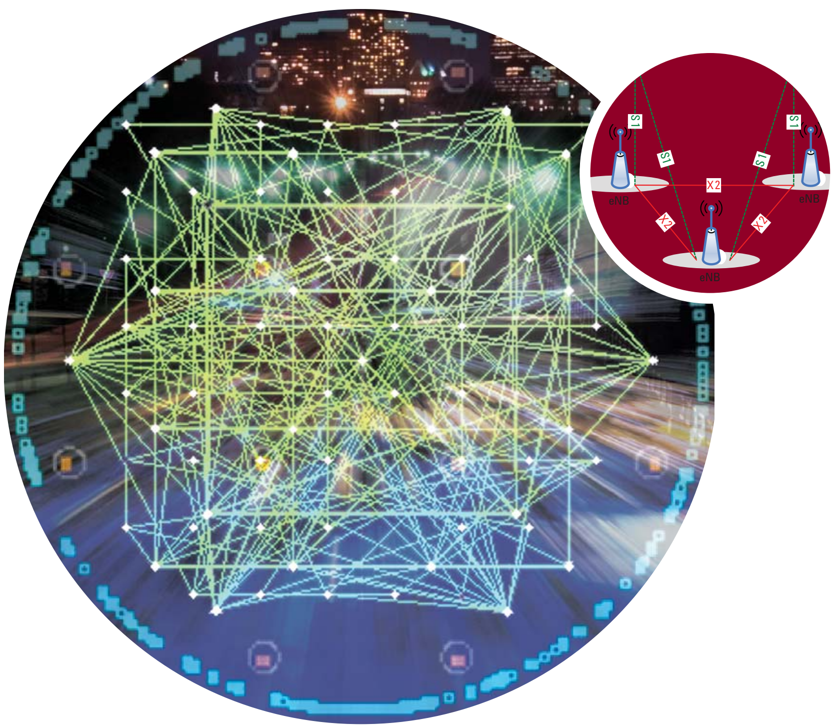
Agilent
3GPP Long Term Evolution:
System Overview, Product Development, and Test Challenges

Application Note



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). Particular attention is given to LTE's use of multiple antenna techniques and to a new modulation scheme called single carrier frequency division multiple access (SC-FDMA) 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.

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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.

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.[1] These are detailed in the LTE feasibility study, 3GPP Technical Report (TR) 25.912[1], and in the LTE requirements document, TR 25.913.[2]

Technical specifications for LTE are scheduled to be completed during the first half of 2008 with the UE conformance test specifications appearing towards the end of 2008. Commercial deployment is not expected before 2010, although there will be many field trials before then. A timeline for LTE is shown in Figure 1.

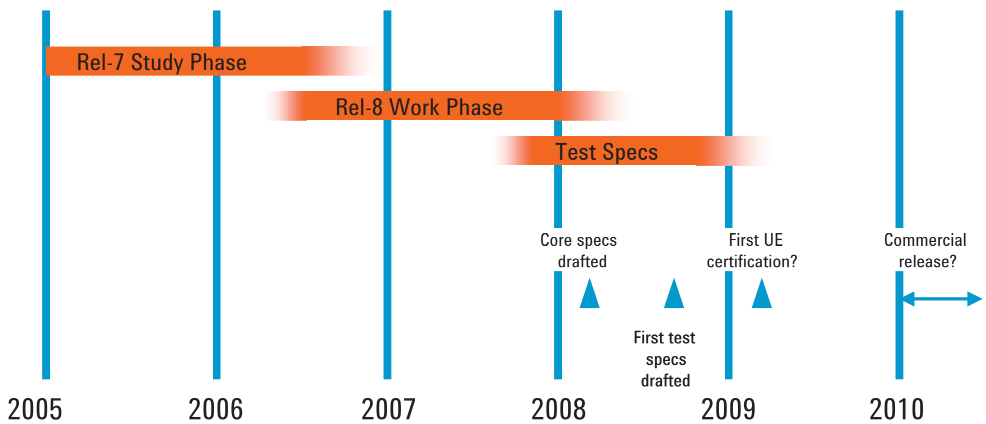

Figure 1. LTE development lifecycle

The above timeline is acknowledged to be aggressive and although major progress has been made, many details are still to be finalized. The test specifications may enable user equipment (UE) certification by the first quarter of 2009, but actual UE certification will only be possible if commercial devices are available before this date to allow test system validation. In practice, test system validation and UE certification are likely to be later.

