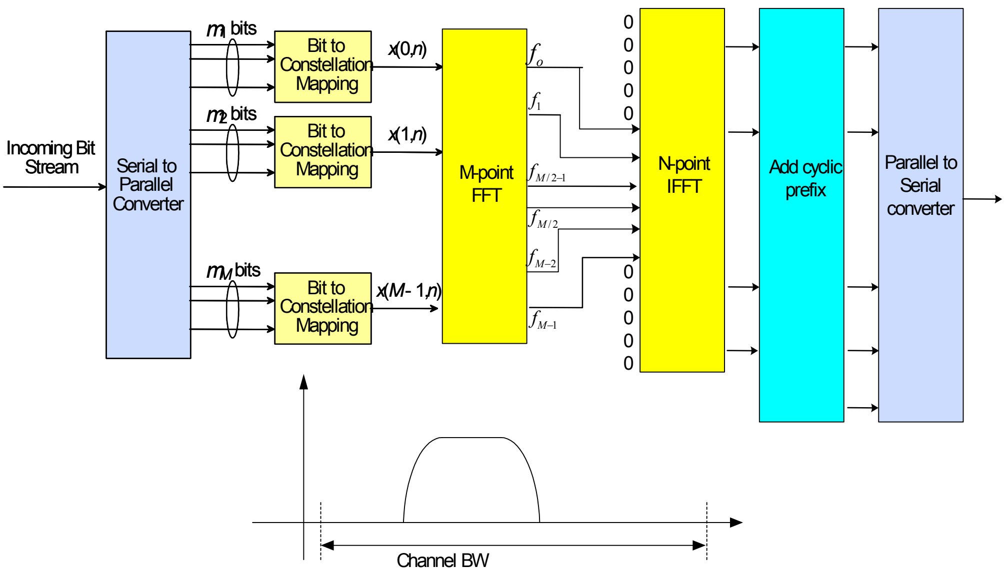


Figure 16: Block diagram of DFT-s-OFDM (localized transmission)

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. This spreading lowers the PAPR compared to OFDMA as used in the downlink. It depends now on the used modulation scheme (QPSK, 16QAM, later on also 64QAM) and the applied filtering, which is not standardized as in WCDMA for example.

4.2 SC-FDMA parameterization

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 17 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 demodulation reference signal (DMRS), being used for coherent demodulation at the eNodeB receiver as well as channel estimation.

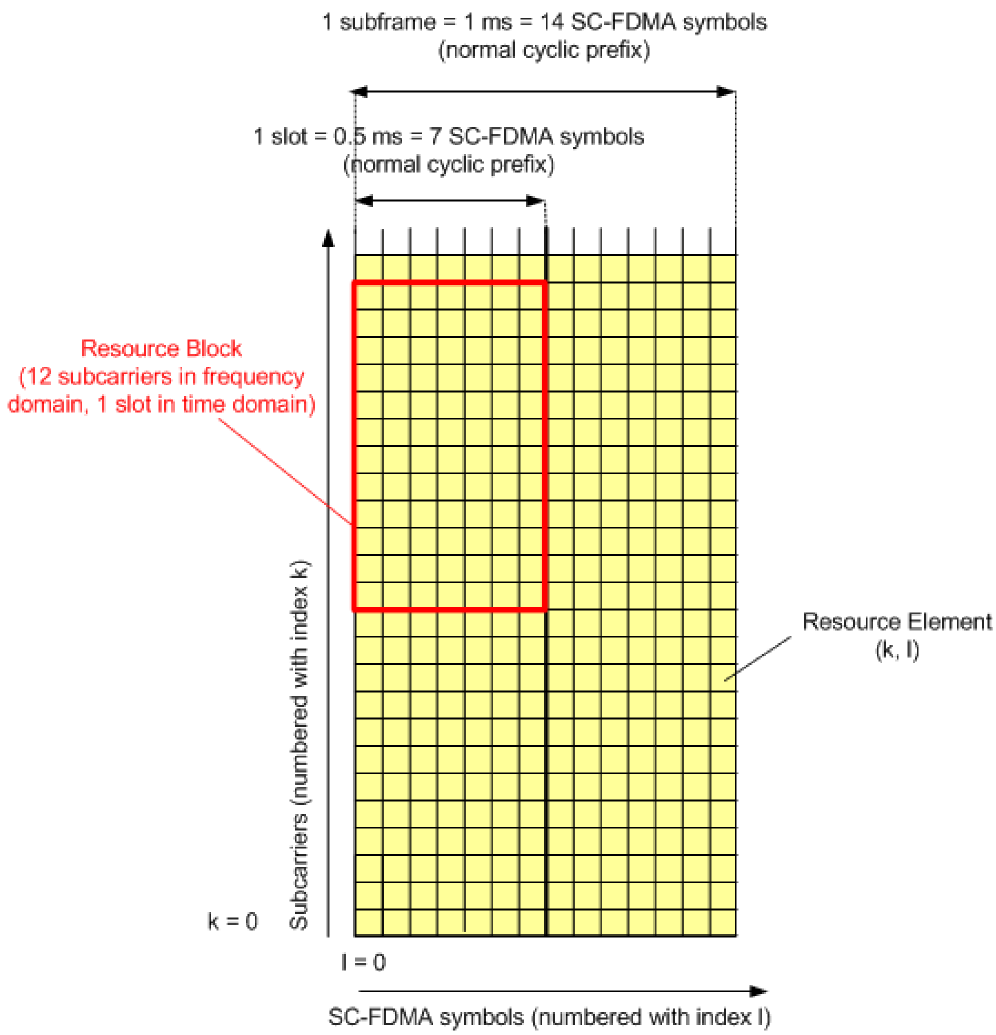


Figure 17: Uplink resource grid [Ref. 3]

Table 11 shows the configuration parameters.

Configuration	Number of Symbols N_{symb}^{UL}	Cyclic prefix length in samples	Cyclic prefix length in µs
Normal cyclic prefix ∆f=15kHz	7	160 for first symbol 144 for other symbols	5.2 µs for first symbol 4.7 µs for other symbols
Ext. cyclic prefix ∆f=15kHz	6	512	16.7 µs

Table 11: Uplink frame structure parameterization (FDD and TDD) [Ref. 3]

4.3 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. Table 12 shows the possible number of RB that can be allocated to a device for uplink transmission.

1	2	3	4	5	6	8	9	10	12
15	16	18	20	24	25	27	30	32	36
40	45	48	50	54	60	64	72	75	80
81	90	96	100						

Table 12: Possible RB allocation for uplink transmission

In LTE Release 8 only contiguous allocation is possible in the uplink, similar to downlink transmissions with resource allocation type 2. The number of allocated RBs is signaled to the UE as RIV.

The uplink transmission time interval is 1 ms (same as downlink). User data is carried on the Physical Uplink Shared Channel (**PUSCH**).

DCI (Downlink Control Information) format 0 is used on PDCCH to convey the uplink scheduling grant, see Table 6. The content of DCI format 0 is listed in Table 13.

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 block 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 sizeIndicates redundancy version to use
New date indicator	1	Indicates whether a new transmission shall be sent

Information type	Number of bits on PDCCH	Purpose
TPC command for scheduled PUSCH	2	Transmit power control (TPC) 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) → aperiodic CQI reporting

Table 13: Contents of DCI format 0 carried on PDCCH [Ref. 5]

Frequency hopping can be applied in the uplink. The uplink scheduling grant in DCI format 0 contains a 1 bit flag for switching hopping ON or OFF. 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. LTE supports both **intra- and inter-subframe frequency hopping**. It is configured per cell by higher layers whether either 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, depending on a pre-defined method. Also, the UE is being told whether to use type 1 or type 2 frequency hopping.

The available bandwidth i.e. 50 RB is divided into a number of sub-bands, 1 up to 4. This information is provided by higher layers. The hopping offset, which comes as well from higher layers, determines how many RB are available in a sub-band. The number of contiguous RB that can be allocated for transmission is therefore limited. Further the number of hopping bits is bandwidth depended, 1 hopping bit for bandwidths with less than 50 RB, 2 hopping bits for bandwidth equals and higher 50 RB. All the principles behind PUSCH hopping in the uplink and the mapping to resources can be found in [Ref. 3] and [Ref. 6]. 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.

Type 1 hopping refers to the use of an explicit offset in the 2nd slot resource allocation. *Figure 18* shows an example, of a complete radio frame for a 10 MHz signal applying a defined PUSCH hopping offset of 5 RB and configuring 4 sub-bands.

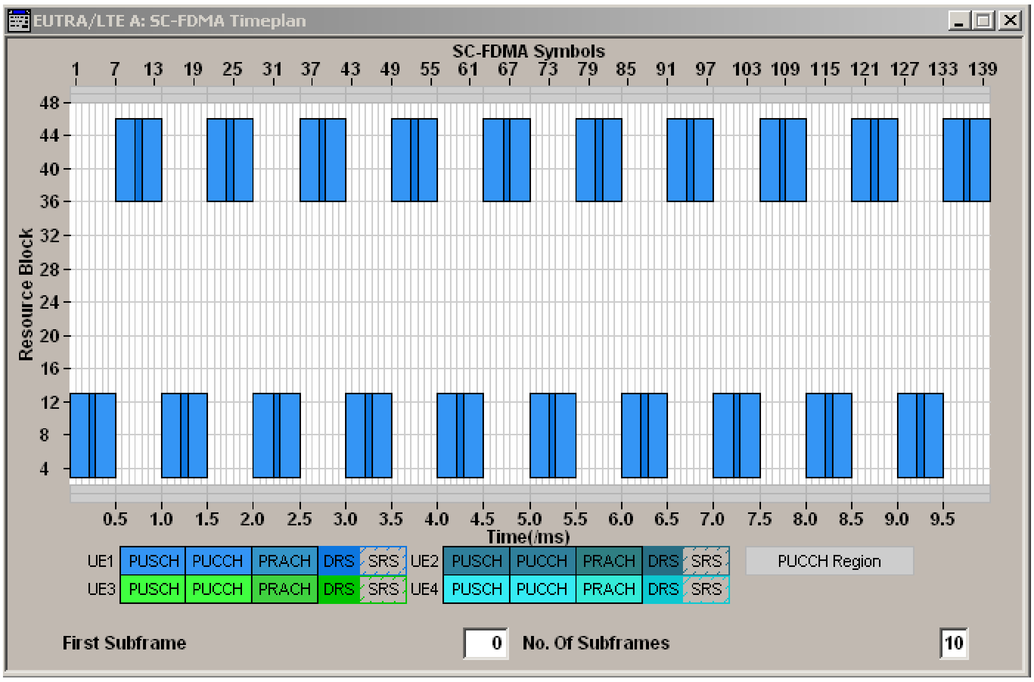


Figure 18: Intra-subframe hopping, Type 1

Type 2 hopping refers to the use of a pre-defined hopping pattern [Ref. 3]. The hopping is performed between sub-bands (from one slot or subframe to another, depending on whether intra- or inter-subframe are configured, respectively). In the example (Figure 19) the initial assignment is 10 RB with an offset of 24 RB.

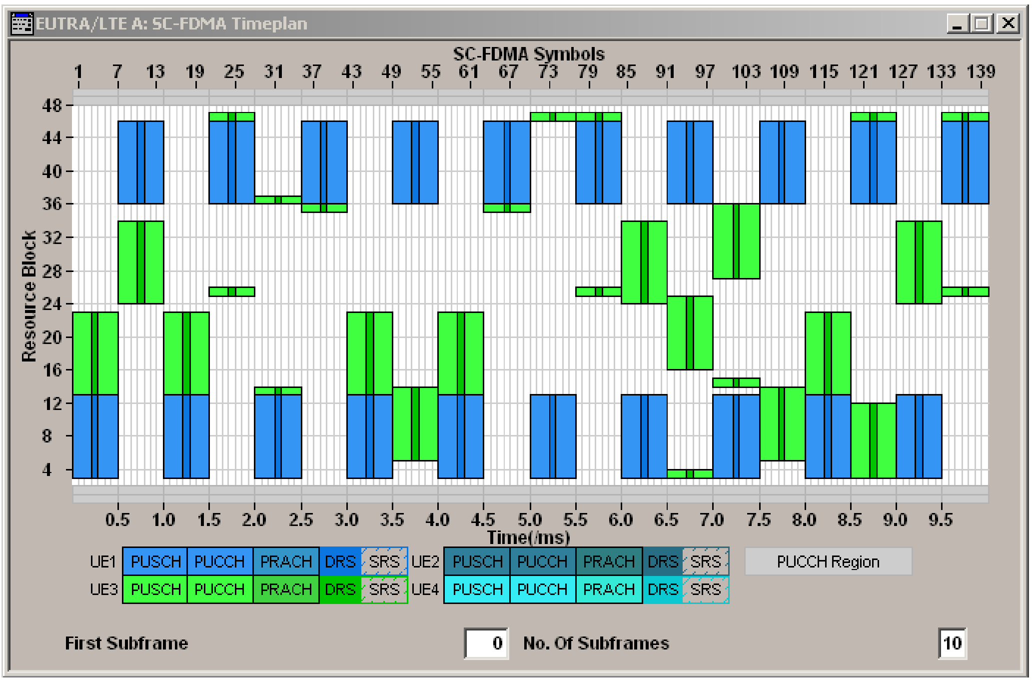


Figure 19: Intra-subframe hopping, Type 1 (blue, UE1) and Type 2 (green, UE3)

4.4 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 20* shows an example for a PUCCH resource allocation. Two UEs are simulated that issuing a PUCCH, but utilizing different formats. The resources reserved for PUCCH transmission at the edges of bandwidth are configured by higher layers. For PUCCH transmission inter-slot hopping is applied, that means the transmission jumps from the lower edge of the bandwidth to the higher and vice versa dependent on the format.

Please note that in TD-LTE the PUCCH is not transmitted in special subframes.

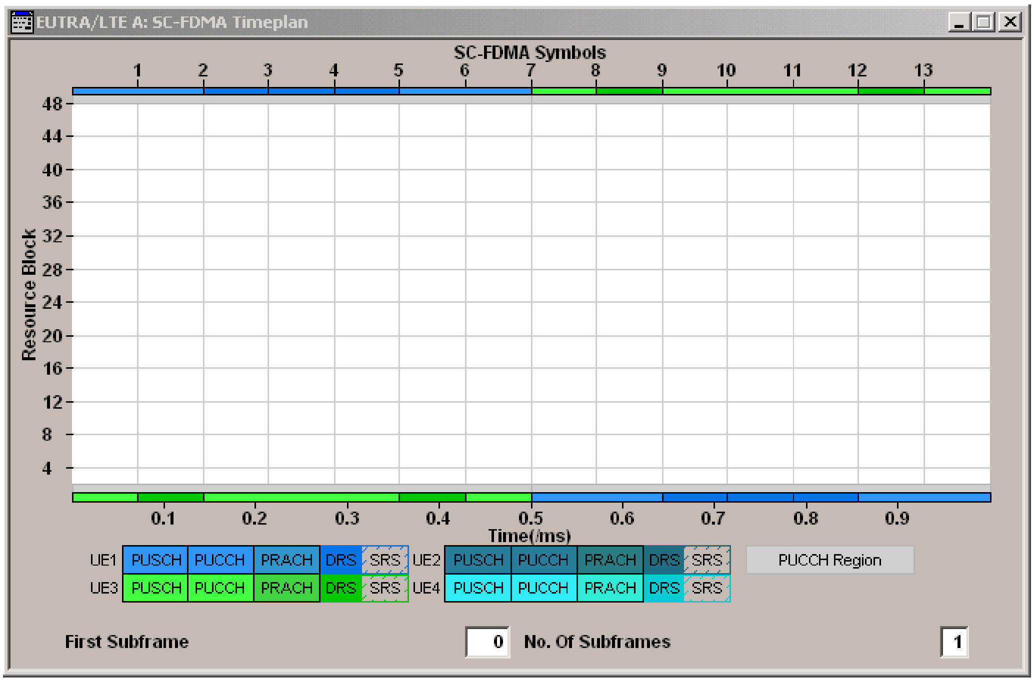


Figure 20: Example for PUCCH resource allocation (UE1: format 1a, UE3: format 2)

In LTE as of 3GPP Release 8 a device uses PUCCH only 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 14.

PUCCH format	Contents	Modulation scheme	Number of bits per subframe M_{bit}
1	Scheduling Request (SR)	N/A	information is carried by presence or absence of transmission

PUCCH format	Contents	Modulation scheme	Number of bits per subframe M_{bit}
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

Table 14: PUCCH formats and contents

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). Additionally the PUCCH resource may be offset by the parameter *N1PUCCH-AN* signaled by higher layers. 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.

4.5 Uplink reference signal structure

There are two types of uplink reference signals:

- The **demodulation reference signal** (DMRS) 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** (SRS) 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 21 shows the complex values of two example reference signals which were generated by two different cyclic shifts of the same sequence.

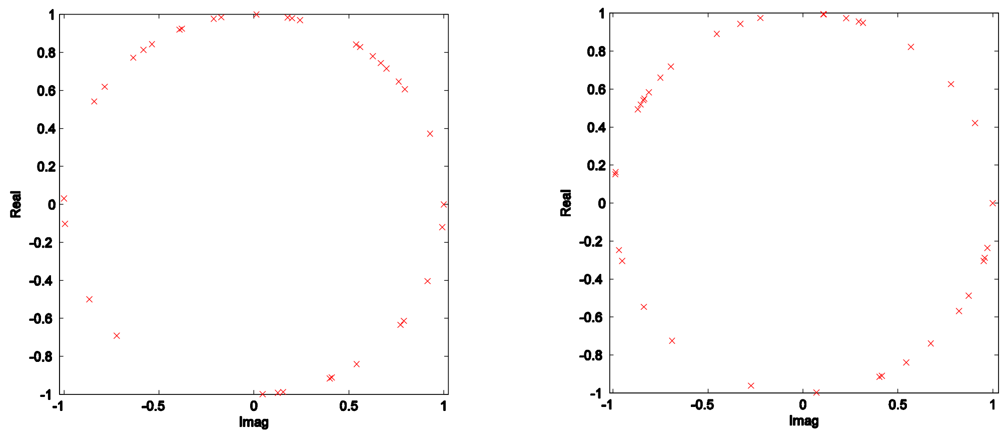


Figure 21: Uplink reference signal sequences for an allocation of three resource blocks, generated by different cyclic shifts of the same base sequence

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.

4.6 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 22.

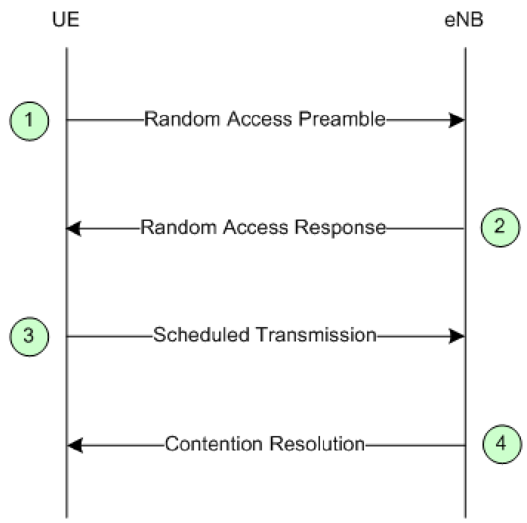


Figure 22: Random access procedure (contention based) [Ref. 7]

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, but the position of that six RB is flexible Different PRACH configurations are defined which indicate system and subframe numbers with PRACH opportunities, as well as possible preamble formats. How to use the RACH and access the PRACH configuration is provided by higher layers and signaled by the network within System Information Block (SIB) Type 2 This includes also the Preamble Initial Target Power, means the power level with which one the device will send the preamble the first time to the network and how much the power level is increased, when the preamble is not acknowledged.

The random access preamble is defined as shown in Figure 23. 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.

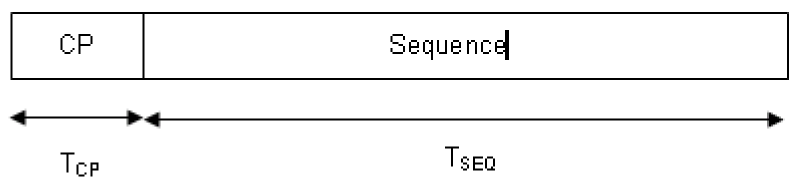


Figure 23: Random access preamble [Ref. 3]

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

In step 1 in Figure 22, 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)), which is picked out of a pool of possible identities.

In step 2, a random access response is generated at the Medium Access Control (MAC) layer of the eNodeB and sent on downlink shared channel. It is addressed to the UE via the previously selected RA-RNTI and contains the initial uplink scheduling grant. That grant provides information on timing advance, measured by the eNB based on preamble transmission, a RB and fixed modulation and coding scheme assignment and a temporary Cellular-RNTI (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 intial 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.

4.7 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 13.

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

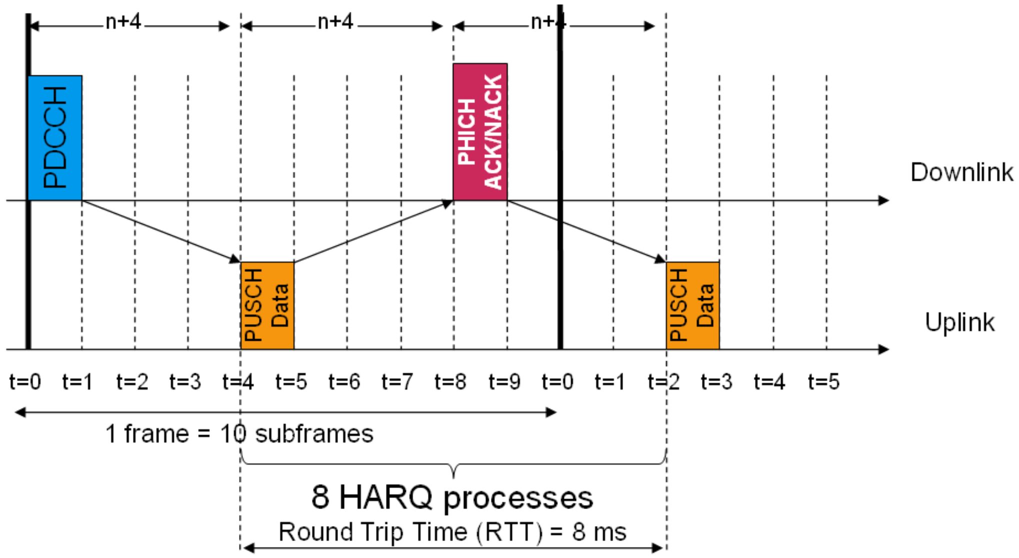


Figure 24: PHICH principle

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 transmitting 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 increasing the overall capacity. Spatial multiplexing is only possible if the mobile radio channel allows it.

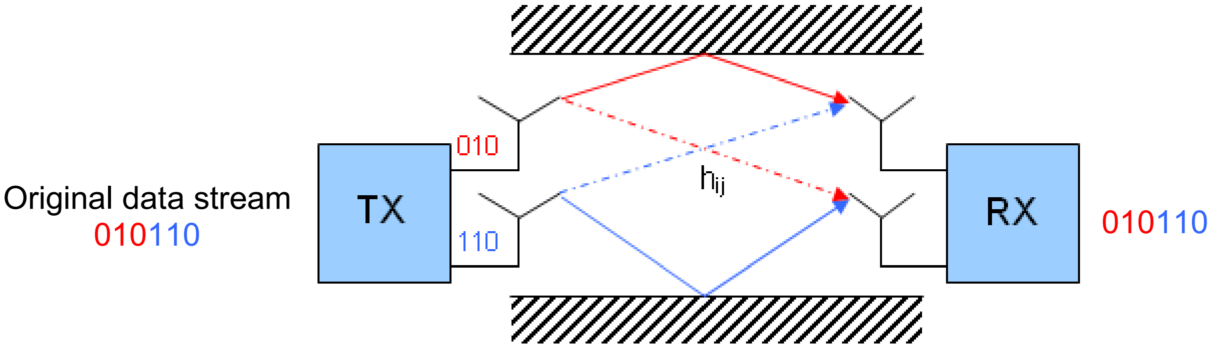


Figure 25: Spatial multiplexing (simplified)

Figure 25 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 25* 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.

5.1 Downlink MIMO modes in LTE as of Release 8

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:

Transmission Mode	Description
TM1	Single Antenna transmission (SISO)
TM2	Transmit Diversity
TM3	Open-loop spatial multiplexing, no UE feedback (PMI) on MIMO transmission provided
TM4	Closed-loop spatial multiplexing, UE provides feedback on MIMO transmission
TM5	Multi-user MIMO (more than one UE is assigned to the same resource block)
TM6	Closed-loop precoding for rank=1 (i.e. no spatial multiplexing, but precoding is used)
TM7	Single-layer beamforming (mandatory TD-LTE, optional LTE FDD)

Table 15: Transmission Modes in LTE as of 3GPP Release 8

Figure 26 gives an overview of LTE downlink baseband signal generation including the steps relevant for MIMO transmission (layer mapper and precoding).

