Agilent
3GPP Long Term Evolution:
System Overview, Product Development, and Test Challenges

Application Note

Current to June 2009
3GPP LTE standard

This application note describes the Long Term Evolution (LTE) of the universal mobile telecommunication system (UMTS), which is being developed by the 3rd Generation Partnership Project (3GPP). Close attention is given to LTE's use of multiple antenna techniques—in particular, Multiple Input Multiple Output (MIMO)—and to a new modulation scheme called single carrier frequency division multiple access (SC-FDMA) that is used in the LTE uplink. Also, because the accelerated pace of LTE product development calls for measurement tools that parallel the standard's development, this application note introduces Agilent's expanding portfolio of LTE design, verification, and test solutions.

Agilent Technologies

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1 LTE Concepts

1.1 Introduction

Third-generation UMTS, based on wideband code-division multiple access (W-CDMA), has been deployed all over the world. To ensure that this system remains competitive in the future, in November 2004 3GPP began a project to define the long-term evolution of UMTS cellular technology. The specifications related to this effort are formally known as the evolved UMTS terrestrial radio access (E-UTRA) and evolved UMTS terrestrial radio access network (E-UTRAN), but are more commonly referred to by the project name LTE. The first version of LTE is documented in Release 8 of the 3GPP specifications.

A parallel 3GPP project called System Architecture Evolution (SAE) is defining a new all-IP, packet-only core network (CN) known as the evolved packet core (EPC). The combination of the EPC and the evolved RAN (E-UTRA plus E-UTRAN) is the evolved packet system (EPS). Depending on the context, any of the terms LTE, E-UTRA, E-UTRAN, SAE, EPC and EPS may get used to describe some or all of the system. Although EPS is the only correct term for the overall system, the name of the system will often be written as LTE/SAE or simply LTE.

3GPP's high-level requirements for LTE include reduced cost per bit, better service provisioning, flexible use of new and existing frequency bands, simplified network architecture with open interfaces, and an allowance for reasonable power consumption by terminals. These are detailed in the LTE feasibility study, 3GPP Technical Report 25.912 [1], and in the LTE requirements document, 25.913 [2].

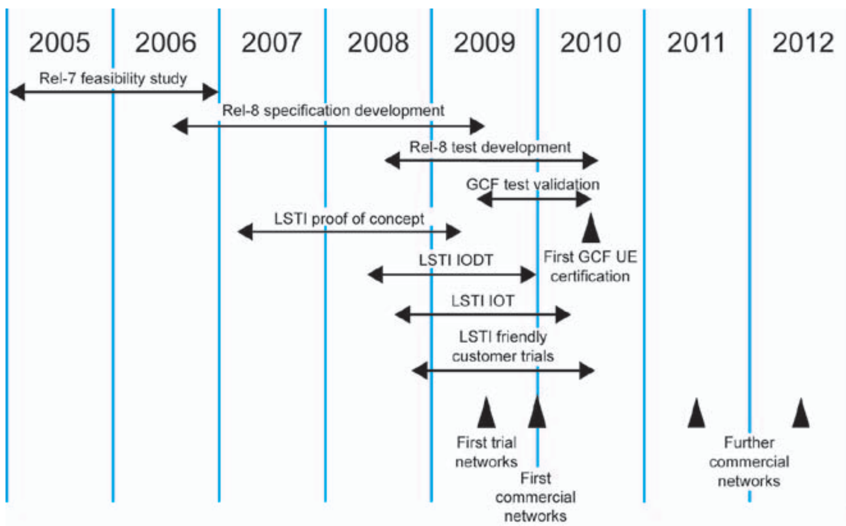

Figure 1. LTE development lifecycle

A timeline for LTE development is shown in Figure 1. This includes the work of 3GPP in drafting the specifications as well as the conformance test activities of the Global Certification Forum (GCF) and the trials being carried out by the LTE/SAE Trial Initiative (LSTI). The LSTI is an industry forum and complementary group who are working in parallel with 3GPP and GCF with the intent of accelerating the acceptance and deployment of LTE as the logical choice of the industry for next generation networks. The work of LSTI is split into four phases. The first phase is proof of concept of the basic principles of LTE and SAE, using early prototypes not necessarily compliant with the specifications. The second phase is interoperability development testing (IODT), which is a more detailed phase of testing using standards-compliant equipment but not necessarily commercial platforms. The third stage is interoperability testing (IOT), which is similar in scope to IODT but uses platforms that are intended for commercial deployment. The final phase is friendly customer trials, which will run until mid-2010 when GCF is expected to certify the first UE against the 3GPP conformance tests. Dates beyond mid-2009 are estimates, and actual dates will depend on industry conditions and progress.

1.2 Summary of LTE requirements

To meet the requirements for LTE outlined in 25.913, LTE aims to achieve the following:

- Increased downlink and uplink peak data rates, as shown in Table 1. Note that the downlink is specified for single input single output (SISO) and multiple input multiple output (MIMO) antenna configurations at a fixed 64QAM modulation depth, whereas the uplink is specified only for SISO but at different modulation depths. These figures represent the physical limitation of the frequency division duplex (FDD) air interface in ideal radio conditions with allowance for signaling overheads. Lower rates are specified for specific UE categories, and performance requirements under non-ideal radio conditions have also been developed. Comparable figures exist in 25.912 for TDD.
- Scalable channel bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz in both the uplink and the downlink
- Spectral efficiency improvements over Release 6 high speed packet access (HSPA) of three to four times in the downlink and two to three times in the uplink
- Sub-5 ms latency for small internet protocol (IP) packets
- Performance optimized for low mobile speeds from 0 to 15 km/h, supported with high performance from 15 to 120 km/h; functional support from 120 to 350 km/h, under consideration for 350 to 500 km/h
- Co-existence with legacy standards while evolving toward an all-IP network

Table 1. LTE (FDD) downlink and uplink peak data rates from TR 25.912 V7.2.0 Tables 13.1 and 13.1a

FDD downlink peak data rates (64QAM)			
Antenna configuration	SISO	2x2 MIMO	4x4 MIMO
Peak data rate Mbps	100	172.8	326.4

FDD uplink peak data rates (single antenna)			
Modulation depth	QPSK	16QAM	64QAM
Peak data rate Mbps	50	57.6	86.4

1.3 History of the UMTS standard

Table 2 summarizes the evolution of the 3GPP UMTS specifications towards LTE. Each release of the 3GPP specifications represents a defined set of features. A summary of the contents of any release can be found at **www.3gpp.org/releases**. The date given for the functional freeze relates to the date when no further new items can be added to the release. Any further changes to the specifications are restricted to essential corrections.

After Release 99, 3GPP stopped naming releases after the year and opted for a new scheme that started with Release 4. Release 4 introduced the 1.28 Mcps narrow band version of W-CDMA, also known as time domain synchronous code division multiple access (TD-SCDMA). Following this was Release 5, in which high speed downlink packet access (HDSPA) introduced packet-based data services to UMTS in the same way that the general packet radio service (GPRS) did for GSM in Release 97 (1998). The completion of packet data for UMTS was achieved in Release 6 with the addition of high speed uplink packet access (HSUPA), although the official term for this technology is enhanced dedicated channel (E-DCH). HSDPA and HSUPA are now known collectively as high speed packet access (HSPA). Release 7 contained the first work on LTE/SAE with the completion of the feasibility studies, and further improvements were made to HSPA such as downlink MIMO, 64QAM on the downlink, and 16QAM on the uplink.

In Release 8, HSPA continues to evolve with the addition of numerous smaller features such as dual cell HSDPA and 64QAM with MIMO. The main work in Release 8, however, is the specification of LTE and SAE. Work beyond Release 8 is also in progress whereby LTE will be enhanced in Release 10 and put forward as LTE-Advanced, a candidate technology for the International Telecommunications Union (ITU) IMT-Advanced program, better known as 4G.

Table 2. Evolution of the UMTS specifications

Release	Functional freeze	Main UMTS feature of release
Rel-99	March 2000	Basic 3.84 Mcps W-CDMA (FDD & TDD)
Rel-4	March 2001	1.28 Mcps TDD (aka TD-SCDMA)
Rel-5	June 2002	HSDPA
Rel-6	March 2005	HSUPA (E-DCH)
Rel-7	December 2007	HSPA+ (64QAM downlink, MIMO, 16QAM uplink) LTE and SAE feasibility study
Rel-8	December 2008	LTE work item – OFOMA/SC-FDMA air interface SAE work item – new IP core network Further HSPA improvements

There are other standardization activities within 3GPP not shown in Table 2 such as those for the GSM Enhanced RAN (GERAN) and the Internet Protocol Multimedia Subsystem (IMS).

1.4 LTE in context

3GPP LTE is one of several evolving 3G wireless standards loosely referred to as 3.9G. The other standards are:

- 3GPP HSPA+
- 3GPP EDGE Evolution
- Mobile WiMAX™ (IEEE 802.16e), which encompasses the earlier WiBro developed by the Telecommunications Technology Association (TTA) in Korea

All have similar goals in terms of improving spectral efficiency, with the widest bandwidth systems providing the highest single-user data rates. Spectral efficiencies are achieved primarily through the use of less robust, higher-order modulation schemes and multi-antenna technology that ranges from basic transmit and receive diversity to the more advanced MIMO spatial diversity.

Of the 3.9G standards, EDGE evolution and HSPA+ are direct extensions of existing technologies. Mobile WiMAX is based on the existing IEEE 802.16d standard and has had limited implementation in WiBro. Of the standards listed above, only LTE is considered "new." Work on the alternative Ultra Mobile Broadband (UMB) standard being developed by 3GPP2 was discontinued in November 2008 in favor of LTE.

1.5 3GPP LTE specification documents

Release 7 of the 3GPP specifications included the study phase of LTE. This study resulted in several Technical Reports, of which 25.912 and 25.913 have been noted.

The specifications themselves for the LTE E-UTRA and E-UTRAN are contained in the 36 series of Release 8, divided into the following categories:

- 36.100 series covering radio specifications and evolved Node B (eNB) conformance testing
- 36.200 series covering layer 1 (physical layer) specifications
- 36.300 series covering layer 2 and 3 air interface signaling specifications
- 36.400 series covering network signaling specifications
- 36.500 series covering user equipment conformance testing
- 36.800 and 36.900 series, which are technical reports containing background information

The SAE specifications are found in the 22 series, 23 series, 24 series, and 33 series of Release 8, with work being done in parallel in Release 9.

The latest versions of the LTE and SAE documents can be found at **http://www.3gpp.org/ftp/specs/latest/Rel-8/**.

1.6 System architecture overview

Figure 2, which is taken from Technical Specification 23.882 [3], illustrates the complexity of the 2G and 3G cellular network today.

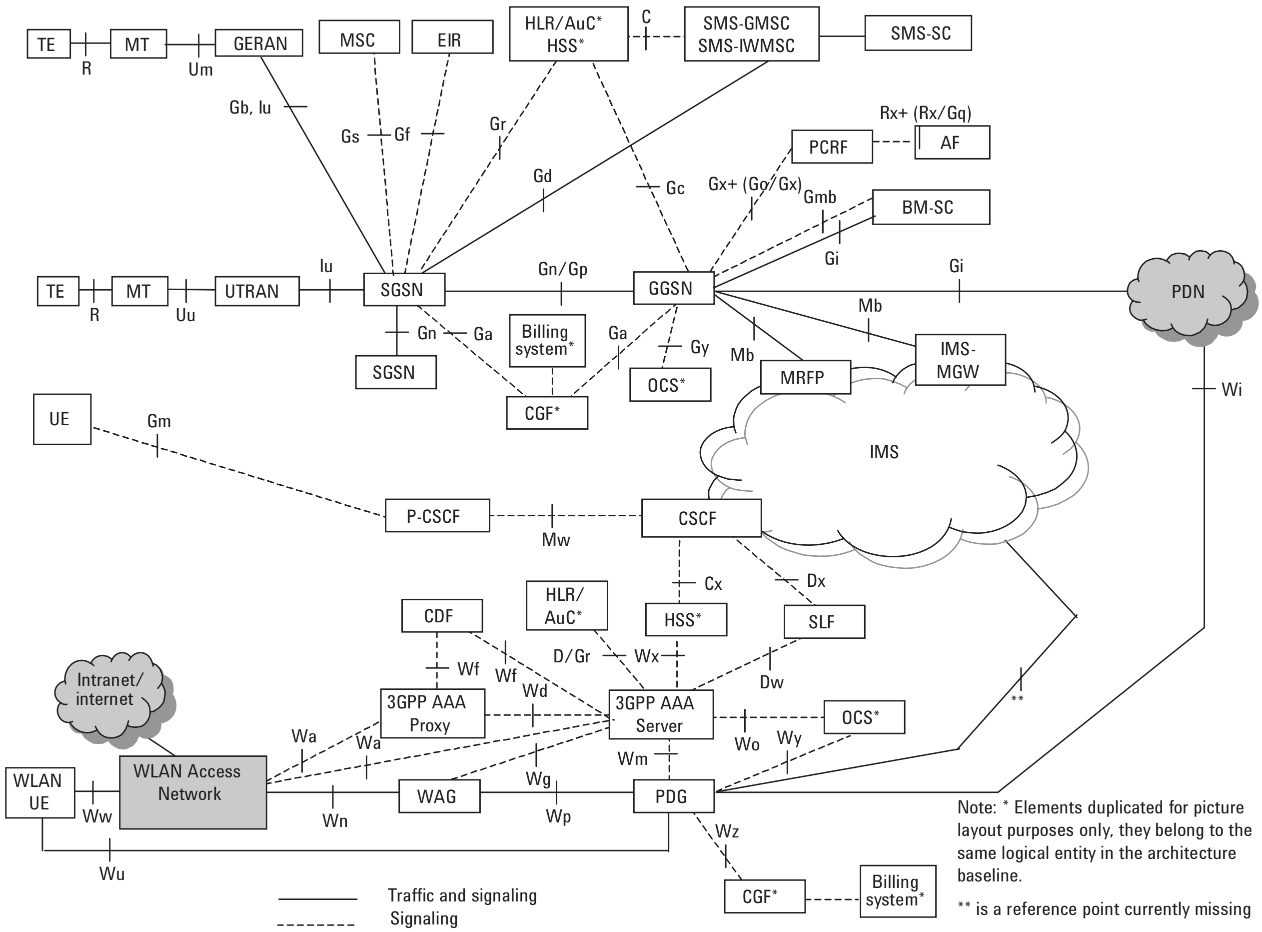

Figure 2. Logical baseline architecture for 3G (23.882 [3] Figure 4.1-1)

3GPP's drive to simplify this architecture is behind the SAE project to define an all-IP, packet-only core network called the evolved packet core or EPC, as noted earlier. Some of the goals of LTE cannot be met unless the EPC is also implemented. In addition to supporting LTE, the EPC supports both legacy 3GPP (UTRAN, GERAN) and non-3GPP (cdma2000, 802.16, etc.) radio access networks (RANs).

Figure 3 shows a high level view of how the LTE evolved RAN and the EPC interact with legacy radio access technologies.

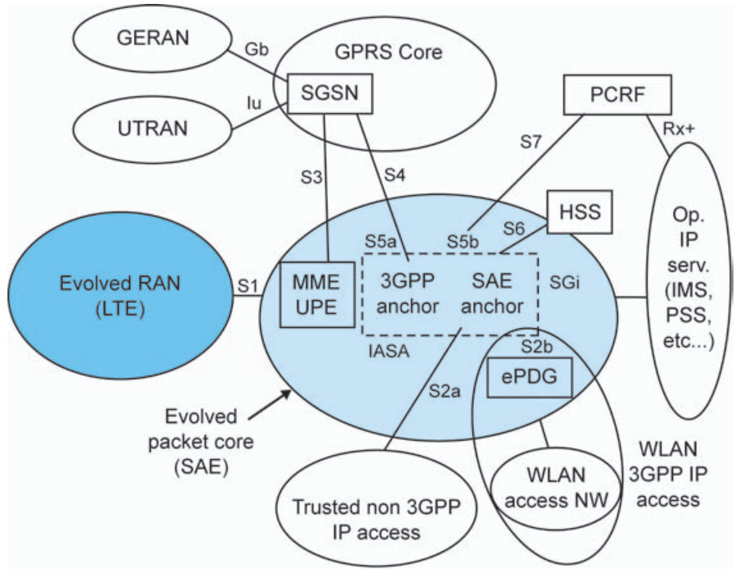

Figure 3. Logical high level architecture for the evolved system (from 23.882 [3] Figure 4.2-1)

Like the EPC, the architecture of the LTE RAN is also greatly simplified. Figure 4, taken from 36.300 [4], shows the E-UTRAN, which contains a new network element— the eNB—that provides the E-UTRA user plane and control plane protocol terminations toward the UE.

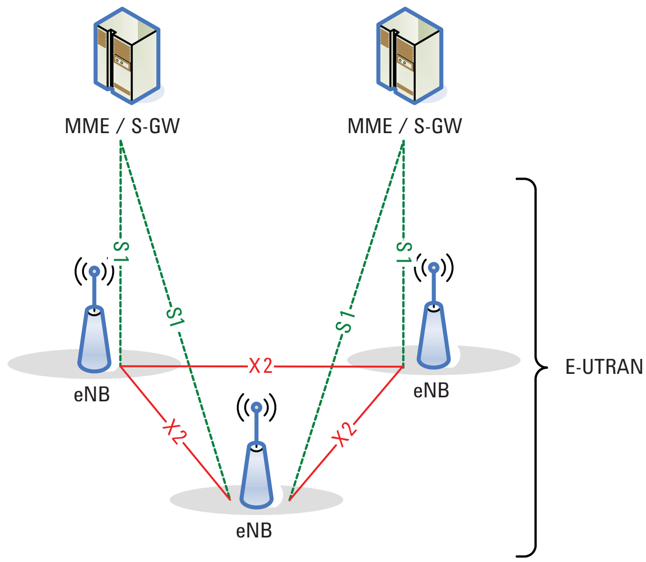

Figure 4. LTE architecture with E-UTRAN (36.300 [4] Figure 4)

A new interface called X2 connects the eNBs as a mesh network, enabling direct communication between the elements and eliminating the need to funnel data back and forth through a radio network controller (RNC).

The E-UTRAN is connected to the EPC via the S1 interface, which connects the eNBs to the mobility management entity (MME) and serving gateway (S-GW) elements through a “many-to-many” relationship.

Figure 5 from 36.300 [4] shows the functional split between the E-UTRAN and the EPC in the EPS. Yellow boxes depict the logical nodes, white boxes the functional entities of the control plane, and blue boxes the radio protocol layers.

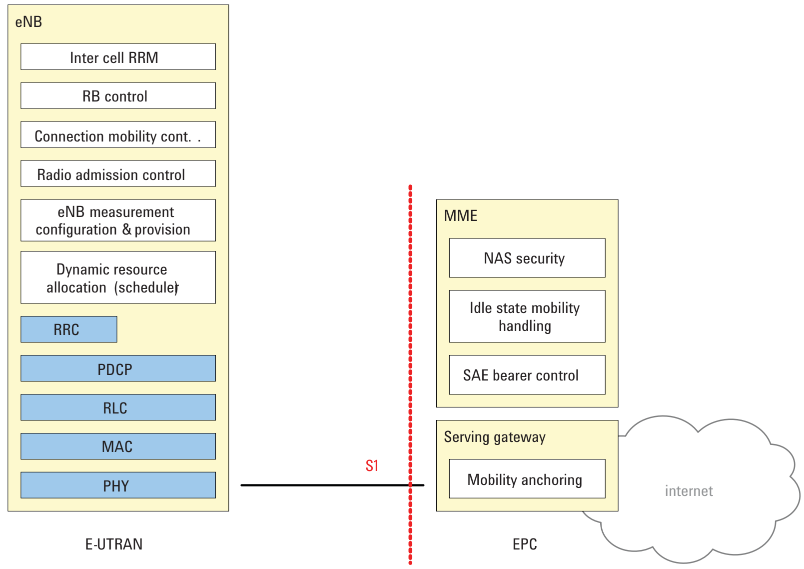

Figure 5. Functional split between E-UTRAN and EPC (36.300 [4] Figure 4.1)

Specifically, the eNB hosts these functions:

- Radio resource management
- IP header compression and encryption
- Selection of MME at UE attachment
- Routing of user plane data towards S-GW
- Scheduling and transmission of paging messages and broadcast information
- Measurement and measurement reporting configuration for mobility and scheduling
- Scheduling and transmission of ETWS messages

The MME hosts many functions including:

- Non-access stratum (NAS) signaling and NAS signaling security
- Access stratum (AS) security control
- Idle state mobility handling
- EPS bearer control

The S-GW provides these functions:

- Mobility anchor point for inter eNB handovers
- Termination of user-plane packets for paging reasons
- Switching of user plane for UE mobility

The packet data network (PDN) gateway (P-GW) functions include:

- UE IP address allocation
- Per-user-based packet filtering
- Lawful interception

More complete listings of the functions hosted by these network elements are found in 23.401 [5].

2 LTE Air Interface Radio Aspects

The LTE radio transmission and reception specifications are documented in 36.101 [6] for the UE and 36.104 [7] for the eNB (base station).

2.1 Radio access modes

The LTE air interface supports both FDD and time division duplex (TDD) modes, each of which has its own frame structure. Additional access modes may be defined, and half-duplex FDD is being considered. Half-duplex FDD allows the sharing of hardware between the uplink and downlink since the uplink and downlink are never used simultaneously. This technique has uses in some frequency bands and also offers a cost saving while halving potential data rates.

The LTE air interface also supports the multimedia broadcast and multicast service (MBMS), a relatively new technology for broadcasting content such as digital TV to UE using point-to-multi-point connections. The 3GPP specifications for MBMS first appeared for UMTS in Release 6. LTE will specify a more advanced evolved MBMS (eMBMS) service, which operates over a multicast/broadcast over single-frequency network (MBSFN) using a time-synchronized common waveform that can be transmitted from multiple cells for a given duration. The MBSFN allows over-the-air combining of multi-cell transmissions in the UE, using the cyclic prefix (CP) to cover the difference in the propagation delays. To the UE, the transmissions appear to come from a single large cell. This technique makes LTE highly efficient for MBMS transmission. The eMBMS service will be fully defined in Release 9 of the 3GPP specifications.

2.2 Transmission bandwidths

LTE must support the international wireless market and regional spectrum regulations and spectrum availability. To this end the specifications include variable channel bandwidths selectable from 1.4 to 20 MHz, with subcarrier spacing of 15 kHz. If the new LTE eMBMS is used, a subcarrier spacing of 7.5 kHz is also possible. Subcarrier spacing is constant regardless of the channel bandwidth. 3GPP has defined the LTE air interface to be "bandwidth agnostic," which allows the air interface to adapt to different channel bandwidths with minimal impact on system operation.

The smallest amount of resource that can be allocated in the uplink or downlink is called a resource block (RB). An RB is 180 kHz wide and lasts for one 0.5 ms timeslot. For standard LTE, an RB comprises 12 subcarriers at a 15 kHz spacing, and for eMBMS with the optional 7.5 kHz subcarrier spacing an RB comprises 24 subcarriers for 0.5 ms. The maximum number of RBs supported by each transmission bandwidth is given in Table 3.

Table 3. Transmission bandwidth configuration (based on 36.101 [6] Table 5.6-1)

Channel bandwidth (MHz)	1.4	3	5	10	15	20
Transmission bandwidth configuration (MHz)	1.08	2.7	4.5	9	13.5	18
Transmission bandwidth configuration (N_{RB}^{UL} OR N_{RB}^{DL}) (RB)	6	15	25	50	75	100

2.3 Supported frequency bands

The LTE specifications inherit all the frequency bands defined for UMTS, which is a list that continues to grow. There are at the time of this writing 15 FDD operating bands and 8 TDD operating bands. Significant overlap exists between some of the bands, but this does not necessarily simplify designs since there can be band-specific performance requirements based on regional needs. There is no consensus on which band LTE will first be deployed, since the answer is highly dependent on local variables. This lack of consensus is a significant complication for equipment manufacturers and contrasts with the start of GSM and W-CDMA, both of which were specified for only one band. What is now firmly established is that one may no longer assume that any particular band is reserved for any one access technology.