1.2 Summary of LTE requirements

To meet the requirements for LTE outlined in TR 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 will be specified for specific UE categories under non-ideal radio conditions

- Scalable bandwidth from 1.4 to 20 MHz in both the uplink and the downlink
- Spectral efficiency, with 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
- Optimized performance for low mobile speeds from 0 to 15 km/h; supported with high performance from 15 to 120 km/h; functional from 120 to 350 km/h. Support for 350 to 500 km/h is under consideration
- Co-existence with legacy standards while evolving toward an all-IP network[3]

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

LTE represents the future of the UMTS standard as it evolves from an architecture that supports both circuit-switched and packet-switched communications to an all-IP, packet-only system. To this end, development of the LTE air interface is linked closely with the concurrent 3GPP system architecture evolution (SAE) project to define the overall system architecture and evolved packet core (EPC) network.

Table 2 summarizes the history of the global system for mobile communication (GSM) and UMTS standards with the major features that have come to be associated with each release. To achieve higher downlink and uplink data rates, UMTS operators today are upgrading their 3G networks with high speed downlink packet access (HSDPA), which is specified in 3GPP Release 5, and high speed uplink packet access (HSUPA), which is specified in 3GPP Release 6. The formal name in the specifications for HSUPA is the enhanced dedicated channel (E-DCH). HSDPA and HSUPA are known collectively as HSPA and they continue to evolve in Release 7 and Release 8 under the name HSPA+.

Release 8 specifies LTE and SAE as well as further enhancements to the existing technologies HSPA+ and EDGE. In September 2007 the LTE physical layer specifications were released at version 8.0.0. Finalization of the rest of the specifications should occur in the first half of 2008, and the UE conformance test specifications will start to appear towards the end of 2008.

Table 2. Progression of 3GPP standards

	Release	Commercial introduction	Main feature of release
1999	Rel-99	2003	Basic 3.84 Mcps W-CDMA (FDD & TDD)
	Rel-4	Trials	1.28 Mcps TDD (aka TD-SCDMA)
	Rel-5	2006	HSDPA
	Rel-6	2007	HSUPA (E-DCH)
	Rel-7	2008+	HSPA+ (64QAM OL, MIMO, 16QAM UL). Many smaller features plus LTE & SAE Study items
	Rel-8	HSPA+ 2009 LTE 2010+	LTE work item - OFOMA air interface SAE work item - New IP core network EDGE Evolution, more HSPA+
2010	Rel-9/10	2011 – 2014	LTE Evolved MBMS, IMT-Advanced (4G)

1.4 LTE in context

3GPP LTE is one of five major wireless standards sometimes referred to as "3.9G." The other so-called 3.9G standards are:

- 3GPP HSPA+
- 3GPP EDGE Evolution
- 3GPP2 ultra-mobile broadband (UMB)
- 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. Both UMB and LTE are considered "new" standards.

1.5 3GPP LTE specification documents

Release 7 of the 3GPP specifications included the study phase of LTE. As a result of this study, requirements were published in TR 25.913 for LTE in terms of objectives, capability, system performance, deployment, E-UTRAN architecture and migration, radio resource management, complexity, cost, and service.

E-UTRA, E-UTRAN, and the EPC are defined in the 36-series of 3GPP Release 8:

- 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 work on the specifications is ongoing, and many of the technical documents are updated quarterly. The latest versions of the 36-series documents can be found at **http://www.3gpp.org/ftp/specs/archive/36_series/**.

1.6 System architecture overview

Figure 2, which is taken from 23.882[4], illustrates the complexity of the cellular network today.