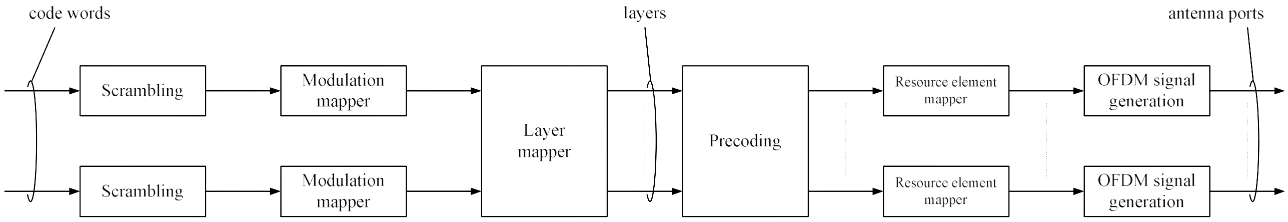


Figure 26: Overview of downlink baseband signal generation [Ref. 3]

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 16. The optimum pre-coding matrix is the one which offers maximum capacity.

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	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	--

Table 16: Precoding codebook for 2 transmit antenna case

The codebook 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 υ=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. At a certain point in time, the antenna ports transmit the same data symbols, but with different coding and on different subcarriers. Figure 27 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).

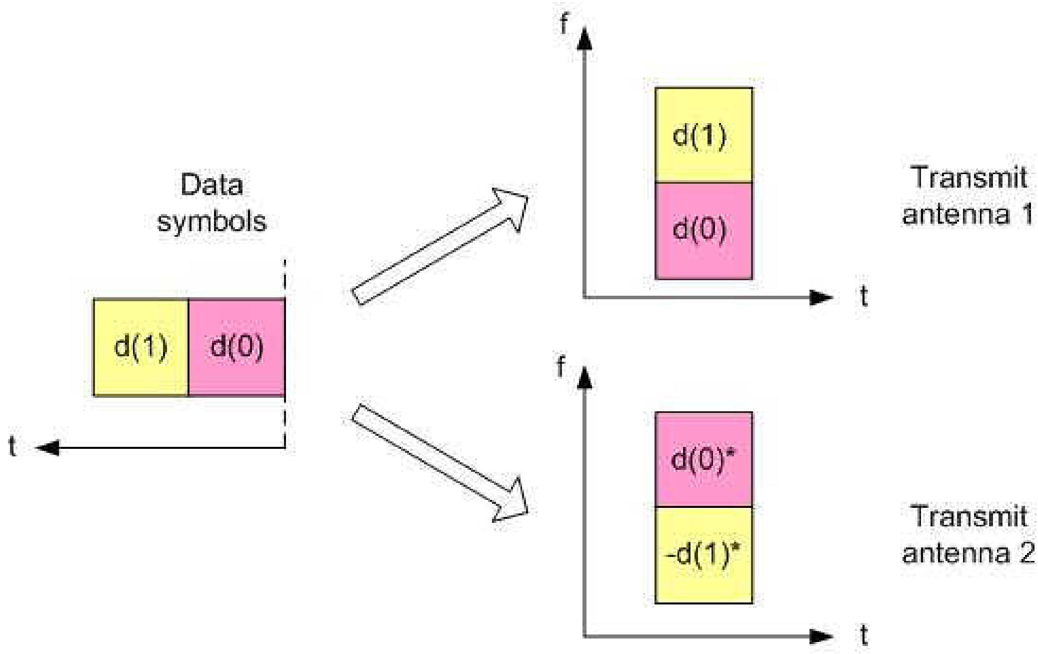


Figure 27: Transmit diversity (SFBC) principle

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.

5.2 Channel State Information (CSI)

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 mode of operation and network choice. The following table provides an overview.

periodic CQI reporting (PUCCH, PUSCH)

aperiodic CQI reporting (PUSCH only)

		PMI Feedback Type		
		No PMI	Single PMI	Multiple PMI
CQI Feedback Type	Wideband CQI	Mode 1-0	Mode 1-1	Mode 1-2
	UE Selected CQI	Mode 2-0	Mode 2-1	Mode 2-2
	Higher-layer configured CQI	Mode 3-0	Mode 3-1	-

Table 17: Reporting modes of channel state information in LTE

The used reporting mode depends further on the transmission mode (see *Table 18*):

Transmission Mode	Reporting modes
TM1	2-0, 3-0
TM2	
TM3	
TM4	1-2, 2-2, 3-1
TM5	3-1
TM6	1-2, 2-2, 3-1
TM7	2-0, 3-0

Table 18: Transmission modes and related reporting modes

So a channel quality report 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.
  - Sub-band CQI reporting can be either configured by higher layers or UE-selective. The later means the UE divides the bandwidth in a number of sub-bands, estimates the channel quality for each of these sub-bands but reports only the best ones. How many RB forming a sub-band as well as how many sub-bands are reported depends on the overall system bandwidth. In terms of 5 MHz equals 25 RB the sub-band size is defined with 2, making it 13 sub-bands, but only the top three of them are reported. For 20 MHz (100 RB) we have 25 sub-bands, only the best six are reported. The reported sub-band CQI values are relative to the estimated wideband CQI value and in that matter always better, but at least equal.
  - For higher-layer configures sub-band CQI reporting the applied principle is modified in that way, that the of a sub-band size is increased (e.g. 20 MHz = 8 RB per sub-band), so that less sub-bands are need to be measured but all of them are reported. For some sub-bands the reported CQI value can be lower than the estimated wideband CQI value, which is in contrast to UE-selected sub-band reporting.
- 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 Table 16. The network configures the number of resource blocks that are represented by a PMI report. Thus to cover the full bandwidth, multiple PMI may be reported, but this depends on the configured reporting mode and transmission mode. PMI reports are required 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 RI is always measured over the entire bandwidth, not for sub-bands. A RI is only reported for transmission modes 3 and 4.

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 13. The UE would send the report on PUSCH. In case of periodic reporting, PUCCH is used in case no PUSCH is available.

5.3 Uplink MIMO

3GPP Release 8 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 as well as transmitter chain 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 transmitter chain and power 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 an UE capability.

6 LTE Protocol Architecture

6.1 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.

6.2 E-UTRAN

An overall E-UTRAN description can be found in [Ref. 7]. The network architecture is illustrated in Figure 28.

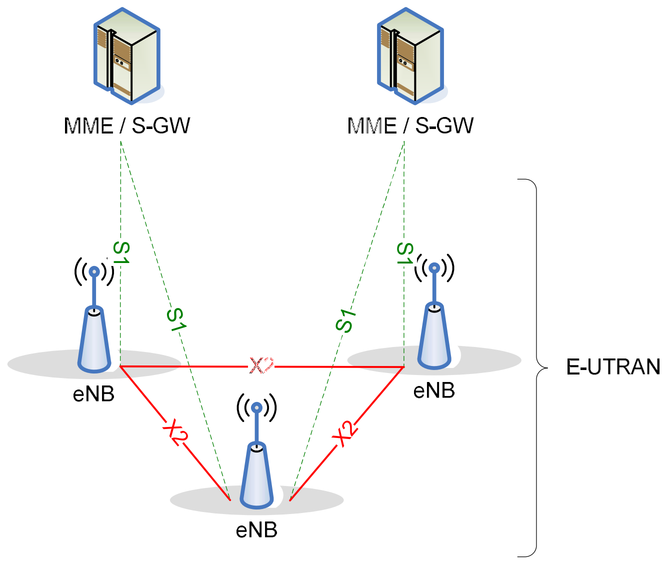


Figure 28: Overall network architecture [Ref. 7]

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). Non-Access Stratum (NAS) protocols are terminated in MME.

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

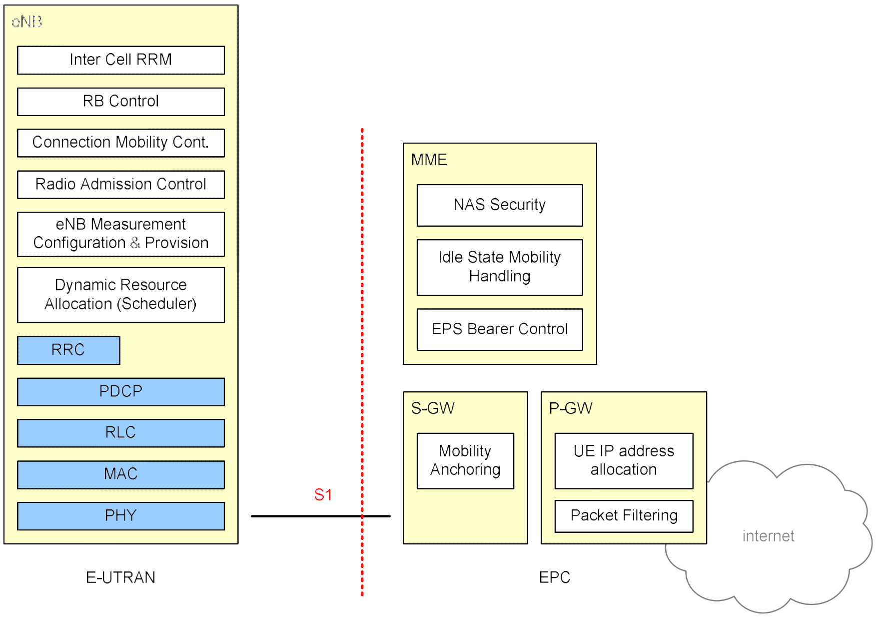


Figure 29: Functional split between E-UTRAN and EPC [Ref. 7]

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 30.

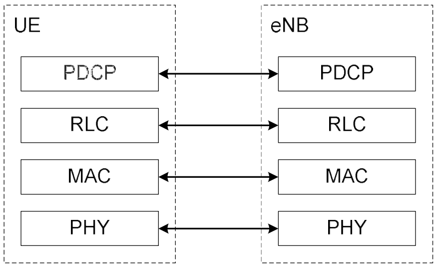


Figure 30: User plane protocol stack [Ref. 7]

The LTE control plane protocol stack is shown in Figure 31.

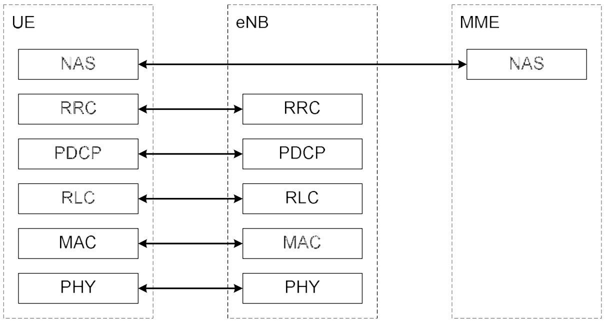


Figure 31: Control plane protocol stack [Ref. 7]

6.3 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 identities
- 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 32 and Figure 33 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.

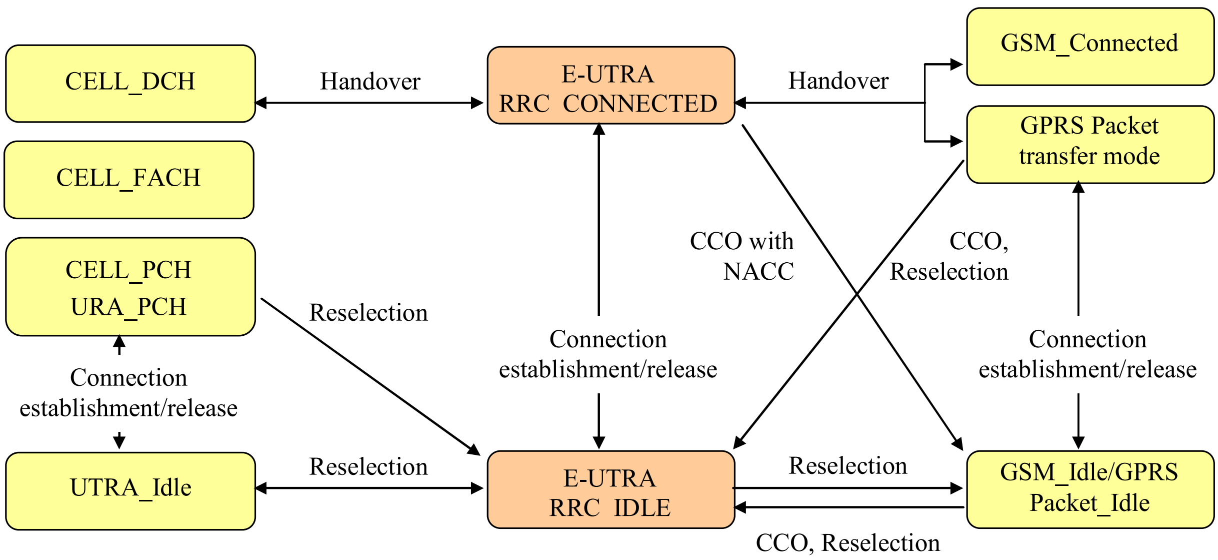


Figure 32: E-UTRA states and inter RAT mobility procedures [Ref. 9], CCO = Cell Change Order

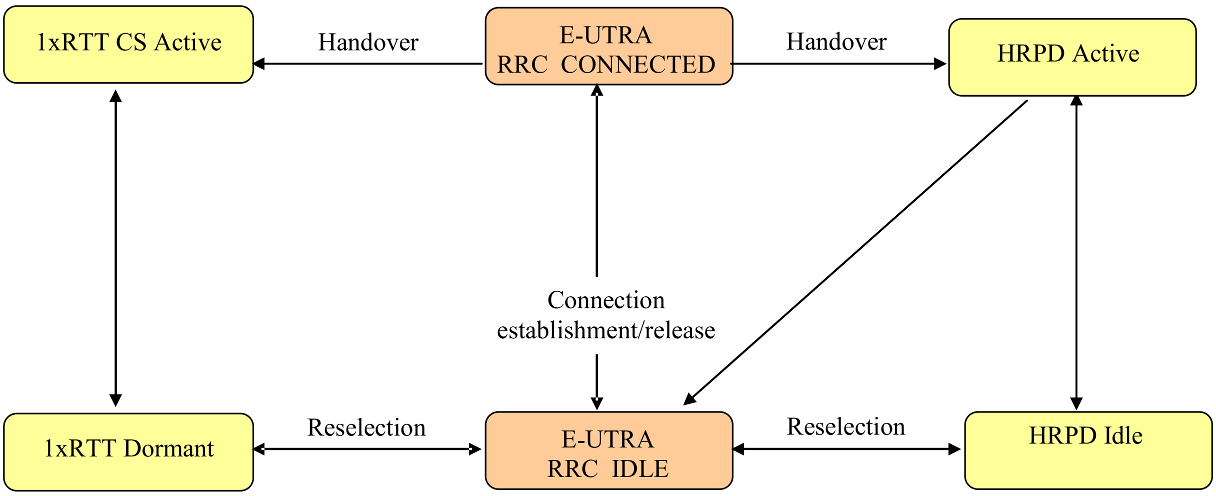


Figure 33: Mobility procedures between E-UTRA and CDMA2000 [Ref. 9], HRPD = High Rate Packet Data

RRC is responsible for configuring the lower layers. For example, Table 19 lists physical layer elements that are configured by RRC messages. This shows that the physical layer parameterization can be optimized by RRC for specific applications and scenarios.

Physical Layer Element	Configurations options by RRC
PDSH	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

Physical Layer Element	Configurations options by RRC
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

Table 19: Physical layer parameters configured by RRC (list not exhaustive)

6.4 Layer 2 structure

Figure 34 and Figure 35 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.

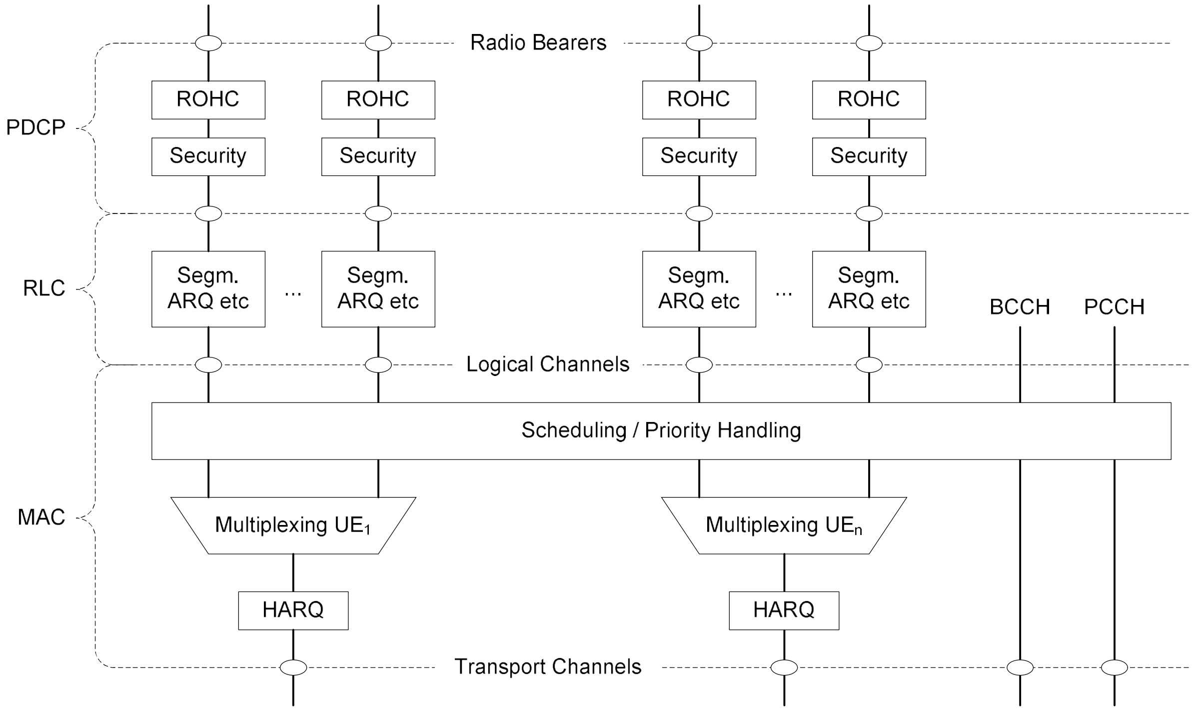


Figure 34: Downlink layer 2 structure [Ref. 7]

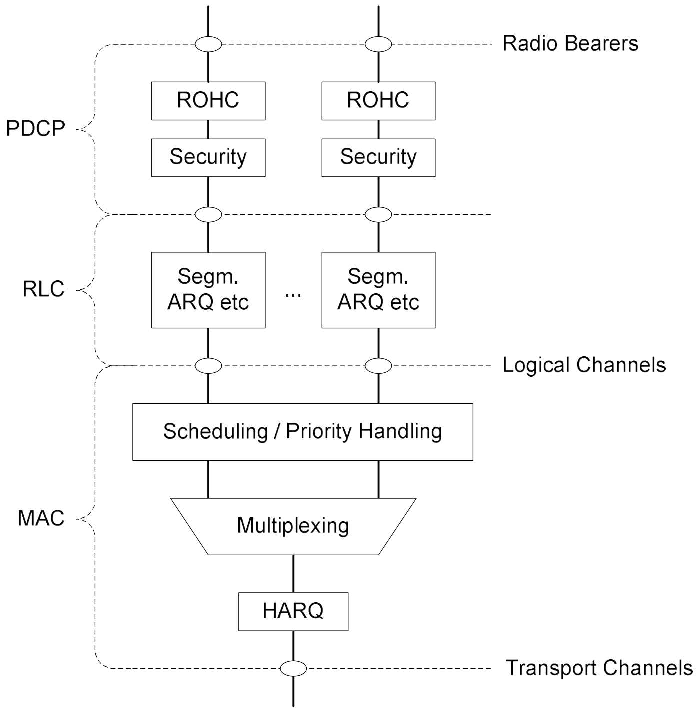


Figure 35: Uplink layer 2 structure [Ref. 7]

6.5 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)

6.6 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.

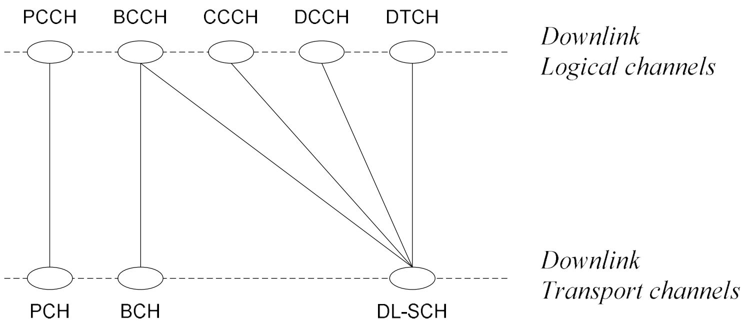


Figure 36: Mapping between DL logical and transport channels [Ref. 10]

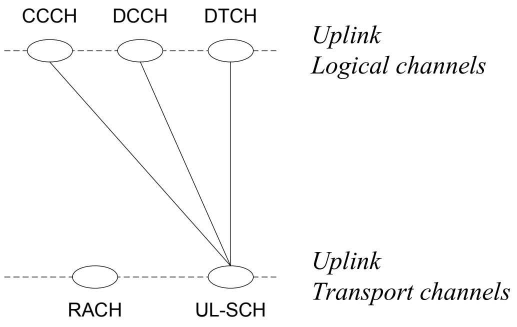


Figure 37: Mapping between UL logical and transport channels [Ref. 10]

6.7 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 38.

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

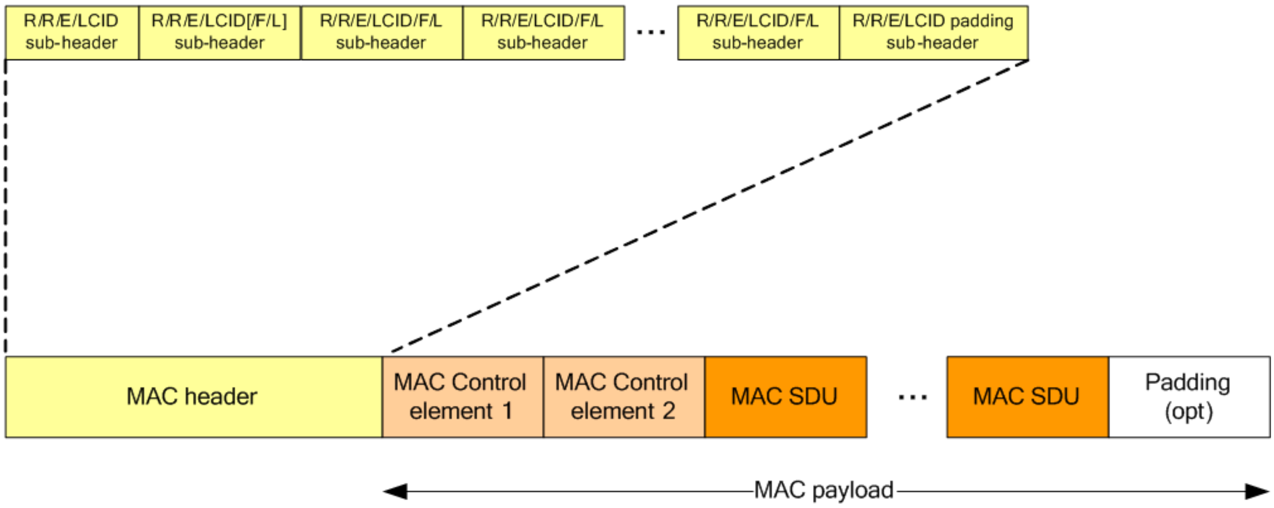


Figure 38: Structure of MAC PDU [Ref. 10]

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 22
- 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 20 and Table 21, 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.

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

Table 20: Downlink UE categories [Ref. 11]

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

Table 21: Uplink UE categories [Ref. 11]

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 Voice and SMS in LTE

LTE/SAE has been designed as an “all-IP”-based network targeting mobile broadband data delivery. The missing circuit-switched domain provides some challenges to deliver two key services via an LTE network: Voice and SMS. Several candidates have been identified to overcome that bottleneck.

8.1 Solutions

Voice over IMS, SMS over IMS: All major network operators have acknowledged that the long-term solution to deliver voice, SMS via their LTE network is based on the IP Multimedia Subsystem (IMS). IMS is an access-independent overlay to existing network architectures, guaranteeing seamless service continuity, not only for voice, but also e.g. for video application. The first version of IMS was standardized in 3GPP release 5, with many enhancements specified in subsequent releases. IMS needs to be implemented on both the network as well as the device side, whereas rollout of IMS in commercial networks was slower than originally expected. In consequence intermediate steps might been taken, dependent on the network operator deployment strategy and its 2G/3G network capabilities.