Table 4. EUTRA operating bands (TS 36.101 [6] Table 5.5-1)

E-UTRA operating band	Uplink (UL) operating band BS receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex mode
	F_{UL_low} – F_{UL_high}	F_{DL_low} – F_{DL_high}	
1	1920 – 1980 MHz	2110 – 2170 MHz	FDD
2	1850 – 1910 MHz	1930 – 1990 MHz	FDD
3	1710 – 1785 MHz	1805 – 1880 MHz	FDD
4	1710 – 1755 MHz	2110 – 2155 MHz	FDD
5	824 – 849 MHz	869 – 894 MHz	FDD
6	830 – 840 MHz	875 – 885 MHz	FDD
7	2500 – 2570 MHz	2620 – 2690 MHz	FDD
8	880 – 915 MHz	925 – 960 MHz	FDD
9	1749.9 – 1784.9 MHz	1844.9 – 1879.9 MHz	FDD
10	1710 – 1770 MHz	2110 – 2170 MHz	FDD
11	1427.9 – 1452.9 MHz	1475.9 – 1500.9 MHz	FDD
12	698 – 716 MHz	728 – 746 MHz	FDD
13	777 – 787 MHz	746 – 756 MHz	FDD
14	788 – 798 MHz	758 – 768 MHz	FDD
...			
17	704 – 716 MHz	734 – 746 MHz	FDD
...			
33	1900 – 1920 MHz	1900 – 1920 MHz	TDD
34	2010 – 2025 MHz	2010 – 2025 MHz	TDD
35	1850 – 1910 MHz	1850 – 1910 MHz	TDD
36	1930 – 1990 MHz	1930 – 1990 MHz	TDD
37	1910 – 1930 MHz	1910 – 1930 MHz	TDD
38	2570 – 2620 MHz	2570 – 2620 MHz	TDD
39	1880 – 1920 MHz	1880 – 1920 MHz	TDD
40	2300 – 2400 MHz	2300 – 2400 MHz	TDD

2.4 Peak single user data rates and UE capabilities

The estimated peak data rates deemed feasible for the LTE system in ideal conditions are very high, and range from 100 to 326.4 Mbps on the downlink and 50 to 86.4 Mbps on the uplink depending on the antenna configuration and modulation depth. These rates represent the absolute maximum the system could support and actual peak data rates will be scaled back by the introduction of UE categories. A UE category puts limits on what has to be supported. There are many dimensions to a UE category but the most significant is probably the supported data rates. Tables 5 derived from 36.306 [8] shows the UE categories and the data they will support.

Table 5. Peak data rates for UE categories (derived from 36.306 [6] Tables 4.1-1 and 4.1-2)

UE category	Peak downlink data rate (Mbps)	Downlink antenna configuration (eNB transmit x UE receive)	Peak uplink data rate (Mbps)	Support for 64QAM in uplink
Category 1	10.296	1 x 2	5.16	No
Category 2	51.024	2 x 2	25.456	No
Category 3	102.048	2 x 2	51.024	No
Category 4	150.752	2 x 2	51.024	No
Category 5	302.752	4 x 2	75.376	Yes

Note that the UE category for the downlink and for the uplink must be the same.

2.5 Multiple access technology in the downlink: OFDM and OFDMA

Downlink and uplink transmission in LTE are based on the use of multiple access technologies: specifically, orthogonal frequency division multiple access (OFDMA) for the downlink, and single-carrier frequency division multiple access (SC-FDMA) for the uplink.

The downlink is considered first. OFDMA is a variant of orthogonal frequency division multiplexing (OFDM), a digital multi-carrier modulation scheme that is widely used in wireless systems but relatively new to cellular. Rather than transmit a high-rate stream of data with a single carrier, OFDM makes use of a large number of closely spaced orthogonal subcarriers that are transmitted in parallel. Each subcarrier is modulated with a conventional modulation scheme (such as QPSK, 16QAM, or 64QAM) at a low symbol rate. The combination of hundreds or thousands of subcarriers enables data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

The diagram in Figure 6 taken from TR 25.892 [9] illustrates the key features of an OFDM signal in frequency and time. In the frequency domain, multiple adjacent tones or subcarriers are each independently modulated with data. Then in the time domain, guard intervals are inserted between each of the symbols to prevent inter-symbol interference at the receiver caused by multi-path delay spread in the radio channel.

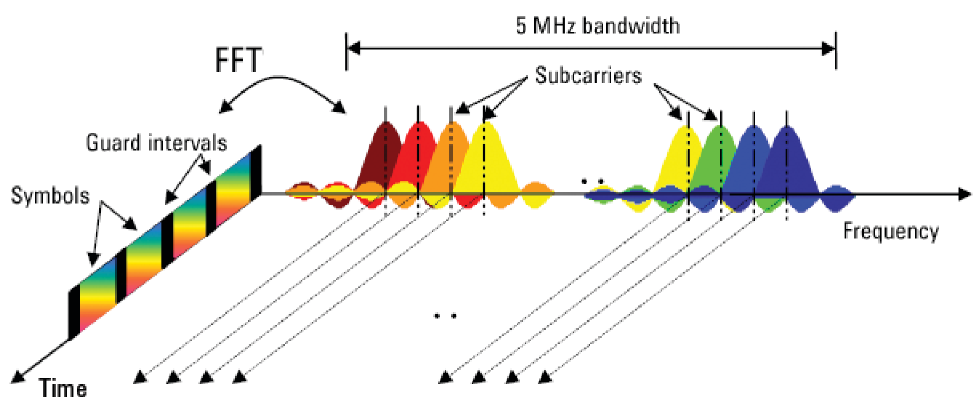

Figure 6. OFDM signal represented in frequency and time (25.892 [9] Figure 1)

Although OFDM has been used for many years in communication systems, its use in mobile devices is more recent. The European Telecommunications Standards Institute (ETSI) first looked at OFDM for GSM back in the late 1980s; however, the processing power required to perform the many FFT operations at the heart of OFDM was at that time too expensive and demanding for a mobile application. In 1998, 3GPP seriously considered OFDM for UMTS, but again chose an alternative technology based on code division multiple access (CDMA). Today the cost of digital signal processing has been greatly reduced and OFDM is now considered a commercially viable method of wireless transmission for the handset.

When compared to the CDMA technology upon which UMTS is based, OFDM offers a number of distinct advantages:

- OFDM can easily be scaled up to wide channels that are more resistant to fading.
- OFDM channel equalizers are much simpler to implement than are CDMA equalizers, as the OFDM signal is represented in the frequency domain rather than the time domain.
- OFDM can be made completely resistant to multi-path delay spread. This is possible because the long symbols used for OFDM can be separated by a guard interval known as the cyclic prefix (CP). The CP is a copy of the end of a symbol inserted at the beginning. By sampling the received signal at the optimum time, the receiver can remove the time domain interference between adjacent symbols caused by multi-path delay spread in the radio channel.
- OFDM is better suited to MIMO. The frequency domain representation of the signal enables easy precoding to match the signal to the frequency and phase characteristics of the multi-path radio channel.

However, OFDM does have some disadvantages. The subcarriers are closely spaced making OFDM sensitive to frequency errors and phase noise. For the same reason, OFDM is also sensitive to Doppler shift, which causes interference between the subcarriers. Pure OFDM also creates high peak-to-average signals, and that is why a modification of the technology called SC-FDMA is used in the uplink. SC-FDMA is discussed later.

It is known that OFDM will be more difficult to operate than CDMA at the edge of cells. CDMA uses scrambling codes to provide protection from inter-cell interference at the cell edge whereas OFDM has no such feature. Therefore, some form of frequency planning at the cell edges will be required. Figure 7 gives one example of how this might be done. The color yellow represents the entire channel bandwidth and the other colors show a plan for frequency re-use to avoid inter-cell interference at the cell edges.

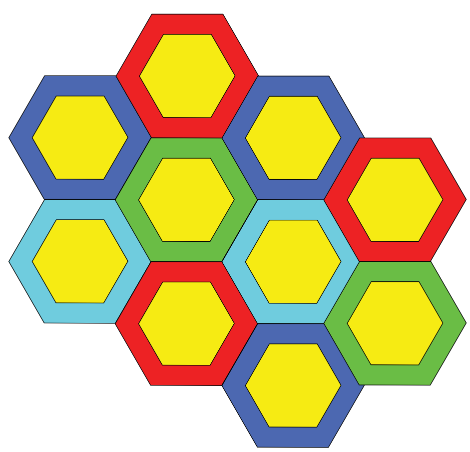

Figure 7. Example of frequency planning to avoid inter-cell interference at the cell edges

The main differences between CDMA and OFDM are summarized in Table 6.

Table 6. Comparison of CDMA and OFDM

Attribute	CDMA	OFDM
Transmission bandwidth	Full system bandwidth	Variable up to full system bandwidth
Frequency-selective scheduling	Not possible	A key advantage of OFDM although it requires accurate real-time feedback of channel conditions from receiver to transmitter
Symbol period	Very short—inverse of the system bandwidth	Very long—defined by subcarrier spacing and independent of system bandwidth
Equalization	Difficult above 5 MHz	Easy for any bandwidth due to signal representation in the frequency domain
Resistance to multipath	Difficult above 5 MHz	Completely free of multipath distortion up to the CP length
Suitability for MIMO	Requires significant computing power due to signal being defined in the time domain	Ideal for MIMO due to signal representation in the frequency domain and possibility of narrowband allocation to follow real-time variations in the channel
Sensitivity to frequency domain distortion and interference	Averaged across the channel by the spreading process	Vulnerable to narrow-band distortion and interference
Separation of users	Scrambling and orthogonal spreading codes	Frequency and time although scrambling and spreading can be added as well

With standard OFDM, very narrow UE-specific transmissions can suffer from narrowband fading and interference. That is why for the downlink 3GPP chose OFDMA, which incorporates elements of time division multiple access (TDMA). OFDMA allows subsets of the subcarriers to be allocated dynamically among the different users on the channel, as shown in Figure 8. The result is a more robust system with increased capacity. This is due to the trunking efficiency of multiplexing low rate users and the ability to schedule users by frequency, which provides resistance to frequency-selective fading.

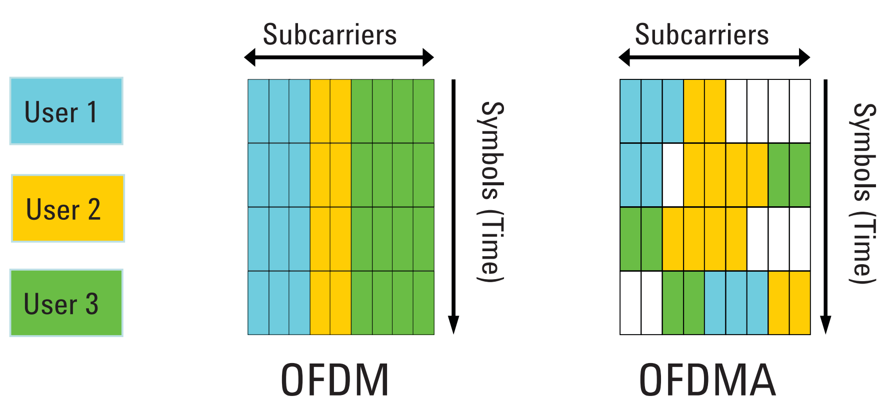

Figure 8. OFDM and OFDMA subcarrier allocation

2.6 Multiple access technology in the uplink: SC-FDMA

The high peak-to-average ratio (PAR) associated with OFDM led 3GPP to look for a different transmission scheme for the LTE uplink. SC-FDMA was chosen because it combines the low PAR techniques of single-carrier transmission systems, such as GSM and CDMA, with the multi-path resistance and flexible frequency allocation of OFDMA.

A mathematical description of an SC-FDMA symbol in the time domain is given in 36.211 [10] sub-clause 5.6. A brief description is as follows: data symbols in the time domain are converted to the frequency domain using a discrete Fourier transform (DFT); then in the frequency domain they are mapped to the desired location in the overall channel bandwidth before being converted back to the time domain using an inverse FFT (IFFT). Finally, the CP is inserted. Because SC-FDMA uses this technique, it is sometimes called discrete Fourier transform spread OFDM or (DFT-SOFDM). SC-FDMA is explained in more detail below.

2.6.1 OFDMA and SC-FDMA compared

A graphical comparison of OFDMA and SC-FDMA as shown in Figure 9 is helpful in understanding the differences between these two modulation schemes. For clarity this example uses only four (M) subcarriers over two symbol periods with the payload data represented by quadrature phase shift keying (QPSK) modulation. As described earlier, real LTE signals are allocated in units of 12 adjacent subcarriers.

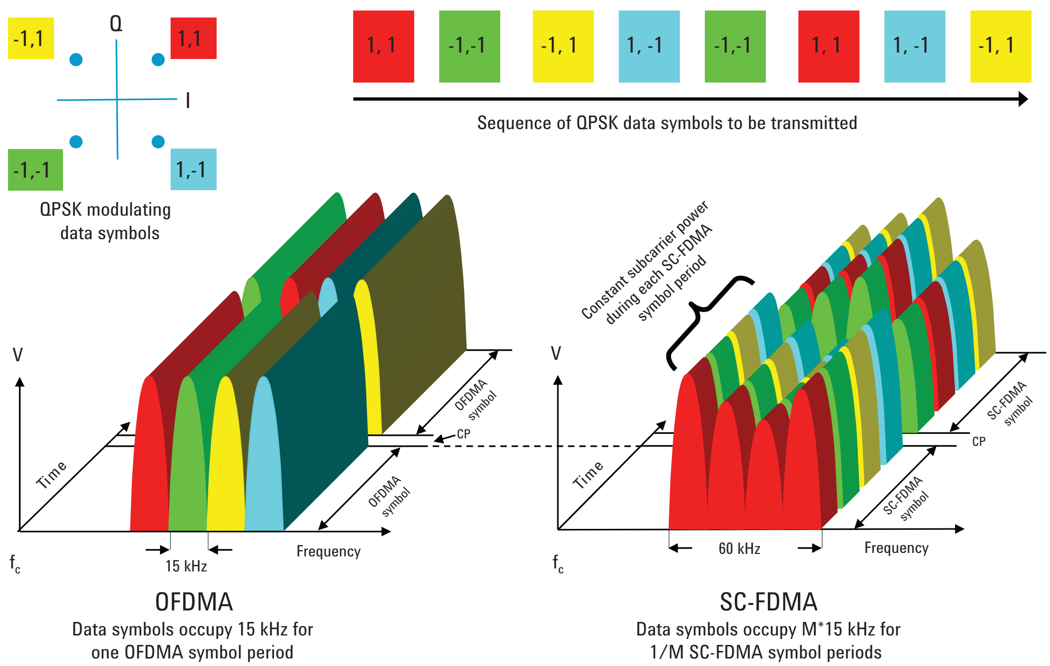

Figure 9. Comparison of OFDMA and SC-FDMA transmitting a series of QPSK data symbols

On the left side of Figure 9, M adjacent 15 kHz subcarriers—already positioned at the desired place in the channel bandwidth—are each modulated for the OFDMA symbol period of 66.7 μs by one QPSK data symbol. In this four subcarrier example, four symbols are taken in parallel. These are QPSK data symbols so only the phase of each subcarrier is modulated and the subcarrier power remains constant between symbols. After one OFDMA symbol period has elapsed, the CP is inserted and the next four symbols are transmitted in parallel. For visual clarity, the CP is shown as a gap; however, it is actually filled with a copy of the end of the next symbol, which means that the transmission power is continuous but has a phase discontinuity at the symbol boundary. To create the transmitted signal, an IFFT is performed on each subcarrier to create M time-domain signals. These in turn are vector-summed to create the final time-domain waveform used for transmission.

SC-FDMA signal generation begins with a special precoding process but then continues in a manner similar to OFDMA. However, before getting into the details of the generation process it is helpful to describe the end result as shown on the right side of Figure 9. The most obvious difference between the two schemes is that OFDMA transmits the four QPSK data symbols in parallel, one per subcarrier, while SC-FDMA transmits the four QPSK data symbols in series at four times the rate, with each data symbol occupying M x 15 kHz bandwidth.

Visually, the OFDMA signal is clearly multi-carrier with one data symbol per subcarrier, but the SC-FDMA signal appears to be more like a single-carrier (hence the “SC” in the SC-FDMA name) with each data symbol being represented by one wide signal. Note that OFDMA and SC-FDMA symbol lengths are the same at 66.7 μs; however, the SC-FDMA symbol contains M “sub-symbols” that represent the modulating data. It is the parallel transmission of multiple symbols that creates the undesirable high PAR of OFDMA. By transmitting the M data symbols in series at M times the rate, the SC-FDMA occupied bandwidth is the same as multi-carrier OFDMA but, crucially, the PAR is the same as that used for the original data symbols. Adding together many narrow-band QPSK waveforms in OFDMA will always create higher peaks than would be seen in the wider-bandwidth, single-carrier QPSK waveform of SC-FDMA. As the number of subcarriers M increases, the PAR of OFDMA with random modulating data approaches Gaussian noise statistics but, regardless of the value of M, the SC-FDMA PAR remains the same as that used for the original data symbols.

2.6.2 SC-FDMA signal generation

As noted, SC-FDMA signal generation begins with a special precoding process. Figure 10 shows the first steps, which create a time-domain waveform of the QPSK data sub-symbols. Using the four color-coded QPSK data symbols from Figure 9, the process creates one SC-FDMA symbol in the time domain by computing the trajectory traced by moving from one QPSK data symbol to the next. This is done at M times the rate of the SC-FDMA symbol such that one SC-FDMA symbol contains M consecutive QPSK data symbols. Time-domain filtering of the data symbol transitions occurs in any real implementation, although it is not discussed here.

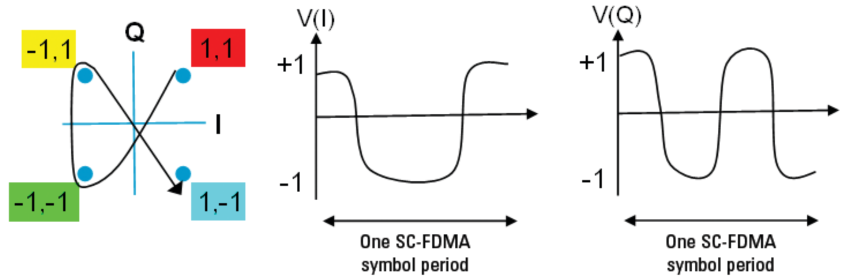

Figure 10. Creating the time-domain waveform of an SC-FDMA symbol

Once an IQ representation of one SC-FDMA symbol has been created in the time domain, the next step is to represent that symbol in the frequency domain using a DFT. This is shown in Figure 11. The DFT sampling frequency is chosen such that the time-domain waveform of one SC-FDMA symbol is fully represented by M DFT bins spaced 15 kHz apart, with each bin representing one subcarrier in which amplitude and phase are held constant for 66.7 μs.

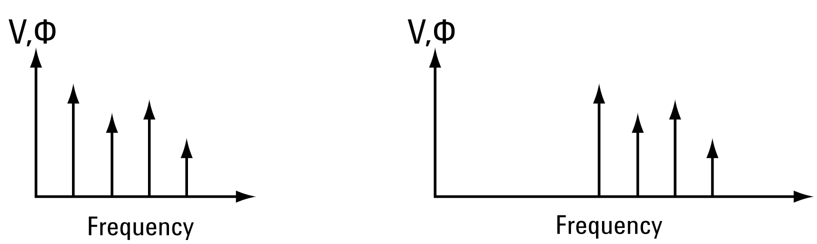

Figure 11. Baseband and frequency shifted DFT representations of an SC-FDMA symbol

A one-to-one correlation always exists between the number of data symbols to be transmitted during one SC-FDMA symbol period and the number of DFT bins created. This in turn becomes the number of occupied subcarriers. When an increasing number of data symbols are transmitted during one SC-FDMA period, the time-domain waveform changes faster, generating a higher bandwidth and hence requiring more DFT bins to fully represent the signal in the frequency domain. Note in Figure 11 that there is no longer a direct relationship between the amplitude and phase of the individual DFT bins and the original QPSK data symbols. This differs from the OFDMA example in which data symbols directly modulate the subcarriers.

The next step of the signal generation process is to shift the baseband DFT representation of the time-domain SC-FDMA symbol to the desired part of the overall channel bandwidth. Because the signal is now represented as a DFT, frequency-shifting is a simple process achieved by copying the M bins into a larger DFT space of N bins. This larger space equals the size of the system channel bandwidth, of which there are six to choose from in LTE spanning 1.4 to 20 MHz. The signal can be positioned anywhere in the channel bandwidth, thus executing the frequency-division multiple access (FDMA) essential for efficiently sharing the uplink between multiple users.

To complete SC-FDMA signal generation, the process follows the same steps as for OFDMA. Performing an IDFT converts the frequency-shifted signal to the time domain and inserting the CP provides the fundamental robustness of OFDMA against multipath. The relationship between SC-FDMA and OFDMA is illustrated in Figure 12.

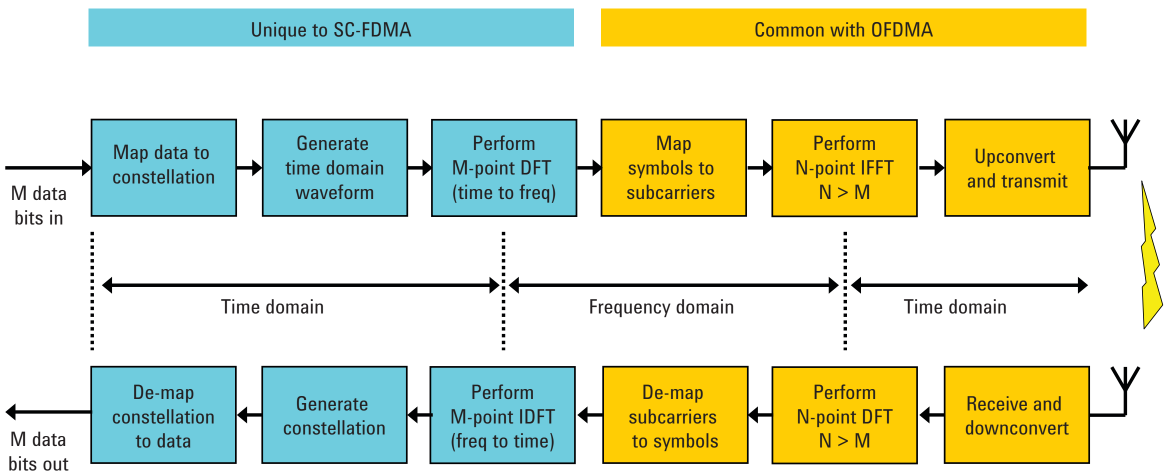

Figure 12. Simplified model of SC-FDMA and OFDMA signal generation and reception

At this point, it is reasonable to ask how SC-FDMA can be resistant to multipath when the data symbols are still short. In OFDMA, the modulating data symbols are constant over the 66.7 μs OFDMA symbol period, but an SC-FDMA symbol is not constant over time since it contains M sub-symbols of much shorter duration. The multipath resistance of the OFDMA demodulation process seems to rely on the long data symbols that map directly onto the subcarriers. Fortunately, it is the constant nature of each subcarrier—not the data symbols—that provides the resistance to delay spread. As shown in Figure 9 and Figure 11, the DFT of the time-varying SC-FDMA symbol generated a set of DFT bins constant in time during the SC-FDMA symbol period, even though the modulating data symbols varied over the same period. It is inherent to the DFT process that the time-varying SC-FDMA symbol, made of M serial data symbols, is represented in the frequency domain by M time-invariant subcarriers. Thus, even SC-FDMA with its short data symbols benefits from multipath protection.

It may seem counter intuitive that M time-invariant DFT bins can fully represent a time-varying signal. However, the DFT principle is simply illustrated by considering the sum of two fixed sine waves at different frequencies. The result is a non-sinusoidal time-varying signal, fully represented by two fixed sine waves.

Table 7 summarizes the differences between the OFDMA and SC-FDMA modulation schemes. When OFDMA is analyzed one subcarrier at a time, it resembles the original data symbols. At full bandwidth, however, the signal looks like Gaussian noise in terms of its PAR statistics and the constellation. The opposite is true for SC-FDMA. In this case, the relationship to the original data symbols is evident when the entire signal bandwidth is analyzed. The constellation (and hence low PAR) of the original data symbols can be observed rotating at M times the SC-FDMA symbol rate, ignoring the seven percent rate reduction that is due to adding the CP. When analyzed at the 15 kHz subcarrier spacing, the SC-FDMA PAR and constellation are meaningless because they are M times narrower than the information bandwidth of the data symbols.