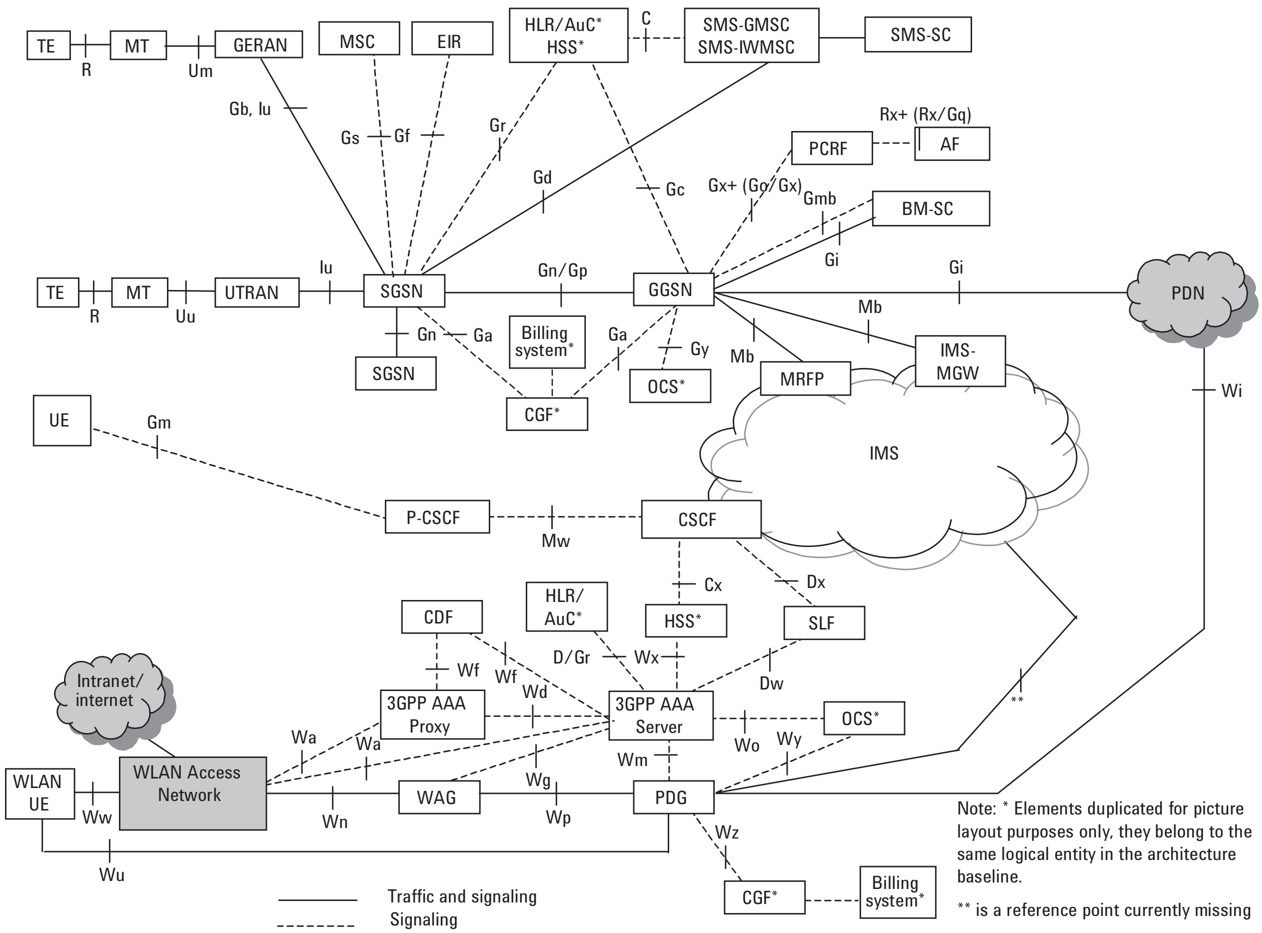

Figure 2. Logical baseline architecture for 3G (TR 23.882 V1.15.0 Figure 4.1-1)

3GPP's drive to simplify this architecture is behind the SAE project to define an all-IP core network. Some of the goals of LTE cannot be met unless SAE is also implemented. The SAE specifications are about six to nine months behind the E-UTRA/E-UTRAN specifications.

The E-UTRAN itself has been greatly simplified. Figure 3, taken from Technical Specification (TS) 36.300[5], shows the E-UTRAN, which contains a new network element—eNB—that provides the E-UTRA user plane and control plane terminations toward the UE.

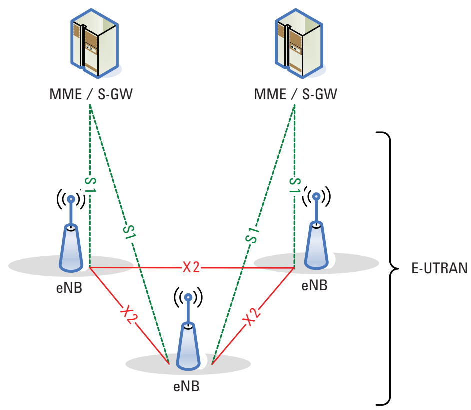

Figure 3. LTE architecture with E-UTRAN (TS 36.300 V8.4.0 Figure 4)

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

The E-UTRAN is connected to the EPC through 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.