Circuit-Switched Fallback (CSFB): The way out for traditional network operators, running a 2G-GSM- and/or 3G-WCDMA-based network is circuit-switched fallback, short CSFB. If there is an incoming (mobile terminated) or outgoing (mobile originated) call, the terminal will establish first a connection with the LTE network, to be redirected to either 2G-GSM or 3G-WCDMA, dependent on the availability or the operators strategy. CSFB is widely acknowledged being the minimum solution to cover also the roaming case. Note, that CSFB is also defined for 3GPP2-based technologies, such as CDMA2000®1xRTT.

Simultaneous Voice and LTE (SV-LTE): Simultaneous Voice and LTE, short SV-LTE, is another deployment strategy that has been utilized by network operator, running CDMA2000®1xRTT networks. In this case, the terminal has two TRX chains, one for LTE and one for 1xRTT. The terminal registers with both networks. Data is routed via LTE, but voice and SMS are transmitted and/or received via CDMA2000®1xRTT. Naturally running two TRX chains has impact on terminal complexity and power consumption of the end user device.

The different types of voice and SMS delivery via LTE are described in great detail in application note 1MA197 [Ref. 26].

9 LTE Testing

LTE testing is a comprehensive subject. Therefore the following sections consider important aspects without the aim to provide a complete description. More detailed information in additional Rohde & Schwarz documents is referenced, when useful.

9.1 General aspects

The new concepts utilized with LTE and enhancements of known functionality from other standards do of course influence the testing on LTE-capable base station and handset as well as for network optimization and maintenance. The challenges coming along from a testing point of view can be summarized as follows:

- Higher bandwidths, up to 20 MHz (100 RB),
- Transmission schemes: OFDMA and SC-FDMA,
- No transmit filter definition as in 3G,
- Multiple antennas, antenna configuration,
- Complex Physical and MAC layer (scheduling, retransmission protocol (HARQ), timing requirements, etc.),
- Signaling aspects (simpler, but new protocol architecture),
- Conformance aspects (RF, RRM, protocol),
- Throughput verification and end-to-end (E2E) performance,
- LTE interworking with legacy standards.

The next sections provide a more detailed look on all these different aspects of testing.

9.2 LTE base station testing (enhanced NodeB, eNB)

As for 3G (UTMS/WCDMA) tests on a base station are done without signaling and are focused on RF conformance only which is described in 3GPP's Technical Specification (TS) 36.141 Evolved Universal Terrestrial Radio Access (E-UTRA) Base Station (BS) conformance testing (Release 8) [Ref. 16]. All tests are based on the core requirements defined within 3GPP TS 36.104 for E-UTRA BS radio transmission and reception (Release 8).

9.2.1 Power amplifier design aspects

As OFDMA is the transmission scheme of choice for the LTE downlink, developers can leverage from their expertise gained with technologies like WiMAX and WLAN that are also utilizing OFDM. But the use of OFDMA with its advantages of robustness against multipath fading and efficient use of the available spectrum comes along with a first challenge. The independent phases of the multiple subcarriers are resulting in a high peak-to-average power ratio (PAPR), also known as crest factor, while adding them up constructively. This puts challenges on power amplifier and transmitter chain design keeping cost versus performance in mind, as a high PAPR requires a wide dynamic range. Estimating the crest factor for example with a CCDF is therefore an important measurement. Design engineers have to perform this measurement for various conditions, where the input signal has different crest factors.

Figure 39 shows a CCDF measurement of an LTE downlink signal. The measured PAPR in LTE are comparable to the one measured for other OFDM-based technologies, for example WiMAX.

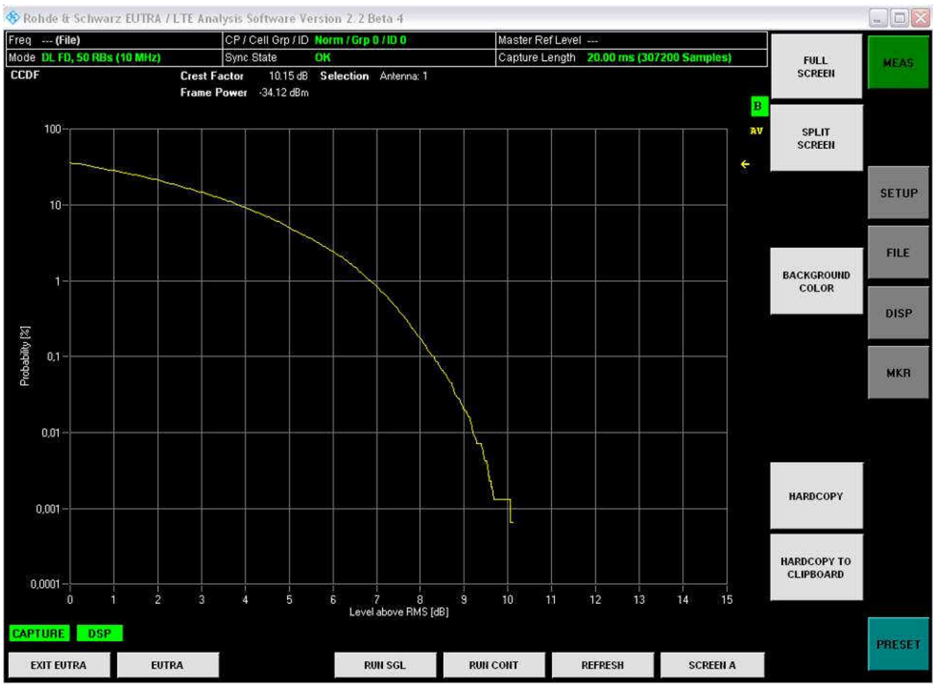


Figure 39: CCDF measurement

Besides estimating the crest factor with a CCDF furthermore power measurements, signal quality measurements and spectrum measurements are executed that help the design engineer to determine the best trade-off within these constraints. Passing these types of measurements is required to meet the requirements in the RF conformance specification, which are discussed in more detail in the next section.

Beside a high crest factor transmission schemes such as OFDM have to deal with memory effects. This means, that the transfer characteristic is dependent on the previous transmitted signal. The output at a given time instance depends not only at the present input signal, but also on the previous signal. A high signal peak may thus change the transfer characteristic for a following much smaller signal level. Typical indications for a memory effect are AM/AM and AM/PM conversion curves with hysteresis and 3^{rd} order intermodulation products (ID3) that show a non-symmetric behavior. A countermeasure for this is to pre-distort the signal. The required pre-distortion model can be created with Rohde & Schwarz R&S®FS-K130PC distortion analysis software. This software computes a mathematical description of the power amplifier, more general device under test (DUT). The software controls a signal generator, to stimulate the DUT as well as a signal and spectrum analyzer to capture the IQ data, measuring harmonics and intermodulation. By knowing input and output signal a model of the DUT can be computed. The basic measurement setup is shown in Figure 40.

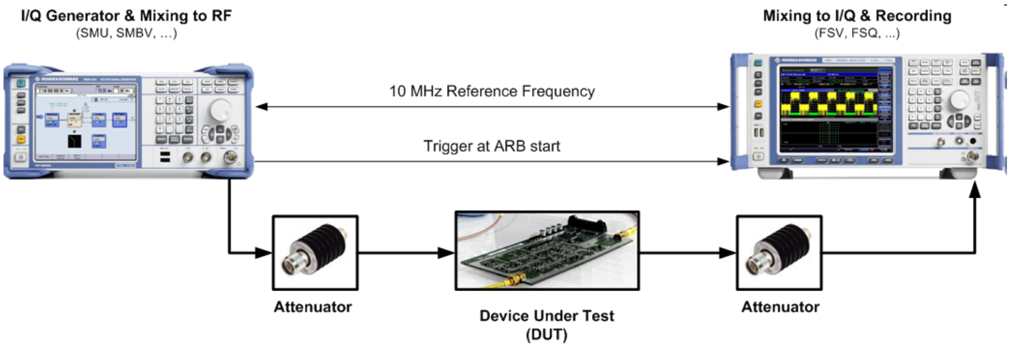


Figure 40: R&S®FS-K130PC distortion analysis software – basic measurement setup

The inverse of this model can be used to pre-distort the signal which linearizes the power amplifier. For modeling the DUT a polynomial approach or Volterra-based approach can be used. Both are supported within the software. The later one provides more freedom and flexibility and is the preferred method to model also memory effects. After applying the calculated pre-distortion model the software offers measurement capabilities (AM-AM, AM-PM, CCDF, EVM, Spectrum (ACLR), etc.) to analyze and visualize the improvement. Furthermore the model can be exported into Matlab to be used in a simulation environment.

9.2.2 eNB transmitter characteristics

The RF conformance aspects of transmitter testing on a LTE-capable base station are covered in section 6 of 3GPP TS 36.141 [Ref. 16].

As in UMTS (WCDMA) the tests do include power measurements, modulation and signal quality measurements and spectrum measurements, which are adapted due to the use of OFDMA as transmission scheme in the downlink. For each measurement an **enhanced transmission model** (E-TM) has been defined. The base station needs to be configured to set up a signal according to the defined E-TM, where the measurement is taken on. The following table provides an overview, showing the measurement category, the actual measurement, the related sub-clause in [Ref. 16] and the test model that is linked to the measurement.

Category	Measurement	Sub-clause TS 36.141	Test Model
Power	Base station output power	6.2.	E-TM1.1
	Resource Element (RE) power control dynamic range	6.3.1.	E-TM used for EVM measurement is sufficient
	Total power dynamic range	6.3.2.	E-TM3.1, E-TM2
	Transmit ON/OFF power, Transmitter transient period (TD-LTE only measurement)	6.4.1., 6.4.2.	E-TM1.1
	DL RS power	6.5.4.	E-TM1.1
Signal quality	Frequency Error	6.5.1.	Tested with EVM
	Error Vector Magnitude	6.5.2.	E-TM3.1, repeated for E-TM3.2, E-TM3.3 and E-TM2
	Time alignment between transmitter branches	6.5.3.	E-TM1.1
Spectrum	Occupied bandwidth	6.6.1	E-TM1.1
	ACLR	6.6.2.	E-TM1.1, repeated for E-TM1.2
	Operating band unwanted emissions	6.6.3	E-TM1.1, repeated for E-TM1.2
	Transmitter spurious emissions	6.6.4	E-TM1.1
Intermodulation	Transmitter Intermodulation	6.7	E-TM1.1

Table 22 : eNB transmitter characteristics measurements according to 3GPP TS 36.141 [Ref. 16]

All defined tests can be carried out using Rohde & Schwarz high end spectrum and signal analyzers **FSW, FSQ** or **FSG** or the mid-range signal analyzer **FSV**. Software options FSQ-K100 / FSV-K100 are needed for LTE downlink signal analysis. Besides using the instrument options Rohde & Schwarz provides also application software that can be installed on an external PC. This software can remotely control the above mentioned instruments, post-process the captured IQ data and displays the results. Both, software and instrument options are supporting all the enhanced test models, which are defined for the different LTE bandwidths.

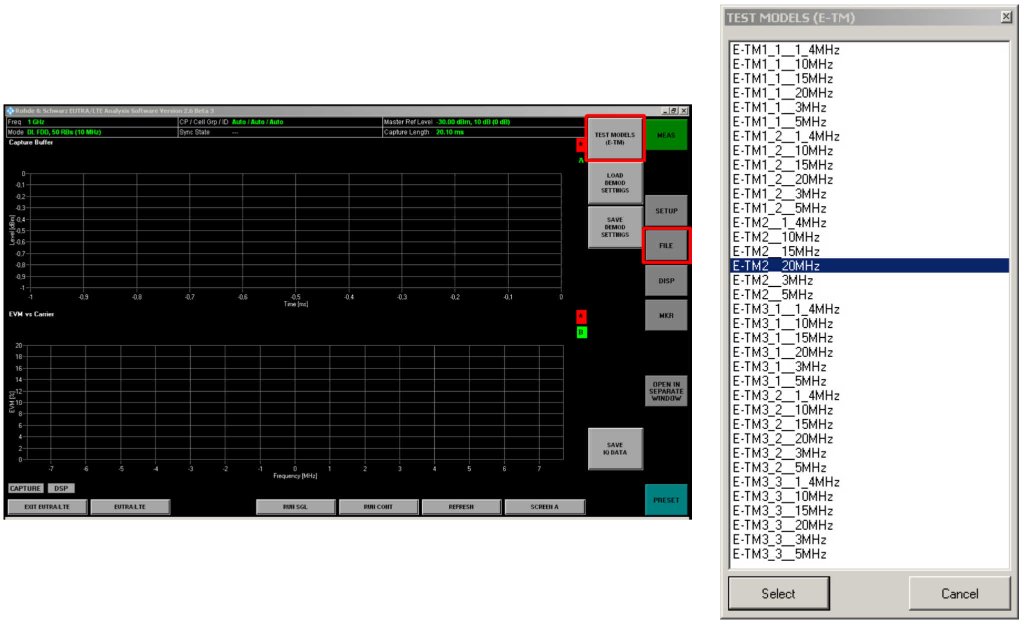


Figure 41: E-TM are supported with the EUTRA/LTE analysis software / instrument options

Rohde & Schwarz signal generator solutions can be used as a reference to generate E-TM for all LTE frequency bands and type of bandwidths. As for signal analysis all test models for LTE FDD and TD-LTE are fully supported.

Figure 42 shows an example of various measurements that can be taken with the PC application LTE software. The upper part of the screen shows the power per resource element (RE) over RB for E-TM3.1 for a 10 MHz signal. The lower part of the screen shows the power for the PDSCH. As it can be seen E-TM3.1 defines an allocation of all 50 available RB.

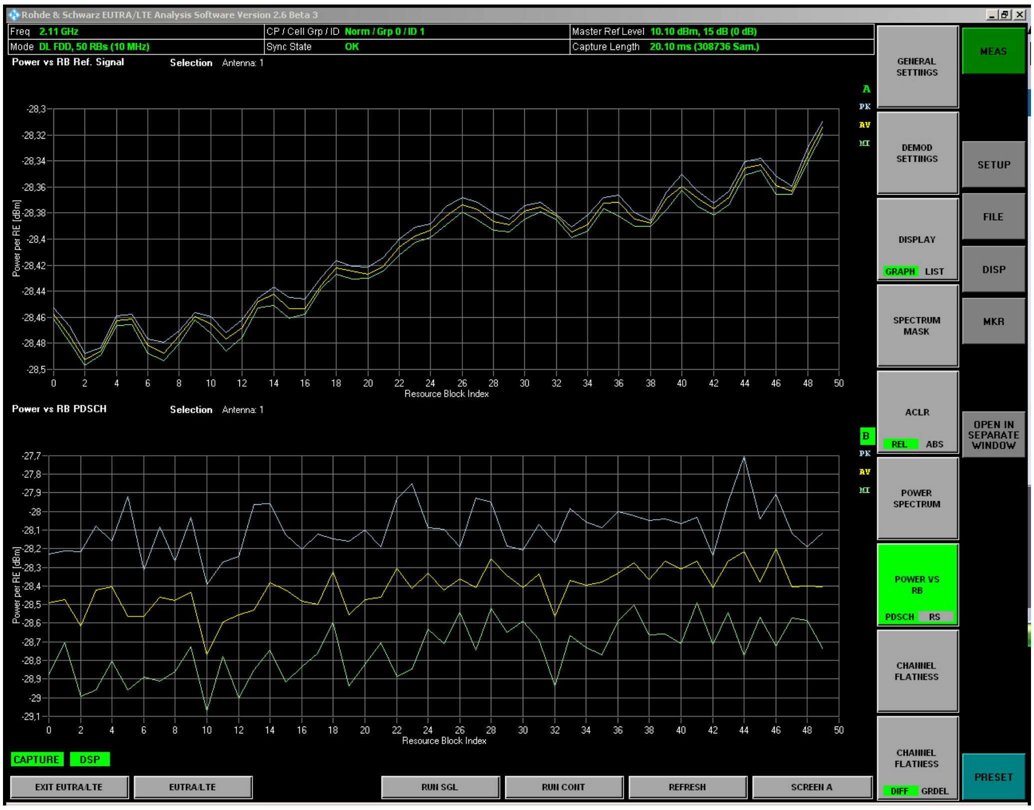


Figure 42: Power vs. RB Reference Signal and RB PDSCH (E-TM3.1, 10 MHz)

Figure 43 shows the same measurement, but this time for E-TM2. Both test models play an important role in estimating the total power dynamic range of a LTE-capable base station.

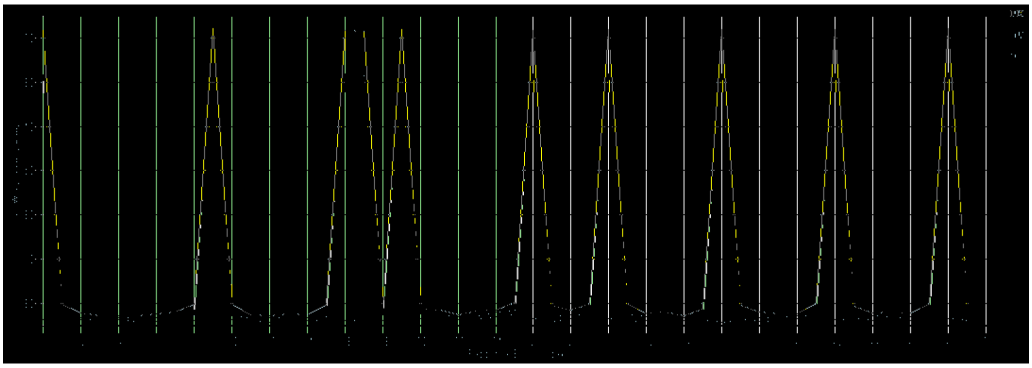


Figure 43: Power vs. PDSCH RB (E-TM2, 10 MHz)

For both test models the ***OFDM Transmit Symbol Power*** **(OTSP)** needs to be measured in order to conduct the total power dynamic range. OSTP is listed in the numeric overview of the most relevant measurement taken by the software. It is taken in the 4th OFDM symbol as this symbol contains only user data. The estimated OSTP is therefore impacted by the allocation, which is different for the two test models. Figure 44 and Figure 45 shows the numeric overview for E-TM3.1 and E-TM2, where the measured value for OSTP is highlighted.

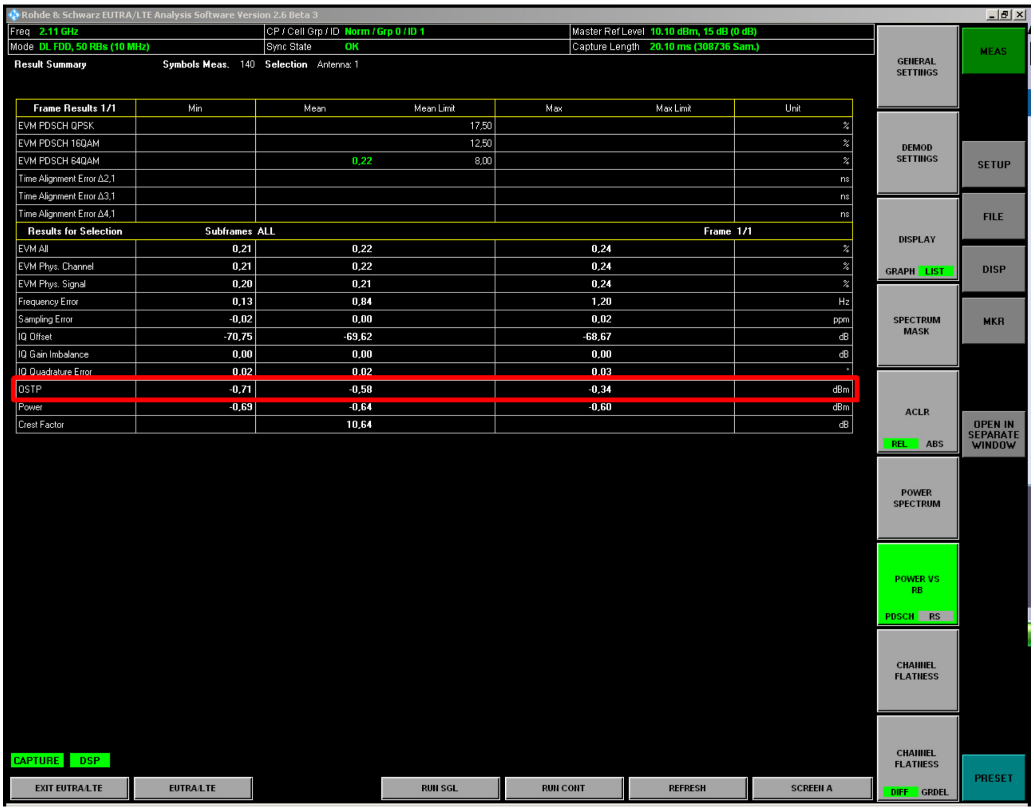


Figure 44: OSTP for E-TM3.1, 10 MHz

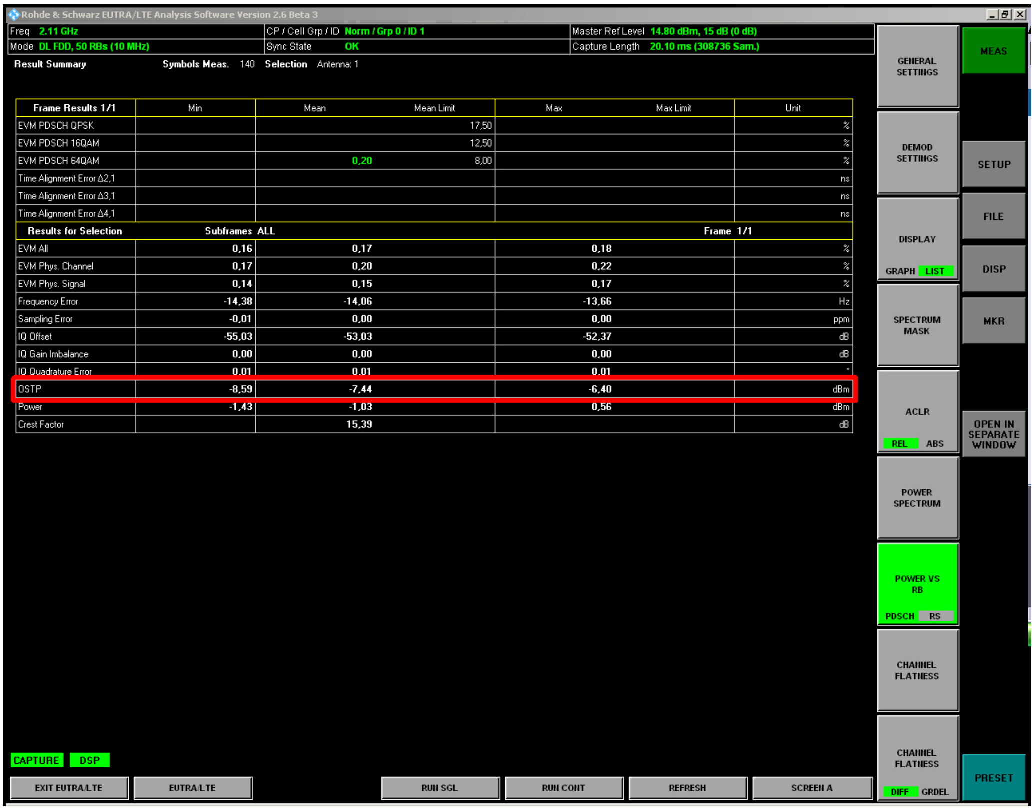


Figure 45: OSTP for E-TM2, 10 MHz

With a total power dynamic range of 9.3 dB it is well in the defined limits, which are shown in Table 23.

E-UTRA channel bandwidth (MHz)	Total power dynamic range (dB)
1.4	7.3
3	11.3
5	13.5
10	16.5
15	18.3
20	19.6

Table 23 : Limits total power dynamic range [Ref. 16]

A detailed description of all transmitter measurements performed on an eNB and how to use Rohde & Schwarz signal and spectrum analyzers for this task can be found in R&S application note 1MA154 [Ref. 24].

9.2.3 eNB receiver characteristics

The receiver aspects of RF conformance testing on a LTE-capable base station are covered in section 7 of 3GPP TS 36.141 [Ref. 16].

Comparable to the E-TM models for transmitter testing, Fixed Reference Channels (FRCs) are defined for base station receiver testing. All FRCs are fully supported with Rohde & Schwarz signal generator solutions. The receiver of a LTE base station will be stimulated with these well-defined signals, where the measurements are taken on. These measurements and the associated FRCs are listed in Table 24.