Table 7. Analysis of OFDMA and SC-FDMA at different bandwidths

Modulation format	**OFDMA**		**SC-FDMA**	
Analysis bandwidth	15 kHz	Signal bandwidth (M * 15 kHz)	15 kHz	Signal bandwidth (M * 15 kHz)
Peak-to-average power ratio	Same as data symbol	High PAPR (Gaussian)	Lower than data symbol (not meaningful)	Same as data symbol
Observable IQ constellation	Same as data symbol at 1/66.7 μs rate	Not meaningful (Gaussian)	Not meaningful (Gaussian)	Same as data symbol at M/66.7 μs rate

2.6.3 Examining an SC-FDMA signal

Unlike the eNB, the UE does not normally transmit across the entire channel bandwidth. A typical uplink configuration with the definition of terms is shown in Figure 13.

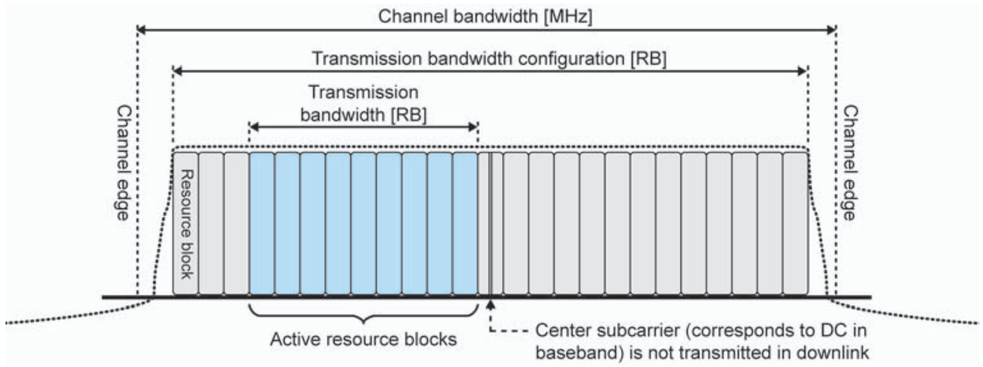

Figure 13. Definition of channel bandwidth and transmission bandwidth configuration for one E-UTRA carrier (36.101 [6] Figure 5.6-1)

Figure 14 shows some of the measurements that can be made on a typical SC-FDMA signal where the allocated transmission bandwidth is less than the transmission bandwidth configuration. Six different views or traces are shown. The constellation in trace A (top left) shows that the signal of interest is a 16QAM signal. The unity circle represents the reference signals (RS) occurring every seventh symbol, which do not use SC-FDMA but are phase-modulated using an orthogonal Zadoff-Chu sequence.

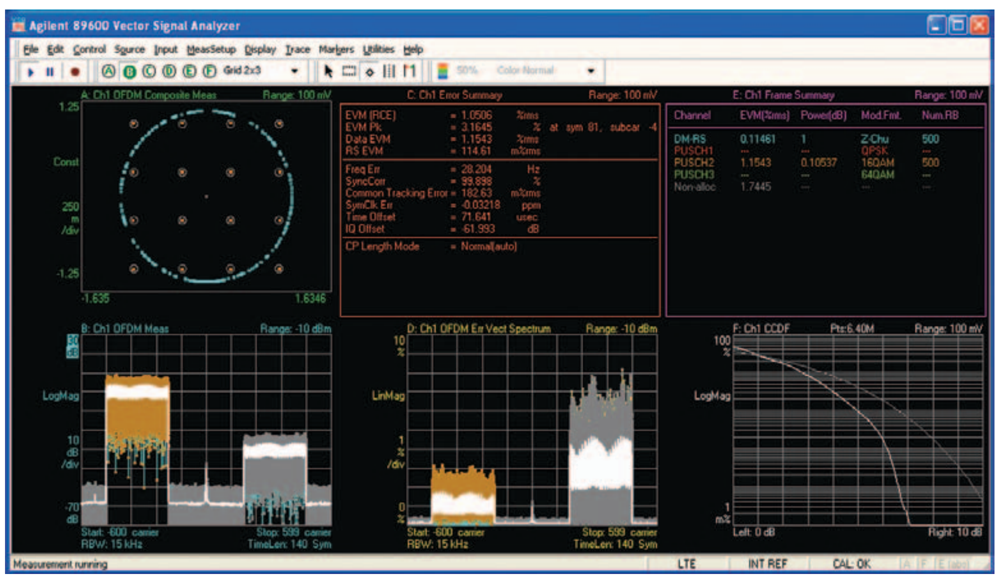

Figure 14. Analysis of a 16QAM SC-FDMA signal

Trace B (lower left) shows signal power versus frequency. The frequency scale is in 15 kHz subcarriers numbered from –600 to 599, which represents a transmission bandwidth configuration of 18 MHz or 100 RB. The channel bandwidth is therefore 20 MHz and the allocated transmission bandwidth is 5 MHz towards the lower end. The brown dots represent the instantaneous subcarrier amplitude and the white dots the average over 10 ms. In the center of the trace, the spike represents the local oscillator (LO) leakage—IQ offset—of the signal; the large image to the right is an OFDM artifact deliberately created using 0.5 dB IQ gain imbalance in the signal. Both the LO leakage and the power in non-allocated subcarriers are limited by the 3GPP specifications.

Trace C (top middle) shows a summary of the measured impairments including the error vector magnitude (EVM), frequency error, and IQ offset. Note the data EVM at 1.15 percent is much higher than the RS EVM at 0.114 percent. This is due to a +0.1 dB boost in the data power as reported in trace E, which for this example was ignored by the receiver to create data-specific EVM. Also note that the reference signal (RS) power boost is reported as +1 dB, which can be observed in the IQ constellation of Trace A because the unity circle does not pass through eight of the 16QAM points. Trace D (lower middle) shows the distribution of EVM by subcarrier. The average and peak of the allocated signal EVM is in line with the numbers in trace C. The EVM for the non-allocated subcarriers reads much higher, although the size of this impairment is specified with a new, "in-band emission" requirement as a power ratio between the allocated RB and unallocated RB. The ratio for this particular signal is around 30 dB as trace B shows. The blue dots (along the X axis) in trace D also show the EVM of the RS, which is very low.

Trace E (top right) shows a measurement of EVM versus modulation type from one capture. This signal uses only the RS phase modulation and 16QAM so the QPSK and 64QAM results are blank. Finally, trace F (lower right) shows the PAR—the whole point of SC-FDMA—in the form of a complementary cumulative distribution function (CCDF) measurement. It is not possible to come up with a single figure of merit for the PAR advantage of SC-FDMA over OFDMA because it depends on the data rate. The PAR of OFDMA is always higher than SC-FDMA even for narrow frequency allocations; however, when data rates rise and the frequency allocation gets wider, the SC-FDMA PAR remains constant but OFDMA gets worse and approaches Gaussian noise. A 5 MHz OFDMA 16QAM signal would look very much like Gaussian noise. From the lower white trace it can be seen at 0.01 percent probability that the SC-FDMA signal is 3 dB better than the upper blue Gaussian reference trace. As every amplifier designer knows, shaving even a tenth of a decibel from the peak power budget is a significant improvement.

2.7 Overview of multiple antenna techniques

Central to LTE is the concept of multiple antenna techniques, which are used to increase coverage and physical layer capacity. Adding more antennas to a radio system gives the possibility of performance improvements because the radiated signals will take different physical paths. There are three main types of multiple antenna techniques. The first makes direct use of path diversity in which one radiated path may be subject to fading loss and another may not. The second uses beamsteering by controlling the phase relationships of the electrical signals radiated at the antennas to physically steer transmitted energy. The third type employs spatial separation (the path differences introduced by separating the antennas) through the use of spatial multiplexing or beamforming, also known as multiple-input, multiple-output (MIMO) techniques.

As Figure 15 shows, there are four ways to make use of the radio channel. For simplicity, the examples depicted use only one or two antennas. Notice that the terms used to label the radio channel access modes refer to inputs and outputs of the radio channel rather than the transmitters and receivers of the devices.

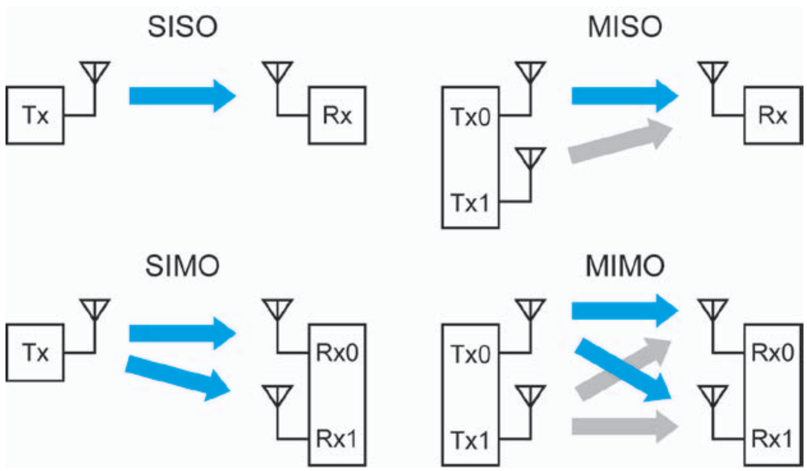

Figure 15. Radio-channel access modes

2.7.1 Single input single output

The most basic radio channel access mode is single input single output (SISO), in which only one transmit antenna and one receive antenna are used. This is the form of communications that has been the default since radio began and is the baseline against which all the multiple antenna techniques are compared.

2.7.2 Single input multiple output

A second mode shown in Figure 15 is single input multiple output (SIMO), which uses one transmitter and two or more receivers. SIMO is often referred to as receive diversity. This radio channel access mode is particularly well suited for low signal-to-noise (SNR) conditions in which a theoretical gain of 3 dB is possible when two receivers are used. There is no change in the data rate since only one data stream is transmitted, but coverage at the cell edge is improved due to the lowering of the usable SNR.

2.7.3 Multiple input single output

Multiple input single output (MISO) mode uses two or more transmitters and one receiver. (Figure 15 shows only two transmitters and one receiver for simplicity.) MISO is more commonly referred to as transmit diversity. The same data is sent on both transmitting antennas but coded such that the receiver can identify each transmitter. Transmit diversity increases the robustness of the signal to fading and can increase performance in low SNR conditions. MISO does not increase the data rates, but it supports the same data rates using less power. Transmit diversity can be enhanced with closed loop feedback from the receiver to indicate to the transmitter the optimum balance of phase and power used for each transmit antenna.

2.7.4 Multiple input multiple output

The final mode shown in Figure 15 is full MIMO, which requires two or more transmitters and two or more receivers. MIMO increases spectral capacity by transmitting multiple data streams simultaneously in the same frequency and time, taking full advantage of the different paths in the radio channel. For a system to be described as MIMO, it must have at least as many receivers as there are transmit streams. The number of transmit streams should not be confused with the number of transmit antennas. Consider the Tx diversity (MISO) case in which two transmitters are present but only one data stream. Adding receive diversity (SIMO) does not turn this configuration into MIMO, even though there are now two Tx and two Rx antennas involved. In other words, SIMO + MISO ≠ MIMO. It is always possible to have more transmitters than data streams but not the other way around. If N data streams are transmitted from fewer than N antennas, the data cannot be fully descrambled by any number of receivers since overlapping streams without the addition of spatial diversity just creates interference. However, by spatially separating N streams across at least N antennas, N receivers will be able to fully reconstruct the original data streams provided the path correlation and noise in the radio channel are low enough.

Another crucial factor for MIMO operation is that the transmissions from each antenna must be uniquely identifiable so that each receiver can determine what combination of transmissions has been received. This identification is usually done with pilot signals, which use orthogonal patterns for each antenna.

The spatial diversity of the radio channel means that MIMO has the potential to increase the data rate. The most basic form of MIMO assigns one data stream to each antenna and is shown in Figure 16.

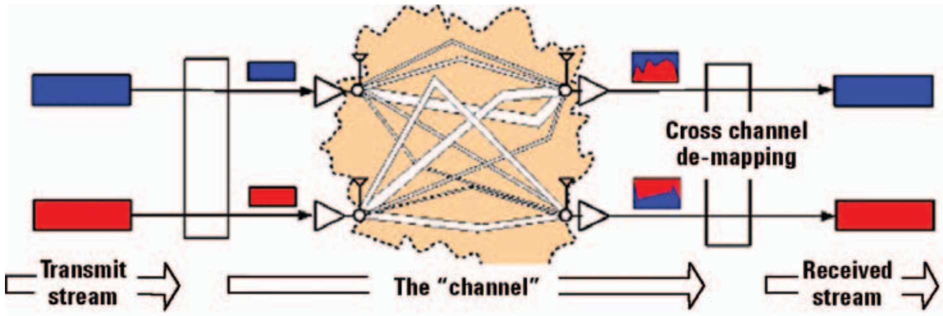

Figure 16. 2x2 MIMO, no precoding

In this form, one data stream is uniquely assigned to one antenna—known as direct mapping. The channel then mixes up the two transmissions such that at the receivers, each antenna sees a combination of each stream. Decoding the received signals is a clever process in which the receivers, by analyzing the patterns that uniquely identify each transmitter, determine what combination of each transmit stream is present. The application of an inverse filter and summing of the received streams recreates the original data.

A more advanced form of MIMO includes special precoding to match the transmissions to the Eigen modes of the channel. This optimization results in each stream being spread across more than one transmit antenna. For this technique to work effectively the transmitter must have knowledge of the channel conditions and, in the case of FDD, these conditions must be provided in real time by feedback from the UE. Such optimization significantly complicates the system but can also provide higher performance. Precoding for TDD systems does not require receiver feedback because the transmitter independently determines the channel conditions by analyzing the received signals that are on the same frequency.

The theoretical gains from MIMO are a function of the number of transmit and receive antennas, the radio propagation conditions, the ability of the transmitter to adapt to the changing conditions, and the SNR. The ideal case is one in which the paths in the radio channel are completely uncorrelated, almost as if separate, physically cabled connections with no crosstalk existed between the transmitters and receivers. Such conditions are almost impossible to achieve in free space, and with the potential for so many variables, it is neither helpful nor possible to quote MIMO gains without stating the conditions. The upper limit of MIMO gain in ideal conditions is more easily defined, and for a 2x2 system with two simultaneous data streams a doubling of capacity and data rate is possible. MIMO works best in high SNR conditions with minimal line of sight. Line of sight equates to high channel correlation and seriously diminishes the potential for gains. As a result, MIMO is particularly suited to indoor environments, which can exhibit a high degree of multi-path and limited line of sight.

2.8 LTE multiple antenna schemes

Having described some basics of multiple antenna techniques, we now look at what LTE has specified, beginning with some terminology. The terms codeword, layer and precoding have been adopted specifically for LTE to refer to signals and their processing. Figure 17 shows the processing steps to which they refer. The terms are used in the following ways:

- Codeword: A codeword represents user data before it is formatted for transmission. One or two codewords, CW0 and CW1, can be used depending on the prevailing channel conditions and use case. In the most common case of single-user MIMO (SU-MIMO), two codewords are sent to a single UE, but in the case of the less common downlink multi-user MIMO (MU-MIMO), each codeword is sent to only one UE.
- Layer: The term layer is synonymous with stream. For spatial multiplexing, at least two layers must be used. Up to four are allowed. The number of layers is denoted by the symbol ν (pronounced nu). The number of layers is always less than or equal to the number of antennas.
- Precoding: Precoding modifies the layer signals before transmission. This may be done for diversity, beamforming or spatial multiplexing. As noted earlier, the MIMO channel conditions may favor one layer (data stream) over another. If the eNB is given information about the channel—for example, information sent back from the UE—it can add complex cross-coupling to counteract the imbalance in the channel.

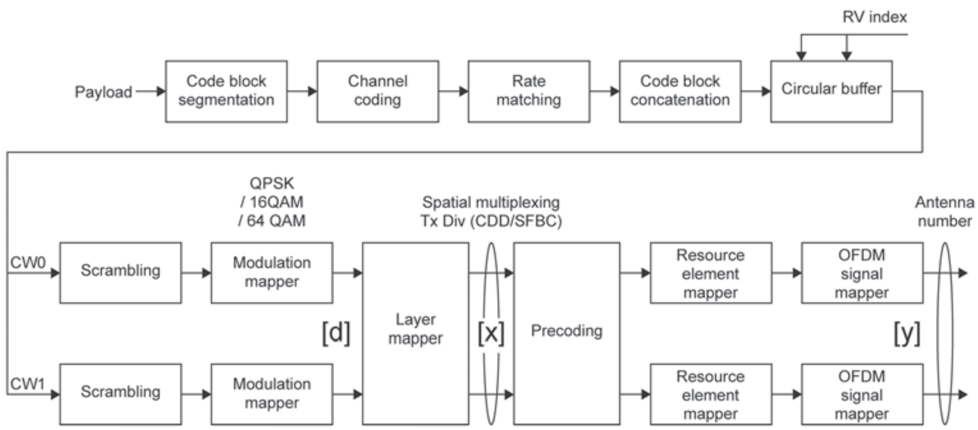

Figure 17. Signal processing for transmit diversity and spatial multiplexing (MIMO) (adapted from 36.211 [10] Figure 6.3-1)

The symbols *d, x,* and *y* are used in the specifications to denote signals before and after layer mapping and after precoding, respectively.

2.8.1 LTE downlink multiple antenna transmission modes

Seven multiple antenna transmission modes have been defined for LTE to optimize downlink performance under varying radio conditions.

1. Single-antenna port; port 0—SIMO
2. Transmit diversity—MISO
3. Open-loop spatial multiplexing—MIMO, no precoding
4. Closed-loop spatial multiplexing—MIMO, precoding
5. Multi-user MIMO—MIMO, separate UE
6. Closed-loop Rank = 1 precoding—MISO, beamsteering
7. Single-antenna port; port 5—MISO, beamsteering

The first mode uses only one transmitter, and since the UE must have at least two receivers, this is a SIMO configuration, better known as, receive diversity. This mode specifies the baseline receiver capability for which performance requirements will be defined. It is typically implemented using maximum ratio combining of the received streams to improve the SNR in poor conditions. Rx diversity provides little gain in good conditions.

The second downlink mode, Tx diversity, is identical in concept to the open-loop Tx diversity introduced in UMTS Release 99. The more complex, closed-loop Tx diversity techniques from UMTS have not been adopted in LTE, which instead uses the more advanced MIMO, which was not part of Release 99. LTE supports either two or four antennas for Tx diversity. The example shown in Figure 17 is a two Tx example in which a single stream of data is assigned to the different layers and coded using space frequency block coding (SFBC). Since this form of Tx diversity has no data rate gain, the code words CW0 and CW1 are the same. SFBC achieves robustness through frequency diversity by using different subcarriers for the repeated data on each antenna.

The third downlink mode is open-loop MIMO spatial multiplexing, which is supported for two and four antenna configurations. Assuming a two-channel UE receiver, this scheme allows for 2x2 or 4x2 MIMO. A four-channel UE receiver, which is required for a 4x4 configuration, has been defined but is not likely to be implemented in the near future. The most common configuration will be 2x2 or 4x2 SU-MIMO. In this case the payload data will be divided into the two code-word streams CW0 and CW1 and processed according to the steps in Figure 16. The open-loop designation refers to the fact that there is no precoding of the streams, which are instead directly mapped to each antenna. However, the UE-preferred rank and the channel quality indicator (CQI) are used to adapt to the channel, which is a form of closed-loop feedback.

The fourth mode is closed-loop MIMO, which requires precoding of the data streams. Depending on the precoding used, each code word is represented at different powers and phases on the antennas.

For the FDD case the transmitter must have knowledge of the channel, which is provided by the UE on the uplink control channel. This knowledge consists of the CQI, the precoding matrix Indicator (PMI), and the rank indication (RI). The PMI feedback uses a codebook approach to provide an index into a predetermined set of precoding matrices. For 2x2 there are three different codewords; for 4x2 there are 16 codewords. Since the channel is continually changing, sub-band CQI and PMI information can be provided for multiple points across the channel band-width, at regular time intervals, up to several hundred times a second. The RI is only provided wideband for the whole channel. The UE that can best estimate the channel conditions and then signal the best coding to use will get the best performance out of the channel. Although the use of a codebook for precoding limits the best fit to the channel, it significantly simplifies the channel estimation process by the UE and the amount of uplink signaling needed to convey the desired precoding.

The fifth transmission mode is MU-MIMO. This is a special case of mode 3 in which the codewords are destined for different UE. Closed-loop MU-MIMO does not apply in this case.

The sixth downlink transmission mode is a form of beamsteering, described here as Closed-loop Rank = 1 precoding and is the fall-back mode when mode 4 reports Rank = 1. Conventional phased-array beamsteering, which can be applied independent of the radio standard, introduces phase and amplitude offsets to the whole of the signal feeding each transmitting antenna. The intention is to focus the signal power in a particular direction. The same technique of applying phase and amplitude offsets can be used on the receiving antennas to make the receiver more sensitive to signals coming from a particular direction. In LTE, the amplitude and phase of individual RBs can be adjusted, making beamsteering far more flexible. In addition to the conventional beamsteering methods, with the sixth transmission mode, beamsteering is implemented by taking advantage of the closed-loop precoding similar to that used for MIMO. Since Rank = 1, only one codeword is used for beamsteering, and the purpose of the precoding function is to correlate the signals from each transmitter towards the receiver of an individual user. Beamsteering does not increase data rates but has a similar effect of increasing signal robustness. The effectiveness of beamsteering increases with the number of transmitting antennas, which allows for the creation of a narrower beam. The gains possible with only two antennas are generally not considered worthwhile and so beamsteering generally is considered only for the four-antenna option.

The seventh and final transmission mode is another form of beamsteering. It is similar to mode 6 except that an additional antenna (port 5) is used to form a dedicated beam towards the UE which also carries a UE-specific beamformed reference signal.

One of the challenges in supporting both MIMO and beamsteering is that conflicting constraints are put on the design of the antennas. Beamsteering relies on correlation of the transmitted signals whereas MIMO relies on de-correlation, reportedly performing best with cross-polarized antennas.

Another technique which can be applied in the downlink is cyclic delay diversity (CDD). This technique introduces a delay between multiple-antenna signals to artificially create multi-path on the received signal. It thus reduces the impact of possible unwanted signal cancellation that can occur if the same signal is transmitted from multiple antennas and the channel is relatively flat. Normally multi-path is considered undesirable, but by creating artificial multi-path in an otherwise flat channel, the eNB UE scheduler can choose to transmit on those RBs that have favorable propagation conditions. LTE uses what is known as large delay. The intent of this technique is to position signals on the peak of the frequency response that results from the addition of a delay. The reference signal subcarriers do not have CDD applied, which allows the UE to report the actual channel response to the scheduler in the eNB, which then uses that information to determine the use of cyclic delay and frequency allocations for that specific UE.

2.8.2 LTE uplink multiple antenna schemes

Three types of multiple antenna techniques are defined for the uplink:

- Receive diversity at the eNB
- SU-MIMO for single UE
- MU-MIMO for multiple UE

Received diversity was described in the previous section.

SU-MIMO is within the scope of LTE but is not fully defined in 3GPP Release 8. To implement SU-MIMO the UE will require two transmitters. This is a significant challenge in terms of cost, size, and battery consumption, and for these reasons SU-MIMO is not currently a priority for development. Also, the increased data rates in the uplink that might be possible from SU-MIMO are not as important as they are in the downlink due to asymmetrical traffic distribution. Furthermore, if the system is deployed to be uplink-performance-limited, it may be impractical to increase the transmit power from the UE sufficiently to achieve the SNR needed at the eNB receivers.

While MU-MIMO does not increase an individual user's data rate, it does offer cell capacity gains that are similar to, or better than, those provided by SU-MIMO. In Figure 18, the two data streams originate from different UE. The two transmitters are much farther apart than in the single user case, and the lack of physical connection means that there is no opportunity to optimize the coding to the channel Eigen modes by mixing the two data streams. However, the extra spatial separation does increase the chance of the eNB picking up pairs of UE which have uncorrelated paths. This maximizes the potential capacity gain, in contrast to the precoded SU-MIMO case in which the closeness of the antennas could be problematic, especially at frequencies less than 1 GHz. MU-MIMO has an additional important advantage: the UE does not require the expense and power drain of two transmitters, yet the cell still benefits from increased capacity. To get the most gain out of MU-MIMO, the UE must be well aligned in time and power as received at the eNB.