Measurement	Sub-clause TS 36.141	FRC[2]
Reference sensitivity	7.2	A1-1, A1-2, A1-3
Dynamic range dynamic range	7.3	A2-1, A2-2, A2-3
In--channel selectivity	7.4	A1-2, A1-3, A1-4, A1-5
Adjacent Channel Selectivity (ACS)	7.5	A1-1, A1-2, A1-3
Blocking	7.6	A1-1, A1-2, A1-3
Receiver spurious emissions	7.7	E-TM 1.1 at Pmax [3]
Receiver intermodulation	7.8	A1-1, A1-2, A1-3

Table 24: eNB receiver characteristic measurements [Ref. 16]

All measurements require the achievement of a certain percentage of the maximum throughput, which depends on the selected FRC. The generation of Fixed Reference Channel (see Figure 46) as well as customized LTE signals for uplink and downlink is supported on Rohde & Schwarz signal generators **SMU200A**, **SMATE200A**, **SMBV100A,** or **SMJ100A**. LTE functionality is simply activated with software option SMx-K55 (*Digital Standard LTE/EUTRA*). 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 on the instrument. 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.

The In-channel selectivity measurement is unique for LTE, where all other measurements in Table 24 are known from UMTS/WCDMA and are only adapted to LTE. In-channel selectivity is the reverse of the In-band emission measurement that is specified for LTE handset testing (see below). With this measurement the ability of the eNB receiver is checked, to maintain a certain throughput while suppressing the IQ leakage. Table 25 shows the requirements for the In-Channel selectivity test for a 10 MHz LTE signal. The required interferer for this test is a second LTE signal, that has the same bandwidth as the wanted signal and which uses an allocation of 25 RB. Wanted and interfering signal have different power settings.

[2] Depending on bandwidth, see [Ref. 16]
[3] Receiver spurious emissions are measured with a specific transmitter reference channel operated at maximum output power of the eNodeB, see [Ref. 16]

E-UTRA channel bandwidth (MHz)	Reference measurement channel	Wanted signal mean power [dBm]	Interfering signal mean power dBm]	Type of interfering signal
10	A1-3	-97.1	-77	10 MHz E-UTRA signal, 25 RBs

Table 25: Requirements In-Channel Selectivity, LTE 10 MHz [Ref. 16]

The FRC that needs to be used for the wanted signal is FRC A1-3. Figure 46 shows how to set up an FRC with the SMU200A.

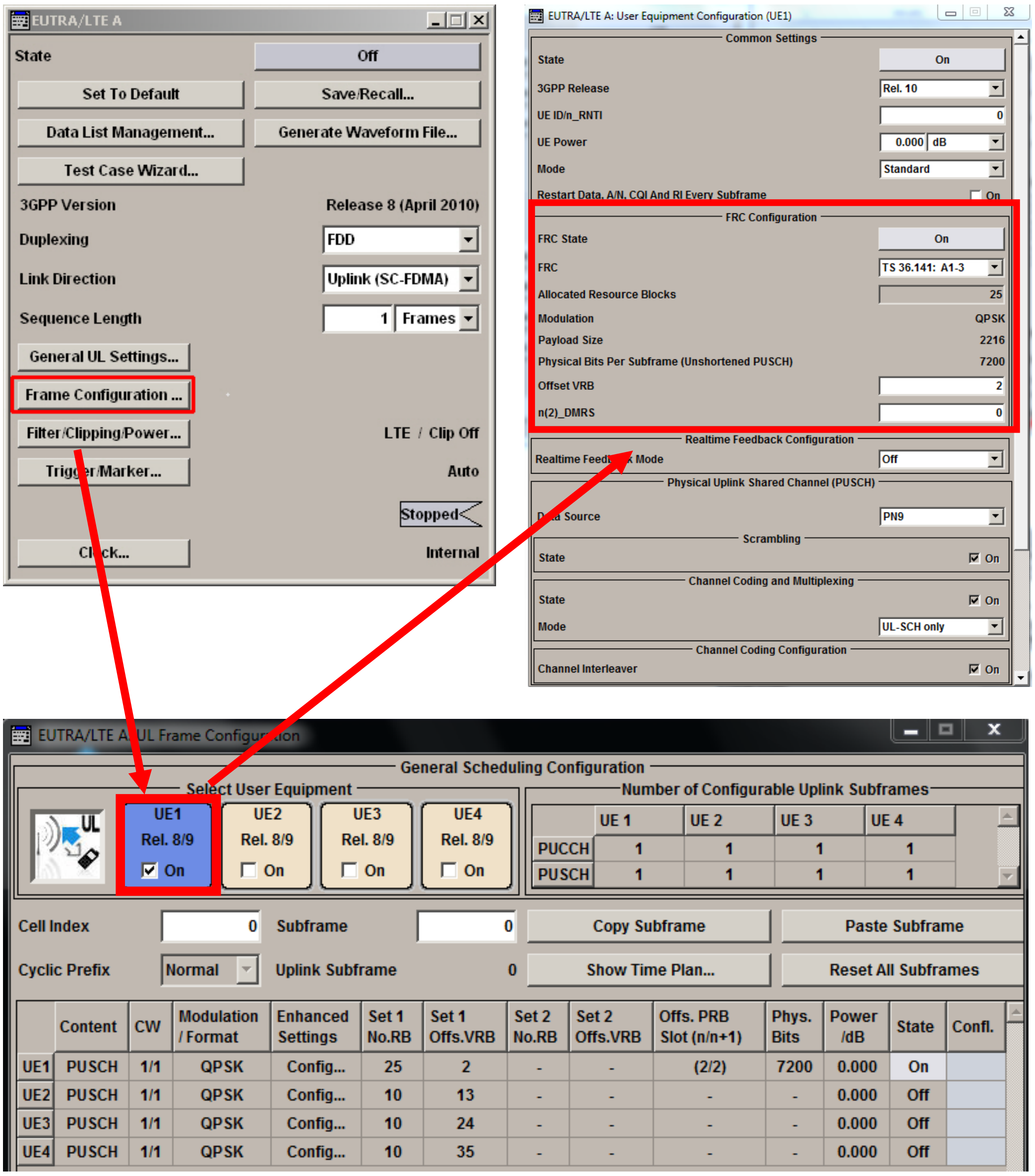


Figure 46: Configuring FRC on R&S®SMU200A Vector Signal Generator

With this and other kinds of test the two-path concept of the SMU200A pays of another time. With two signal generators in one instrument the test setup stays simple and the design engineer does not need to worry about reference clock settings and triggering. Figure 47 shows the block diagram for the In-Channel selectivity test with the SMU200A.

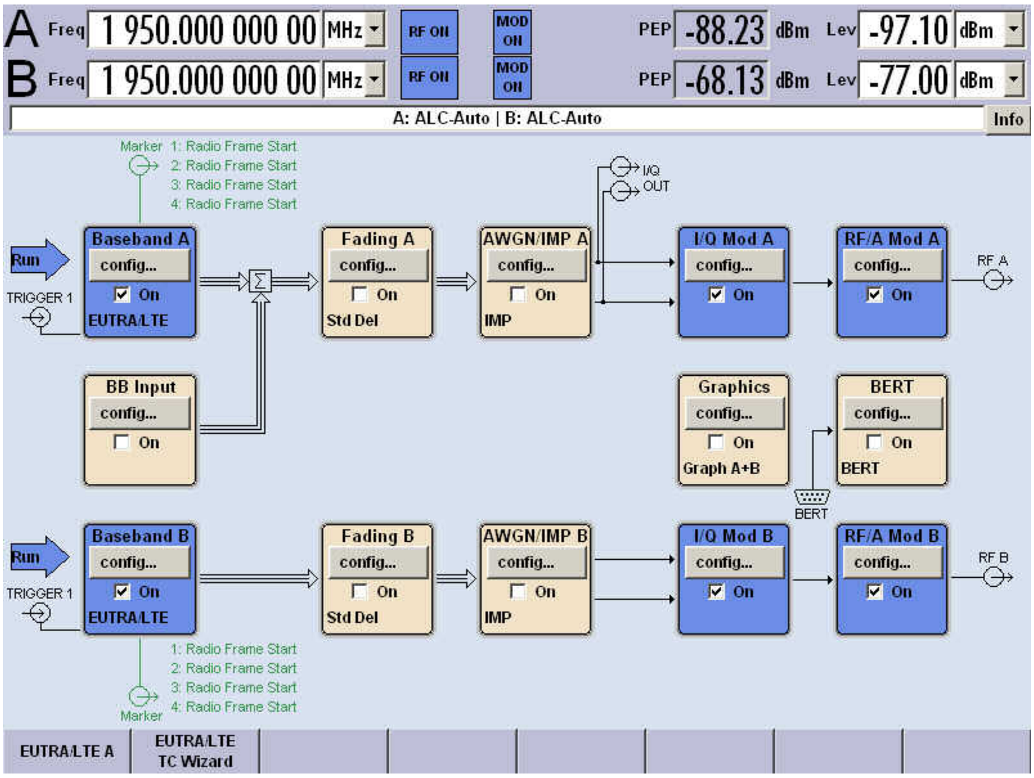


Figure 47: Block diagram SMU200A for In-Channel Selectivity according to TS 36.141 [Ref.16]

A detailed description of all receiver tests performed on an eNB and how to use Rohde & Schwarz signal generators for these tasks can be found in application note 1MA154 [Ref. 24]. Note that some receiver tests exist, which need an additional analyzer (e.g. spurious emission tests).

9.2.4 eNB performance aspects

Performance testing on an eNB is covered in section 8 of 3GPP TS 36.141 [Ref. 16]. Table 26 provides an overview.

Measurement	Sub-clause TS 36.141	FRC[4]
Performance requirements PUSCH (QPSK, 16QAM, 64QAM)	8.2.1	A3-1, A3-2, A3-3, A3-4, A3-5, A3-6, A-37; A4-1, A4-2, A4-3, A4-4, A4-5, A4-6, A4-7; ; A5-1, A5-2, A5-3, A5-4, A5-5, A5-

[4] Depending on bandwidth, see [Ref. 16]

		6, A5-7;
Performance requirements PUSCH - UL timing adjustment (Scenario 1, Scenario 2)	8.2.2	A7-1, A7-2, A7-3, A7-4, A7-5, A7-6; A8-1, A8-2, A8-3, A8-4, A8-5, A8-6
Performance requirements for HARQ-ACK multiplexed on PUSCH	8.2.3	A3-1, A4-3, A4-4, A4-5, A4-6, A4-7, A4-8
Performance requirements for High Speed Train conditions	8.2.4	A3-2, A-3-3, A3-4, A3-5, A3-6, A3-7
Performance requirements for PUCCH	8.3.1 – 8.3.3	-
Performance requirements for PRACH	8.4	-

Table 26: eNB receiver characteristic performance measurements [Ref. 16]

Performance tests on a base station are designed to estimate the throughput of the eNB receiver and related algorithms under various channel propagation conditions. Additionally, the performance of the eNB with regards to UL timing adjustment or HARQ operation is assessed. For the latter, in the past a Test UE or UE simulator was the instrument of choice performing this type of testing. Reason being is the closed-loop nature of these tests.

The instrument has to react on the feedback from the base station to adjust its transmission. Rohde & Schwarz offers a cost-effective solution based on the SMU200A vector signal generator for these closed-loop feedback tests. With a simple serial command, which is provided by the eNB under test, the SMU200A will adjust its transmission accordingly. For example, testing Timing Advance (TA) as specified in section 8.2.2. of TS 36.141 [Ref. 16], is now easily possible. The signal generator advances or delays its transmission, based on the feedback information received from the eNB. Timing Advance is important as all transmissions of all terminals in a cell have to arrive at the receiver at the same time to keep the orthogonality between transmissions and avoid inter-carrier interference.

For LTE this particular test case has been designed in that way, that two terminals need to be simulated: One stationary terminal as reference for the measurement and a second terminal that is subject to fading to simulate a moving device causing a varying relative delay of the received LTE signals. Additional receiver noise is simulated by superimposing additive white Gaussian noise (AWGN). Both devices transmit a defined FRC with a known maximum possible. Based on its timing measurement the base station design needs to provide timing advance commands for one or both simulated terminals, in order to maintain the required data throughput.

Figure 48 shows the modified measurement setup, based on the connection diagram that is provided within TS 36.141 [Ref. 16].

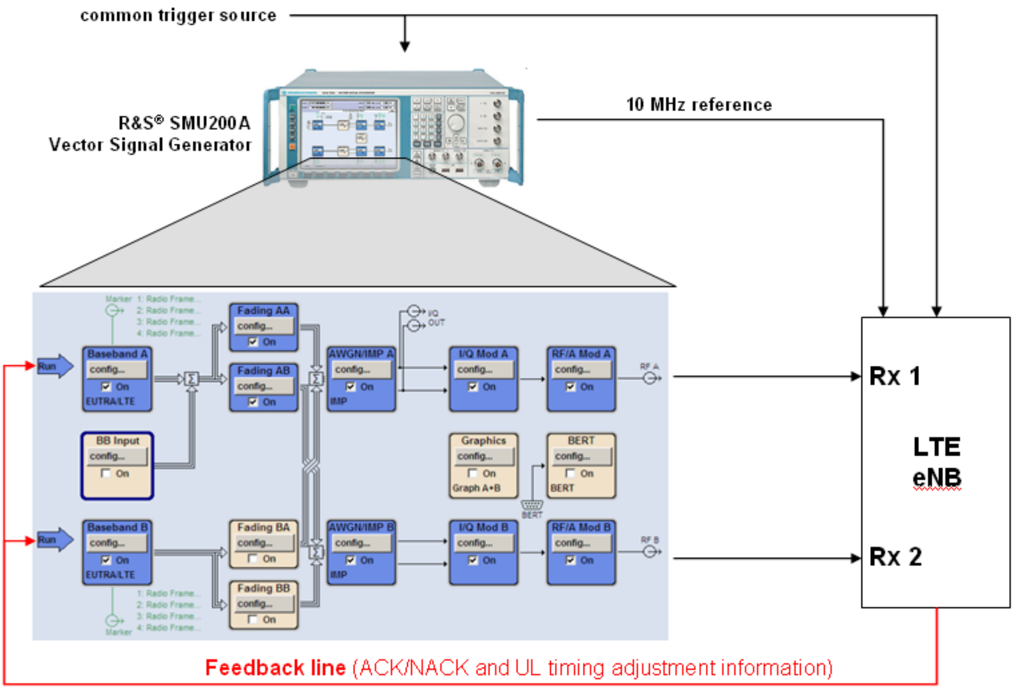


Figure 48: Measurement setup for UL timing adjustment acc. to section 8.2.2. in TS 36.141 [Ref.16]

The described functionality is provided with software option SMx-K69. To use this option the LTE personality (Option SMx-K55) for the signal generator is mandatory. A more detailed introduction on all eNB performance tests using Rohde & Schwarz SMU200A Vector Signal Generator can be found in application note 1MA162 [Ref. 25].

9.2.5 LTE test case wizard

A few examples of eNB receiver and performance tests have been discussed in the previous sections. Most of these tests are performed while a broadband interferer, noise and/or fading is present. This is to simulate realistic environments for testing. Due to the broadband nature of LTE and complex test cases defined applying the right settings is quite challenging in terms of right power levels, setting noise level and bandwidth, etc. As explained above the test setup stays already simple using a two-channel SMU200A, but Rohde & Schwarz simplifies the testing further while offering a test case wizard for LTE as integral part of the signal generator firmware. The test case wizard has already been introduced with WCDMA and has been extended to support LTE. By simply selecting the test case following the definitions in 3GPP TS 36.141 the SMU200A is configured automatically and ready to be used for receiver characteristic and performance test. For eNB transmitter testing the LTE test case wizard supports also the transmitter inter-modulation test case [Section 6.7, [Ref. 16]], where also a signal generator is needed. The receiver intermodulation test [Section 7.8, [Ref. 16]], as an example, requires three signal sources. The wanted signal, an interfering signal and a CW signal. With a traditional test approach this would require up to three signal generators. With the SMU200A all required signals can be generated with one instrument. Using the LTE test case wizard it is further reduced to nearly a single button operation. Figure 49 shows the test case wizard, where the intermodulation test case has been pre-selected.

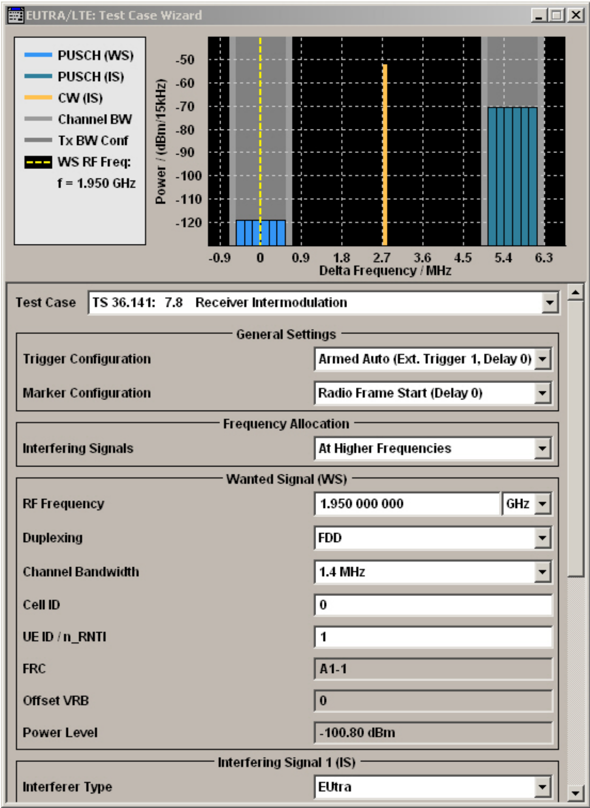


Figure 49: LTE test case wizard, configuring receiver intermodulation test acc. to TS 36.141 [Ref. 16]

As shown on the very top the test case wizard provides a small graphic to visualize the settings for each test case. Figure 50 shows the block diagram of the SMU200A for this particular test case after applying the settings. The two basebands (A and B) generate the LTE signals (wanted, interferer), where the AWGN functional block is used to generate the required CW interferer.

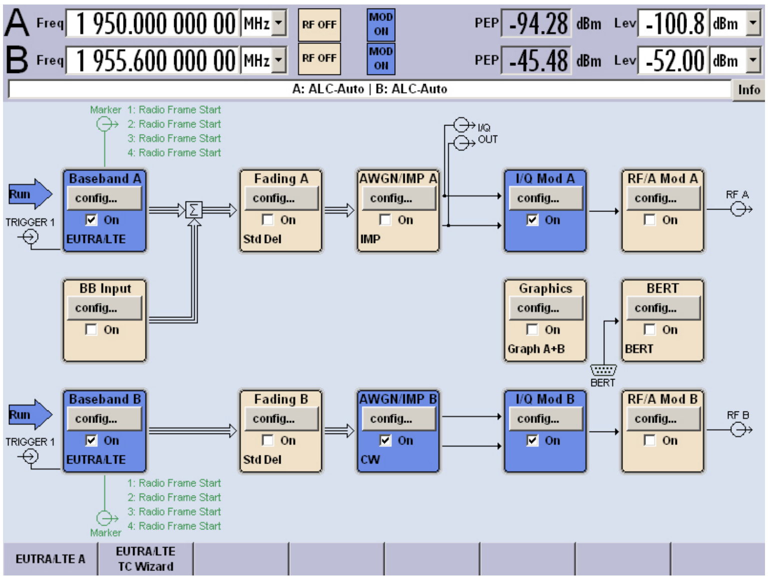


Figure 50: SMU200A block diagram for receiver intermodulation acc. to TS 36.141 [Ref. 16]

Furthermore, even test cases that – due to their definition – require two signal generators are handled by the test case wizard conveniently. An example is the Multi-user PUCCH test case defined in section 8.3.3. of 3GPP TS 36.141 [Ref. 16], where four separate LTE terminal signals (1 wanted + 3 interferers) need to be generated and faded individually. Due to the dual-path concept of the SMU200A, this test case can be covered by only two signal generators. In this particular example the user has only to select which SMU200A generates the wanted and first interfering signal and which instrument the other two interferers.

A prerequisite for using the LTE test case wizard are software options SMU-K55 and SMU-K69.

9.2.6 Overload testing

In line with the 3GPP specification the focus of standardized tests is RF conformance. That includes transmitter and receiver evaluation as well as performance tests. Rohde & Schwarz signal generator solutions can be used to further challenge the receiver implementation and related algorithms of the LTE base station design. Using basic instrument functions, allows performing a type of semi-dynamic overload testing.

One example for overload testing would be the simulation of several devices that attempt to access the network while performing the random access procedure. The SMU200A can easily be used for this type of testing based on the integrated arbitrary waveform replay functionality. In a first step basic system parameters need to be defined on the SMU200A, such as PRACH configuration and PRACH frequency offset. This type of information is provided in a real LTE network via system information towards the devices in the radio cell. In a second step, up to four devices are configured, where each carries its individually configured PRACH preamble, simulating the attempt to access the network. Depending on the previously configured settings these preambles could be send in even or odd numbered radio frames, and further in all or only specific subframes. In a real network the device would pick one of these possible subframes in a radio frame. Simulating this with a SMU200A is not a problem as all this is configurable. The created signal, simulating four different UEs, is stored in an Arbitrary Waveform (ARB) file. This process can be repeated as often as required, keeping the basic system parameters (see Figure 51).

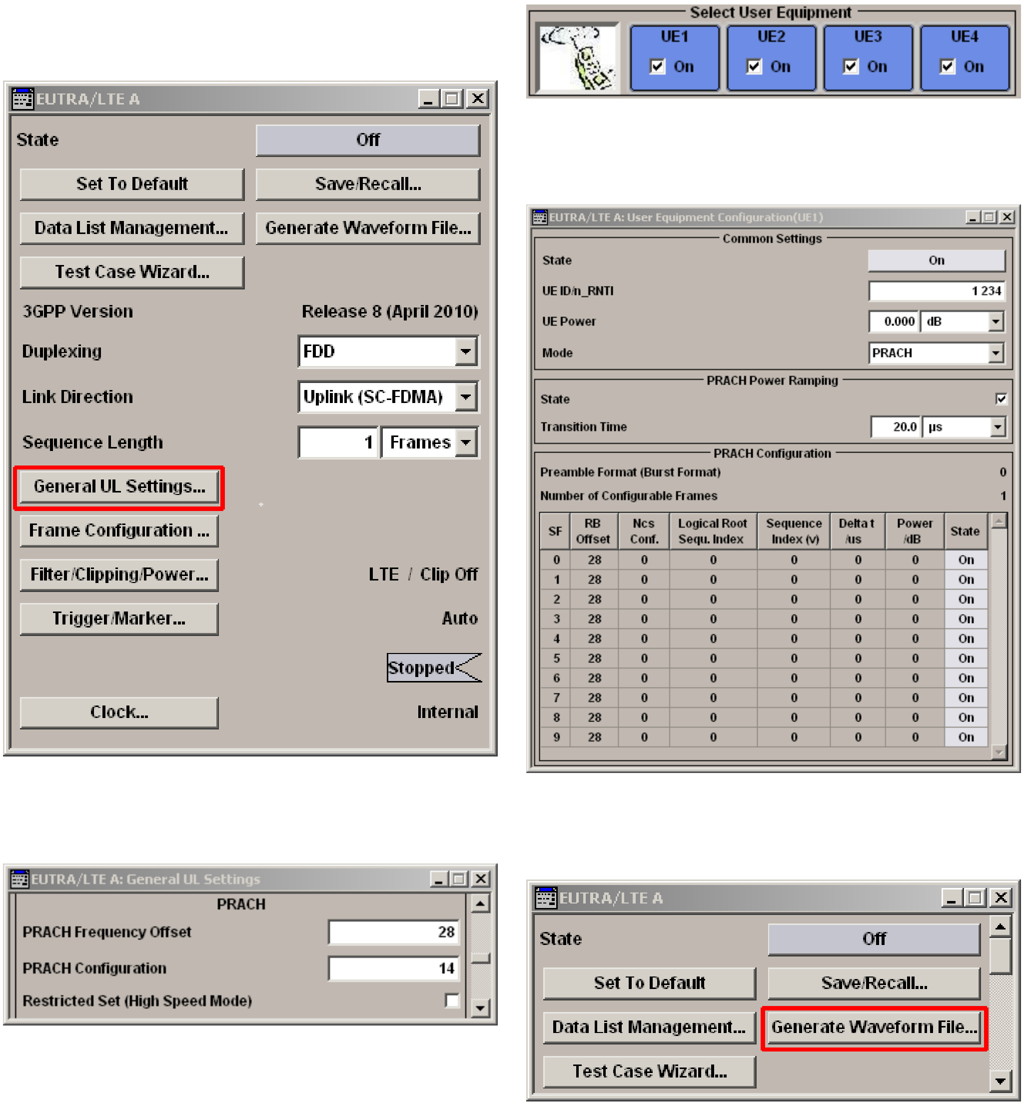


Figure 51: Basic parameter for PRACH overload testing with R&S®SMU200A Vector Signal Generator

While using the multi-carrier functionality within the ARB replay functionality of the SMU200A all created ARB files can be merged into one ARB file. A number of carriers will be defined, that need to match the number of previously created ARB files. With help of the carrier table one ARB file is mapped to one carrier. For each carrier a gain, phase or delay can be defined. It is important to set the carrier spacing to 0 Hz.