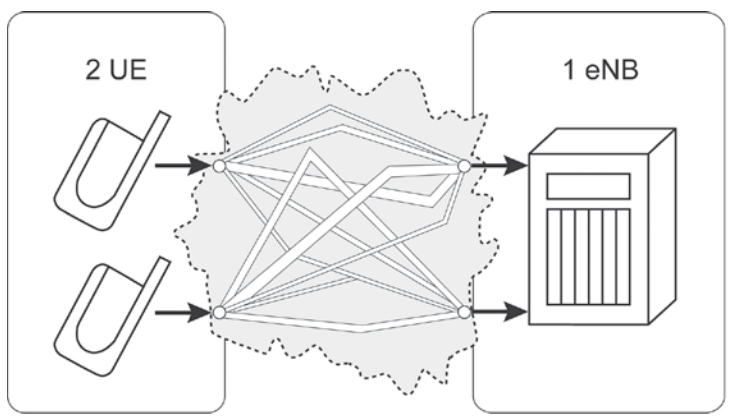

Figure 18. Multi-user MIMO in the uplink

2.8.3 Co-operative MIMO

Co-operative MIMO is sometimes referred to as network MIMO or Co-operative Multi-point (CoMP). Using transmitters from different cells, it resembles multi-user MIMO in the uplink. Data is shared across the network and sent to an individual UE. Co-operative MIMO is not currently defined for LTE in Release 8; however, it is being actively pursued as a technique for LTE-Advanced in 3GPP Release 10. The primary challenge for co-operative MIMO is the need to share vast quantities of baseband data between the transmitting entities. Within the confines of a single device, such as a UE or eNB, this sharing can be accomplished on-chip or between modules. In the case of co-operative MIMO, however, the distances between transmitting elements may be hundreds of meters or even several kilometers. The provision of sufficient backhaul transmission bandwidth via the X2 interface with the necessary latency of perhaps 1 ms is a significant challenge.

3 LTE Air Interface Protocol Aspects

Figure 19 from 36.201 [11] shows the E-UTRA radio interface protocol architecture around the physical layer (Layer 1). The physical layer provides data transport services to the higher layers. These services are accessed through transport channels via the MAC sub-layer. The physical layer provides transport channels to the Layer 2 MAC sub-layer, and the MAC sub-layer provides logical channels to the Layer 2 radio link control (RLC) sub-layer. Transport channels are characterized by how the information is transferred over the radio interface, whereas logical channels are characterized by the type of information transferred. In the Figure 19 diagram, the circles between different layers or sub-layers indicate service access points (SAPs). Layer 1 also interfaces to the Layer 3 radio resource control (RRC) layer.

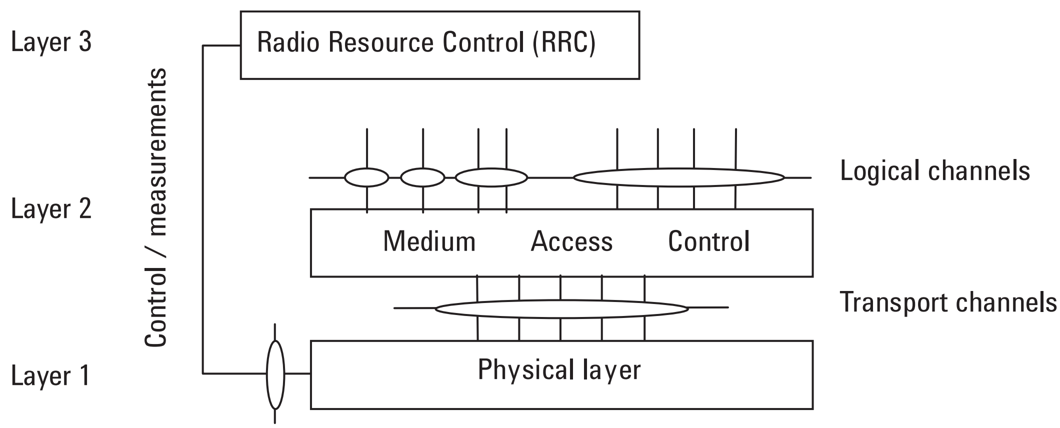

Figure 19. Radio interface protocol architecture around the physical layer (36.201 [11] Figure 1)

To enable data transport service to the higher layers, the physical layer performs a series of functions that include the following:

- Error detection on the transport channels
- Forward error correction (FEC) encoding/decoding of the transport channels
- Hybrid automatic repeat request (HARQ) soft-combining
- Rate matching and mapping of coded transport channels to physical channels
- Power weighting of physical channels
- Modulation and demodulation of physical channels
- Frequency and time synchronization
- Radio characteristics measurements and indication to higher layers
- MIMO antenna processing
- Transmit diversity
- Beamsteering
- RF processing

3.1 Physical layer overview

In addition to the overview specification (36.201), the physical layer specification is further divided among four technical specification documents as shown in Figure 20.

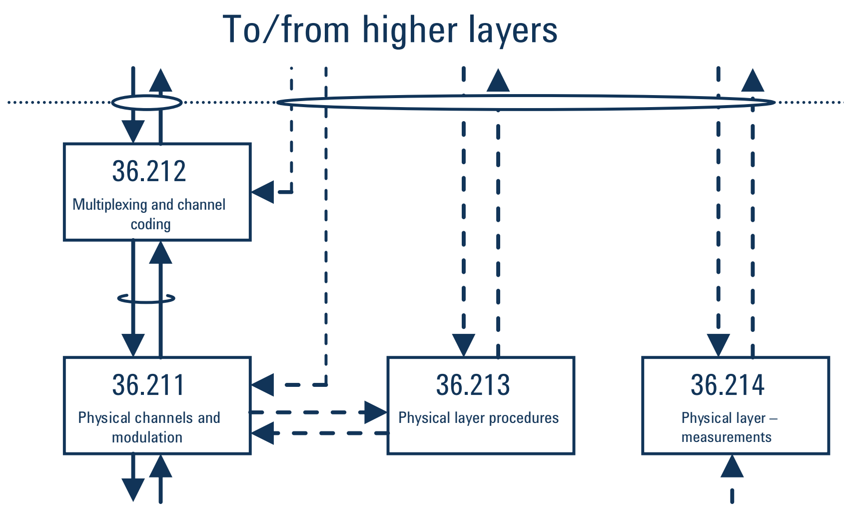

Figure 20. Relation between physical layer specifications (36.201 [11] Figure 2)

36.211 [11] physical channels and modulation
This specification describes the uplink and downlink physical signals and physical channels, how they are modulated, and how they are mapped into the frame structure. Included is the processing for the support of multiple antenna techniques.

36.212 [12] multiplexing and channel coding
This specification describes the transport channel and control channel data processing, including multiplexing, channel coding schemes, coding of Layer 1 and Layer 2 control information, interleaving, and rate matching.

36.213 [13] physical layer procedures
This specification describes the characteristics of the physical layer procedures including synchronization procedures, cell search and timing synchronization, power control, random access procedure, CQI reporting and MIMO feedback, UE sounding, HARQ, and ACK/NACK detection.

36.214 [14] physical layer measurements
This specification describes the characteristics of the physical layer measurements to be performed in Layer 1 by the UE and eNB, and how these measurement results are reported to higher layers and the network. This specification includes measurements for handover support.

Radio resource management
Although not strictly a part of the physical layer, the requirements for radio resource management (RRM) detailed in 36.133 [15] will be summarized since they are closely linked to the physical layer measurements.

3.2 Physical channels and modulation (36.211)

The LTE air interface consists of physical signals and physical channels, which are defined in 36.211 [10]. Physical signals are generated in Layer 1 and used for system synchronization, cell identification, and radio channel estimation. Physical channels carry data from higher layers including control, scheduling, and user payload.

Physical signals are summarized in Table 8. In the downlink, primary and secondary synchronization signals encode the cell identification, allowing the UE to identify and synchronize with the network.

In both the downlink and the uplink there are reference signals (RS), known as pilot signals in other standards, which are used by the receiver to estimate the amplitude and phase flatness of the received signal. The flatness is a combination of errors in the transmitted signal and additional imperfections that are due to the radio channel. Without the use of the RS, phase and amplitude shifts in the received signal would make demodulation unreliable, particularly at high modulation depths such as 16QAM or 64QAM. In these high modulation cases, even a small error in the received signal amplitude or phase can cause demodulation errors.

Table 8. LTE physical signals

Downlink physical signals	Purpose
Primary synchronization signal	Used for cell search and identification by the UE. Carries part of the cell ID (one of three orthogonal sequences)
Secondary synchronization signal	Used for cell search and identification by the UE. Carries the remainder of the cell ID (one of 168 binary sequences)
Reference signal	Used for downlink channel estimation. Exact sequence derived from cell ID (one of 3 x 168 = 504 pseudo random sequences)
Uplink physical signals	**Purpose**
Reference signals (demodulation and sounding)	Used for synchronization to the UE and for UL channel estimation

Alongside the physical signals are physical channels, which carry the user and system information. These are summarized in Table 9. Notice the absence of dedicated channels, which is a characteristic of packet-only systems. The shared channel structure of LTE is closer to HSPA than it is to the original W-CDMA, the latter being based on alloting dedicated channels to single users.

Table 9. LTE physical channels

DL channels	Full name	Purpose
PBCH	Physical broadcast channel	Carries cell-specific information
PMCH	Physical multicast channel	Carries the MCH transport channel
PDCCH	Physical downlink control channel	Scheduling, ACK/NACK
PDSCH	Physical downlink shared channel	Payload
PCFICH	Physical control format indicator channel	Defines number of PDCCH OFDMA symbols per subframe (1, 2, 3, or 4)
PHICH	Physical hybrid ARQ indicator channel	Carries HARQ ACK/NACK
UL channels	**Full name**	**Purpose**
PRACH	Physical random access channel	Call setup
PUCCH	Physical uplink control channel	Scheduling, ACK/NACK
PUSCH	Physical uplink shared channel	Payload

3.2.1 Frame structure

The physical layer supports the two multiple access schemes previously described: OFDMA on the downlink and SC-FDMA on the uplink. In addition, both paired and unpaired spectrum are supported using frequency division duplexing (FDD) and time division duplexing (TDD), respectively.

Although the LTE downlink and uplink use different multiple access schemes, they share a common frame structure. The frame structure defines the frame, slot, and symbol in the time domain. Two radio frame structures are defined for LTE and shown in Figures 21 and 22.

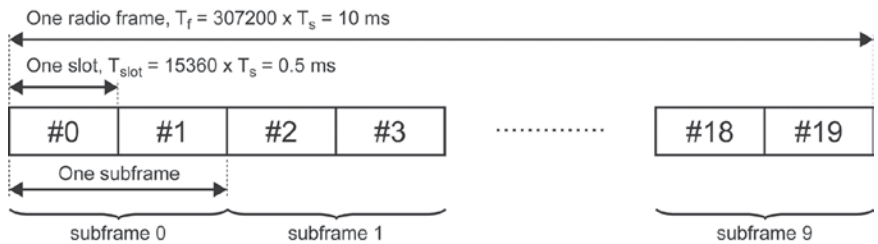

Figure 21. LTE frame structure type 1 (36.211 [10] Figure 4.1-1)

Frame structure type 1 is defined for FDD mode. Each radio frame is 10 ms long and consists of 10 subframes. Each subframe contains two slots. In FDD, both the uplink and the downlink have the same frame structure though they use different spectra.

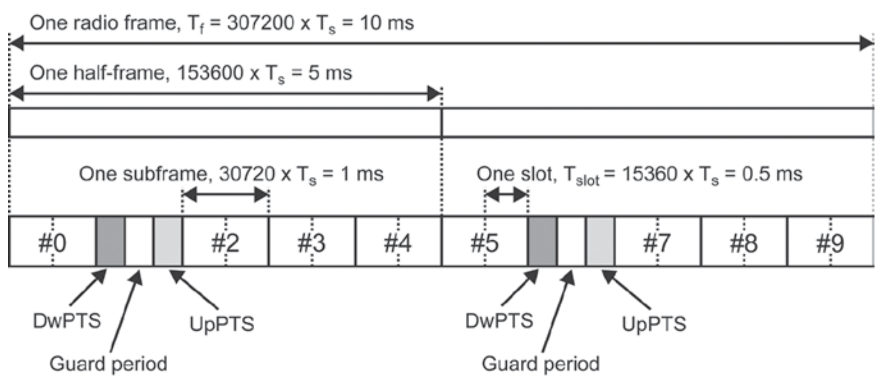

Figure 22. LTE frame structure type 2 for 5 ms switch-point periodicity (based on 36.211 [10] Figure 4.2-1)

Frame structure type 2 is defined for TDD mode. An example is shown in Figure 22. This example is for 5 ms switch-point periodicity and consists of two 5 ms half-frames for a total duration of 10 ms. Subframes consist of either an uplink or downlink transmission or a special subframe containing the downlink and uplink pilot timeslots (DwPTS and UpPTS) separated by a transmission gap guard period (GP). The allocation of the subframes for the uplink, downlink, and special subframes is determined by one of seven different configurations. Subframes 0 and 5 are always downlink transmissions, subframe 1 is always a special subframe, and subframe 2 is always an uplink transmission. The composition of the other subframes varies depending on the frame configuration. For a 5 ms switch-point configuration, subframe 6 is always a special subframe as shown in Figure 22. With 10 ms switch-point periodicity, there is only one special subframe per 10 ms frame.

3.2.2 OFDM symbol and cyclic prefix

One of the key advantages in OFDM systems (including SC-FDMA in this context) is the ability to protect against multipath delay spread. The long OFDM symbols allow the introduction of a guard period between each symbol to eliminate inter-symbol interference due to multipath delay spread. If the guard period is longer than the delay spread in the radio channel, and if each OFDM symbol is cyclically extended into the guard period (by copying the end of the symbol to the start to create the cyclic prefix), then the inter-symbol interference can be completely eliminated.

Figure 23 shows the seven symbols in a slot for the normal cyclic prefix case.

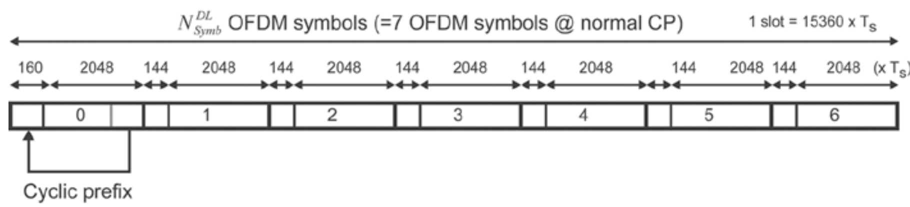

Figure 23. OFDM symbol structure for normal prefix case (downlink)

Cyclic prefix lengths for the downlink and the uplink are shown in Table 10. In the downlink case, Δf represents the 15 kHz or 7.5 kHz subcarrier spacing. The normal cyclic prefix of 144 x T_s protects against multi-path delay spread of up to 1.4 km. The longest cyclic prefix provides protection for delay spreads of up to 10 km.

Table 10. OFDM (downlink) and SC-FDMA (uplink) cyclic prefix length (based on 36.211 [10] Tables 6.12-1 and 5.6-1)

OFDM configuration (downlink)		**Cyclic prefix length** $N_{CP,l}$
Normal cyclic prefix	Δf = 15 kHz	160 for $l = 0$ 144 for $l = 1,2,...,6$
Extended cyclic prefix	Δf = 15 kHz	512 for $l = 0,1,...,5$
	Δf = 7.5 kHz	1024 for $l = 0,1,2$
SC-FDMA configuration (uplink)		**Cyclic prefix length** $N_{CP,l}$
Normal cyclic prefix		160 for $l = 0$ 144 for $l = 1,2,...,6$
Extended cyclic prefix		512 for $l = 0,1,...,5$

3.2.3 Resource element and resource block

A resource element is the smallest unit in the physical layer and occupies one OFDM or SC-FDMA symbol in the time domain and one subcarrier in the frequency domain. This is shown in Figure 24.

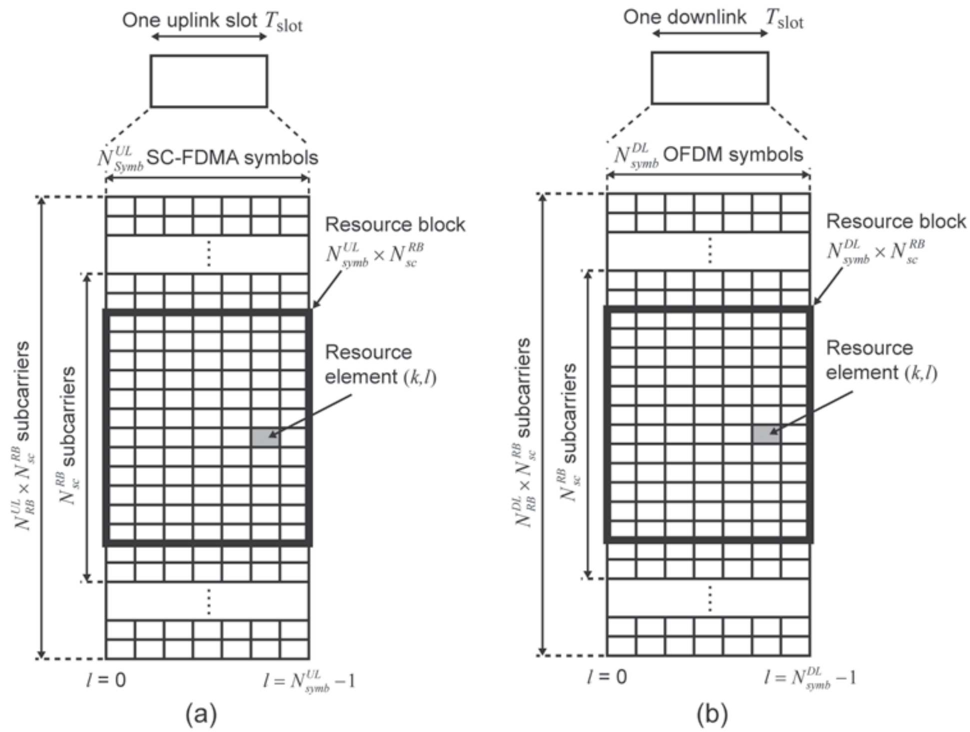

Figure 24. Resource grid for uplink (a) and downlink (b) (36.211 Figures 5.2.1-1 and 6.2.2-1)

A resource block (RB) is the smallest unit that can be scheduled for transmission. An RB physically occupies 0.5 ms (1 slot) in the time domain and 180 kHz in the frequency domain. The number of subcarriers per RB and the number of symbols per RB vary as a function of the cyclic prefix length and subcarrier spacing, as shown in Table 11. The obvious difference between the downlink and uplink is that the downlink transmission supports 7.5 kHz subcarrier spacing, which is used for multicast/broadcast over single frequency network (MBSFN). The 7.5 kHz subcarrier spacing means that the symbols are twice as long, which allows the use of a longer CP to combat the higher delay spread seen when receiving from multiple MBSFN cells.

Table 11. Physical resource block parameters (36.211 [10] Tables 6.2.3-1 and 5.2.3-1)

Downlink configuration		N^{RB}_{sc}	N^{DL}_{symb}
Normal cyclic prefix	Δf = 15 kHz	12	7
Extended cyclic prefix	Δf = 15 kHz		6
	Δf = 7.5 kHz	24	3
Uplink configuration		N^{RB}_{sc}	N^{UL}_{symb}
Normal cyclic prefix		12	7
Extended cyclic prefix		12	6

3.2.4 Example: FDD downlink mapping to resource elements

The primary and secondary synchronization signals, reference signals, PDSCH, PBCH, and PDCCH are almost always present in a downlink radio frame. There is a priority rule for allocation (physical mapping) as follows. Signals (reference signal, primary/secondary synchronization signal) take precedence over the PBCH. The PDCCH takes precedence over the PDSCH. The PBCH and PDCCH are never allocated to the same resource elements, thus they are not in conflict.

Figures 25 and 26 show an LTE FDD mapping example. The primary synchronization signal is mapped to the last symbol of slot #0 and slot #10 in the central 62 subcarriers. The secondary synchronization signal is allocated in the symbol just before the primary synchronization signal. The reference signals are located at symbol #0 and symbol #4 of every slot. The reference signal takes precedence over any other allocation.

The PBCH is mapped to the first four symbols in slot #1 in the central 6 RB. The PDCCH can be allocated to the first three symbols (four symbols when the number of RB is equal or less than 10) of every subframe as shown in Figure 25. The remaining unallocated areas can be used for the PDSCH.

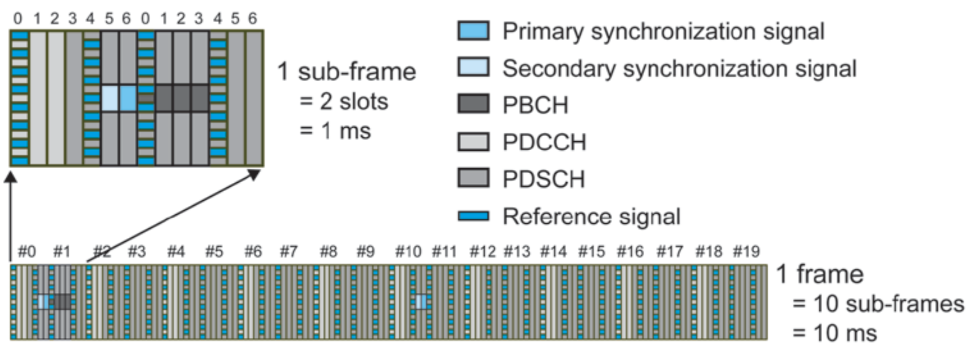

Figure 25. Example of downlink mapping (normal cyclic prefix)

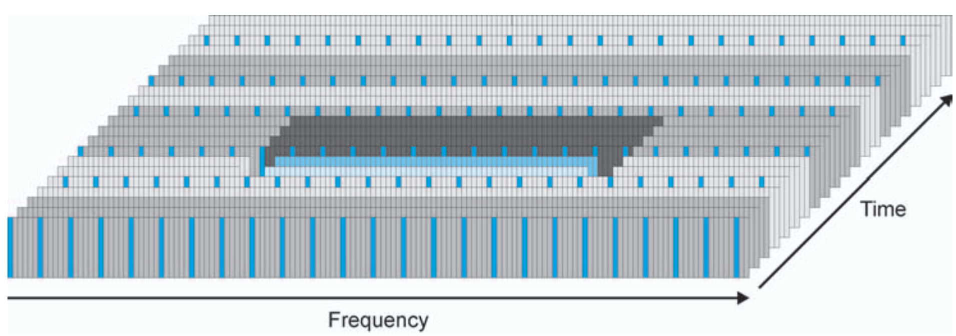

Figure 26. Example of downlink mapping showing frequency (subcarriers) vs. time

3.2.5 Example: Uplink mapping to resource elements

Figure 27 shows an example of an uplink mapping. For the control channels on the outermost RB, the same RB in time is allocated to multiple UE, which are identified using orthogonal spreading codes as in CDMA.

The constellations for PUCCH and the demodulation reference signal for PUCCH and PUSCH may be rotated based on parameters given by higher layers; for example, cyclic shift and sequence index. The constellations shown in Figure 27 are without rotation.

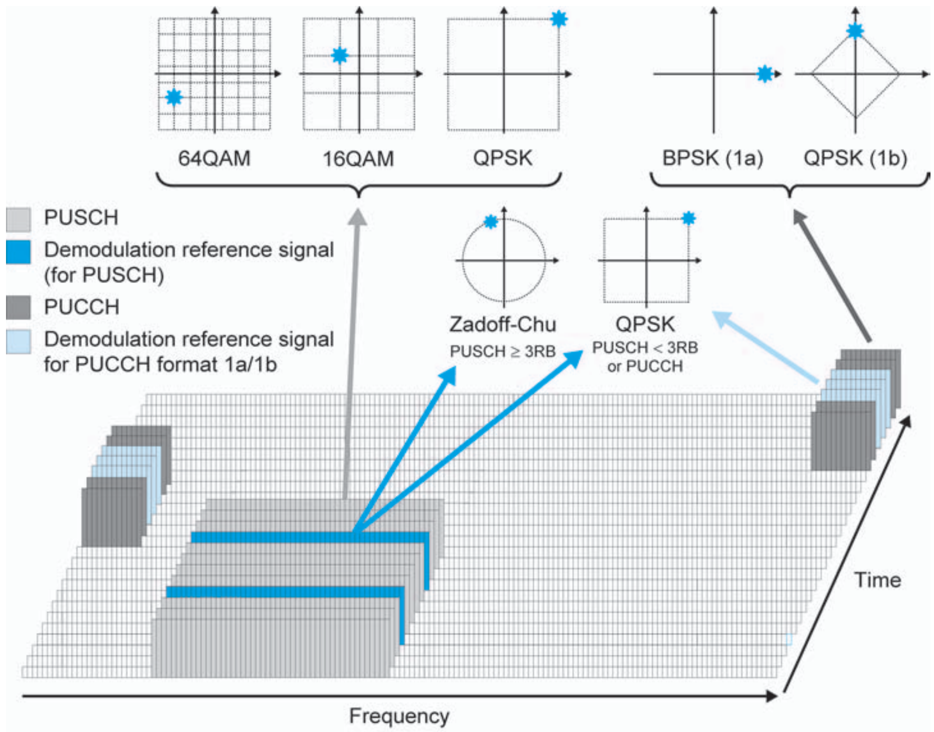

Figure 27. Example of uplink mapping showing frequency (subcarriers) vs. time

3.2.6 Example: TDD mapping to resource elements

Figures 28 and 29 show examples of 5 ms and 10 ms TDD switch point periodicity. The primary synchronization signal is mapped to the third symbol of slot #2 and slot #12 in the central 62 subcarriers. The secondary synchronization signal is allocated in the last symbol of slot #1 and slot #11. The reference signals are located at symbol #0 and symbol #4 of every slot. The reference signal takes precedence over any other allocation. The PBCH is mapped to the first four symbols in slot #1 in the central 6 RB. The PDCCH can be allocated to the first three symbols of every subframe as shown here. The remaining unallocated areas can be used for the PDSCH.

Note that the acronyms P-SS for primary synchronization signal and S-SS for secondary synchronization signal are not formally defined in the 3GPP specifications but are used here for convenience.

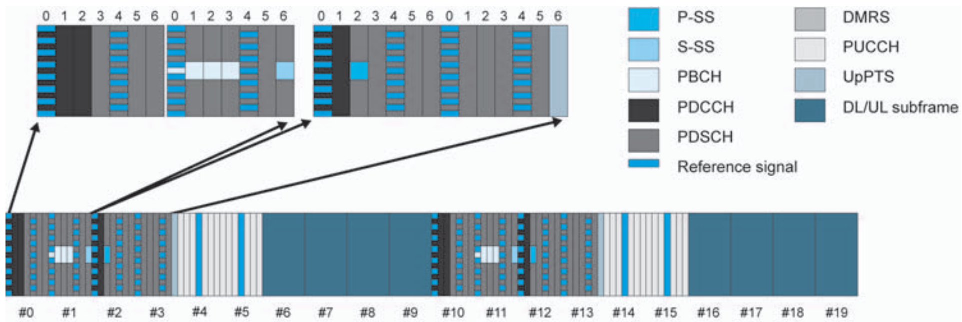

Figure 28. Example of LTE TDD 5 ms switch periodicity mapping

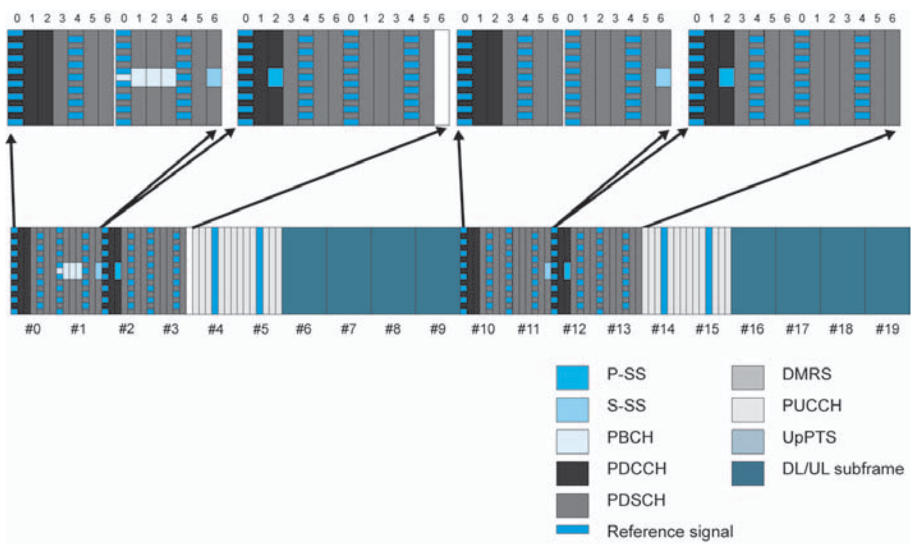

Figure 29. Example of LTE TDD 10 ms switch periodicity mapping

3.2.7 Modulation

The allowed signal and channel modulation schemes for the downlink and uplink are shown in Table 12. Detailed specifications for the physical signals and channels, along with their modulation and mapping, are documented throughout 36.211 [10].

Table 12. Modulation schemes for the LTE downlink and uplink (based on 36.211 [10])

Downlink	
Downlink channels	**Modulation scheme**
PBCH	QPSK
PDCCH	QPSK
PDSCH	QPSK, 16QAM, 64QAM
PMCH	QPSK, 16QAM, 64QAM
PCFICH	QPSK
PHICH	BPSK modulated on I and Q with the spreading factor 2 or 4 Walsh codes
Physical signals	**Modulation scheme**
RS	Complex I+jQ pseudo random sequence (length-31 Gold sequence) derived from cell ID
Primary synchronization	One of three Zadoff-Chu sequences
Secondary synchronization	Two 31-bit BPSK M-sequence
Uplink	
Physical channels	**Modulation scheme**
PUCCH	BPSK, QPSK
PUSCH	QPSK, 16QAM, 64QAM
PRACH	uth root Zadoff-Chu
Physical signals	**Modulation scheme**
Demodulation RS	Zadoff-Chu
Sounding RS	Based on Zadoff-Chu

3.3 Multiplexing and channel coding (36.212)

The physical layer offers data transport services to the higher layers through transport channels (TrCH) and control information channels. Table 13 lists the types of downlink and uplink TrCH channels, which are defined in 36.212. Table 14 lists the control information defined in the same document.

Table 13. Transport channel types

Transport channel type		Functions
Downlink		
Downlink shared channel	DL-SCH	Support for HARQ, dynamic link modulation, dynamic and semi-static resource allocation, UE discontinuous reception, and MBMS transmission Possibility to be broadcast in entire cell coverage area to allow beamforming
Broadcast channel	PBCH	Fixed transport format Must be broadcast in entire cell coverage area
Paging channel	PCH	Support for UE discontinuous reception Must be broadcast in entire cell coverage area, mapped to physical resources
Multicast channel	MCH	Support for MBSFN, semi-static resource allocation Must be broadcast in entire cell coverage area
Uplink		
Uplink shared channel	UL-SCH	Support for dynamic link adaptation, HARQ, dynamic, and semi-static resource allocation Possibility to use beamforming
Random access channel	RACH	Limited control information, collision risk

Table 14. Control information

Downlink	
Control format indicator	CFI
HARQ indicator	HI
Downlink control information	DCI
Uplink	
Uplink control information	UCI

TrCH and control channel information is mapped to the corresponding physical channels as shown in Table 15.

Table 15. Mapping to physical channels (based on 36.212 [12] Tables 4.2-1 and 4.1-1])

Downlink	
TrCH	**Physical channel**
DL-SCH	PDSCH
BCH	PBCH
PCH	PDSCH
MCH	PMCH
Control information	**Physical channel**
CFI	PCFICH
HI	PHICH
DCI	PDCCH
Uplink	
TrCH	**Physical channel**
UL-SCH	PUSCH
RACH	PRACH
Control information	**Physical channel**
UCI	PUCCH, PUSCH

3.3.1 Channel coding

The data and control streams to and from the MAC layer are encoded and decoded using channel coding schemes. Channel coding is a combination of error detection, segmentation, error correction, rate matching, concatenation, and interleaving.

Channel coding gives FEC to the transport channel and control information. Two channel coding schemes are used in LTE for the TrCH: turbo coding for the UL-SCH, DL-SCH, PCH, and MCH; and tail-biting convolutional coding for the BCH. For both schemes, the coding rate is R = 1/3 (that is, for every bit that goes into the coder, three bits come out).

Control information is coded using various schemes, including tail-biting convolutional coding, block code, repetition code, and various coding rates.

Precise details of the physical layer processing for transport channels vary by TrCH type and are specified throughout 36.212.

3.3.2 HARQ and AMC

Latency and throughput are two important measures of performance for digital communication systems. LTE uses a number of mechanisms in the physical layer to improve performance in both of these areas; notably, hybrid automatic repeat requests (HARQ) processing and adaptive modulation and coding (AMC).

HARQ is a technique for ensuring that data is sent reliably from one network node to anther, identifying when transmission errors occur and facilitating retransmission from the source. LTE uses Type-II HARQ protocols, similar to HSPA and HSPA+.

AMC is the mechanism used for link adaptation to improve data throughput in a fading channel. This technique varies the downlink modulation coding scheme based on the channel conditions of each user. When the link quality is good, the LTE system can use a higher order modulation scheme (more bits per symbol) or less channel coding, which results in higher data rates. When link conditions are poor because of problems such as signal fading or interference, the system can use a lower modulation depth or stronger channel coding to maintain acceptable margin in the radio link budget.

Type-II HARQ and AMC work together to provide a very adaptive transport mechanism in LTE. Adaptive modulation and coding tunes the initial HARQ transmission to use a coding rate that results in approximately the ideal frame error rate from a throughput perspective. Type-II HARQ then uses incremental redundancy to add redundancy bits for each successive retransmission, thereby reducing the effective code rate until the packet can be decoded correctly. The result, although not perfect, is a means of optimizing the overall throughput over wide ranges of dynamically changing channel conditions while holding latency to a minimum.

3.4 Physical layer procedures (36.213)

A number of physical layer procedures are associated with LTE operation and defined in 36.213 [13]. Not all the physical layer procedures have been fully specified but the general principles of the main procedures are outlined here. Details relate mainly to FDD operation, but TDD is also covered in the specifications.

3.4.1 Synchronization procedures

Two synchronization procedures are identified: cell search and timing synchronization. Cell search is the procedure by which a UE acquires time and frequency synchronization with a cell and detects that cell's physical layer cell ID. To enable cell search the eNB transmits the primary synchronization signal and secondary synchronization signal. Because the synchronization signals are located in the central part of the channel, one LTE cell search procedure supports a scalable overall transmission bandwidth of 6 or more RBs.

Timing synchronization procedures include radio link monitoring, inter-cell synchronization, and transmission timing adjustments.

3.4.2 Power control

Power control procedures include the uplink power control and downlink power allocation. Power control determines the energy per resource element (EPRE). Power control in OFDMA systems is less critical than in CDMA systems, since in OFDMA the UE are separated in time and frequency whereas in CDMA they share the same physical channel and are separated by spreading code, which requires much tighter limits on received power. The importance of power control grows with MU-MIMO, which works best when the received power from each UE at the eNB is balanced.

For the uplink, detailed definitions of power control involving upwards of nine parameters cover the PUSCH, PUCCH, and sounding reference signal (SRS). Special procedures apply to the RB allocated to UE at the cell edge, where UE are most sensitive to inter-cell interference.

For the downlink, all power is referenced to the RS, which is transmitted at constant power across the entire system channel bandwidth. The ratio between the RS EPRE and the PDSCH for one user is settable. Boosting the RS is also supported.

3.4.3 Random access procedures

These procedures cover the transmission of the random access preamble (carried on the PRACH) and the random access response. A PRACH occupies six resource blocks in a subframe or set of consecutive subframes reserved for random access preamble transmissions.

3.4.4 PDSCH-related procedures

The first procedure defines the way in which the PDCCH allocates resources to the UE for receiving the PDSCH. There are three types of allocation mechanisms varying from a simple bitmap (type 0) through the most complex (type 2), which also has the most flexibility.

Additional procedures define how the UE reports the CQI, the precoding matrix indicator (PMI), and the rank. These reports can be periodic or aperiodic. The CQI is used to report the UE-perceived channel quality. For a single antenna, the CQI is a five-bit index in a table of 32 CQI values that define the modulation scheme and channel coding rate. For increased performance a frequency-selective report, known as subband CQI, can be created by splitting the channel into several subbands. The number of subbands depends on the channel bandwidth and is shown in Table 16. Alternatively the entire channel can be reported once as wideband CQI.

Table 16. Subband size versus downlink system bandwidth (based on 36.213 [13] Table 7.2.1-3)

System bandwidth (resource blocks)	Subband size (k)
6–7	(wideband CQI only)
8–10	4
11–26	4
27–63	6
64–110	8

Periodic CQI reports can be carried on the PUCCH when the UE is not scheduled for transmission and on the PUSCH when the UE is scheduled. The PUCCH has only a few bits of capacity but the PUSCH is much less limited. Aperiodic reports are always carried on the PUSCH. If the scheduling of periodic and aperiodic reports collide, the aperiodic reports always take precedence. The shorter PUCCH report always contains independently useful information for the eNB, whereas the PUSCH reports contain more data and can only be decoded from several transmissions.

There are numerous options for CQI reporting of both PUCCH and PUSCH including UE-assisted subband selection and periodic reporting of different wideband CQI types. When compared to the single CQI report of HSDPA, LTE has a massively more complex reporting structure with the potential for increased performance.

The PMI report is used in conjunction with MIMO to indicate to the eNB which of the available precoding matrices would result in the best performance. The PMI can be a single value or multiple subband values configured by the network for specific RBs. The PMI carries an index to a codebook of predetermined precoding matrices. For the simplest downlink configuration of 2x2 SU-MIMO there are four possible matrices but only three are defined. For the most complex 4x4 configuration there are 16 matrices that cover MIMO for Rank = 2 and beamsteering when Rank = 1.

RI defines the preferred number of parallel MIMO data streams and is always reported as a single wideband value for the channel. This significantly reduces the amount of feedback data since RI affects the CQI and PMI. RI reporting is needed about once per frame (10 ms) and is slower than CQI and PMI reporting that can be done at the subframe rate.

3.4.5 PUSCH-related procedures

The UE allocation for transmission of the PUSCH is provided by a scheduling grant message carried on the PDCCH, providing the UE with the starting RB and length of contiguous RB for PUSCH transmission.

The UE transmission of SRS for uplink channel estimation is used when no PUCCH or PUSCH are scheduled. Parameters provided by the upper layers include SRS periodicity and duration, symbol location in the subframe, frequency hopping, cyclic shift, and repetition factors.

3.4.6 PDCCH-related procedures

The UE is required to monitor the downlink for the presence of the PDCCH. The PCFICH indicates the number of PDCCH symbols (1, 2, or 3) in each subframe to monitor and the PHICH symbol duration, which is read from the P-BCH. The PHICH duration is less than or equal to the number of PDCCH symbols and is 1 or 3 for unicast operation, and 1 or 2 for MBSFN operation.

3.4.7 PUCCH-related procedures

The position of the ACK/NACK sent in the PUCCH for scheduled PSDSCH transmissions is determined implicitly from the associated PDCCH. For a PDSCH detected in subframe n, the associated ACK/NACK messages are transmitted in subframe n+4. This delay is a key parameter in determining the overall latency for retransmission, which is eight subframes (8 ms).

3.5 Physical layer measurements (36.214)

The UE and the eNB are required to make physical layer measurements of the radio characteristics. The measurement definitions are specified in 36.214 [14]. Measurements are reported to the higher layers and are used for a variety of purposes including intra- and inter-frequency handover, inter-radio access technology (inter-RAT) handover, timing measurements, and other purposes in support of RRM.

Although the physical layer measurements are defined in 36.214 [14], the measurement conditions and accuracy requirements are provided in subclauses 9 and 10 of the RRM specification 36.133 [15].

3.5.1 UE physical layer measurements

The UE physical layer measurements are all either measures of absolute power or power ratios. They are defined for operation within LTE-only systems. In addition, to enable interworking of LTE with other radio access technologies, LTE UE must have the ability to measure equivalent parameters from the other systems LTE is defined to work with. These are UMTS FDD, UMTS TDD, GSM and cdma2000 based systems.

Reference signal receive power

Reference signal receive power (RSRP) is the most basic of the UE physical layer measurements and is the linear average (in watts) of the downlink reference signals (RS) across the channel bandwidth. Since the RS exist only for one symbol at a time, the measurement is made only on those resource elements (RE) that contain cell-specific RS. It is not mandated for the UE to measure every RS symbol on the relevant subcarriers. Instead, accuracy requirements have to be met. There are requirements for both absolute and relative RSRP. The absolute requirements range from ±6 to ±11 dB depending on the noise level and environmental conditions. Measuring the difference in RSRP between two cells on the same frequency (intra-frequency measurement) is a more accurate operation for which the requirements vary from ±2 to ±3 dB. The requirements widen again to ±6 dB when the cells are on different frequencies (inter-frequency measurement).

Knowledge of absolute RSRP provides the UE with essential information about the strength of cells from which path loss can be calculated and used in the algorithms for determining the optimum power settings for operating the network. Reference signal receive power is used both in idle and connected states. The relative RSRP is used as a parameter in multi-cell scenarios.

Reference signal receive quality

Although RSRP is an important measure, on its own it gives no indication of signal quality. Reference signal receive quality (RSRQ) provides this measure and is defined as the ratio of RSRP to the E-UTRA carrier received signal strength indicator (RSSI). The RSSI parameter represents the entire received power including the wanted power from the serving cell as well as all co-channel power and other sources of noise. Measuring RSRQ becomes particularly important near the cell edge when decisions need to be made, regardless of absolute RSRP, to perform a handover to the next cell. Reference signal receive quality is used only during connected states. Intra- and inter-frequency absolute RSRQ accuracy varies from ±2.5 to ±4 dB, which is similar to the interfrequency relative RSRQ accuracy of ±3 to ±4 dB.

UTRA FDD CPICH received signal code power

Received signal code power (RSCP) is inherited from UMTS and is a measure of the absolute power of one code channel within the overall UTRA CDMA signal. UTRA FDD CPICH RSCP is therefore a measure of the code power of the common pilot indicator channel (CPICH) and is used for interworking between LTE and UMTS. It has the same basic function as RSRP in LTE and is used in LTE inter-RAT idle and inter-RAT connected states.

UTRA FDD carrier received signal strength indicator

UTRA FDD received signal strength indicator (RSSI) is also inherited from UMTS. It is a measure of the total received power, including thermal noise and noise generated in the receiver, within the bandwidth defined by the receiver pulse shaping filter. It is the UTRA equivalent of the E-UTRA carrier RSSI defined as part of RSRQ.

UTRA RDD CPICH E_c/N_0

This final measurement from UMTS is the ratio of the CPICH to the power density in the channel. If receive diversity is not being used by the UE, CPICH E_c/N_0 is the same as CPICH RSCP divided by RSSI. A typical value in a UMTS cell without significant noise would be around –10 dB; indicating the CPICH had been set 10 dB below the total power of the cell. UTRA FDD CPICH E_c/N_0 is used in LTE inter-RAT idle and connected states.

GSM carrier RSSI

When LTE has to interwork with GSM-based systems including GPRS and E-GPRS (EDGE), the GSM version of RSSI must be measured. GSM RSSI is measured on the Broadcast Control Channel (BCCH). It is used in LTE inter-RAT idle and connected states.

UTRA TDD carrier RSSI

This measurement is used for interworking with UTRA TDD systems and performs the same basic function as the other RSSI measurements. It is used in LTE inter-RAT idle and connected states.

UTRA TDD P-CCPCH RSCP

This measurement is the UTRA TDD equivalent of RSRP. It is a measure of the code power of the Primary CommonControl Physical Channel (P-CCPCH) and is used in LTE inter-RAT idle and connected states.

cdma2000 1xRTT pilot strength

This measurement is the RSRP equivalent for cdma2000-based technologies. These technologies all share the same radio transmission technology (RTT) bandwidth based on the 1.2288 Mcps chip rate that is referred to as 1x. Multi-carrier versions of cdma2000 such as 3xRTT have been standardized but no multicarrier measurement is yet defined. The cdma2000 pilot is carried on Walsh code 0, typically at around –7 dB from the total downlink power.

cdma2000 high rate packet data pilot strength

High rate packet data (HRPD) systems including 1xEV-DO Releases 0, A and B do not use the code domain pilot signal defined for the speech-capable cdma2000. The cdma2000 HRPD pilot is defined in the time domain, existing for 9.375% of the frame. Its measurement is therefore necessary for LTE interworking with HRPD systems and is another version of LTE RSRP.

3.5.2 eNB physical layer measurements

There are fewer physical layer measurements for the eNB than for the UE, primarily because the base station is not mobile and does not need to measure non-LTE systems.

Downlink RS Tx power

The first eNB measurement is different in two respects from the UE measurements described so far: first, it describes the eNB transmission itself rather than a transmission from another entity, and second, it is not so much a measurement as a report generated by the eNB reflecting the transmitted power. Even so, the report has to be accurate and take into account losses between the baseband (where power is defined) through the transmit chain to the antenna connector.

Received interference power

The uplink received interference power is a measure of the interference power and thermal noise within an RB that is not scheduled for transmission within the cell. The absolute accuracy has to be ±4 dB for interference measured between –117 dBm and –96 dBm. This measure will be used to identify narrowband co-channel interference from neighbor cells on the same frequency.

Thermal noise power

The uplink thermal noise power measurement is a broadband version of received interference power and is measured optionally at the same time under the same conditions. The definition is (N_0*W) where N_0 is the white noise power spectral density and W is the transmission bandwidth configuration.

3.6 Radio resource management (36.133)

The requirements for RRM are defined in 36.133 [15] and are divided into two major parts. First are the individual performance requirements for the core functions supporting RRM. These are defined in subclauses 4 through 10. Second, Annex A provides normative test case descriptions that will be used as the basis for the RRM conformance tests. These test cases combine many of the underlying core requirements into typical operating scenarios, which is preferable to testing each function individually. Subclauses 9 and 10 specify requirements for the physical layer measurements described in Section 3.5.

3.6.1 E-UTRAN RRC_IDLE state mobility

Refer to 36.133 [15] subclause 4. This section covers the two most basic of procedures carried out when the UE is in idle state (not on a call). These procedures are cell selection, which is performed after the UE is switched on, and cell re-selection, which is the procedure performed when the UE moves from one cell to another.

Cell selection

The most obvious parameter to specify for cell selection performance is the time taken to camp onto an appropriate cell for a given radio scenario. One of the most complex scenarios commonly occurs when the UE is switched on in a rich radio environment; for example, in a foreign airport where competition for roaming customers can be fierce. There are many ways of configuring parameters in the network that can influence the behavior of the UE when it initially chooses a cell on which to camp. It is perhaps due to the complexity of the cell selection process that in UMTS, no requirements were specified. It is likely that LTE will take the same approach. This might seem surprising but as things stand, this aspect of UE performance is left as a competitive rather than a regulated issue.

Cell re-selection

For cell re-selection, the situation is quite different as LTE specifies numerous performance requirements for this process. When the UE is camped on the serving cell, it will be commanded to detect, synchronize and monitor intra-frequency, inter-frequency and inter-RAT cells to determine whether a more suitable cell on which to camp can be found. Sometimes the serving cell will provide a neighbor list for the intra-frequency and inter-frequency LTE cells, but at other times only the carrier frequency and bandwidth will be provided. The rules for neighbor cell reporting allow the UE to limit its measurement activity in complex situations.

The goal of the cell re-selection process is the evaluation of the cell selection criterion S for each detected cell. This measure is based on relative and absolute power measurements and is used to determine the most favorable cell for the UE to camp on. The cell re-selection performance requirements are defined in terms of three time allowances: the time allowed to detect and evaluate S for a new cell, the time allowed to re-evaluate S for an existing cell and the maximum time allowed between measurements of the cell. One of the important parameters impacting cell re-selection performance is the discontinuous reception (DRX) cycle length. This is the time between attempts by the UE to measure cells other than the serving cell. There is clearly a trade-off between a long DRX cycle that does not interrupt normal operation in the serving cell but gives slow re-selection times, and a much shorter DRX cycle that speeds up detection but interrupts normal operation. The defined DRX cycle lengths in seconds are 0.32, 0.64, 1.28 and 2.56.