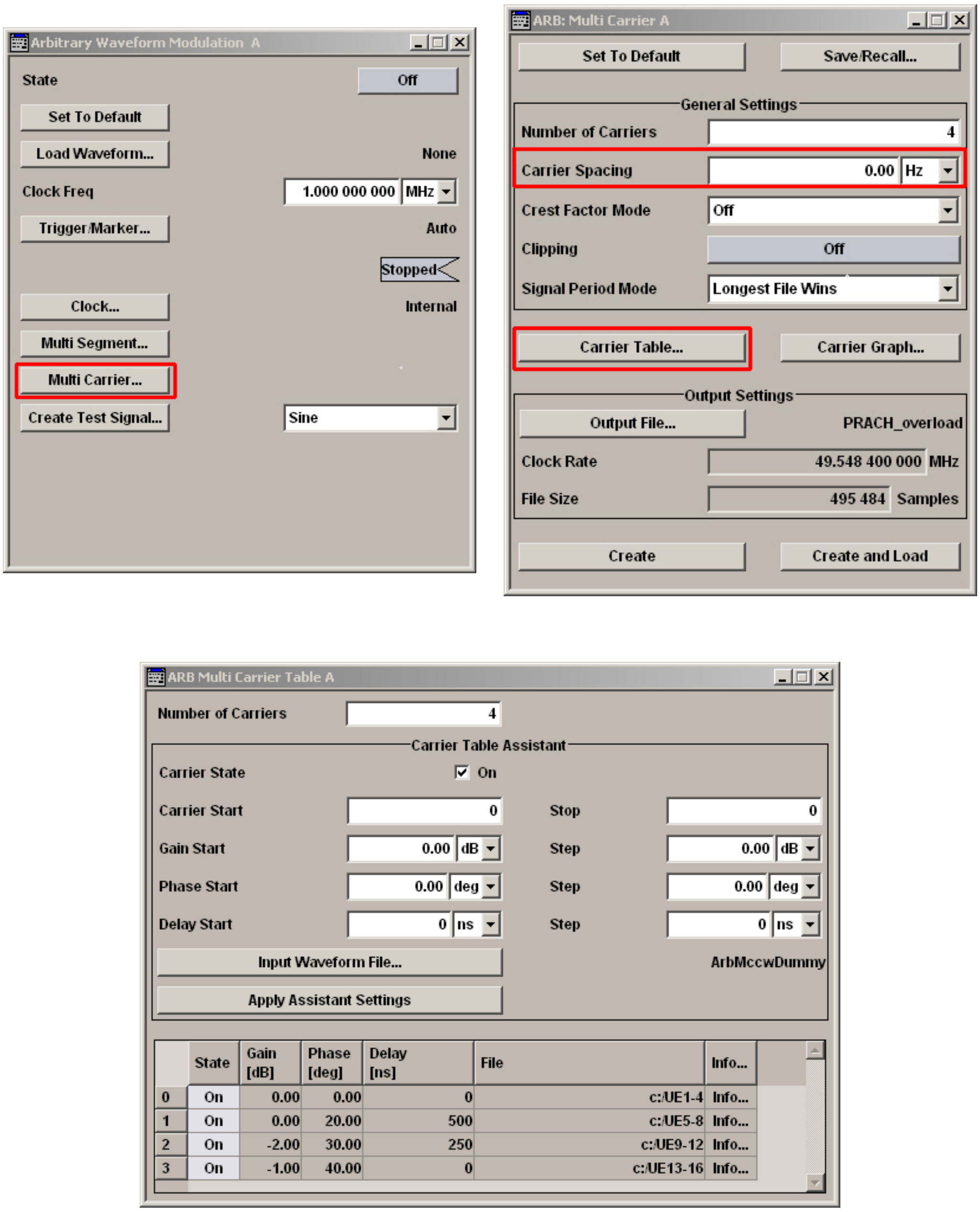


Figure 52: Creating a Multi-carrier ARB file for LTE PRACH overload testing

The described process can be easily automated by programming a small software application as all described parameters are fully accessible via remote control (GPIB or LAN interface).

9.2.7 LTE logfile generation – SMx-K81

Option SMx-K81 allows the user to access the intermediate results of the forward error correction chain during the internal signal generation process. The intermediate results are stored in text files that are freely accessible. By means of this feature, cross-verification of the forward error correction (FEC) chain for uplink and downlink of users own LTE implementation can easily be performed.

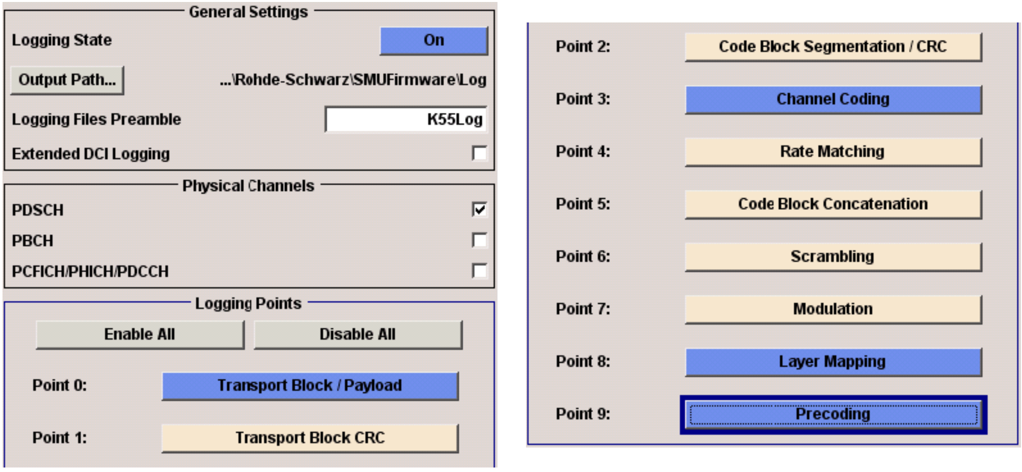


Figure 53: SMx-K81 - LTE logfile generation

For testing the TX or RX implementation the coded bit stream of the signal generator simply needs to be compared to the output of the TX and RX module, respectively. This eases debugging, optimizes the design flow and shortens development times.

9.2.8 Digital IQ interface – CPRI™

Traditionally, a base station was a rack of equipment inside a shelter, connected by RF cable to a tower mounted amplifier and the antenna. Nowadays, base stations implement remote radio equipment. The complete RF module or Remote Radio Head (RRH) – more general radio equipment (RE) – is placed into a weatherproof box mounted on the tower close to the antenna. The main unit that contains the control and baseband signal processing is called Radio Equipment Control, REC. The REC communicates with the remote RF module via a digital data connection. Network operators intend to combine REC and RE manufactured by different vendors. Thus, these base station components are often developed and manufactured independently and also have to be tested. The industry has agreed upon defining digital interface protocol standards for the communication between the two main parts of a base station. The most widely spread protocol standard for this purpose is the common public radio interface (CPRI™). Test solutions thus need to provide the possibility to connect to the device under test utilizing a digital baseband interface.

The Rohde & Schwarz solution to address these test needs is based on the **R&S®EX-IQ-BOX** digital signal interface module**.** The EX-IQ-BOX can be used to convert custom or standardized digital IQ formats, such as e.g. CPRI™, into the internal digital IQ format, that is used on Rohde & Schwarz signal generators, spectrum analyzers and wireless communication testers.

Figure 54: Rohde & Schwarz EX-IQ-BOX digital signal interface module

An introduction to the EX-IQ-BOX is given in application note 1MA168 [Ref. 22].

The physical connection to different types of IQ interfaces – custom or standardized – is realized using different adapter boards (=break-out boards) that are plugged into the EX-IQ-BOX. Figure 55 shows the CPRI break-out board as an example.

Figure 55: EX-IQ-BOX CPRI break-out board

With the EX-IQ-BOX the radio equipment or radio equipment control can be tested.

Figure 56 and Figure 57 illustrate as an example the test setup for radio equipment testing via CPRI™ for downlink and uplink, respectively.

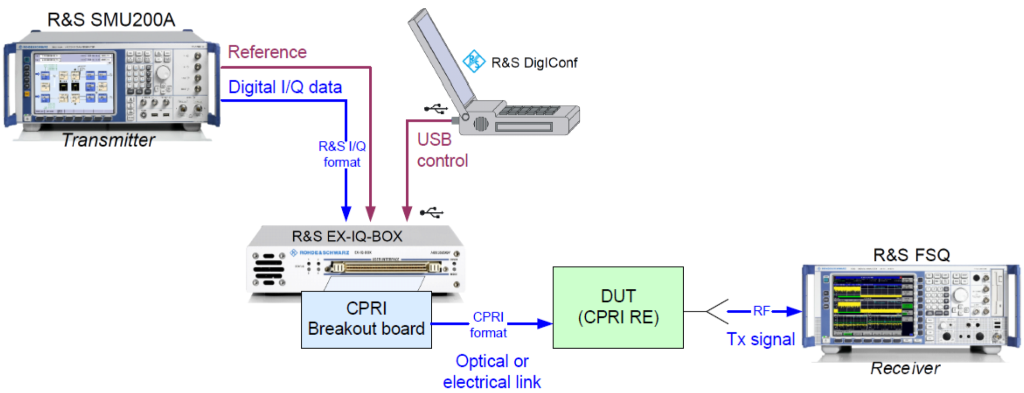


Figure 56: Test setup for RE testing (Downlink)

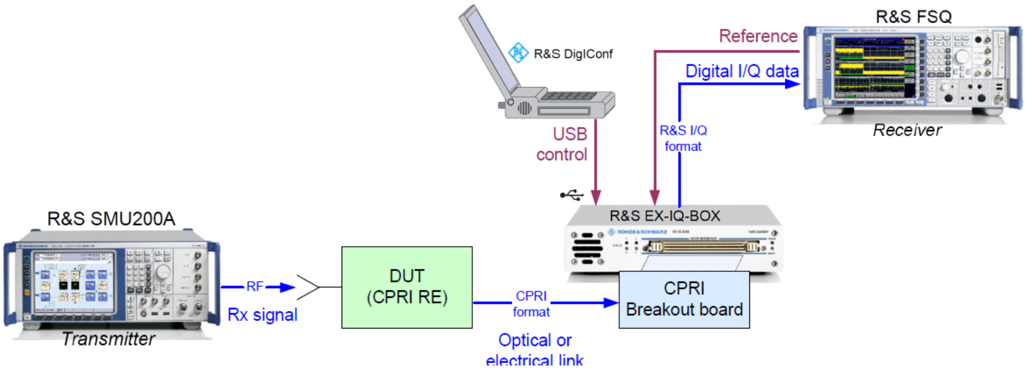


Figure 57: Test setup for RE testing (Uplink)

Further details on CPRI™ and related testing of radio equipment can be found in application note 1GP78 [Ref. 17].

Besides the radio equipment, or Remote Radio Head (RRH), the EX-IQ-BOX can be used to test the digital baseband of the base station, referred to as Radio Equipment Control (REC). The test setup is shown in Figure 58.

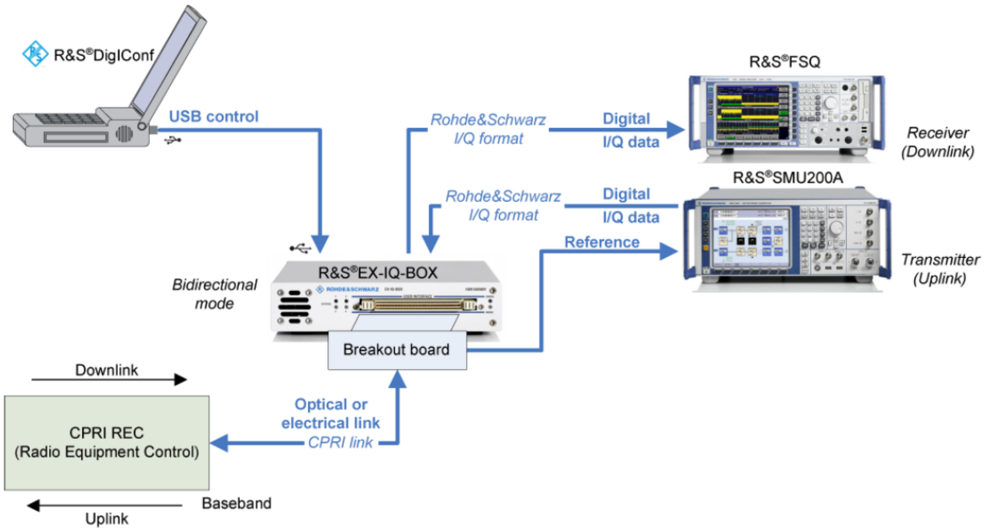


Figure 58: Test setup Radio Equipment Controller (REC) testing with R&S EX-IQ-BOX

Convenient configuration of the EX-IQ-BOX is done via an easy-to-use software tool named DigIConf. The software allows setting of all relevant digital signal parameters as well as configuration of the physical interface. Pre-defined interface settings for all state-of-the art standards such as 3GPP FDD (incl. HSDPA, HSUPA, HSPA+), LTE, WiMAX, and CDMA2000®1xRTT further simplify the test setup configuration. For further details please take a look at application note 1GP78 [Ref. 17].

9.3 LTE terminal testing (User Equipment, UE)

9.3.1 Rohde & Schwarz CMW500 Wideband Radio Communication Tester

Figure 59: R&S®CMW500 Wideband Communication Tester, configured as LTE protocol tester

The **Rohde & Schwarz CMW500 Wideband Radio Communication Tester** (Figure 59) is an universal hardware platform for all stages of LTE terminal testing from physical layer (Layer 1, L1) up to protocol (L2, L3), and from early R&D up to conformance, towards manufacturing, production and service.

Figure 60 summarizes the fields of application for the CMW500.

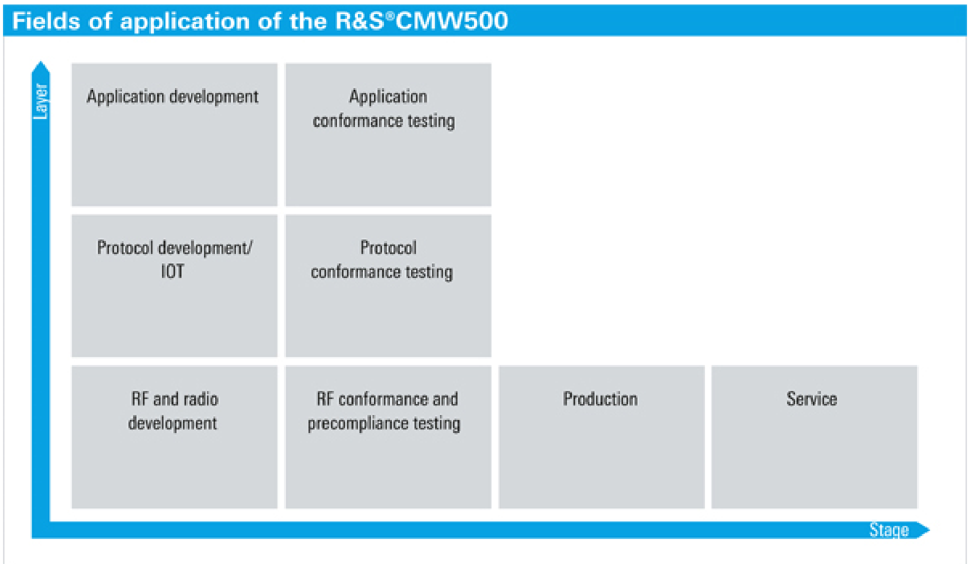


Figure 60: Fields of application for the R&SCMW500 Wideband Radio Communication Tester

Due to providing a flexible hardware configuration and software option concept the instrument can be easily adapted to the above mentioned applications. Note that the instrument is not designed for LTE only, instead all major cellular technologies as well as supplementary standards are supported that may be available in a wireless device. Table 27 gives an overview of supported standards and technologies.

Cellular	Broadcast	Connectivity
– LTE FDD / TD-LTE	– DVB-T	– WLAN a/b/g/n
– Mobile WiMAX™	– FM stereo	– Bluetooth®
– TD-SCDMA	– CMMB	
– CDMA2000® 1xRTT	– MediaFLO™	
– CDMA2000® 1xEV-DO	– T-DMB	
– WCDMA/HSPA		**Satellite Navigation**
– HSPA+		– GPS
– GSM		
– GPRS		
– EDGE		
– EDGE Evolution		
– VAMOS		

Table 27: Standards and technologies supported by R&S®CMW500 Wideband Radio Communication Tester

Due to multiple technology support the CMW500 is the right choice for mobility testing, commonly known as handover. The CMW500 supports intra-frequency and inter-frequency handovers for LTE as well as Inter-RAT for instance to GSM, WCDMA and CDMA2000®1xRTT and 1xEV-DO, not to forget LTE FDD to TD-LTE handover and vice versa.

9.3.2 LTE RF parametric testing

As discussed in the previous paragraph the CMW500 can be used for standalone RF parametric testing.

Figure 61: R&S®CMW500 Radio Wideband Communication Tester for LTE RF parametric testing

The scope of RF parametric testing on a LTE-capable handset is comparable to what is known from UMTS/WCDMA. From a transmitter perspective power, power control, transmit signal quality and spectrum will be tested. But the tests have been adapted to the use of SC-FDMA as uplink transmission scheme. As this is scheme is not known from other standards yet uplink signal characteristics need to be investigated with particular caution. Know measurement such as Adjacent Channel Power Leakage Ratio (ACLR) have been enhanced in that way, that the measurement is taken in two steps. Once, when the presence of another LTE carrier same bandwidth is assumed, and once when a 5 MHz WCDMA signal is present.

Beside the well understood measurements of Error Vector Magnitude (EVM), ACLR and others there are new measurements defined related to the OFDM-based transmission scheme and the bandwidth of transmission. The In-band emission measurement or EVM versus symbol are two examples, which are shown in Figure 62. With In-Band Emission the impact to non-allocated resource blocks is evaluated.

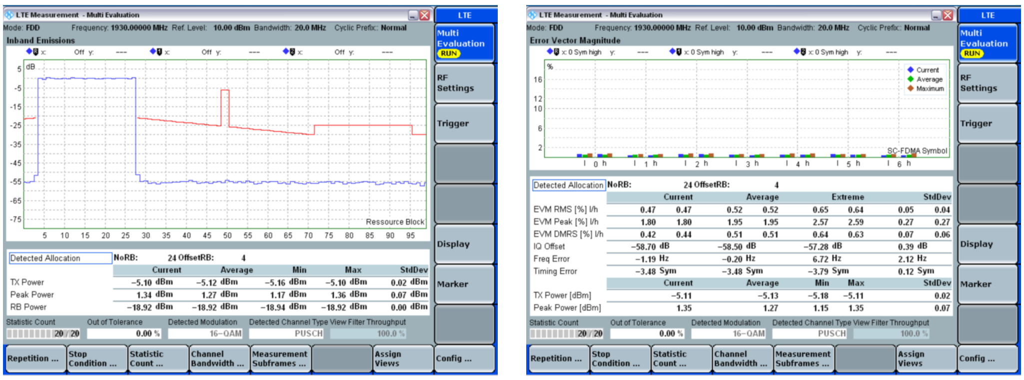


Figure 62: In-band emission (left) and EVM versus symbol measurement (right) [Ref. 18]

The EVM versus symbol measurement can be used to estimate the impact of the transmission filter to signal degradation. In contrast to 3G (WCDMA) there is no transmission filter defined in LTE. The design need to match the in-channel requirements (EVM, In-band emission) and out-of-channel requirements (ACLR, SEM). Principles of OFDM (or SC-FDMA) signal generation between two consecutive OFDM (or SC-FDMA) symbols can lead to spectral spikes in the frequency domain, degrading out-of-channel performance. A common way for improvement is applying time windowing to allow a smooth transition between generation of OFDM symbols. But this adds artificial inter-symbol interference to the signal, which results in a degraded EVM versus symbol, but is barley seen in the standard EVM versus subcarrier measurement.

Another example is the PRACH time mask measurement, which is shown in Figure 63.

Figure 63: PRACH time mask measurement [Ref. 18]

A more detailed introduction to LTE RF measurements, evaluating transmitter and receiver of a LTE-capable device using the CMW500 is given in application note 1CM94 [Ref. 23].

Beside the CMW500 Rohde & Schwarz FSx family of spectrum and signal analyzer is providing the required functionality to analyzer to perform RF signal analysis on the UE's transmitter. Figure 64 shows as an example the constellation diagram of an LTE uplink signal where the user data is using 16QAM modulation measured with the PC application EUTRA/LTE analysis software. The constellation points on the circle represent the demodulation reference signal which is based on a Zadoff-Chu type of sequence. Uplink signal analysis with the FSx option FS-K101 is required.

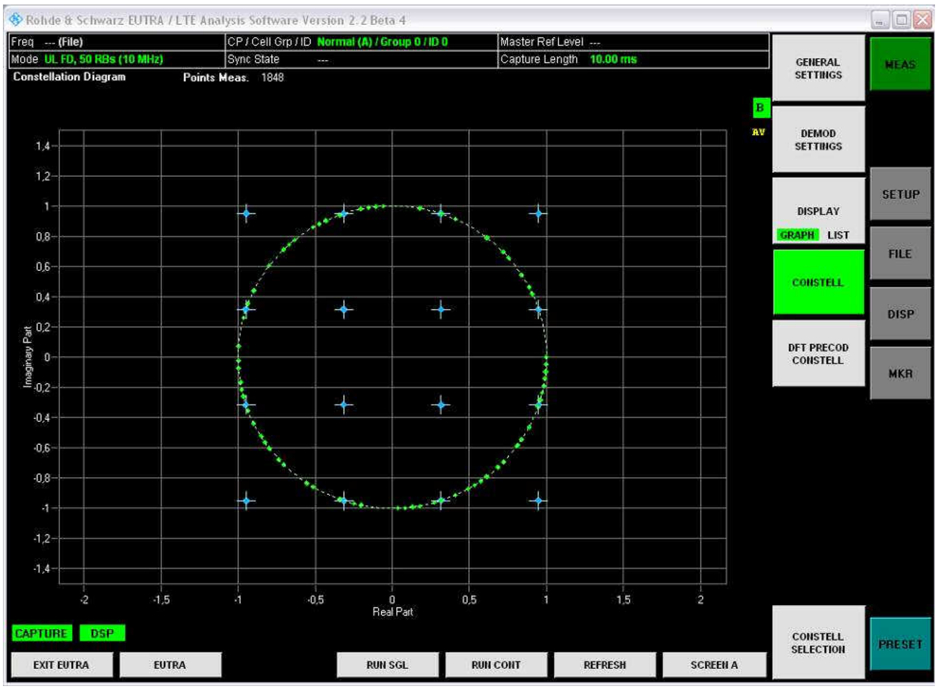


Figure 64: LTE uplink constellation diagram (16QAM)

9.3.3 Testing the physical layer of a LTE-capable device

The LTE physical layer (Layer 1, L1) has significant functionality and handles a lot of tasks. Beside the physical signals and physical channels in downlink and uplink, the associated physical layer procedures such as cell search, Hybrid ARQ (HARQ) retransmission protocol, scheduling, link adaptation, timing advance and uplink power control, buffer status report (BSR), power head room (PHR) reporting have stringent timing requirements. Therefore thorough testing of layer 1 and procedures is needed to guarantee LTE performance. Physical layer testing can be sub-divided into three major categories:

1. Data-path testing,
2. Functional testing and
3. Performance testing.

Data-path testing is understood as verifying the correct implementation of the LTE downlink and uplink physical channels. Testing starts with low-level block testing, and a stepwise integration of all functional blocks. **Functional testing** includes for example fixed scheduling, HARQ operation or report of channel quality (CQI, RI, PMI) under defined conditions in a static environment without applying fading and/or noise. **Performance testing** is performed in a full closed-loop operation, including dynamic scheduling in downlink and uplink, applying varying power levels as well as interferer and/or noise under fading conditions.