The cell re-selection rules are complex and are only briefly described here. The UE is required to continuously monitor the serving cell and should it fail to fulfill the cell selection criteria, the UE has to immediately measure all the neighbor cells indicated by the serving cell, regardless of any rules currently limiting UE measurements. The UE is required to identify detectable intra-frequency E-UTRAN cells and measure the RSRP without prior knowledge of the physical cell identity. Cells are considered detectable if they exceed certain absolute power and SNR limits. For detectable cells, the key performance requirement is the time allowed to evaluate the cell selection criterion S. The rules for inter-frequency E-UTRAN cells have additional complexity but the key performance requirement remains the time taken to evaluate S.

As might be expected the situation gets significantly more complex for inter-RAT cell re-selection. Cell re-selection performance requirements exist for UTRA FDD, UTRA TDD, GSM, HRPD and cdma2000 1xRTT. The specification of further RATs is likely in the future.

3.6.2 E-UTRAN RRC_CONNECTED state mobility

Refer to 36.133 [15] subclause 5. The requirements for mobility while connected are more generally known by the term handover. The combinations of handover for which performance requirements have been defined fall into two categories:

E-UTRAN handover

E-UTRAN FDD to FDD
E-UTRAN FDD to TDD
E-UTRAN TDD to FDD
E-UTRAN TDD to TDD

Handover to other RAT

E-UTRAN to UTRAN FDD
E-UTRAN to UTRAN TDD
E-UTRAN to GSM
E-UTRAN to HRPD
E-UTRAN to cdma2000 1xRTT

For each scenario two performance parameters are defined. These are the handover delay and the interruption time. Both parameters are necessary as the first is a measure of the delay from the start of the process to its completion and needs to be kept low, while the second parameter is the shorter period of time during which communication is interrupted.

3.6.3 RRC connection mobility control

Refer to 36.133 [15] subclause 6. The requirements for RRC connection mobility control are for RRC re-establishment following a failure in the RRC connection and for random access. The most likely causes of a failure are if the radio link drops below an acceptable quality or if a handover fails. The requirements are written based on the time allowed to re-establish the RRC connection.

The re-establishment delay is determined by four parameters: the number of frequencies being monitored, the time to search each frequency, the time to read the system information from each cell and the delay in the PRACH procedure. For simple cases in which the target cell is known by the UE and has been recently measured, the delay may be as short as 160 ms. More difficult situations that require searching for a suitable cell on which to reestablish the link could be in the order of one second per frequency searched.

The requirements for random access relate to correct behavior when a random access response and other messages are received from the eNB.

3.6.4 Timing and signaling characteristics

Refer to 36.133 [10] subclause 7.

UE transmit timing

A critical performance requirement in any wireless system is the ability of the UE to maintain timing synchronization with the base station. The unit for measuring timing is T_s, where $T_s = 1/(15000*2048)$ seconds. The timing reference point for the UE is the first detected path from the eNB. The nominal transmit timing of the UE is specified in advance of this reference time as $N_{TA} * T_s$, where N_{TA} is the timing advance parameter.

Requirements exist for the initial timing accuracy, the maximum step in any one timing adjustment and finally the maximum and minimum timing adjustment rates. These requirements are necessary in order that the worst case timing error between the eNB and UE is bounded. Timing errors can be caused by large changes in multipath delay (such as with shadow fading) or by a handover to a cell with different timing.

The initial timing accuracy requirement is $\pm 12 * T_s$ and should this be exceeded, the UE is required to adjust its timing to get to within the allowed range. During the adjustment process the maximum allowed step size is $\pm 2 * T_s$ and the rate of change has to be between $2 * T_s$ and $7 * T_s$ seconds per second.

UE timer accuracy

Many of the RRM processes require that the UE start and stop various timers. For timers of less than four seconds the accuracy is fixed at 0.1 seconds and for longer timers the UE is given a greater allowance of 0.25%. These are not critical figures but are specified in order to give guidance to the UE designer about the precision required for timer implementation.

Timing advance

When the UE receives a new timing advance command in frame number n it is required to implement the new timing in frame $n + 6$ to an accuracy of $\pm 4 * T_s$.

Cell phase synchronization accuracy (TDD)

This requirement controls the frame start timing for any two cells that share the same frequency and overlap coverage areas. It is necessary to control the timing between such cells to avoid the transmission from one cell occurring at the same time as reception by the other. The requirement for small cells is less than 3 µs. The definition for large cells remains open as does the definition for the break point between small and large cells.

Synchronization requirements for E-UTRAN to cdma2000 1xRTT/HSPD handovers
In order for successful handover to cdma2000 1xRTT and HRPD it is necessary for the UE to know the CDMA system timing reference. This is achieved by the eNB providing the timing via a system information message. Once the UE knows the system timing, it can report the timing of the target system's pilot signals. The basic requirement is for the eNB to be within ±10 μs of the CDMA system time. The eNB is expected to be synchronized to GPS time and to maintain ±10 μs accuracy for a period of up to 8 hours should GPS synchronization be lost. The eNB also has to ensure that the message transmitting the CDMA system time is transmitted within 10 μs of the expected time.

Radio link monitoring
The UE is required to monitor the quality of the downlink for the purposes of determining if the radio link is good enough to continue transmission. This is done through the parameters Q_{out} and Q_{in}. The threshold for Q_{out} is defined as the level at which the downlink radio link cannot be reliably received. There is no direct measure, but the assumption is that Q_{out} corresponds to an approximate 10% block error ratio of a hypothetical PDCCH transmission taking into account a number of network settings and radio conditions. Q_{in} is defined as having a much higher probability of reception than Q_{out}. The Q_{in} threshold is nominally a 2% block error ratio of the hypothetical PDCCH for a defined set of network settings and radio conditions. The requirements for the UE to monitor the radio link quality are specified in terms of how long the UE takes to switch off when the quality drops below Q_{out} and how long it takes for the UE to switch back on when the quality rises above Q_{in}.

3.6.5 UE measurement procedures in RRC_CONNECTED state

Refer to 36.133 [15] subclause 8. In cellular systems, knowing when and where to make a handover can be difficult. To make good handover decisions requires knowledge of the environment. By measuring and reporting the radio environment when in a connected state, the UE provides the system with the raw material needed to make the correct handover decisions. Many parameters can be measured, and the rules for how and when to gather and report these parameters are complex. The requirements, which are split according to RAT, are the following: E-UTRA intra-frequency, E-UTRA inter-frequency, inter-RAT UTRA FDD, UTRA TDD and GSM. The required measurement accuracy is defined in 36.133 [15] subclause 9.

With the exception of intra-frequency measurements, it is not possible for the UE to gather information on different frequencies or RATs without implementing a transmission gap. During this period the UE is able to retune its receiver (DRX) to monitor other frequencies. The options for configuring the UE can become quite complex, especially when the radio environment includes multiple bands and RATs. Trade-offs have to be made between the desire for full knowledge of the radio environment, which requires frequent gaps, and the desire for less interruption and fewer measurements, which leads to slower and less optimized handover decisions.

E-UTRAN intra-frequency measurements

- E-UTRAN FDD intra frequency measurements
- E-UTRAN TDD intra frequency measurements

E-UTRAN inter-frequency measurements

- E-UTRAN FDD to FDD inter frequency measurements
- E-UTRAN TDD to TDD inter frequency measurements
- E-UTRAN TDD to FDD inter frequency measurements
- E-UTRAN FDD to TDD inter frequency measurements

Inter-RAT measurements

- E-UTRAN FDD to UTRAN FDD measurements
- E-UTRAN TDD to UTRAN FDD measurements
- E-UTRAN TDD to UTRAN TDD measurements
- E-UTRAN FDD to UTRAN TDD measurements
- E-UTRAN FDD to GSM measurements
- E-UTRAN TDD to GSM measurements
- E-UTRAN FDD to UTRAN FDD measurements for SON
- E-UTRAN TDD to UTRAN FDD measurements for SON
- E-UTRAN FDD to cdma2000 1xRTT measurements
- E-UTRAN TDD to cdma2000 1xRTT measurements
- E-UTRAN FDD to HRPD measurements
- E-UTRAN TDD to HRPD measurements

Measurement performance requirements for UE

- E-UTRAN measurements
  - Intra-frequency RSRP accuracy measurements
  - Inter-frequency RSRP accuracy requirements
  - RSRP measurement report mapping
  - Intra-frequency RSRQ accuracy requirements
  - Inter-frequency RSRQ accuracy requirements
  - RSRQ measurement report mapping
  - Power headroom
- UTRAN FDD measurements
  - UTRAN FDD CPICH RSCP
  - UTRAN FDD carrier RSSI
  - UTRAN FDD CPICH $E_{c/N0}$
- UTRAN TDD measurements
  - UTRAN TDD P-CCPCH RSCP
  - UTRAN TDD carrier RSSI
- GSM measurements
  - GSM carrier RSSI
  - CDMA2000 1x RTT measurements
  - CDMA2000 1x RTT pilot strength

Measurement performance requirements for E-UTRAN

Received interference power

4 RF Conformance Tests

The goal of the LTE conformance tests is to ensure a minimum level of performance. For the UE, conformance testing comprises three types of tests: RF, RRM, and signaling. For the base station (eNB), only RF conformance tests are defined. This application note is limited to RF conformance testing. Tables 17 and 18 show the key specifications relating to RF conformance tests for the UE and eNB, respectively.

Table 17. UE RF FDD and TDD conformance test specifications

Specification	Title	Purpose
36.124 [16]	Electromagnetic Compatibility (EMC) Requirements for Mobile Terminals and Ancillary Equipment	Tests for EMC emissions and immunity
36.521-1 [17]	User Equipment (UE) Conformance Specification; Radio Transmission and Reception Part 1: Conformance Testing (FDD/TDD)	The RF conformance tests primarily based on 36.101 [6]
36.521-2 [18]	User Equipment (UE) Conformance Specification; Radio Transmission and Reception Part 2: Implementation Conformance Statement (ICS)	Definition of applicability of tests for different UE capabilities
36.521-3 [19]	User Equipment (UE) Conformance Specification; Radio Transmission and Reception Part 3: Radio Resource Management Conformance Testing	The RRM conformance tests based on test parameters defined in 36.133 Annex A [15]

Table 18. Base station (eNB) RF FDD and TDD conformance test documents

Specification	Title	Purpose
36.113 [20]	Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) and Repeater Electromagnetic Compatibility (EMC)	Tests for EMC emissions and immunity
36.141 [21]	Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) Conformance Testing	The RF conformance tests primarily based on 36.104 [7]
36.143 [22]	Evolved Universal Terrestrial Radio Access (E-UTRA); FDD Repeater Conformance Testing	The repeater conformance tests primarily based on 36.106 [23]

The structure of the UE RF conformance test follows a set pattern that consists of the following steps:

- Test purpose
- Test applicability
- Minimum conformance requirements
- Test description:
  - Initial conditions
  - Test procedure
  - Message contents
- Test requirements

The eNB RF conformance tests cover the same list in a slightly different order, and the message contents are not required since the eNB tests are done without signaling.

4.1 UE RF conformance tests

The UE RF conformance tests defined in 36.521-1 [17] are divided into four main sections: RF transmitter characteristics, RF receiver characteristics, RF performance characteristics, and radio resource management (RRM). At the time of this writing the RF conformance tests are still in development and in some areas the level of detail in the specifications is limited. The intention here is to provide an overview of the overall scope with some LTE-specific discussion. The tables reflect the 3GPP RAN5 LTE work plan for UE testing as of August 2009.

4.1.1 UE RF transmitter characteristics

Table 19 lists the transmitter test cases defined in 36.521-1 [17]. Note that the ACLR additional requirements subclause 6.6.2.4 described in previous versions of the specification has been removed.

Table 19. UE RF transmitter test cases

36.521-1 subclause	Test case
6.2.2	UE maximum output power
6.2.3	Maximum power reduction (MPR)
6.2.4	Additional maximum power reduction (A-MPR)
6.2.5	Configured UE transmitted output power
6.3.2	Minimum output power
6.3.3	Transmit OFF power
6.3.4.1	General ON/OFF time mask
6.3.4.2	PRACH and SRS time mask
6.3.5.1	Power control absolute power tolerance
6.3.5.2	Power control relative power tolerance
6.3.5.3	Aggregate power control tolerance
6.5.1	Frequency error
6.5.2.1	Error vector magnitude (EVM)
6.5.2.2	IQ-component
6.5.2.3	In-band emissions for non-allocated RB
6.5.2.3	Spectrum flatness
6.6.1	Occupied bandwidth
6.6.2.1	Spectrum emission mask
6.6.2.2	Additional spectrum emission mask
6.6.2.3	Adjacent channel leakage power ratio (ACLR)
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

The scope of these RF transmitter tests will be familiar from UMTS and are modified only in the details as they pertain to LTE and the SC-FDMA uplink modulation format. The transmitter tests are carried out using uplink reference measurement channels (RMCs). The RMCs fall into three main categories—fully allocated, partially allocated, and single RB—and were defined based on the simulation assumptions used to derive the requirements. The number of different RMC configurations defined for testing is a balance between thoroughness and excessive test time.

4.1.2 UE RF receiver characteristics

Table 20 lists the UE receiver test cases defined in 36.521-1 [17].

Table 20. UE RF receiver test cases

36.521-1 subclause	Test case
7.3	Reference 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
7.8.1	Wide band intermodulation
7.9	Spurious emissions

These test cases are similar to the UE RF test cases for UMTS. One difference worth noting is that the receiver minimum requirements for UMTS were typically specified in terms of a bit error ratio (BER) as distinct from the BLER used in the UMTS performance tests. This difference was due to somewhat arbitrary choices made during the early development of UMTS when some requirements simulation work was done using BER and others using BLER. Because a verifiable BER result requires the transmitted data to be looped back to the test system, it is a more difficult measure to make than simply counting the UE's ACK and NACK reports necessary for calculating BLER. That said, BER is more subtle in its ability to pick up small variations in performance compared to BLER and remains a useful measure during product development. For LTE the receiver minimum requirements are expressed in terms of a percentage throughput (> 95%) of the RMC used in the test. Since BLER can be mapped directly to throughput, the LTE receiver tests are brought in line with the performance tests that have always been based on BLER and throughput.

4.1.3 UE RF performance requirements

The UE RF performance requirements are defined in 36.521-1 [17], as shown in Table 21.

Table 21. UE RF performance test cases

36.521-1 subclause	Test case
8.2.1.1	FDD PDSCH single antenna port performance (cell-specific reference symbols)
8.2.1.2	FDD PDSCH transmit diversity performance (cell-specific reference symbols)
8.2.1.3	FDD PDSCH open loop spatial multiplexing performance (cell-specific reference symbols)
8.2.1.4	FDD PDSCH closed loop spatial multiplexing performance (cell-specific reference symbols)
8.2.2.1	TDD PDSCH single antenna port performance (cell-specific reference symbols)
8.2.2.2	TDD PDSCH transmit diversity performance (cell-specific reference symbols)
8.2.2.3	TDD PDSCH open loop spatial multiplexing performance (cell-specific reference symbols)
8.2.2.4	TDD PDSCH closed loop spatial multiplexing performance (cell-specific reference symbols)
8.3.2.1	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 transmission 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
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 – PUCCH 1-0
9.3.2.1.2	TDD frequency non-selective scheduling mode – PUCCH 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

4.2 UE RRM conformance tests

The RRM requirements are defined in 36.133 [15] and the conformance tests in 36.521-3 [19]. However, as a result of the complexity of the RRM requirements in terms of the number of variables that can affect performance, the core specification (36.133) includes Annex A, which provides guidance on test case configuration for conformance testing. The RRM conformance tests are based on this annex rather than on the core requirements directly.

The RRM core requirements are divided into six main parts and the annex follows the same six-part structure. Table 22 lists the RRM test cases defined in 36.521-3 [19].

Table 22. UE RRM test cases

36.521-3 subclause	Test case
4.2.1	E-UTRAN FDD – FDD cell re-selection intra frequency case
4.2.2	E-UTRAN TDD – TDD cell re-selection intra frequency case
4.2.3	E-UTRAN FDD – FDD cell re-selection inter frequency case
4.2.4	E-UTRAN FDD – TDD cell re-selection inter frequency case
4.2.5	E-UTRAN TDD – FDD cell re-selection inter frequency case
4.2.6	E-UTRAN TDD – TDD cell re-selection inter frequency case
4.3.1.1	E-UTRA FDD-UTRAN FDD cell reselection: UTRA FDD is of higher priority
4.3.1.2	E-UTRAN FDD – UTRAN FDD cell re-selection: UTRA FDD is of lower priority
4.3.2	E-UTRAN FDD – UTRAN TDD cell re-selection
4.3.3	E-UTRAN TDD – UTRAN FDD cell re-selection
4.3.4.1	E-UTRA TDD-UTRAN TDD cell re-selection: UTRA is of higher priority
4.3.4.2	E-UTRAN TDD – UTRAN TDD cell re-selection: UTRA is of lower priority
4.4.1	E-UTRAN FDD – GSM cell re-selection
4.4.2	E-UTRAN TDD – GSM cell re-selection
4.5.1.1	E-UTRAN FDD – HRPD cell reselection: HRPD is of Lower Priority
4.6.1	E-UTRAN FDD – cdma2000 1x cell reselection: cdma2000 1X is of lower priority
5.1.1	E-UTRAN FDD-FDD handover intra frequency case
5.1.2	E-UTRAN TDD-TDD handover intra frequency case
5.1.3	E-UTRAN FDD-FDD handover inter frequency case
5.1.4	E-UTRAN TDD-TDD hndover inter frequency case
5.2.1	E-UTRAN FDD – UTRAN FDD handover
5.2.2	E-UTRAN TDD – UTRAN FDD handover
5.2.3	E-UTRAN FDD – GSM handover
5.2.4	E-UTRAN TDD – UTRAN TDD handover

Table 22. UE RRM test cases *(continued)*

36.521-3 subclause	Test case
5.2.5	E-UTRAN FDD – UTRAN TDD handover
5.3.1	E-UTRAN FDD – HRPD handover
5.3.2	E-UTRAN FDD – cdma2000 1xRTT handover
6.1.1	E-UTRAN FDD Intra-frequency RRC re-establishment
6.1.2	E-UTRAN FDD Inter-frequency RRC re-establishment
6.2.1	E-UTRAN FDD – contention based random access test
6.2.2	E-UTRAN FDD – non-contention based random access test
6.2.3	E-UTRAN TDD – contention based random access test
6.2.4	E-UTRAN TDD – non-contention based random access test
7.1.1	E-UTRAN FDD – UE transmit timing accuracy
7.1.2	E-UTRAN TDD – UE transmit timing accuracy
7.2.1	E-UTRAN FDD – UE timing advance adjustment accuracy
7.2.2	E-UTRAN TDD – UE timing advance adjustment accuracy
7.3.1	E-UTRAN FDD radio link monitoring test for out-of-sync
7.3.2	E-UTRAN FDD radio link monitoring test for in-sync
7.3.3	E-UTRAN TDD radio link monitoring test for out-of-sync
7.3.4	E-UTRAN TDD radio link monitoring test for in-sync
8.1.1	E-UTRAN FDD-FDD intra frequency event triggered reporting under fading propagation conditions in asynchronous cells
8.1.2	E-UTRAN FDD-FDD intra frequency event triggered reporting under fading propagation conditions in synchronous cells
8.1.3	E-UTRAN FDD-FDD intra frequency event triggered reporting under fading propagation conditions in synchronous cells with DRX
8.2.1	E-UTRAN TDD-TDD intra-frequency event triggered reporting under fading propagation conditions in synchronous cells
8.2.2	E-UTRAN TDD-TDD intra-frequency event triggered reporting under fading propagation conditions in synchronous cells with DRX
8.3.1	E-UTRAN FDD-FDD inter frequency event triggered reporting under fading propagation conditions in asynchronous cells
8.3.2	E-UTRAN FDD-FDD Inter-frequency event triggered reporting when DRX is used under fading propagation conditions in asynchronous cells
8.4.1	E-UTRAN TDD-TDD Inter-frequency event triggered reporting under fading propagation conditions in synchronous cell
8.4.2	E-UTRAN TDD-TDD Inter-frequency event triggered reporting when DRX is used under fading propagation conditions in synchronous cells

Table 22. UE RRM test cases *(continued)*

36.521-3 subclause	Test case
8.5.1	E-UTRAN FDD – UTRAN FDD Inter-frequency event triggered reporting under fading propagation conditions in synchronous cell
8.5.2	E-UTRAN FDD – UTRAN FDD SON ANR cell search reporting under AWGN propagation conditions
8.6.1	E-UTRAN TDD – UTRAN FDD event triggered reporting under fading propagation conditions
8.7.1	E-UTRAN TDD – UTRAN TDD event triggered reporting under fading propagation conditions
8.8.1	E-UTRAN FDD – GSM event triggered reporting in AWGN
8.9.1	E-UTRAN FDD – UTRAN TDD event triggered reporting under fading propagation conditions
8.10.1	E-UTRAN TDD – GSM event triggered reporting in AWGN
9.1.1.1	FDD intra frequency absolute RSRP accuracy
9.1.1.2	FDD intra frequency relative accuracy of RSRP
9.1.2.1	TDD intra frequency absolute RSRP accuracy
9.1.2.2	TDD Intra frequency relative accuracy of RSRP
9.1.3.1	FDD – FDD inter frequency absolute RSRP accuracy
9.1.3.2	FDD – FDD inter frequency relative accuracy of RSRP
9.1.4.1	TDD – TDD inter frequency absolute RSRP accuracy
9.1.4.2	TDD – TDD inter frequency relative accuracy of RSRP
9.2.1.1	FDD intra frequency absolute RSRQ accuracy
9.2.2.1	TDD intra frequency absolute RSRQ accuracy
9.2.3.1	FDD – FDD inter frequency absolute RSRQ accuracy
9.2.3.2	FDD – FDD inter frequency relative accuracy of RSRQ
9.2.4.1	TDD – TDD inter frequency absolute RSRQ accuracy
9.2.4.2	TDD – TDD inter frequency relative accuracy of RSRQ

4.3 eNB RF conformance tests

Base station (eNB) conformance testing for LTE is similar to that of UMTS except for those areas of testing affected by the change to using an OFDMA modulation scheme. The eNB RF conformance tests are defined in 36.141 [21] and are based on the core requirements for eNB radio transmission and reception in 36.104 [7]. They are divided into three main sections: RF transmitter characteristics, RF receiver characteristics, and RF performance characteristics.

4.3.1 eNB RF transmitter characteristics

Table 23 lists the eNB RF transmitter characteristics test cases defined in 36.141 [21]. These tests closely follow the pattern of the UMTS tests with differences due mainly to the use of OFDMA.

The time alignment test is particularly important for LTE because of the widespread use of transmit diversity, spatial multiplexing, and beamsteering. The requirement for time alignment is 65 ns, which is the same as the UMTS requirement of ¼ chip (65 ns). The downlink reference signal power test is the equivalent of the CPICH power accuracy test for UMTS.

Table 23. eNB RF transmitter characteristics tests

36.141 [21] subclause	Test case
6.2	Base station output power
6.3.1	Resource element (RE) power control dynamic range
6.3.2	Total power dynamic range
6.4.1	Transmitter OFF power
6.4.2	Transmitter transient period
6.5.1	Frequency error
6.5.2	Error vector magnitude (EVM)
6.5.3	Time alignment between transmitter branches
6.5.4	Downlink reference signal power
6.6.1	Occupied bandwidth
6.6.2	Adjacent channel leakage power ratio (ACLR)
6.6.3	Operating band unwanted emissions
6.6.4	Transmitter spurious emissions
6.7	Transmitter intermodulation

4.3.2 eNB RF receiver characteristics

Table 24 lists the eNB RF receiver characteristics test cases defined in 36.141 [21]. Of note is the in-channel selectivity test, which is unique to OFDMA. This test checks the receiver's ability to maintain a particular throughput on an allocation on one side of the central subcarrier reserved for LO leakage when a larger signal is present on the opposite side. The test checks for IQ distortion in the receiver and is the reverse of the UE transmitter IQ image requirement for in-band emissions.

Table 24. eNB RF receiver characteristics

36.141 [21] subclause	Test case
7.2	Reference sensitivity level
7.3	Dynamic range
7.4	In-channel selectivity
7.5	Adjacent channel selectivity (ACS) and narrow-band blocking
7.6	Blocking
7.7	Receiver spurious emissions
7.8	Receiver intermodulation

4.3.3 eNB RF performance requirements

The eNB RF performance tests are still in development at the time of this writing. Table 25 lists some of the requirements as defined in 36.104 [7].

Table 25. eNB RF performance tests

36.141 [21] subclause	Test case
8.2.1	Performance requirements of PUSCH in multipath fading conditions
8.2.2	Performance requirements for UL timing adjustment
8.2.3	Performance requirements for HARQ-ACK multiplexed on PUSCH
8.2.4	Performance requirements for High Speed Train conditions
8.3.1	ACK missed detection requirements for PUCCH format 1a
8.3.2	CQI missed detection for PUCCH format 2
8.3.3	ACK missed detection for multi-user PUCCH format 1a
8.4.1	PRACH false alarm probability and missed detection

4.3.4 Downlink test models

The eNB transmitter conformance tests are carried out using downlink configurations known as E-UTRA test models (E-TM). This concept has been inherited from UMTS, although any similarity stops there. The highly flexible nature of the downlink OFDMA modulation scheme means that a large number of parameters are required to fully define any signal. An inspection of the definition of the E-TM in 36.141 [21] subclause 6.1.1 shows how much more complex the signal structure is compared to UMTS. There are three distinct classes of test model defined: E-TM1, E-TM2 and E-TM3. The first and third classes have further subclasses. All test models have the following attributes:

- Single antenna port, single codeword, single layer with no precoding
- Duration of one frame (10 ms)
- Normal cyclic prefix
- Localized virtual resource blocks, no intra-subframe hopping for PDSCH
- Cell-specific reference signals only; no use of UE-specific reference signals

The data content of the PDSCH is generated from a sequence of zeros scrambled using a length-31 Gold code according to 36.211 [10], which also defines the reference signals and the primary and secondary synchronization signals. The physical channels PBCH, PCFICH, PHICH, and PDCCH all have detailed definitions. For each E-TM, the physical signals and physical channels are allocated into the channel at a specific power relative to the RS power. There are six different mappings for each E-TM to account for the six different channel bandwidths. Each E-TM is defined for specific use as shown in Table 26.

Table 26. Evolved Test Model mapping to test cases

E-TM	Notes	Test case
E-TM1.1	Maximum power tests	Output power, occupied bandwidth, ACLR, operating band unwanted emissions, transmitter spurious emissions, transmitter intermodulation, reference signal absolute accuracy
E-TM1.2	Includes power boosting and de-boosting	ACLR, operating band unwanted emissions
E-TM2	Minimum power tests	Total power dynamic range (lower OFDM symbol power limit at min power), EVM of single 64QAM PRB allocation (at min power), frequency error (at min power)
E-TM3.1		Total power dynamic range (upper OFDM symbol power limit at max power with all 64QAM PRBs allocated), frequency error, EVM for 64QAM (at max power)
E-TM3.2	Includes power boosting and de-boosting	Frequency error, EVM for 16QAM
E-TM3.3	Includes power boosting and de-boosting	Frequency error, EVM for QPSK

4.3.5 Uplink fixed reference channels

The eNB receiver and performance tests make use of fixed reference channels (FRCs). The eNB FRCs are, in most cases, single-ended signals that can be generated in a signal generator without the need for any real-time feedback.

Table 27 shows the FRC parameters for 64QAM performance requirements. This example uses a code rate of 5/6, which is intended for testing the highest throughput requirements. For the 100 RB case of A5-7, there are 86,400 bits per 1 ms subframe indicating a maximum throughput of 86.4 Mbps. The eNB performance requirements measured under fading conditions will be based on reaching a percentage of the maximum throughput under particular conditions. For example, 36.141 [21] Table 8.2.1.5-6 indicates that a two channel eNB receiver operating in a pedestrian A channel with 5 Hz Doppler is required to reach 70% of the A5-7 FRC maximum throughput when the SNR is above 19.7 dB.

Table 27. FRC parameters for performance requirements (64QAM 5/6) (36.141 [21] Table A.5-1)

Reference channel	A5-1	A5-2	A5-3	A5-4	A5-5	A5-6	A5-7
Allocated resource blocks	1	6	15	25	50	75	100
DFT-OFDM symbols per subframe	12	12	12	12	12	12	12
Modulation	64QAM	64QAM	64QAM	64QAM	64QAM	64QAM	64QAM
Code rate	5/6	5/6	5/6	5/6	5/6	5/6	5/6
Payload size (bits)	712	4392	11064	18336	36696	55056	75376
Transport block CRC (bits)	24	24	24	24	24	24	24
Code block CRC size (bits)	0	0	24	24	24	24	24
Number of code blocks - C	1	1	2	3	6	9	13
Coded block size including 12 bits trellis termination (bits)	2220	13260	16716	18444	18444	18444	17484
Total number of bits per subframe	864	5184	12960	21600	43200	64800	86400
Total symbols per subframe	144	864	2160	3600	7200	10800	14400

5 LTE Product Development Challenges

The compressed timeline for LTE standards development is mirrored by aggressive schedules for LTE product development. Successful proof-of-concept tests, trial networks, and test calls have been reported, and the first commercial services are expected within the next few years.

Nevertheless, the newness and the complexity of LTE give rise to a number of product development challenges. Not least is the fact that LTE is an evolving standard, and as such, it is open to change and interpretation. From the technology perspective, a number of new techniques add substantial complexity. For example, the use of multiple antenna configurations to support high data rates makes the design of UE more complicated, as does the introduction of the new uplink modulation scheme, SC-FDMA. It may be some time before the "real-world" behavior of these enhancements is well understood and products optimized accordingly.

The six channel bandwidths specified for LTE, while increasing the flexibility and capability of the system, at the same time add to its overall complexity. Moreover, LTE UE are likely to incorporate GSM and UMTS operating modes, and possibly other emerging formats as well. Thus the ability to interwork seamlessly with other technologies will be an important factor in LTE's success. The integration of the TD-SCDMA standard into the 3GPP specifications for LTE has put a renewed emphasis on developing systems with TDD capability. New components in the network architecture such as IP multimedia subsystems (IMS) and femtocells further add to the complexity.

Along with LTE-specific development challenges are those generally associated with designing products for emerging wireless systems. Product designs tend to be mixed-signal in nature, consisting of baseband and RF sections. Overall system performance depends on the performance of both categories, and each is associated with particular impairments—for example, non-linearities and effective noise figure in an RF up-converter or down-converter; phase and amplitude distortion from a power amplifier; channel impairments such as multi-path and fading; and impairments associated with the fixed bit-width of baseband hardware. With performance targets for LTE set exceptionally high, system engineers have to allocate resources to cover each critical part of the transmit and receive chain. Astute decisions regarding system performance budgets will be key in meeting system-level specifications as well as time-to-market goals.

5.1 Design simulation and verification

Design simulation tools help system engineers address LTE development challenges and verify their interpretations of the standard. Typically, models simulated at various levels of abstraction are needed to support the progression from product concept through detailed design. Performance of both baseband and RF sections must be evaluated individually and together to minimize the problems and surprises encountered during system integration and other phases of the development cycle. Finally, during the transition to hardware testing, a means of moving smoothly back and forth between design simulation and testing is needed to ensure that engineers are not forced to redesign the product on the bench to get it to work.

Figure 30 shows how an LTE system can be modeled and tested using Agilent's connected solutions, which integrate simulation and test capability for verifying system-level performance with real device component hardware in the simulation path.

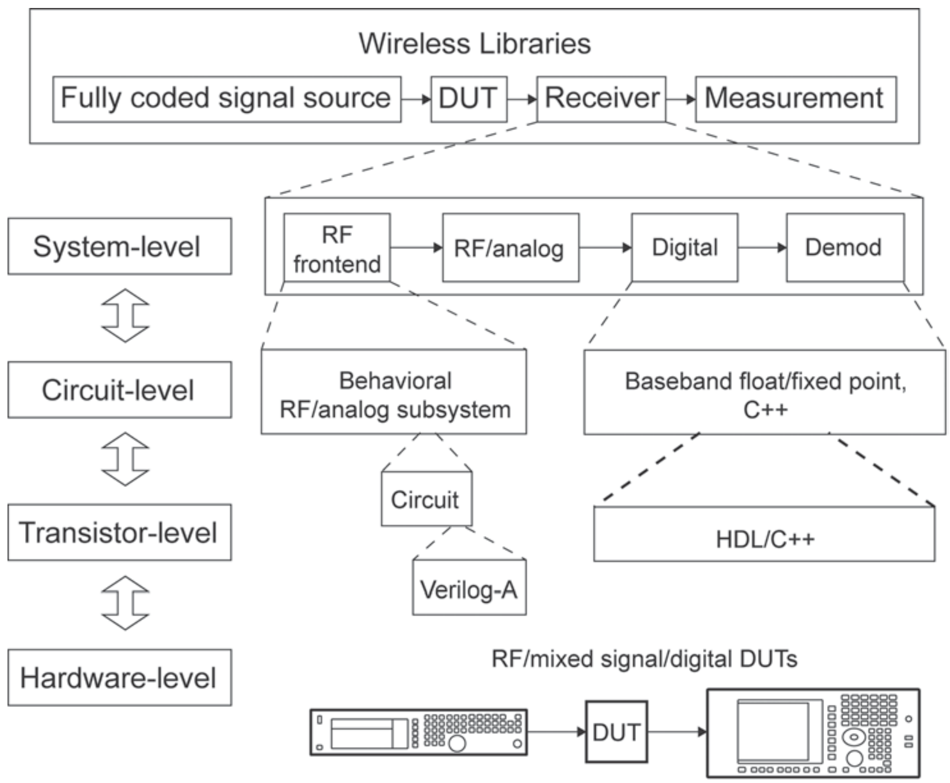

Figure 30. Simulation conceptual overview

5.1.1 Baseband design and verification

Agilent SystemVue is a powerful, electronic system level design environment for baseband PHY architectures and algorithms. SystemVue provides two levels of capability for LTE that bring instrument-like compliance to product designs at the earliest stages of development. First, SystemVue's baseband verification libraries offer pre-built LTE reference models that provide a "gold standard" to compare waveforms and generate test vectors at any point within a signal processing chain, down to the block level. The baseband verification libraries include compiled sources, receivers, function blocks, and reference designs that adhere to the physical layer of modern emerging standards. With native TCP/IP connectivity, they also support co-design with test equipment and hardware development boards for both baseband and modulated-carrier signals.

Second, SystemVue's exploration libraries go further to provide an open platform for innovative PHY designs that includes working, native source code for PHY blocks (math format) and documentation of the standards. Exploration libraries are polymorphic, incorporating compiled models for simulation speed, and are open to user-supplied IP for easy comparison. For designers working at the cutting edge of emerging standards, they a tremendous learning tool and productivity aid. See Figure 31.

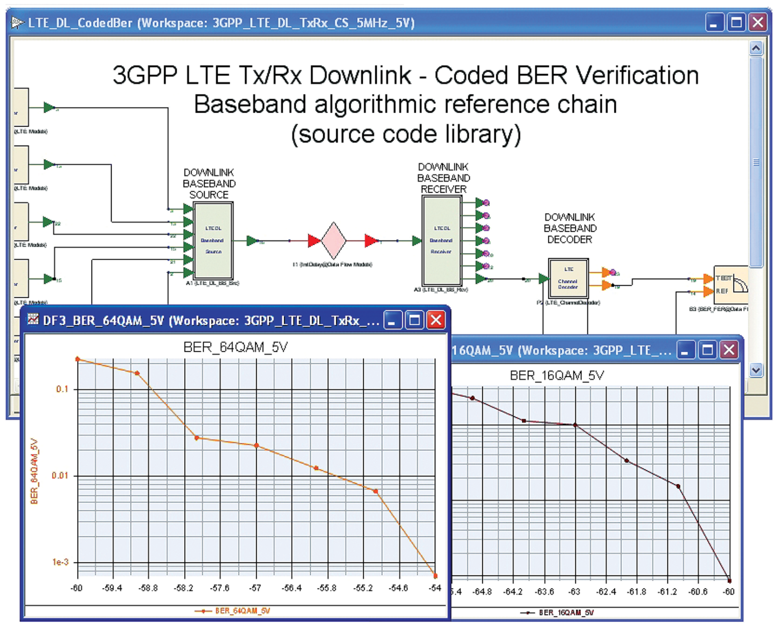

Figure 31. LTE downlink simulation example using SystemVue software

5.1.2 RF design and verification

Agilent's 3GPP LTE Wireless Library for ADS saves valuable design and verification time for RF designers and system integrators, and helps improve raw, uncorrected PHY performance. The 3GPP LTE Wireless Library provides signal processing models and preconfigured simulation setups for use within Agilent's ADS software. It creates and demodulates spectrally correct test signals that comply with the latest LTE specifications, including MIMO and TDD. This enables early verification of PHY performance of RF hardware before committing RFIC and board designs to fabrication, saving costly design turns. Designers can combine live, high-performance RF simulations, baseband simulations and standards-compliant measurements from the real world to measure EVM, PAPR, CCDF, and ACLR performance of RF components.

5.1.3 Connected solutions

At the hardware level, Agilent's simulation tools work seamlessly with test instruments to verify performance with actual device components added to the simulated model. For example, a simulated signal from SystemVue or ADS can be downloaded to a signal generator and effectively turned into a physical, real-world test signal. The test signal is run through the hardware device under test, and the device output is captured with a signal analyzer. The captured signal can then be read back into SystemVue or ADS for simulation post-processing.

Using this approach engineers can perform measurements such as coded bit error ratio and coded packet error ratio on RF device hardware using the simulated baseband coding and decoding capability to represent the missing baseband hardware functionality. An example of a SISO BER test setup is shown in Figure 32.

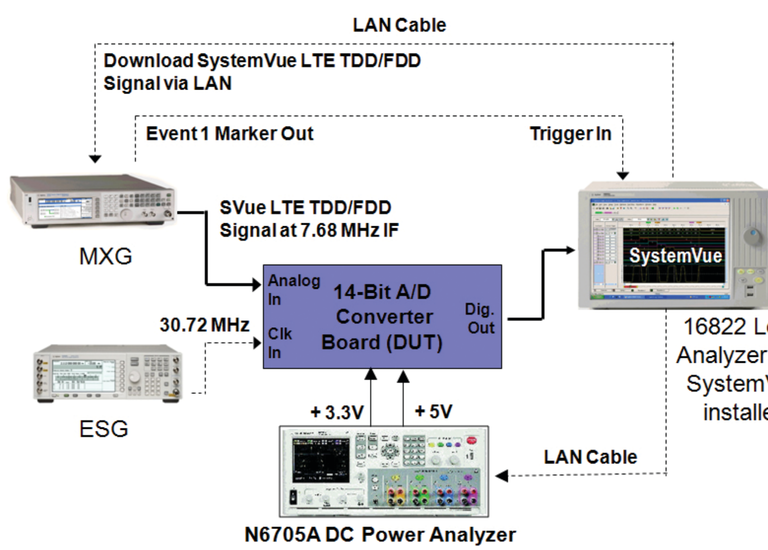

Figure 32. LTE OFDMA SISO BER test setup using connected solutions

5.2 Uplink and downlink signal generation

Agilent has built a solid reputation in the mobile communications industry with the combination of signal generators and Signal Studio signal creation software. Signal Studio is available for the development and manufacturing of existing and evolving 2G, 3G, 3.5G and 4G communication systems. With this software, it is easy to create performance-optimized LTE reference signals for component-level parametric test, baseband subsystem verification, receiver performance verification and advanced functional evaluation. See Figure 33.

Signal Studio applications for LTE enable the configuration of standards-based FDD and TDD LTE test signals to verify the performance of components, receivers, and baseband ASICs. The software can be used with the Agilent MXG signal generator to provide the industry's best adjacent channel leakage ratio (ACLR) performance for the characterization and evaluation of base transceiver station (BTS) components such as multi-carrier power amplifiers.

For applications that require lower phase noise, the best level accuracy, or digital I/Q inputs and outputs, Signal Studio can be used with the Agilent ESG signal generator. The software also can be used with the Agilent PXB MIMO receiver tester for applications that require MIMO fading, creation of interfering stimulus, digital I/Q inputs and outputs, real-time signal creation or closed loop testing of advanced LTE capabilities such as HARQ.

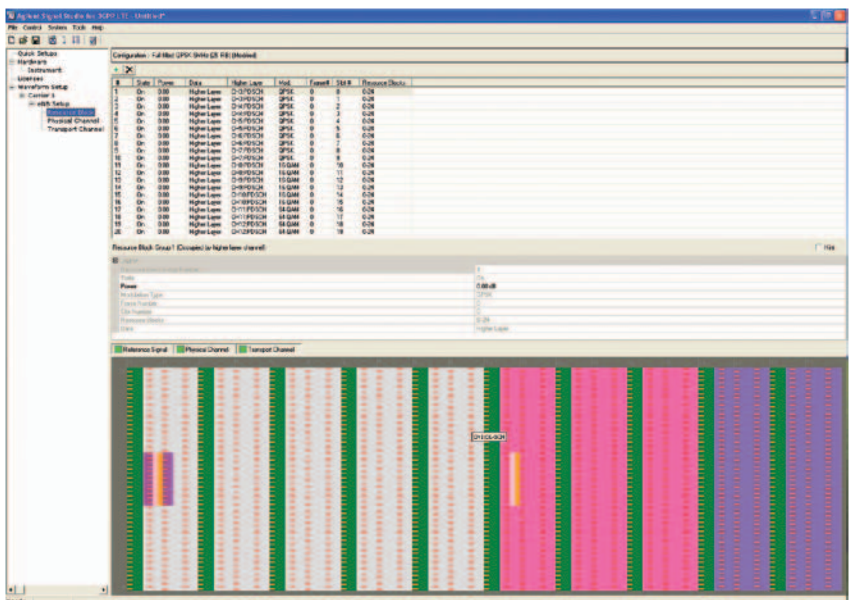

Figure 33. Resource mapping with scalable system bandwidth using Signal Studio software

5.3 Baseband analysis

5.3.1 Logic analysis

In next-generation architectures, the physical link between the RF front-end and baseband processing is evolving from an analog to parallel, or high-speed, serial digital bus. New interface standards require test equipment with appropriate serial digital inputs and outputs. Agilent is providing the necessary capability in its test equipment to meet these cross-domain test challenges, as shown in Figure 34.

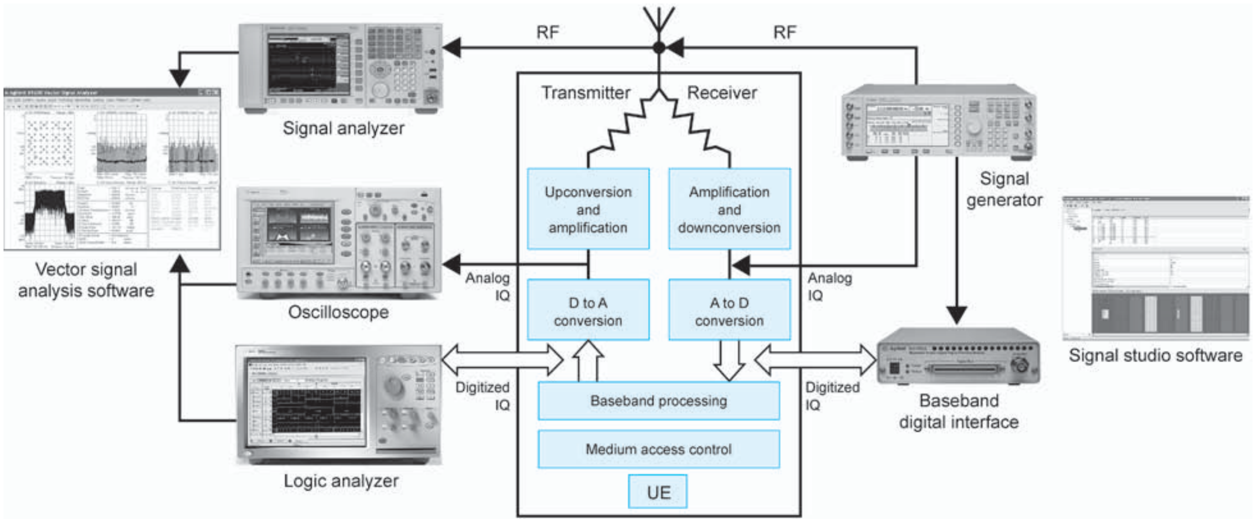

Figure 34. Cross-domain solutions for characterizing the behavior of devices from baseband to antenna, with access throughout the block diagram

The combination of an Agilent RDX tester or logic analyzer and Vector Signal Analysis (VSA) software provides the only digital VSA (DVSA) package for digital baseband, IF, and RF signal analysis. This combination enables digital signal processing (DSP) designers to effectively design and debug interfaces that once were analog and now are digital. The VSA software performs signal analysis functions such as I/Q analysis, EVM, and Fourier spectrum using the digital signal captured by the logic analyzer as the input.

To validate RFIC operation, engineers also can leverage the combination of signal generation software and RDX tester connected to the system-under-test through a DigRF v3 or v4 digital connection to test the transmit signal path.

R&D engineers who are designing or integrating MIPI (Mobile Industry Processor Alliance) D-PHY devices within a mobile handset can use the same logic analysis solution to test MIPI D-PHY protocols, with support for display (DSI) and camera (CSI-2) interfaces. The solution includes a configurable stimulus platform that offers bit-to-video level test capability for embedded displays, real-time analysis capability, and protocol viewing capability. Engineers can gain valuable insight into the exchanges between MIPI D-PHY enabled devices.

5.3.2 Digital real-time decode and debug

The VSA software works with the Agilent's Infiniium 90000A series oscilloscopes to analyze wide-bandwidth signals. The Infiniium scopes provide up to 13 GHz of analysis bandwidth and are well suited to digitizing down-signals. Two-channel Infiniium scopes can make the coherent two-channel MIMO measurements needed for IEEE 802.11n and WiMAX™. The digitized signals are transferred via GPIB, USB, or LAN to the PC running the VSA software, whose frequency, time, and modulation analysis tools can be used to evaluate and troubleshoot the signal.

The Agilent Infiniium 90000A oscilloscopes are high performance, real-time scopes that deliver superior signal integrity, deep application analysis, and excellent insight. They offer the industry's lowest noise floor, the deepest memory (1 Gpts), the only three-level sequence triggering, and the widest selection of applications.

5.3.3 DigRF digital interface

For engineers using the DigRF (v3 or v4) baseband IC-to-RFIC interface, the Agilent RDX platform provides a comprehensive test solution that brings insight into both the digital and RF domains. The RDX platform allows engineers to work in either the digital or RF domain for digital protocol test as well as RF (digital IQ) physical layer stimulus and analysis. The RDX platform integrates with the Agilent RF portfolio to provide cross-domain solutions for deploying DigRF designs, aiding baseband and RF IC development, debug, and characterization. The RDX analyzer is shown in Figure 35.

Figure 35. Test platform for access to DigRF v3 and v4 interfaces as well as digital IQ data

5.4 Uplink and downlink signal analysis

The complexity of LTE systems requires signal analysis with in-depth modulation analysis as well as RF power measurements. Agilent signal and spectrum analyzers measure complex LTE signals with world-class accuracy, repeatability, and standards-compliant measurement applications.

For research and design, the analyzers can be used with the Agilent VSA software to create the industry's most sophisticated, general purpose and standards-compliant signal analysis and troubleshooting tools. The VSA software provides solutions for both FDD and TDD signals supporting up to 4x4 MIMO with per-layer analysis.

For design verification, early manufacturing, or early conformance testing, the Agilent X-Series signal analyzers (MXA/EXA) in combination with the N9080A LTE FDD and N9082A LTE TDD measurement applications provide standard compliance one-button power measurements such as ACLR and SEM as well as modulation quality measurements with SCPI programming interface.

Both the 89600 VSA and the N908xA measurement solutions offer downlink and uplink measurement capability in a single option. They measure all LTE bandwidths and modulation schemes and provide a recall function to recall E-UTRA test models (E-TM) to make measurement according to the eNB transmitter conformance tests. A rich selection of in-channel measurements and traces including overall/data/RS EVM, EVM per channel, carrier, symbol, resource block, and slot are also provided. An example of how the VSA software is used to analyze an SC-FDMA signal is provided earlier in this application note. An additional example of downlink signal analysis is shown in Figure 36.