Rohde & Schwarz provides for both LTE modes (FDD and TDD) extensive physical layer test case packages, covering all testing aspects mentioned above. Packages R&S®CMW-KF506 and R&S®CMW-KF507 are designed for LTE FDD and include in total 100 test scenarios. KF506 focuses on basic procedure verification, such as cell search, system information acquisition and paging. In addition test scenarios for downlink and uplink forward error correction (FEC) chain verification are available as well as for enhanced procedure verification such as HARQ (Downlink (SISO, MIMO), Uplink), uplink power control or timing advance. Figure 65 shows as an example the block diagram for PUSCH power control testing.

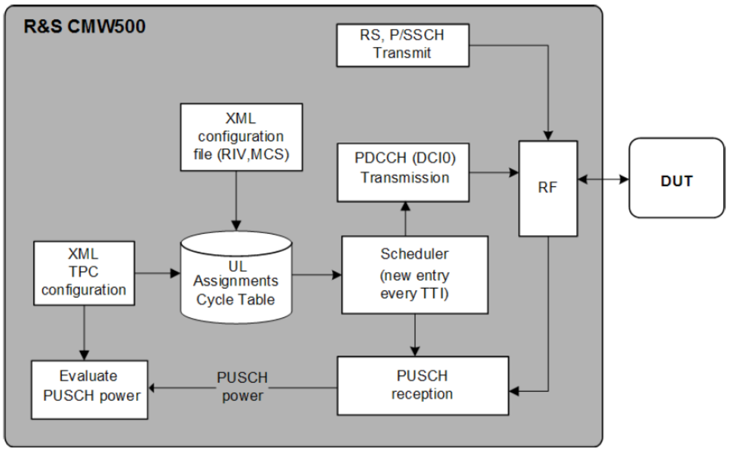


Figure 65: Block diagram for testing PUSCH power control (uplink), R&S®CMW-KF506

Test cases in package CMW-KF507 are designed to further analyze the correct transmission of uplink control information (UCI) on PUCCH and PUSCH, periodic or aperiodic (PUSCH-only). The corresponding package for TD-LTE physical layer testing is CMW-KF556, which includes all relevant test cases to verify the important timing aspects for TDD in terms of HARQ, scheduling, power control to name a few.

Beside the CMW500 a signal generator or spectrum analyzer can be used to check the correct implementation of downlink and uplink physical channels, respectively. 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 66.

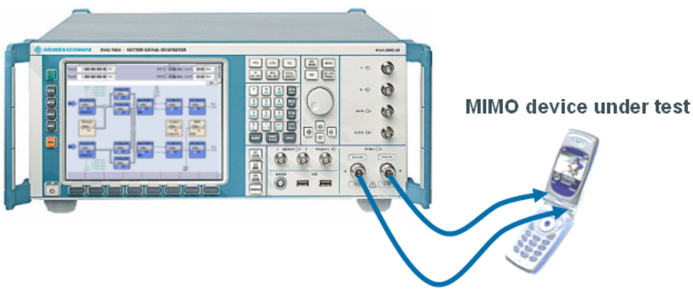


Figure 66: Downlink MIMO receiver test: Signal generator SMU200A provides LTE downlink signals from two transmit antennas including channel simulation

Figure 67 shows the user interface of the **SMU200A** for this setup in more detail.

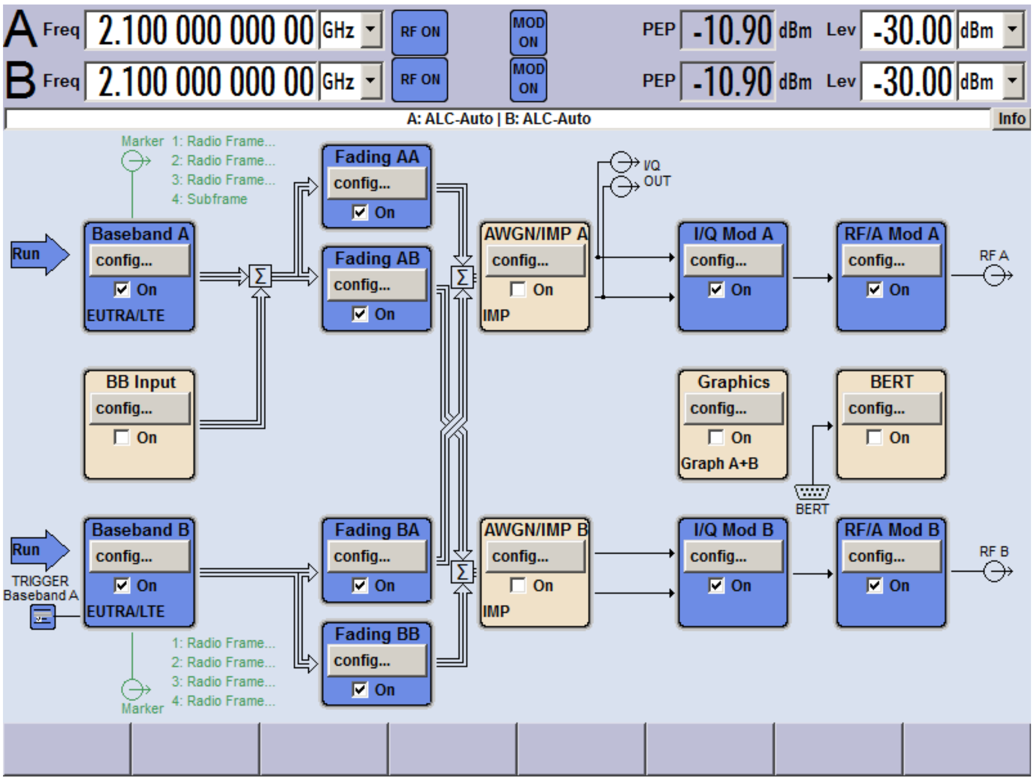


Figure 67: User interface of the SMU200A signal generator for 2x2 MIMO tests: The signal flow is shown from the generation of the two baseband LTE signals on the left via the four fading channels to the two RF outputs on the right.

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 configured. By use of a second signal generator, an extension to a 4x2 MIMO scenario is easily possible as well.

One highlight of Rohde & Schwarz signal generator solutions is the ability to schedule PDSCH resources automatically by configuring the appropriate DCI formats, transmitted on the PDCCH. Figure 68 shows as an example the configuration of DCI format 2, which is used to schedule a device for closed-loop spatial multiplexing (2x2 MIMO). The Resource Block assignment is done by directly setting the resource indication value (RIV). The transport blocks that are assigned to the two used LTE codewords of this spatial multiplexing scenario can be configured individually. Parameters like for example the used modulation and coding scheme, codeword swap or transmitted pre-coding information can be set.

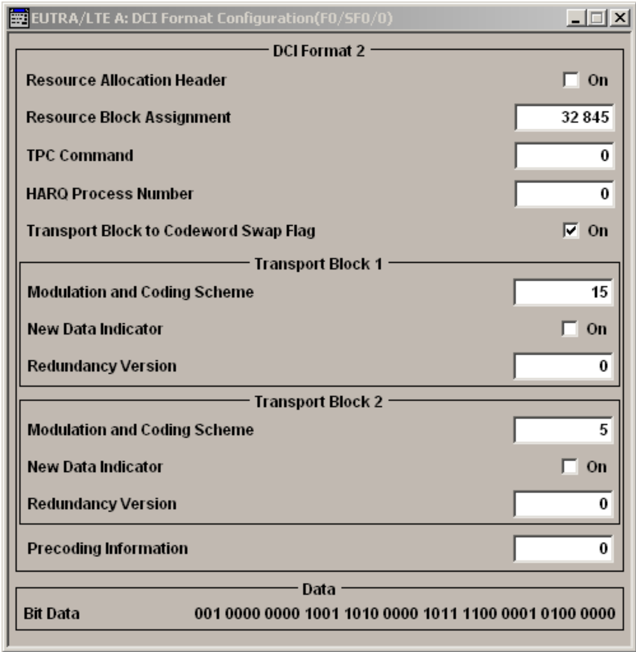


Figure 68: Configuration of DCI format 2 on R&S®SMU200A Vector Signal Generator

With this functionality the correct implementation of physical channels in the downlink as well as the algorithms and functions within the UE's receiver can be easily verified.

After testing the correct implementation of downlink channels for LTE MIMO the performance of the UE's receiver can be tested while adding fading and noise to the signal. 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 $(N_tN_r)x(N_tN_r)$ 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.

Fading for LTE MIMO is required during performance tests, as part of RF conformance testing on LTE-capable devices, which is specified in [Ref. 18]. Section 8 in [Ref. 18] covers all necessary aspects. Performance requirements are not only the demodulation of the PDSCH in presence of noise and fading while having Transmit Diversity or Spatial Multiplexing active. It is further required to decode also the control channels (PCFICH, PDCCH), being transmitted in Transmit Diversity applying fading and noise to the downlink signal. All fading profiles, which are used, depend on the executed performance test cases. For further details please check the latest version of [Ref. 18]. All these fading profiles are supported by SMU200A and AMU200A.

9.3.4 LTE UE protocol testing

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[5] 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 parameterization possibilities are needed for R&D purposes

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. 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 starts.

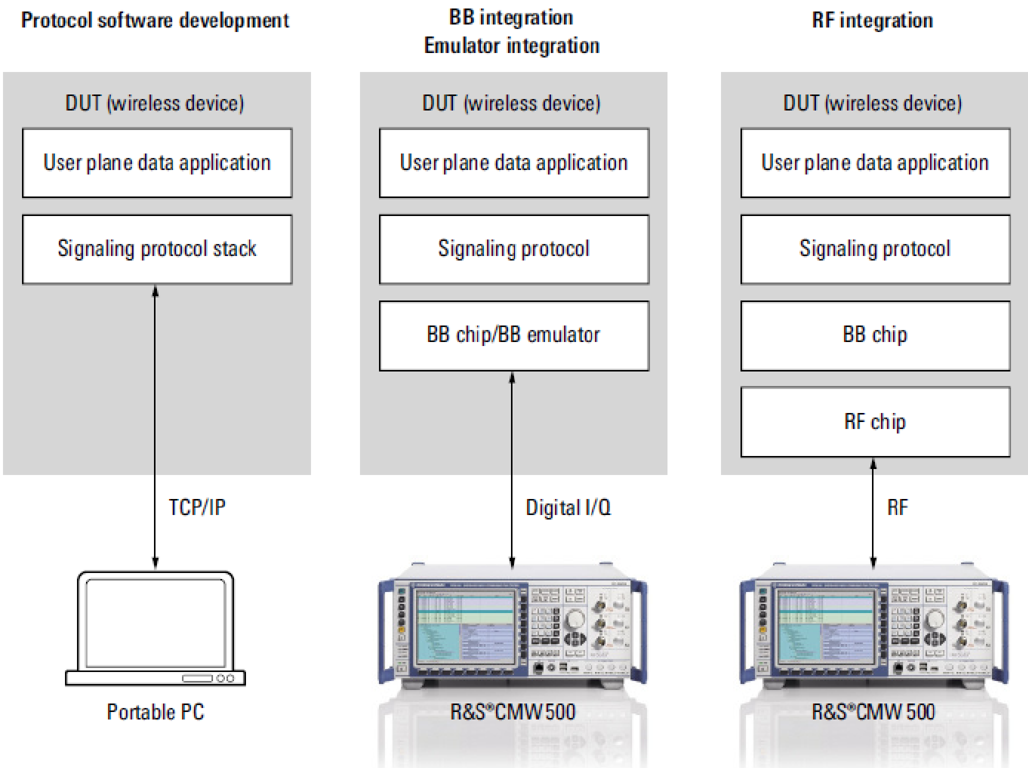


Figure 69: R&S® CMW500 provides different interfaces to do protocol testing

Protocol tests and verification of throughput under realistic propagation conditions is possible by connecting the **AMU200A** fading simulator to the **CMW500**. For further details please refer to application note 1MA177 [Ref. 21].

Maximum flexibility must be provided for developing test scenarios so that numerous aspects can be covered and complex sequences can be recorded.

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

The **CMW500** distinguishes between the low-level application programming interface (LLAPI) and medium-level application programming interface (MLAPI), depending on whether the interface accesses Layer 2 or Layer 3. The LLAPI offers direct access to protocol Layers 1 and 2, which provides extra flexibility in programming the instrument. The **CMW500** can also be programmed using the testing and test control notation 3 (TTCN-3) programming language. Signaling conformance test cases have been agreed by 3GPP written in this programming language. In addition to test cases for RF and Radio Resource Management (RRM), 3GPP agreed that numerous Layer 2, Layer 3, and non-access stratum test cases should be written in this programming language. The R&S CMW500 has the required software tools for creating, implementing, and preparing these test cases. A number of software tools help to develop test cases based on LLAPI and MLAPI, to reconfigure, run, and manage test campaigns, and to analyze test results. The same software tools are reused for the CMW500 as for the Rohde & Schwarz CRTU-G/W protocol test platform. The test case development is based on Microsoft Visual Studio (R&S® CMW-XT015 option). The other tools are the *R&S® Project Explorer*, *R&S® Message Analyzer*, *R&S® Message Composer* explained in the following sections, and *R&S® Automation Manager*. The automation manager (R&S® CMW–KT014) is used to remotely control the DUT by using well-defined AT commands. It can control other test equipment such as the R&S® AMU200A baseband signal generator and fading simulator. One of these tools, the **Project Explorer**, is shown in Figure 70. The Project Explorer is used to run and manage test campaigns, regardless if programmed in LLAPI, MLAPI or TTCN-3.

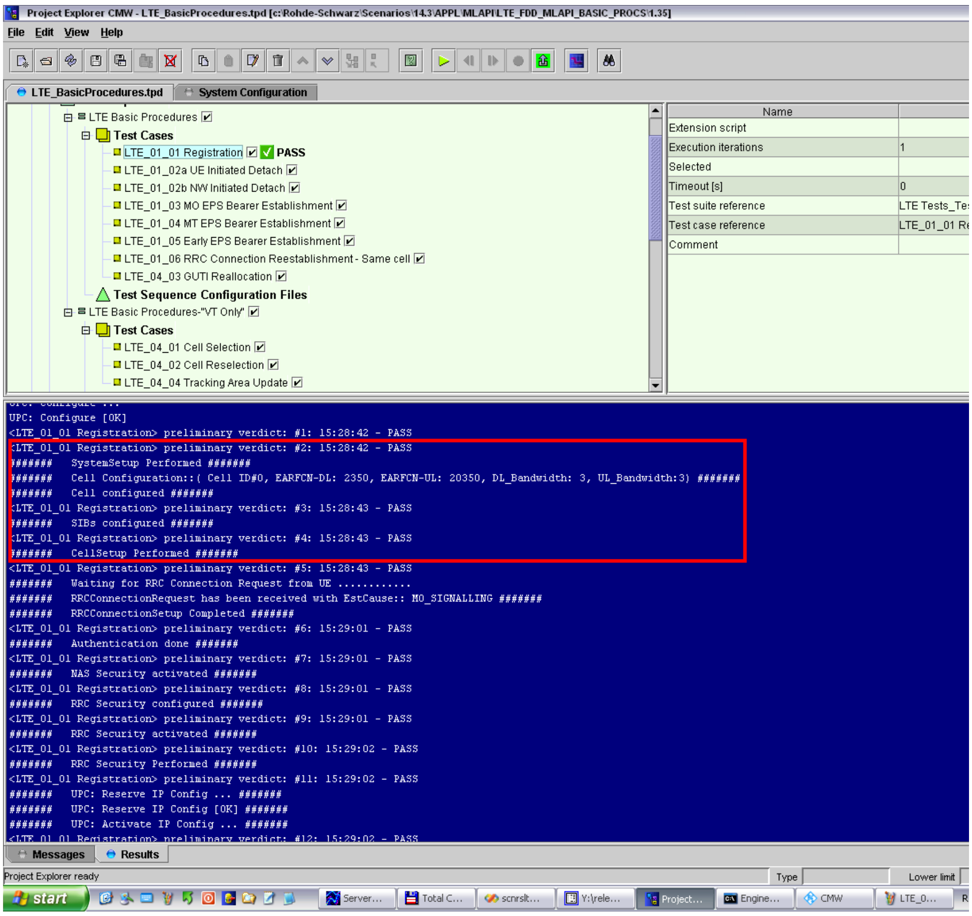


Figure 70: R&S®Project Explorer running IOT package CMW-KF502

Rohde & Schwarz has designed various MLAPI-based test case packages for protocol testing in terms of basic procedures, LTE-mobility, or handover to other cellular technologies. Table 28 provides an overview of the available test case packages and their meaning.

Package	Package Description
CMW-KF500	MLAPI LTE example scenarios
CMW-KF502	Testing basic LTE procedures
CMW-KF503	Verify EPS radio bearer procedures in LTE
CMW-KF504	Verify Intra-LTE handover and mobility procedures
CMW-KF520	LTE-to-GSM handover procedures and vice versa
CMW-KF530	LTE-to-WCDMA handover procedures and vice versa
CMW-KF588	LTE-to-1xEV-DO handover procedures and vice versa
CMW-KF532	LTE, WCDMA and GSM handover scenarios and vice versa
CMW-KF588	LTE-to-1xEV-DO handover procedures and vice versa

Table 28: CMW MLAPI scenario packages for LTE protocol testing

9.3.5 LTE UE conformance testing

Conformance testing, also understood as certification, has been established to ensure global interoperability between mobile devices and networks. The goal is to ensure a minimum level of performance. There are two major certification bodies: Global Certification Forum (GCF) and PCS Type Certification Review Board (PTCRB). The certification process is based on technical requirements as specified within dedicated test specifications provided by the 3GPP, OMA, IMTC, the GSM Association and others. During the certification of a device the implementation of functionality according to a particular release of the specification is verified. December 2009 3GPP baseline has been initially selected for LTE terminal certification.

Certification includes three areas, Radio Frequency (RF), Radio Resource Management (RRM) and protocol conformance, which meaning is explained in detail in the following sections. A device can only be called certified, if all test cases for RF, RRM and protocol are successfully passed. These test cases are defined as prose version by 3GPP Radio Access Network Working Group 5, in charge for terminal test specification. The number of available RF and RRM test cases in terms of LTE FDD and TD-LTE differ slightly. In terms of protocol conformance, a special working group (ETSI MTF160) creates executable test cases, written in a common programming language called TTCN-3. All test cases need to be verified and validated for each prioritized frequency band on an approved test platform, such as the R&S®CMW500 Wideband Radio Communication Tester. As there are several LTE frequency bands for FDD and TDD operation both certification bodies (GCF, PTCRB) have prioritized frequency bands, where each one is covered in an own work item. Verification needs only one handset implementation to pass the requirements for that particular test case, whereas validation requires two independent devices implementation from two different vendors to do so. Figure 71 summarizes the certification process based on LTE.

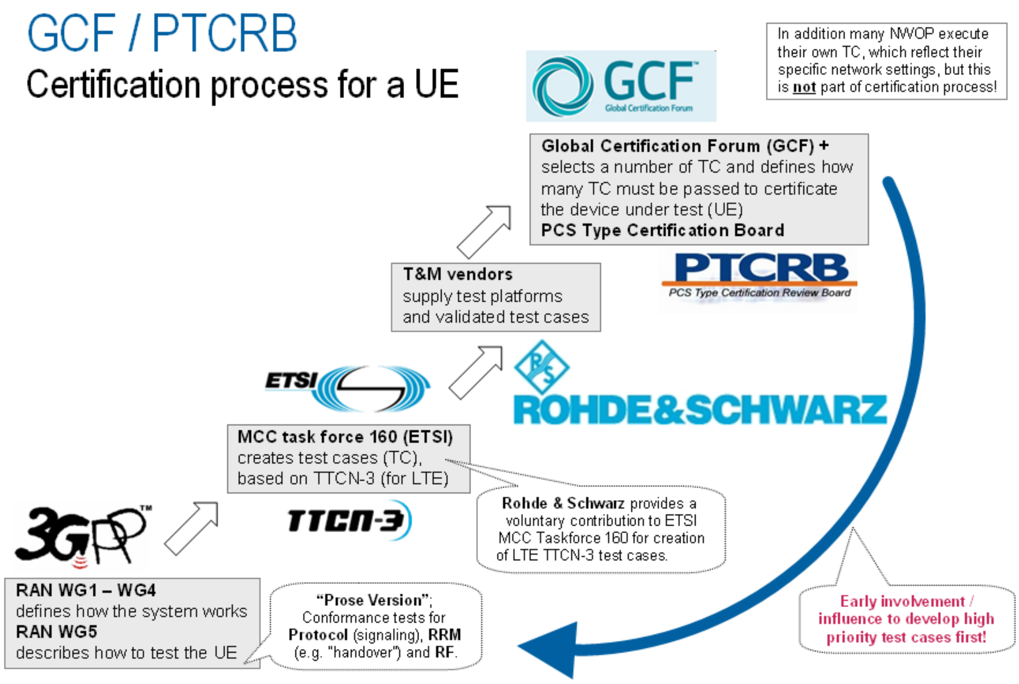


Figure 71: General work-flow of UE certification process, example LTE

Rohde & Schwarz is one of the few test and measurement equipment manufacturers, which offers a complete solution for RF / RRM and protocol conformance testing, that is based on and designed around the R&S®CMW500 Wideband Radio Communication Tester.

9.3.5.1 RF / RRM conformance

LTE UE RF and RRM conformance tests are captured in 3GPP TS 36.521. Part 1 [Ref. 18] deals with RF conformance, where part 3 [Ref. 20] covers RRM. The RF conformance specification is subdivided into four areas of testing: transmitter and receiver characteristic (section 6 and 7), performance (section 8) and radio channel quality reporting (section 9).

All defined tests are executed on Reference Measurement Channels (RMC), which define a full resource allocation, partial resource allocation or just a single RB allocation.

Transmitter Tests	Receiver Tests
TS 36.521 Part 1, section 6	**TS 36.521 Part 1, section 7**
6.2.2. Maximum Output Power 6.2.3. Maximum Power Reduction 6.2.4. Additional Maximum Power Reduction 6.2.5. Configured UE transmitted Output Power 6.3.2. Minimum Output Power 6.3.3. Transmit ON / OFF Power 6.3.4. ON / OFF time mask 6.3.5. Power control 6.5.1. Frequency Error	7.3. Receiver sensitivity level 7.4. Maximum input level 7.5. Adjacent Channel Selectivity (ACS) 7.6.1. In-band blocking 7.6.2. Out-of-band blocking 7.6.3. Narrow band blocking 7.7. Spurious response 7.8. Intermodulation characteristics 7.9. Spurious emissions

6.5.2.1. Error Vector Magnitude (EVM) 6.5.2.2. IQ component 6.5.2.3. In-band emission for non-allocated RB 6.5.2.4. Spectrum flatness 6.6.1. Occupied Bandwidth (OBW) 6.6.2.1 Spectrum Emission Mask (SEM)' 6.6.2.2. Additional Spectrum Emission Mask 6.6.2.3. Adjacent Channel Leakage Power Ratio (ACLR) 6.6.2.4. Additional ACLR requirements 6.6.3.1 Transmitter Spurious Emissions 6.6.3.2. Spurious emission band UE co-existence 6.6.3.3. Additional spurious emissions 6.7. Transmit Intermodulation	
Performance requirements	
TS 36.521 Part 1, section 8	
8.1.1. Dual-antenna receiver capability 8.2.1.1. FDD PDSCH Single Antenna Port Performance 8.2.1.2. FDD PDSCH Transmit Diversity Performance 8.2.1.3. FDD PDSCH Open Loop Spatial Multiplexing Performance 8.2.1.4. FDD PDSCH Closed Loop Spatial Multiplexing Performance 8.2.2.1. TDD PDSCH Single Antenna Port Performance 8.2.2.2. TDD PDSCH Transmit Diversity Performance 8.2.2.3. TDD PDSCH Open Loop Spatial Multiplexing Performance 8.2.2.4. TDD PDSCH Closed Loop Spatial Multiplexing Performance 8.2.3.1. TDD PDSCH Performance (UE-Specific Reference Symbols) 8.4.1.1. FDD PCFICH/PDCCH Single-antenna Port Performance 8.4.1.2. FDD PCFICH/PDCCH Transmit Diversity Performance 8.4.2.1. TDD PCFICH/PDCCH Single-antenna Port Performance 8.4.2.2. TDD PCFICH/PDCCH Transmit Diversity Performance 8.5.1.1. FDD PHICH Single-antenna Port Performance 8.5.1.2. FDD PHICH Transmit Diversity Performance 8.5.2.1. TDD PHICH Single-antenna Port Performance 8.5.2.2. TDD PHICH Transmit Diversity Performance 8.6. Demodulation of PBCH	
Channel reporting	
TS 36.521 Part 1, section 9	
9.2.1.1 FDD CQI Reporting under AWGN conditions – PUCCH 1-0 9.2.1.2 TDD CQI Reporting under AWGN conditions – PUCCH 1-0 9.2.2.1 FDD CQI Reporting under AWGN conditions – PUCCH 1-1 9.2.2.2 TDD CQI Reporting under AWGN conditions – PUCCH 1-1 9.3.1.1.1. FDD Frequency-selective scheduling mode – PUSCH 3-0 9.3.1.1.2. TDD Frequency-selective scheduling mode – PUSCH 3-0 9.3.2.1.1. FDD Frequency non-selective scheduling mode – PUSCH 1-0 9.3.2.1.2. TDD Frequency non-selective scheduling mode – PUSCH 1-0 9.4.1.1.1. FDD Single PMI – PUSCH 3-1 9.4.1.1.2. TDD Single PMI – PUSCH 3-1 9.4.2.1.1. FDD Multiple PMI – PUSCH 1-2 9.4.2.1.2. TDD Multiple PMI – PUSCH 1-2	

Table 29: Overview 3GPP LTE RF conformance test cases [Ref. 18]

All receiver and performance tests are based on a Block Error Rate (BLER) measurement. The selected RMC defines a maximum possible throughput. By simply counting ACK and NACK transmitted in the uplink a BLER can be computed, which results in an average throughput. For each test case a minimum performance requirement in throughput percentage (e.g. >70%) is defined, that need to be passed by the test device. 3GPP RF conformance testing is based on Rohde & Schwarz modular R&S®TS8980 test system family. Starting with a stand-alone CMW500 the system can be expanded to a fully-automated conformance test systems configured for running validated RF conformance test cases in design, pre-certification and type approval of mobile stations. The TS8980 is automated and controlled by R&S®CONTEST. To a certain degree RF conformance test can be executed on a stand-alone CMW500. Please see section 9.3.2 in this application note for further details.