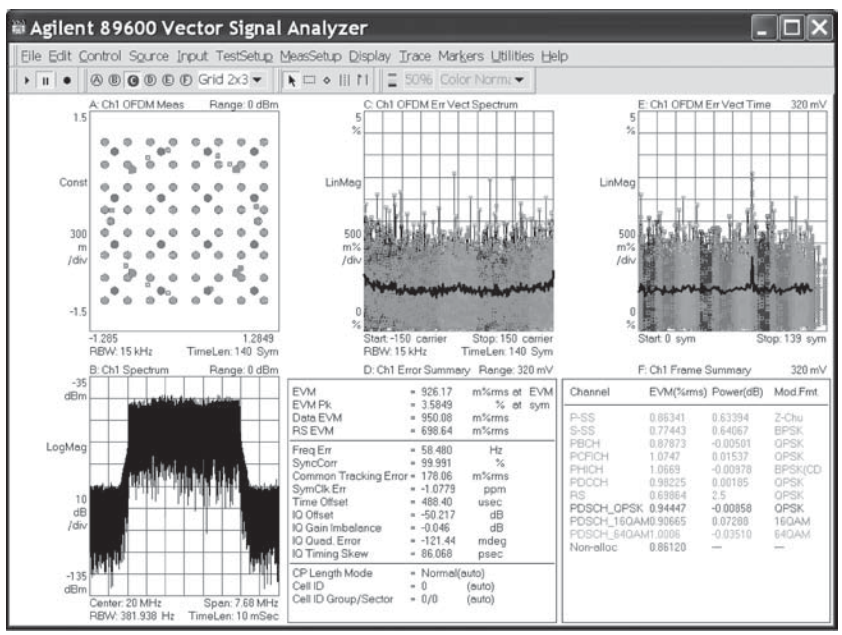

Figure 36. Analysis of digitally demodulated 5 MHz LTE downlink signal using VSA software

5.5 UE development

5.5.1 UE development test set

The Agilent PXT E6620A wireless communications test set, shown in Figure 37, is designed to provide leading-edge solutions for the LTE UE development life-cycle from early protocol development through RF and protocol conformance test and interoperatiblity test. Built on Agilent's 4G-ready platform, the PXT E6620A test set uses the same 3GPP-compliant LTE protocol stack across all solutions to shorten design cycles and ensure consistent testing leading to the highest quality UE designs.

Highlights of the PXT E6620A for UE development include the following:

- Scripting interface for protocol development and conformance testing
- Real-time, benchtop network emulation for easy-to-use, real-world design integration and validation testing
- Integrated LTE fading channel models
- LTE Tx and Rx measurement suite
- L1/L2/L3 uplink and downlink via RF or digital baseband
- MIMO 2x2 (4.2 future)
- 2.7 GHz frequency range and internal PC controller with Windows XP®

Figure 37. Protocol test set for early protocol development through RF and protocol conformance test

5.5.2 RF design and conformance test systems

Agilent GS-8860, GS-8870, and GS-8890 scalable test systems are built around the PXT E6620A wireless communications test set. They cover LTE device test, RF design verification, and RF conformance test. The systems are compliant to 3GPP TS 36.521-1 requirements with support of Section 6 transmitter test, Section 7 receiver test, and Section 8 performance test requirements.

These systems make use of the measurements, speed, accuracy, and repeatability of the PXT E6620A and Agilent sources and analyzers to create reliable, high performance test systems ideal for wireless test laboratories, device manufac-turers, reference designers, and chipset vendors. The use of common software and hardware across the lifecycle enhances development efficiency and time to market.

5.6 UE protocol development and conformance test

5.6.1 Protocol development and testing

New handset designs must meet the standards expected by the consumer—not to mention those required by industry bodies such as the GCF or PTCRB—and that means carrying out earlier and more comprehensive development, design verification and regression testing. In order to achieve this goal, versatile but rigorous test solutions are required. The Anite SAT protocol tester and development toolset with the Agilent PXT E6620A can shorten development time and validate LTE designs from pre-silicon protocol module development through system integration and verification.

With the Anite SAT LTE solution engineers can cost effectively analyze LTE UE product designs early in the process. Emerging issues can be resolved before they become costly problems. These tools can simulate and test a broad range of functionality, helping assure that products will meet or exceed industry certification and quality requirements. An example configuration is shown in Figure 38.

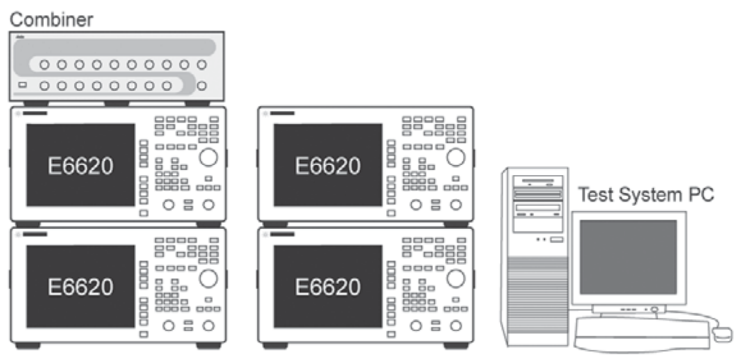

Figure 38. Example of RF-based Anite test system

5.6.2 Battery current drain measurement and analysis

The Agilent 14565B software and 66319D/21D DC source provide a ready-to-use solution for battery current drain measurement and analysis for optimizing the power consumption of LTE devices. The 66319D/21D is a specialized DC source for testing LTE and other wireless mobile devices. It has a 15V, 3A output; a high-speed 64KSa/sec 16 bit digitizer; and three current measurement ranges for making accurate current drain measurements from microamps to amps. The system measures current drain in the off, sleep, and active operating modes of the DUT.

5.7 Network deployment and optimization

5.7.1 Signaling analysis

The Agilent signaling analyzer platform is an industry-leading solution for 3G, 2G, and IMS networks today. With the addition of LTE and SAE technology support, the signaling analyzer software provides a common and intuitive user interface to support all mobile and IMS technologies.

Together with a new, high-density probing solution the signaling analyzer software enables passive probing and analysis of LTE network interfaces (S1, X2, S3, S4, S5, etc.) with total visibility of all layers (L1 through L7). Complete decoding of all protocol messages is provided. Other features include full hardware and software reassembly at each layer in the protocol stack; real-time KPIs, statistics, and distributed performance management; and real-time call/session tracing on a single or multiple interfaces including mixed technology interfaces

This powerful combination of distributable hardware pre-processing with scalable software architecture meets the current and future performance requirements necessary for the successful deployment of an integrated LTE/SAE network.

5.7.2 Drive test

The Agilent E6474A network optimization platform addresses wireless voice and data network performance issues by quickly and accurately measuring network RF performance and identifying problems. A fully flexible user interface together with outdoor and indoor navigation options makes this scalable platform customizable to specific needs.

Two LTE receiver measurement software options extend the capabilities of this multi-technology drive-test platform for both FDD-LTE and TD-LTE. The platform also covers HSPA+, UMTS, GPRS, cdma2000, 1xEVDO, iDEN, TD-SCDMA, and WiMAX. The software is combined with Agilent's W1314A multi-band, multi-technology receiver hardware to allow simultaneous measurements of multiple technologies. The LTE receiver measurements include primary synchronization signal RSSI, secondary synchronization signal RSSI, LTE Physical Layer-cell-ID, RF spectrum, and CW RF measurements.

Figure 39. Drive test system used for LTE network planning, deployment, and maintenance

5.7.3 RF analyzer for installation and maintenance

The Agilent FieldFox RF analyzer (4 GHz/ 6 GHz) is the world's most integrated, fast, and rugged handheld RF analyzer for wireless network installation and maintenance. This six-in-one RF tester combines cable and antenna analysis, spectrum analysis, interference analysis, power meter measurement, vector network analysis, and a vector voltmeter into one rugged, compact, lightweight, and weather-resistant package. FieldFox supports power suite measurements for LTE as well as for GSM and W-CDMA.

For LTE testing, one-button GSM/WCDMA/LTE power measurements make Node B transmitter tests much easier and worry free. LTE TDD spectrum analysis power measurement enables identification of uplink interference during network operation.

FieldFox's speed of 1.5 updates per second is the world's fastest in the commonly used 20 MHz span and the 3 kHz resolution bandwidth. The handheld analyzer offers the best dynamic range in spectrum analyzer mode (96 dB) and the fastest sweep times for interference detection with resolution bandwidths under 30 kHz.

FieldFox meets current and future wireless network installation and maintenance challenges with superior performance in all measurements. The tester's interference analyzer option allows test engineers to detect intermittent signals more quickly using the built-in spectrogram and waterfall display along with record and playback functions.

An integrated QuickCal capability is used to calibrate the instrument without a calibration kit for worry-free accuracy and repeatability, and a CalReady feature makes the tester calibration-ready at the test port immediately after power-up.

Figure 40. Handheld RF analyzer that combines the functions of six instruments in one integrated, fast, and rugged package

6 Looking Ahead

Fourth generation (4G) wireless has been anticipated for quite some time. The formal definition of 4G wireless is being developed by Working Party 5D of the International Telecommunications Union Radiocommunication Sector (ITU-R). A timeline for their IMT-Advanced program and the parallel activities of 3GPP for LTE-Advanced is shown in Figure 41.

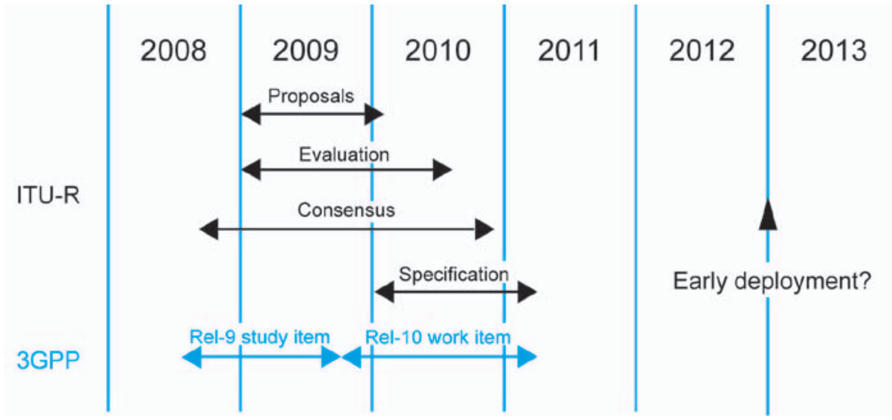

Figure 41. Overall IMT-Advanced and LTE-Advanced timeline

The ITU's goal is to approve candidate 4G technologies by the end of 2009 with standards development and implementation to follow. This puts 4G about two years behind Release 8 LTE/SAE, suggesting that 4G commercial service will appear certainly no earlier than 2012. This aggressive timeline is possible because the two most likely 4G candidate technologies (evolutions of IEEE's 802.16e and 3GPP's LTE/SAE) are evolutions of already specified technologies. The enhancements required to these technologies to meet 4G's requirements are not considered major.

6.1 IMT-Advanced high level requirements

The high level requirements for IMT-Advanced defined by ITU-R are the following:

- A high degree of common functionality worldwide while retaining the flexibility to support a wide range of local services and applications in a cost efficient manner
- Compatibility of services within IMT and with fixed networks
- Capability of interworking with other radio access systems
- High quality mobile services
- User equipment suitable for worldwide use
- User-friendly applications, services and equipment
- Worldwide roaming capability
- Enhanced downlink peak data rates to support advanced services and applications (100 Mbps for high mobility and 1 Gbps for low mobility were established as targets for research).

The work by 3GPP to define a candidate radio interface technology starts in Release 9 with the study phase of LTE-Advanced. The requirements for LTE-Advanced are given in 36.913, "Requirements for further advancements for E-UTRA LTE-Advanced" [22]. These requirements are based on the ITU-R requirements for IMT-Advanced as well as on 3GPP operators' own requirements for advancing LTE. Key elements include the following:

- Continual improvement to the LTE radio technology and architecture
- Scenarios and performance requirements for interworking with legacy radio access technologies (RATs)
- Backward compatibility of LTE-Advanced with LTE; i.e., an LTE terminal can work in an LTE-Advanced network, and an LTE-Advanced terminal can work in an LTE network. Any exceptions will be considered by 3GPP.
- Account to be taken of recent WRC-07 decisions for new IMT spectrum as well as existing frequency bands to ensure that LTE-Advanced accommodates geographically available spectrum for channel allocations above 20 MHz. Also, requirements must recognize those parts of the world in which wideband channels will not be available.

6.2 LTE-Advanced solution proposals

The LTE-Advanced study item is in full flow and a large number of solutions are being considered by 3GPP. Several categories of research are highlighted below, each of which addresses a specific IMT-Advanced requirement.

The decisions for the LTE-Advanced physical layer are being documented in 36.814, "Further Advancements for E-UTRA Physical Layer Aspects." [23]. One recent decision has been to enhance the uplink multiple access scheme by adopting clustered discrete Fourier transform spread OFDM (DFT-S-OFDM). This scheme is similar to SC-FDMA but has the advantage that it allows non-contiguous (clustered) groups of subcarriers to be allocated for transmission by a single UE, thus increasing the flexibility available for frequency-selective scheduling. This scheme was chosen in preference to pure OFDM in order to avoid a large increase in peak-to-average power ratio (PAPR). In addition, it has been decided to allow simultaneous transmission of control and data on the uplink.

6.2.1 Bandwidth aggregation

This solution is aimed at addressing the LTE-Advanced requirements for the 100 MHz of spectrum needed to support 1 Gbps peak data rates. It is expected that this required 100 MHz will be created by the aggregation of non-contiguous channels from different bands in a multi-transceiver mobile device. The proposal to extend aggregation up to 100 MHz in multiple bands raises questions about the viability of solutions due to the added cost and complexity to the UE. Contiguous aggregation of two 20 MHz channels may be a more achievable goal provided the spectrum can be found.

6.2.2 Higher order MIMO and beamsteering

The potential reception gains from MIMO systems and from beamsteering are a function of the number of antennas, and proposals are being considered that would increase this number for systems up to 8x8. Although the theoretical potential of such systems can be simulated, practical considerations make commercial deployment more challenging. At the eNB, such an increase could require the use of tower-mounted radio heads to avoid the need to run 8 sets of expensive and lossy cables up the tower. The increased power consumption of MIMO systems must also be considered. There is a trade-off between number of antennas per sector and the number of sectors per cell, so it may be preferable to use a six sector cell with four antennas per sector rather than a three-sector cell with eight antennas per sector.

At the UE, the main issue with higher order MIMO is the physical space required for the antennas. Laptop data-only systems clearly have an advantage over handheld devices in terms of size, power handling, and throughput requirements. Moreover, it is very hard in a small device to achieve the necessary spatial separation of the antennas in order to exploit spatial beamforming in the channel.

6.2.3 Co-operative MIMO

The concept of co-operative MIMO was introduced in Section 2.8.3. Co-operative MIMO allows physically separate transmitters belonging to different UEs to be linked and to share playload data, thus obtaining the full benefit of closed-loop performance using precoding. This scenario is possible only in the downlink, and it presents new challenges for inter-eNB communication over the X2 interface. In some ways co-operative MIMO is a more advanced form of the macro diversity used to enable soft handovers. The advantage over soft handovers is that the transmission of two streams over what is likely to be uncorrelated channel conditions will lead to a higher probability of increased data rates for cell-edge users. Both techniques, however, reduce overall system capacity due to the scheduling of downlink resources in more than one cell, though co-operative MIMO will be more efficient. The impact of co-operative MIMO therefore could be some rise or fall in system capacity depending on the fairness criteria of the scheduler.

6.2.4 In-channel relay

Another method of improving coverage in difficult conditions is the use of relaying. The concept of relaying is not new but the level of sophistication continues to grow. The most basic relay method is the use of a repeater, which receives, amplifies and then retransmits the downlink and uplink signals to overcome areas of poor coverage. Repeaters can improve coverage but do not substantially increase capacity. More advanced relays can in principle decode transmissions before retransmitting them. This gives the ability to selectively forward traffic to and from the UE local to the relay station thus minimizing interference. The relay station can also be applied in low density deployments where a lack of suitable backhaul would otherwise preclude use of a cellular network. The use of in-band or in-channel backhaul can be optimized using narrow point-to-point connections to avoid creating unnecessary interference in the rest of the network. Multi-hop relaying is also possible.

6.2.5 Cell-edge interference coordination and cancellation

The introduction of OFDMA to cellular systems has significantly changed the nature of cell edge interference. In OFDMA the potential for frequency-selective scheduling within the channel opens up new possibilities for optimizing intra-cell performance, but the inter-cell co-channel interference created is far more dynamic. Work is ongoing to better understand the effect this interference may have on operational performance. In particular the behavior of subband CQI and PMI reporting will be influenced by the narrowband statistical nature of the interference. In OFDMA systems that employ frequency-selective scheduling, for example, from the time of CQI reporting to the impact on the next scheduled transmission the interference conditions may have changed from being present to absent or vice versa.

The interference protection between cells offered in CDMA by whitening of noise is not available in narrowband OFDMA transmissions, which increases the vulnerability of narrowband signals to narrowband interference. Techniques to overcome such interference include making transmissions more robust by repeating (spreading) information across a wider allocation. A technique known as block repeat OFDM is being considered as a backward compatible enhancement to LTE to mitigate the impact of interference. The downside is that there is a reduction in system capacity. Other methods for controlling interference are still being researched.

6.2.6 Self-optimizing networks

Today's cellular systems are very much centrally planned and the addition of new nodes to the network involves expensive and time-consuming work, site visits for optimization, etc. One of the enhancements being considered for LTE-Advanced is the self-optimizing network (SON) concept. The intent is to substantially reduce the effort required to introduce new nodes to the network. There are implications for radio planning as well as for the operations and maintenance (O&M) interface to the eNB. Some limited SON capability will be introduced in Release 8 and will be further elaborated in Release 9 and Release 10.

6.2.7 Femtocells

The final category of network enhancement is the femtocell, also known as the Home Node B (HNB) or Home eNB. The femtocell concept is not unique to LTE-Advanced, but an opportunity exists to incorporate this technology from the start rather than retrospectively designing it into systems. From a radio deployment perspective, the femtocell operates over a small area within a larger cell. The radio channel could be the same as the larger cell (known as co-channel deployment) or could be on a dedicated channel. The femtocell concept is fundamentally different from relaying since the femtocell connection back into the core network is provided locally by an existing DSL internet connection rather than over the air back to the macrocell. Most femtocell deployments will be indoors, which will help provide isolation between the femtocell and macrocell. The two main deployment scenarios for femtocells are in rural areas with poor or no (indoor) coverage, probably using co-channel deployment, and in dense areas to provide high data rates and capacity.

6.3 Conclusion

LTE and LTE-Advanced the potential to enhance current deployments of 3GPP networks and enable significant new service opportunities. However, LTE's commercial success requires the availability of measurement solutions that parallel the standard's development.

In the measurement domain, Agilent is at the forefront with design automation tools and flexible instrumentation for early R&D in components, base station equipment, and mobile devices. Agilent, along with its partners, will continue to provide a broad, comprehensive portfolio of solutions that address the entire LTE product development life cycle—from early design through to production test and deployment. LTE may present many development challenges, but with early and powerful test equipment solutions, these challenges can be met.

7 More Information

For more information about the 3GPP, visit the 3GPP home page
http://www.3gpp.org/

3GPP specifications home page
http://www.3gpp.org/specs/specs.htm

3GPP Series 36 (LTE) specifications
http://www.3gpp.org/ftp/Specs/archive/36_series

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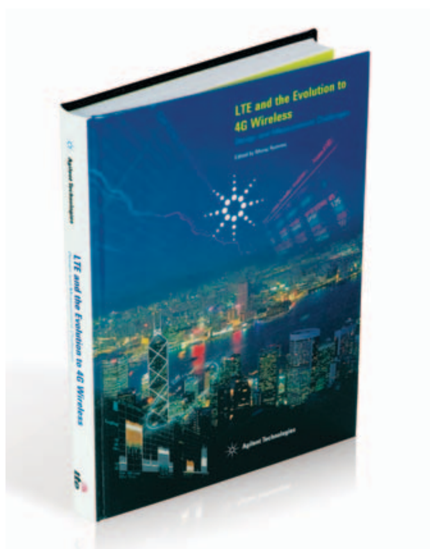

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8 List of Acronyms

3G	3rd Generation
3GPP	3rd Generation Partnership Project
ACLR	Adjacent channel leakage ratio
ACS	Adjacent channel selectivity
ADS	Advanced Design System
AMC	Adaptive modulation and coding
A-MPR	Additional maximum power reduction
ARQ	Automatic repeat request
BCCH	Broadcast control channel
BTS	Base transceiver station
CCDF	Complementary cumulative distribution function
CDD	Cyclic delay diversity
CDMA	Code division multiple access
CFI	Control format indicator
Co-MIMO	Cooperative MIMO
CP	Cyclic prefix
CPICH	Common pilot channel
CQI	Channel quality indicator
CRC	Cyclic redundancy check
DCI	Downlink control indicator
DFT	Discrete Fourier transform
DFT-SOFDM	Discrete Fourier transform spread OFDM
DL	Downlink (base station to subscriber transmission)
DL-SCH	Downlink shared channel
D-PHY	500 Mbps physical layer
DSP	Digital signal processing
DVSA	Digital vector signal analysis
E-DCH	Enhanced dedicated channel
E-UTRAN	Evolved UMTS terrestrial radio access network
eMBMS	Evolved multimedia broadcast multicast service
eNB	Evolved Node B
EPC	Evolved packet core
EPRE	Energy per resource element
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved UTRA
E-UTRAN	Evolved UTRAN
EVM	Error vector magnitude
FDD	Frequency division duplex
FFT	Fast Fourier transform
FRC	Fixed reference channel
FS1	Frame structure type 1
FS2	Frame structure type 2
GSM	Global system for mobile communication
HARQ	Hybrid automatic repeat request
HI	HARQ indicator

8 List of Acronyms
(Continued)

HSPA	High speed packet access
HSUPA	High speed uplink packet access
IFFT	Inverse FFT
IOT	Interoperability test
IP	Internet protocol
LO	Local oscillator
LTE	Long term evolution
MAC	Medium access control
MBMS	Multimedia broadcast multicast service
MBSFN	Multicast/broadcast over single-frequency network
MCH	Multicast channel
MIMO	Multiple input multiple output
MISO	Multiple input single output
MME	Mobility management entity
MPR	Maximum power reduction
MU-MIMO	Multiple user MIMO
NAS	Non-access stratum
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
PAPR	Peak-to-average power ratio
PAR	Peak-to-average ratio
PBCH	Physical broadcast channel
P-CCPCH	Primary common control physical channel
PCFICH	Physical control format indicator channel
PCH	Paging channel
PDCCH	Physical downlink control channel
PDCP	Packet data convergence protocol
PDSCH	Physical downlink shared channel
PHICH	Physical hybrid ARQ indicator channel
PHY	Physical layer
PRACH	Physical random access channel
PMCH	Physical multicast channel
PMI	Pre-coding matrix indicator
PUCCH	Physical uplink control channel
PUSCH	Physical uplink shared channel
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
RACH	Random access channel
RAT	Radio access technology
RB	Resource block
RF	Radio frequency
RLC	Radio link control
RMC	Reference measurement channel

8 List of Acronyms
(Continued)

RNC	Radio network controller
RRC	Radio resource control
RRM	Radio resource management
RS	Reference signal
RSCP	Received signal code power
RSRP	Reference signal received power
RSRQ	Reference signal received quality
RSSI	Received signal strength indicator
SAE	System architecture evolution
SAP	Service access point
SC-FDMA	Single carrier frequency division multiple access
SFBC	Space-frequency block coding
S-GW	Serving gateway
SIMO	Single input multiple output
SISO	Single input single output
SNR	Signal-to-noise ratio
SRS	Sounding reference signal
SU-MIMO	Single user MIMO
TDD	Time division duplex
TDMA	Time division multiple access
TR	Technical report
TrCH	Transport channel
TS	Technical specification
TTA	Telecommunications Technology Association
UCI	Uplink control indicator
UE	User equipment
UL	Uplink (subscriber to base station transmission)
UL-SCH	Uplink shared channel
UMB	Ultra-mobile broadband
UMTS	Universal mobile telecommunications system
UTRA	Universal terrestrial radio access
UTRAN	Universal terrestrial radio access network
VSA	Vector signal analyzer
W-CDMA	Wideband code division multiple access

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