R&S®TS8980S		R&S®TS8980FTA
Starter Configuration		**Full Type Approval**
		
3GPP TS 36.521 Part1 coverage (RF)		
Section 6	(✓)*)	✓
Section 7	(✓)*)	✓
Section 8	✓	✓
Section 9	✓	✓
3GPP TS 36.521 Part3 coverage (RRM))**		
✓		✓

Note: TS8980FTA is a validated conformance test platform by GCF / PTCRB
*) Some RF tests cases require additional equipment, for interference generation or spurious measurements.
**) Some RRM test setups require a multiple cell setup as well as a second R&S®AMU200A

Table 30: Overview R&S®TS8980 test system family

As shown in Table 30 the TS8980 test system family can be used for RRM conformance testing. This type of testing is divided into six major blocks, listed below. Some setup

1. EUTRAN RRC IDLE state mobility,
2. EUTRAN RRC_CONNECTED state mobility,
3. RRC Connection mobility control,
4. Timing and signaling characteristics (FDD and TDD),
5. UE measurement procedures,
6. Measurement performance requirements (RSRP, RSRQ).

RRC_IDLE state means that the device has a passive connection with the network. It is basically registered, but has not an active connection, means receiving or transmitting data. With these test cases the ability of the device is tested to perform LTE cell selection and reselection. LTE will be first deployed in hot spot area. Thus it is important that the device can also select other radio access technologies (WCDMA, GSM, CDMA®1xRTT and 1xEV-DO) if they are supported by the device. In the RRC_CONNECTED state the device has an active connection with the network and receives or transmits data. The ability of the device is tested, if the connection is maintained while performing handover in LTE or to other radio access technologies. RRC connection control checks if for example RRC connection re-establishment is performed properly. Within timing and signaling characteristics transmit timing of the device, timing accuracy and timing advance is tested for example. Measuring the link quality of LTE and other technologies is important, and is another RRM testing aspect. RSRP and RSRQ are the physical layer measurements that have been defined for LTE. These ones are used to estimate the channel quality. RSRP can be measured in IDLE and CONNECTED state, where RSRQ is only measured in CONNECTED state. Both are important measurements and impact mobility. So their performance is checked as part of RRM.

9.3.5.2 Protocol conformance

Protocol conformance is captured in 3GPP TS 36.523 Part 1 [Ref. 20]. Table 31 summarizes all relevant Rel-8 test cases.

IDLE mode operations	Medium Access Control (MAC) layer	Radio Link Control (RLC) layer	Packet Data Convergence Protocol (PDCP)
e.g. PLMN selection, cell selection and reselection, Inter-RAT PLMN selection, cell selection closed-subscriber group cells (= femto-cell)	e.g. RACH, DL-SCH data transfer, UL-SCH data transfer, DRX operation, Transport Block Size (TBS) selection	Unacknowledged Mode, Acknowledged Mode	Maintenance of sequence numbers, ciphering, integrity protection, handover, discard
Radio Resource Control (RRC) layer	**Evolved Packet System (EPS) mobility management.**	**EPS session management.**	**General Tests, E-UTRA radio bearer tests**
Connection management procedures, RRC connection reconfiguration, measurement control and reporting, Inter-RAT handover, Radio Link Failure, UE capability transfer	EMM common and specific procedures (attach, detach, tracking area update), connection management procedures (service request, paging), NAS security	e.g. EPS bearer context modification, deactivation, UE requested PDN connectivity and disconnect.	SMS over SGs, E-UTRA radio bearer MIMO configured: Y/N?
Multi-layer procedures	**Mobility management based on DSMIPv6**		
Call setup, RRC connection reconfiguration,	Discovery, registration, re-registration, return to home link, dual-stack detach.		

Table 31: Summary of protocol conformance test cases according to 3GPP TS 36.523-1 [Ref. 20]

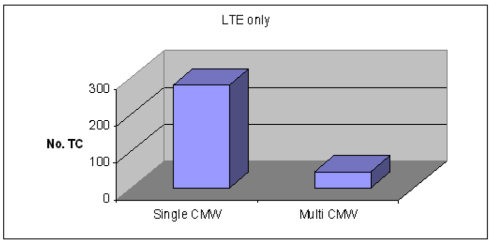
At an early stage of test case definition 3GPP invited certification bodies (e.g. GCF) to participate in the process, such that only test cases are being standardized that are required and moreover used to ensure minimum protocol conformance for LTE. Nevertheless the total number of test cases (= 467) identified was very high, thus a prioritization took place, resulting into four priority groups. Each priority group includes a different set of test cases. GCF decided, that certification can be activated and passed by a device while only passing test cases out of priority group 1 and 2 (in total 208 test cases out of the mentioned 467). This allowed an early activation for certification and thus worked in favor for early time to market LTE devices. Furthermore for each of the initially identified, high-priority frequency bands (LTE FDD: 1, 7, 13, 20; TD-LTE: 38, 40) an own work item has been created to not further delay time to market.

Rohde & Schwarz solution for protocol conformance testing is based on the R&S®CMW500 Wideband Radio Communication Tester. With a single instrument, about 90% of all defined protocol conformance test cases can be validated and verified. Some of these test cases, mainly for mobility, different PLMN and cell selection scenarios[6] as well as neighbor cell measurements, a CMW multi-box setup is required as shown in Figure 72. The setup consists of two, up to three CMW500. One CMW500 acts as a master, the other(s) as slave. The synchronization is realized with a highly flexible baseband link, thus all CMW's need to be equipped with option R&S®CMW-S550M. In addition an external RF combiner (R&S®CMW-Z24) is required. The whole setup is controlled by controller unit (CMW-CU), where all hardware resources seem to belong to one "virtual" instrument, and available software licenses are collected across synchronized instruments.

Figure 72: Multi-box CMW setup for full LTE protocol conformance testing

[6] up to 6 cells, providing different technologies (GSM, WCDMA, LTE etc.)

Figure 73 gives an overview on test cases for LTE and Inter-RAT (I-RAT), which are supported by Multi-CMW setup in addition to the ones supported with a single CMW500.



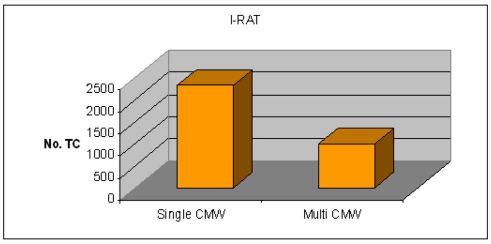


Figure 73: Test case support Single CMW500 vs. Multi-CMW setup

9.3.5.3 Network-operator specific testing

On top of 3GPP-specified RF, RRM and protocol conformance tests, which are adopted by the certification bodies (GCF and PTCRB) for certification of LTE-capable devices, several network operators have defined their own test plans. These test plans ensure optimal performance in their networks. Very often network-specific settings are incorporated into the test cases.

Rohde & Schwarz conformance test systems are designed to support on top of 3GPP conformance also network operator specific test plans. Easily additional hardware can be integrated into the conformance system. As an example TV transmitters have been integrated. This allows the user to generate real TV signals, which are used as interferer to judge device performance.

Figure 74: R&S®TS8980FTA with TV Interferers SFE100 (option for network operator specific testing)

9.3.6 Data throughput testing, End-to-end testing

Device performance is a very important aspect in user experience and so does data throughput. This is impacted by various parameters. As each device behaves different, using the right settings is essential for example to reach maximum data throughput.

Rohde & Schwarz is the right partner for performing any type of (maximum) throughput testing, data end-to-end (E2E) and application testing under ideal and realistic conditions. For each type of testing the right solution is available, that are introduced in the next sections.

9.3.6.1 Maximum throughput testing

The goal for maximum throughput testing is to validate, that the device hardware is capable of handling what is defined for the supported device category. Maximum throughput is always based on conducted testing, under ideal conditions, where no fading or noise is applied to the signal.

The CMW500 configured as LTE protocol tester is the right instrument to carry out this type of testing. You can easily have access to any type of settings that have an impact on throughput. This could be one or a combination of the following parameters:

- Power settings (downlink and uplink),
- Resource allocation,
- Modulation and Coding Scheme (MCS), Transport Block Size (TBS),
- RLC mode (Acknowledged / Unacknowledged),
- Type of Header Compression,
- IP settings (IPv4 or IPv6, TCP window size, etc.)

MLAPI scenarios, which are used for protocol testing, are based on xml-files. These xml-files, where also all parameters that impact throughput are found, can be easily edited using the R&S®Message Composer. To allow an easy access and configuration of the CMW500 protocol stack for maximum throughput testing Rohde & Schwarz offers the **Throughput Configuration Tool for LTE (TCT4LTE)**. This software tool is used to configure parameters in xml-files that define a MLAPI scenario, which optimizes the CMW500 protocol stack for maximum throughput testing.

The graphical user interface of this free-of-charge software tool is shown in Figure 75.

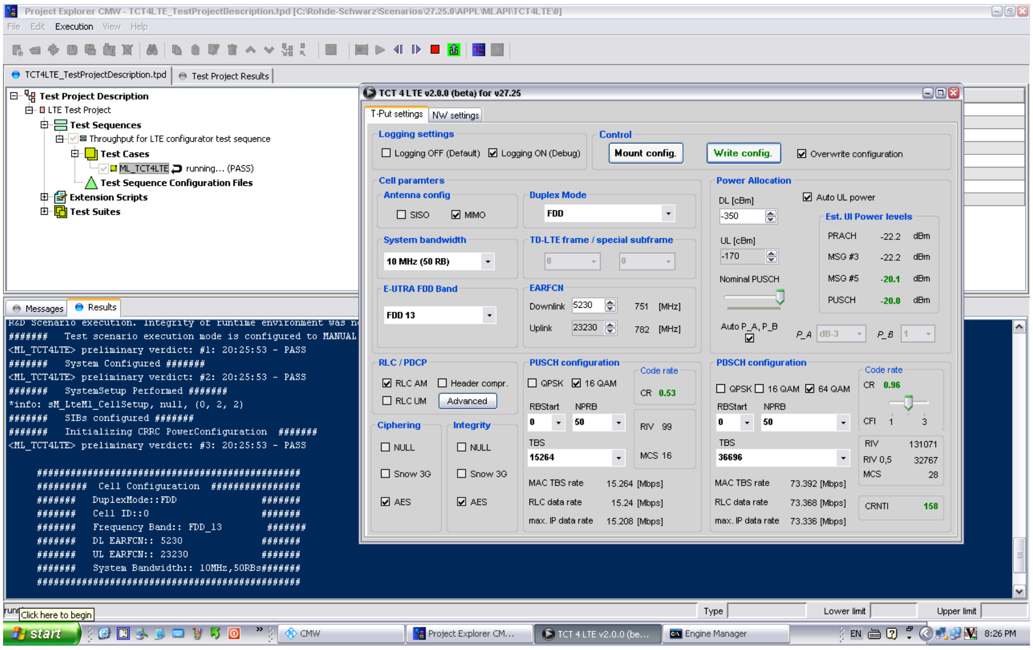


Figure 75: Throughput Configuration Tool for LTE (TCT4LTE) for R&S CMW500 LTE Protocol Tester

Drop down menus allow an easy selection of duplex mode, frequency band and bandwidth. Channel numbers to test on and power levels to test with are easily incremented or decremented using the appropriate menus. The tool offers further configuration possibilities for RLC and PDCP layer, ciphering and integrity as well as for the channels that carry data in downlink and uplink (PDSCH, PUSCH). All dependencies, for example running SISO versus MIMO, are covered by the tool and automatically applied while choosing the one or other configuration.

9.3.6.2 CMW – Performance Quality Analysis (PQA)

Besides maximum throughput testing to verify the capabilities of the used hardware it is important to carry-out performance analysis of throughput under realistic conditions, means when noise and fading is present. Rohde & Schwarz answer for this demand of testing is the CMW-PQA system, where PQA stands for Performance Quality Analysis. The general setup consists of the CMW500 Wideband Radio Communication Tester, configured as LTE Protocol Tester, and the AMU200A Baseband Signal Generator and Fading Simulator. The test setup is shown in Figure 76.

Figure 76: R&S®CMW-PQA

Rohde & Schwarz CONTEST software controls the setup. *Figure 77* shows as an example the configuration possibilities for LTE.

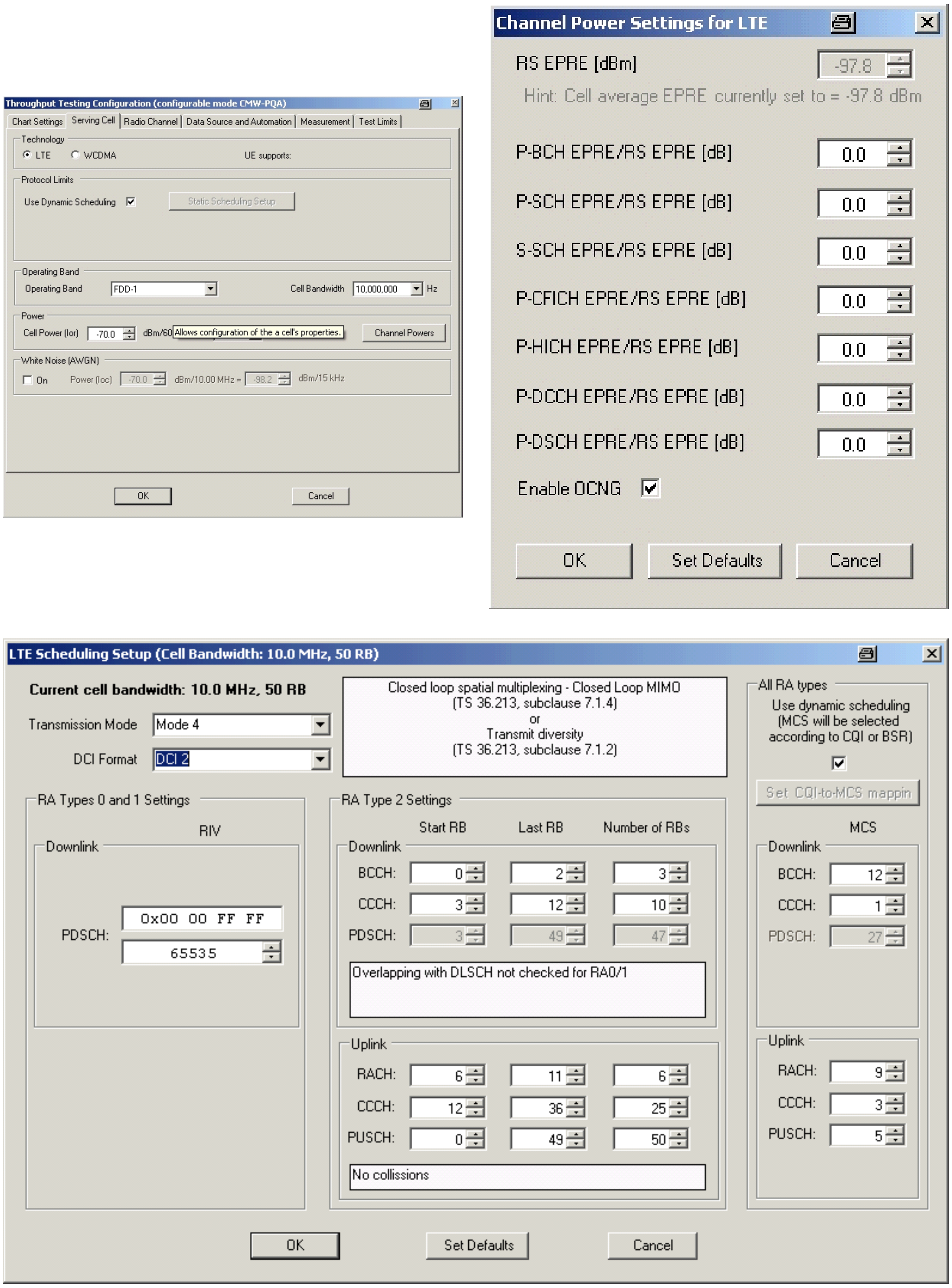


Figure 77: R&S®CONTEST software to drive CMW-PQA

The software can be also used to automate the device under test by using defined AT commands. CMW-PQA is furthermore the basis for supporting network operator specific data rate test plans for LTE or WCDMA/HSPA(+).

9.3.6.3 Data Application Unit (DAU)

As basis for data end-to-end (E2E) testing Rohde & Schwarz has integrated into the R&S®CMW500 an additional piece of hardware called Data Application Unit (DAU, option R&S CMW-B450A). The DAU provides additional functionality, simplifies the measurement setup and saves test time while automating the configuration.

It allows to test End-to-End (E2E) IP data transfer and to perform user plane (U-plane) tests for an IP connection to a mobile, set up via a signaling application or a protocol test application. The DAU is independent of the underlying radio access network. It provides a common user plane handling and ensures data continuity during handover from one radio access technology to another one. The DAU also allows to run pre-installed IP services on the R&S CMW500. The services are optimized for high throughput and run in an isolated controlled environment to ensure reproducible test results. The currently pre-installed services are:

- File transfer via File Transfer Protocol (FTP)
- Web browsing via Hypertext Transport Protocol (HTTP)
- IP Multimedia Subsystem (IMS) server supporting voice calls and SMS over IMS (R&S CMW-KAA20 required)
- DNS server supporting DNS requests of type A, AAAA and SRV

You can use the FTP and HTTP services for example to access the built-in DAU Web server from the mobile. If desired own web pages can be added to the server. An additional hard disk provided with the DAU allows the storage of large media files for data transfer tests.

The IMS server emulates a P-CSCF, so that the mobile can register to the IMS domain. Optionally an authentication can be performed. After successful registration, a voice call to the mobile can be initiated (mobile terminated call) or the mobile can initiate a voice call over IMS (mobile originated call). Sending and receiving of short messages via IMS is also supported. The DNS server can be used to answer DNS queries for IPv4 addresses, IPv6 addresses and domains supporting a specific service. The DNS server database is configurable. Thus you can for example redirect the mobile to the Web server of the DAU when it tries to browse a specific Internet domain. DNS queries for which the local database contains no matching entry can be forwarded to an external DNS server. If connected to an external network, the DAU acts as IP gateway, separating the R&S CMW500 internal IP network from the external IP network. The mobile can use both the embedded IP services provided by the DAU and the IP services provided by the external network. For example it can access Web servers and DNS servers both in the internal network and in the external network. For DAU measurements, option R&S CMW-KM050 is required. It provides the following measurement applications for testing the properties of an IP connection to the mobile:

- Ping measurement, testing the network latency
- IPerf measurement, testing the throughput and reliability, using TCP/IP and UDP/IP
- Throughput measurement, indicating the total throughput at the DAU on IP level
- DNS request measurement, monitoring all DNS queries addressed to the internal DNS server
- IP logging application, creating log files of the IP traffic at the LAN DAU connector or between DAU and mobile

The DAU supports internet protocol IPv4 only, or IPv4 and IPv6. IPv4 requires option R&S CMW-KA100, IPv6 requires additionally option R&S CMW-KA150. You can control the DAU manually via a graphical user interface or remotely via SCPI commands. Protocol test applications can control the DAU via the CDAU interface.

Figure 78 - Figure 80 provide example measurements using the DAU on R&S CMW500.

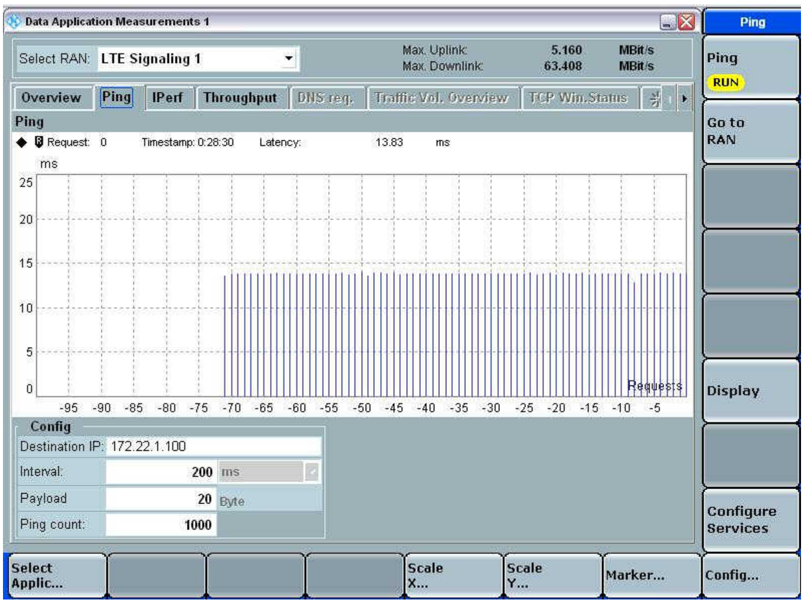


Figure 78: Data Application Measurements - Ping tab

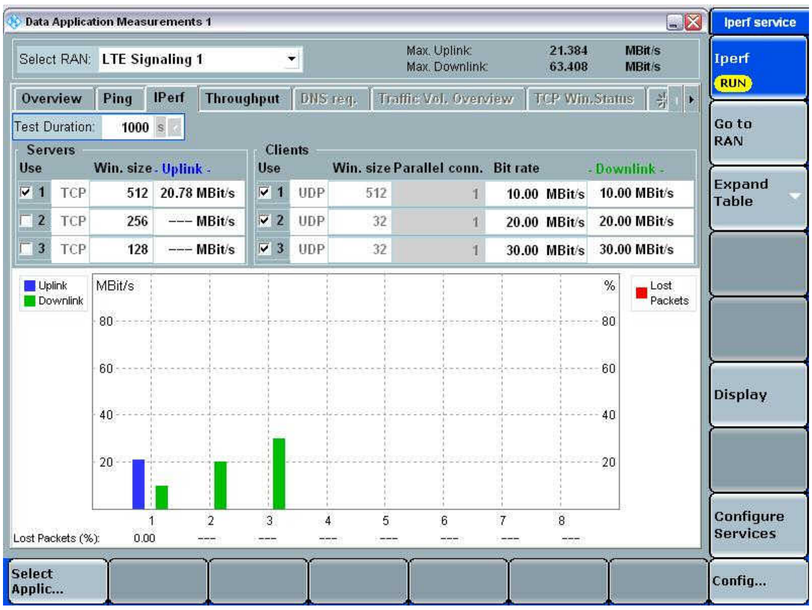


Figure 79: Data Application Measurements - IPerf tab

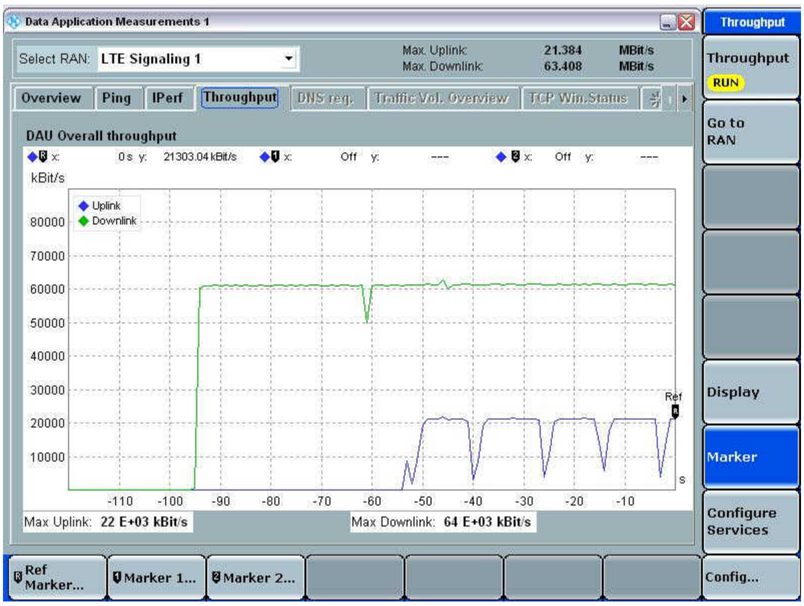


Figure 80: Data Application Measurements - Throughput tab

9.4 Network deployment, optimization and maintenance

9.4.1 Spectrum clearing

LTE is currently deployed in several new frequency bands. 3GPP frequency band 7 (Europe, 2.6 GHz), Band 13 (US, 700 MHz) or Band 20 (Europe, Digital Dividend, 800 MHz) are only a few examples. Some of them have been used by other technologies or other systems such as analog TV. For a network operator it is therefore important to run spectrum clearing measurements before deploying LTE.

In general the radio spectrum is getting more and more crowded. The national regulatory bodies as well as mobile operators are facing the increasingly complex problem of monitoring and managing spectrum usage. Rohde & Schwarz provides variable solutions for radio monitoring and spectrum management tasks - from stand-alone systems to completely automated nationwide networks as recommended and specified by the International Telecommunications Union (ITU). Monitoring the entire frequency band from 100 Hz to 40 GHz around the clock and nationwide is obviously a huge and complex task. Rohde & Schwarz provides a modular solution that can be adapted to meet all national radio monitoring requirements. Please see R&S Monitoring Solutions for a complete list of available solutions.

Typical spectrum monitoring tasks can be classified as follows:

- Investigation of interference due to co-channel emissions, out-of-channel emissions and intermodulation
- Monitoring of technical transmitter parameters (short-term, long-term, deviation measurements of FM broadcast transmitters)
- Field strength measurements

- Identification of unlicensed stations
- Spectrum occupancy measurements

Planning and management of transmitters Rohde & Schwarz's highly sophisticated Spectrum Monitoring and Management System R&S® ARGUS-IT is the perfect solution to all measurement and analysis problems related to spectrum monitoring and management. R&S® ARGUS-IT is modular, scalable and upgradeable. Therefore, a user can select a basic version according to the available budget, just starting with a core set of equipment for a modest amount outlay. A nationwide system can be created incrementally just by adding additional hardware and software modules.

Another solution is the R&S®DDF550 Wideband Direction Finder. The fast R&S®DDF550 wideband direction finder offers outstanding realtime bandwidth and DF scan speed as well as high DF accuracy, sensitivity and immunity to reflections. The unit has compact dimensions and is optionally available as a DC-powered model, which makes it ideal for mobile applications.

9.4.2 LTE network deployment, optimization – Drive test solution

Rohde & Schwarz drive test solution is based on the **R&S®TSMW network scanner** and **R&S®ROMES drive test software**. This is topped of to a complete solution with the integration of the application programming interfaces (API) from various handset and chipset manufacturers to display and analyze the RF and Layer 1 information a handset is reporting back to the network.

TSMW and ROMES support multiple technologies scanning, all at once, with one single instrument. This includes – besides **LTE FDD and TD-LTE** – WiMAX, CDMA®2000 1xRTT/1xEV-DO, GSM and WCDMA/HSPA.

The **TSMW-Z3** backpack (*Figure 81*) enables the Rohde & Schwarz drive test solution being used for indoor coverage measurements, such as airports, shopping malls, football and soccer stadium and other sports arenas.

An unique feature is the measurement of the channel impulse response (CIR, Figure 82). With that the multi-path propagation of the channel can be estimated and a clear indication is given if the cyclic prefix is violated, which causes Inter-Symbol Interference (ISI).

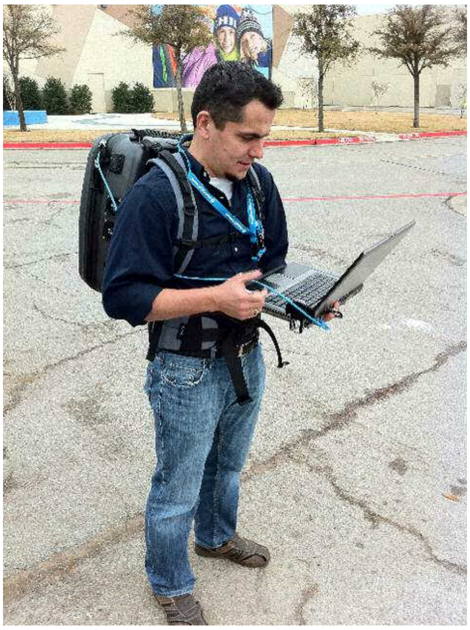


Figure 81: R&S TSMW-Z3 backpack

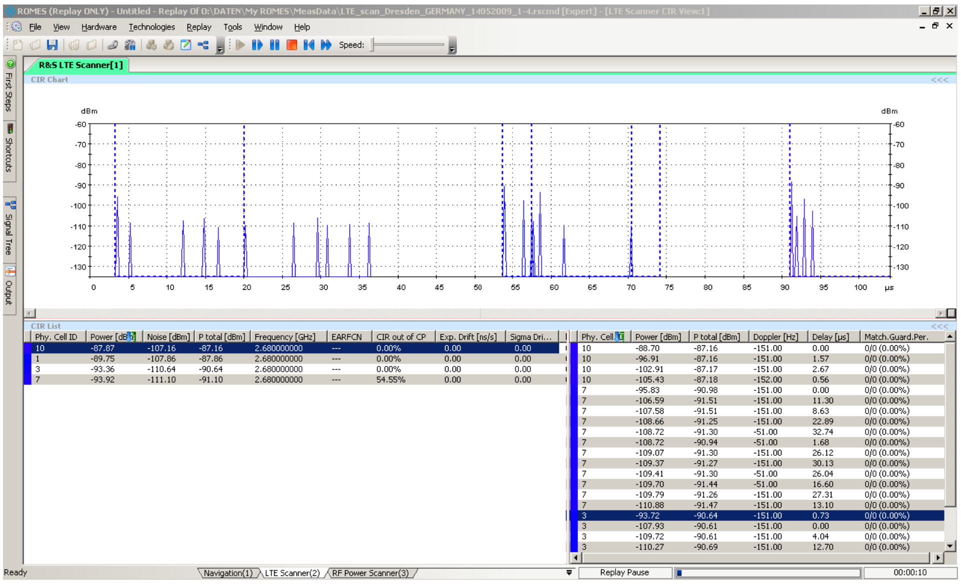


Figure 82: Channel Impulse Response (CIR) measurement displayed in R&S®ROMES

The TSMW also measures Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) as a LTE-capable handset does. The scanner measurement will deliver a clear indication if there is for example pilot pollution or any other kind of interference that may impact the network performance.

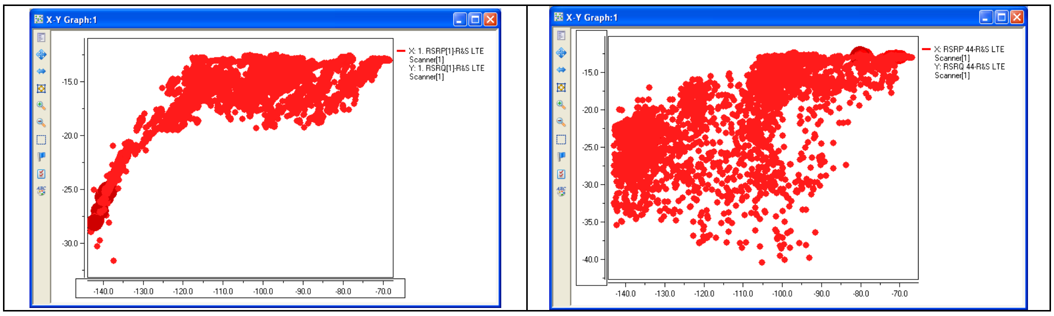


Figure 83: RSRP (x-axis) versus RSRQ (y-axis) comparison, indicating no pilot pollution (left) and pilot pollution (right)

With the **Data Quality Analyzer (DQA)**, which is integrated into **ROMES**, performance measurements like throughput analysis can be conducted without the need of any post-processing tools.

Last but not least all measurement data can be exported into Google Earth for easy visualization of network performance to higher management for example.

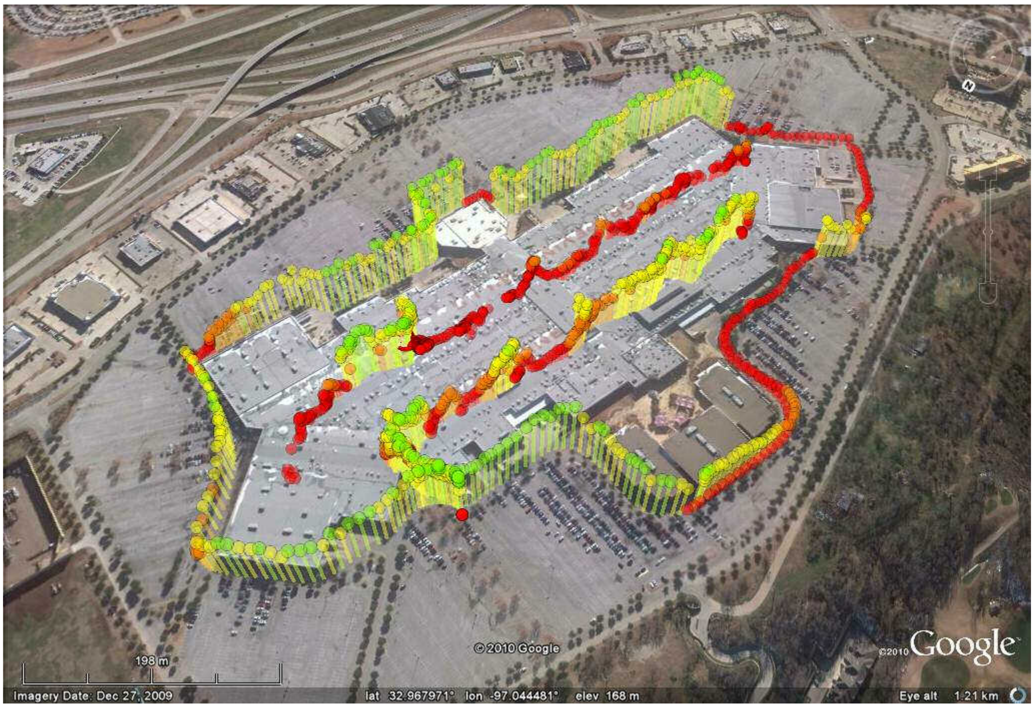


Figure 84: Average downlink throughput (outdoor and indoor) visualization in Google Earth

9.4.3 LTE base station maintenance

Besides measuring the performance in the field, LTE base stations need to be installed and maintained during operation. In this area efficient and easy to use handheld spectrum analyzers are needed. For LTE transmitter installation basic measurements like output power, adjacent channel power or spurious emissions are needed. Additionally cable and antennas installation need to be verified as well as the LTE signal quality.

The R&S®FSH4/FSH8 is a spectrum analyzer and – depending on the model and the options installed – a power meter, a cable and antenna tester and a two-port vector network analyzer, which fulfills all the before mentioned testing needs. It provides the three most important RF analysis functions that an RF service technician or an installation and maintenance team needs to solve daily routine measurement tasks. The R&S®FSH4/FSH8 spectrum analyzer is rugged, handy and designed for use in the field. Its low weight, its simple, well-conceived operation concept and the large number of measurement functions make it an indispensable tool for anyone who needs an efficient measuring instrument for outdoor work.

If you do not need the advantages of vector network analysis for reflection and transmission measurements, the R&S®FSH models featuring a built-in tracking generator are a more cost-effective solution for determining the transmission characteristics of cables, filters and amplifiers. The R&S®FSH models with a built-in VSWR bridge (models .24 and .28) can additionally measure the matching (return loss, reflection coefficient or VSWR), e.g. of an antenna. Also the distance-to-fault, caused by a pinched cable or by loose or corroded cable connections, is determined quickly and precisely (see Figure 85).

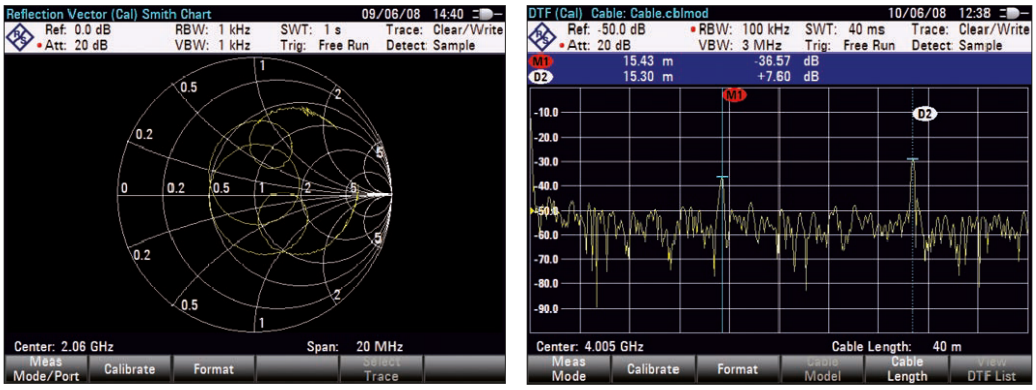


Figure 85: Vector network analysis: measurement with Smith chart; Distance-to-fault measurements (DTF)

The R&S®FSH-K50/-K51 option equips the R&S®FSH4/FSH8 for measurements on LTE FDD and LTE TDD eNodeB transmitters. It can analyze all signal bandwidths up to 20 MHz that are defined in the LTE standard. Both options support all important LTE measurements – from single input single output (SISO) to 4x4 multiple input multiple output (MIMO) transmissions. In addition to the total power, the R&S®FSH-K50/-K51 determines the power of the reference signal, the power of the physical control format indicator channel (PCFICH), the physical broadcast channel (PBCH) and the two synchronization channels PSYNC and SSYNC. It also measures and displays the carrier frequency offset and EVM value of the reference signal and the useful data. Users can now detect transmitter impairments such as clipping or intermodulation that are difficult to recognize in the spectrum. See Figure 86 for example measurements using the LTE demodulation option.

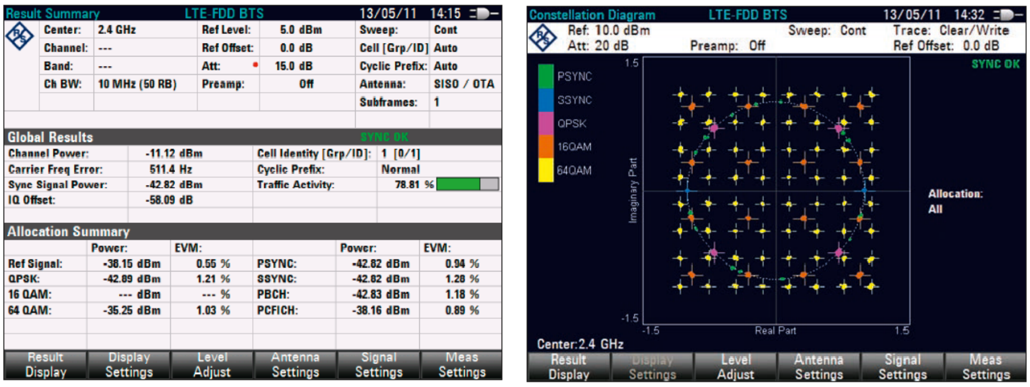


Figure 86: Result Summary screen (left) and Constellation Diagram for LTE

10 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
PRACH	Physical Random Access Channel
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

11 Additional Information

This Application Note is subject to improvements and extensions.

Please visit our website in order to download the latest version.

Please send any comments or suggestions about this Application Note to TM-Applications@rohde-schwarz.com.

12 Literature

[Ref. 1]	**3GPP TS 25.913**; Requirements for E-UTRA and E-UTRAN (Release 8)
[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)
[Ref. 12]	1MA205; HSPA+ Technology Introduction White Paper, February 2012
[Ref. 13]	1MA150; Cell Search and cell selection in UMTS LTE, September 2009
[Ref. 14]	1MA191; LTE Release 9 – White Paper, December 2011
[Ref. 15]	1MA169; LTE-Advanced – Technology Introduction, July 2010
[Ref. 16]	**3GPP TS 36.141**; Evolved Universal Terrestrial Radio Access (E-UTRA) Base Station (BS) conformance testing (Release 8)
[Ref. 17]	1GP78; CPRI RE testing, October 2010
[Ref. 18]	**3GPP TS 36.521-1**; User Equipment (UE) conformance specification for radio transmission and reception, Part 1: Conformance Testing (Release 8)
[Ref. 19]	**3GPP TS 36.521-3**; User Equipment (UE) conformance specification for radio transmission and reception, Part 3: Radio Resource Management (RRM) conformance testing (Release 8)
[Ref. 20]	**3GPP TS 36.523-1**; User Equipment (UE) conformance specification, Part 1: Protocol conformance specification (Release 8)
[Ref. 21]	1MA177; LTE terminal tests under fading conditions with R&S®CMW500 and R&S®AMU200A, November 2010
[Ref. 22]	1MA168; Starting successfully with the R&S® EX-IQ-BOX, June 2010
[Ref. 23]	1CM94;LTE RF measurements with CMW500 according to 3GPP TS 36.521-1, December 2010

[Ref. 24]	1MA154; LTE Base Station Tests according to TS 36.141, November 2009
[Ref. 25]	1MA162; LTE Base Station Performance Tests according to TS 36.141, February 2010
[Ref. 26]	1MA197; Voice and SMS in LTE, May 2011

13 Ordering Information

Ordering Information		
Signal Generators		
R&S® SMU200A	**Vector Signal Generator**	**1141.2005.02**
R&S® SMU-B102	Frequency range 100 KHz to 2.2 GHz for 1st RF Path	1141.8503.02
R&S® SMU-B103	Frequency range 100 KHz to 3 GHz for 1st RF Path	1141.8603.02
R&S® SMU-B104	Frequency range 100 KHz to 4 GHz 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 (64 M Samples)	1141.7007.02
R&S® SMU-B11	Baseband Generator with digital modulation (realtime) and ARB (16 M Samples)	1159.8411.02
R&S® SMU-B13	Baseband Main Module	1141.8003.02
R&S® SMU-B14	Fading simulator	1160.1800.02
R&S® SMU-B15	Fading simulator extension	1160.2288.02
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-K69	LTE Closed-Loop BS Test	1408.8117.02
R&S® SMU-K74	2x2 MIMO Fading	1408.7762.02
R&S® SMU-K81	LTE Logfile Generation	1408.8169.02
R&S® SMBV100A	**Vector Signal Generator**	**1407.6004.02**
R&S®SMBV-B103	9 kHz to 3.2 GHz	1407.9603.02
R&S®SMBV-B106	9 kHz to 6 GHz	1407.9703.02

Ordering Information		
R&S®SMBV-B10	Baseband Generator with Digital Modulation (realtime) and ARB (32 Msample), 120 MHz RF bandwidth	1407.8607.02
R&S®SMBV-B50	Baseband Generator with ARB (32 Msample), 120 MHz RF bandwidth	1407.8907.02
R&S®SMBV-B51	Baseband Generator with ARB (32 Msample), 60 MHz RF bandwidth	1407.9003.02
R&S®SMBV-K18	Digital Baseband Connectivity	1415.8002.02
R&S®SMBV-K55	EUTRA/LTE	1415.8177.02
R&S® SMBV-K255	Digital Standard 3GPP EUTRA/LTE for WinIQSIM2	1415.8360.02
R&S® SMJ100A	**Vector Signal Generator**	**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 (realtime) and ARB (64MSamples)	1403.8902.02
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® SMJ-K69	LTE Closed-Loop BS Test	1409.3002.02
R&S® SMJ-K81	LTE Logfile Generation	1409.3054.02
R&S® SMATE200A	**Vector Signal Generator**	**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 6 GHz for 2nd RF Path	1401.1400.02

Ordering Information		
R&S® SMATE-B206	Frequency range 100 KHz to 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 (real time) and ARB (64 M samples)	1401.2707.02
R&S® SMATE-B11	Baseband Generator with digital modulation (real time) and ARB (16 M samples)	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® SMATE-K69	LTE Closed-Loop BS Test	1404.8564.02
R&S® SMATE-K81	LTE Logfile Generation	1404.8612.02
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 digital modulation (realtime) and ARB (64 MSamples)	1402.5300.02
R&S® AMU-B11	Baseband generator with digital modulation (realtime) and ARB (16 MSamples)	1402.5400.02
R&S® AMU-B13	Baseband main module	1402.5500.02
R&S® AMU-B14	Fading Simulator	1402.5600.02
R&S® AMU-B15	Fading Simulator extension	1402.5700.02
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-K69	LTE Closed-Loop BS Test	1403.0501.02
R&S® AMU-K74	2x2 MIMO Fading	1402.9857.02
R&S® AMU-K81	LTE Logfile Generation	1403.0553.02
Signal Analyzers		
R&S®FSW8	**2 Hz to 8 GHz**	**1312.8000K08**
R&S®FSW13	**2 Hz to 13.6 GHz**	**1312.8000K13**
R&S®FSW26	**2 Hz to 26.5 GHz**	**1312.8000K26**
R&S® FSQ3	**20 Hz to 3.6 GHz**	**1155.5001.03**

Ordering Information		
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® FSV13	**10 Hz to 13.6 GHz**	**1307.9002K13**
R&S® FSV30	**10 Hz to 30 GHz**	**1307.9002K30**
R&S® FSV40	**10 Hz to 40 GHz** **Maximum bandwidth 10 MHz**	**1307.9002K40**
R&S® FSV40	**10 Hz to 40 GHz**	**1307.9002K39**
R&S®FSH4 (model 04)	**9 kHz to 3.6 GHz with preamplifier**	**1309.6000.04**
R&S®FSH4 (model 14)	**9 kHz to 3.6 GHz with preamplifier and tracking generator**	**1309.6000.14**
R&S®FSH4 (model 24)	**100 kHz to 3.6 GHz with preamplifier, tracking generator and internal VSWR bridge**	**1309.6000.24**
R&S®FSH8 (model 08)	**9 kHz to 8 GHz, with preamplifier**	**1309.6000.08**
R&S®FSH8 (model 18)	**9 kHz to 8 GHz with preamplifier and tracking generator**	**1309.6000.18**
R&S®FSH8 (model 28)	**100 kHz to 8 GHz, with preamplifier, tracking generator and internal VSWR bridge**	**1309.6000.28**
R&S® FSW-K100	EUTRA/LTE Downlink / BS Analysis	1313.1554.02
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
R&S® FSV-K102	EUTRA/LTE Downlink MIMO Analysis	1310.9151.02

Ordering Information		
R&S® FSW-K104	Analysis of EUTRA/LTE TDD Downlink Signals	1313.1574.02
R&S® FSQ-K104	Analysis of EUTRA/LTE TDD Downlink Signals	1309.9422.02
R&S®FSV-K104	EUTRA/LTE TDD Downlink Analysis	1309.9774.02
R&S® FSQ-K105	Analysis of EUTRA/LTE TDD Uplink Signals	1309.9516.02
R&S®FSV-K105	EUTRA/LTE TDD Uplink Analysis	1309.9780.02
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R&S®FS-K101PC	LTE FDD UL Measurement Software	1309.9922.02
R&S®FS-K102PC	LTE DL MIMO Measurement Software	1309.9939.02
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R&S®FS-K104PC	LTE TDD DL Measurement Software	1309.9951.02
R&S®FS-K105PC	LTE TDD UL Measurement Software	1309.9968.02
R&S®FS-K130PC	Distortion Analysis Software	1310.0090.06
Radio Wideband Communication Tester		
R&S®CMW500	Wideband Radio Communication Tester, RF Production Tester	1201.0002K50
R&S®CMW500-PT	HSPA+ and LTE Protocol Tester	1201.0002K50
Conformance and Pre-conformance Testers		
R&S®TS8980FTA	Conformance Test System	0999.1902.86
R&S®TS8980IB	RF Conformance Test System Integrated test system for LTE conformance tests	0999.1902.84
R&S®TS8980S	Pre-Compliance Test System	0999.1902.82
Drive test Tools		
R&S®TSMW	Universal Radio Network Analyzer	1503.3001.03
R&S®ROMES4	Drive Test Software	1117.6885.04
R&S®ROMES4REP	R&S®ROMES4 Drive Test Software Replay Version, with data export	1117.6885.34

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Environmental commitment

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