One of the simplifications of this architecture is to push more signaling down to the eNBs by splitting the user plane and mobility management entities. This functional split is depicted in Figure 4.[5]

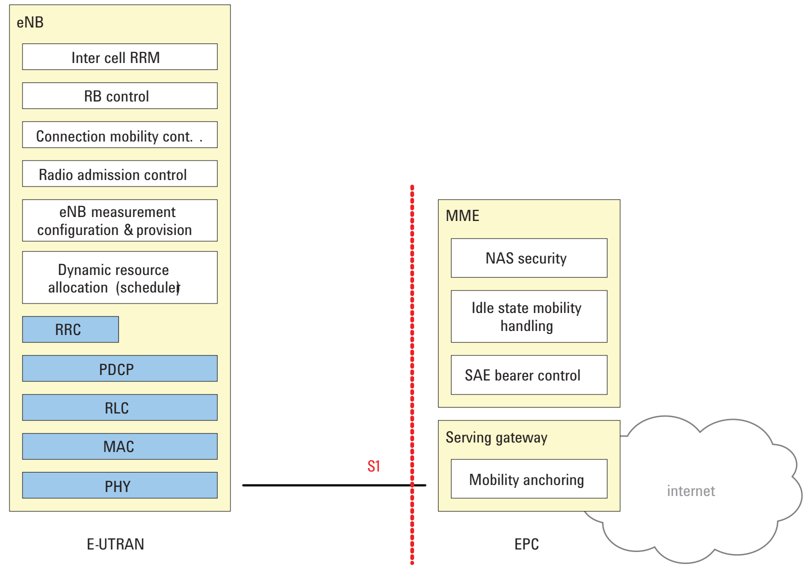

Figure 4. Functional split between E-UTRAN and EPC (TS 36.300 V8.4.0 Figure 4.1)

The eNB now 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
- Mobility measurement and reporting configuration

The MME functions include:

- Distribution of paging messages to eNBs
- Security control
- Idle state mobility control
- SAE bearer control
- Ciphering and integrity protection of non-access stratum (NAS) signaling

The S-GW hosts these functions:

- Termination of user-plane packets for paging reasons
- Switching of user plane for UE mobility

The radio protocol architecture of E-UTRAN is specified for the user plane and the control plane. The user plane comprises the packet data convergence protocol (PDCP), radio link control (RLC), medium access control (MAC), and physical layer (PHY); the control plane performs the radio resource control (RRC). Both the user plane and control plane are terminated in the eNB. A detailed description of the radio protocol architecture is beyond the scope of this application note; however, more information is available in TS 36.300[5] and other documents in the 36.300 series.

2 LTE Air Interface Radio Aspects

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

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 at the expense of a halving of 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 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 (TS 36.101 V8.1.0 Table 5.4.2-1)

Channel bandwidth (MHz)	1.4	3.0	5	10	15	20
Nominal transmission bandwidth configuration (resource blocks)	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 now 13 FDD bands and 8 TDD 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. Frequency bands supported in LTE (TS 36.101 V8.1.0 Table 5.2-1)

E-UTRA band	Uplink (UL) UE transmit eNB receive	Downlink (DL) eNB transmit UE receive	UL-DL band separation	Duplex mode
	$F_{UL\_low} – F_{UL\_high}$	$F_{DL\_low} – F_{DL\_high}$	$F_{DL\_low} – F_{UL\_high}$	
1	1920 – 1980 MHz	2110 – 2170 MHz	130 MHz	FDD
2	1850 – 1910 MHz	1930 – 1990 MHz	20 MHz	FDD
3	1710 – 1785 MHz	1805 – 1880 MHz	20 MHz	FDD
4	1710 – 1755 MHz	2110 – 2155 MHz	355 MHz	FDD
5	824 – 849 MHz	869 – 894MHz	20 MHz	FDD
6	830 – 840 MHz	875 – 885 MHz	35 MHz	FDD
7	2500 – 2570 MHz	2620 – 2690 MHz	50 MHz	FDD
8	880 – 915 MHz	925 – 960 MHz	10 MHz	FDD
9	1749.9 – 1784.9 MHz	1844.9 – 1879.9 MHz	60 MHz	FDD
10	1710 – 1770 MHz	2110 – 2170 MHz	340 MHz	FDD
11	1427.9 – 1452.9 MHz	1475.9 – 1500.9 MHz	23 MHz	FDD
....				
13	777 - 787 MHz	746 - 756 MHz	21 MHz	FDD
14	788 - 798 MHz	758 - 768 MHz	20 MHz	FDD
....				
33	1900 – 1920 MHz	1900 – 1920 MHz	N/A	TDD
34	2010 – 2025 MHz	2010 – 2025 MHz	N/A	TDD
35	1850 – 1910 MHz	1850 – 1910 MHz	N/A	TDD
36	1930 – 1990 MHz	1930 – 1990 MHz	N/A	TDD
37	1910 – 1930 MHz	1910 – 1930 MHz	N/A	TDD
38	2570 – 2620 MHz	2570 – 2620 MHz	N/A	TDD
39	1880 – 1920 MHz	1880 – 1920 MHz	N/A	TDD
40	2300 – 2400 MHz	2300 – 2400 MHz	N/A	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 and 6 taken from TS 36.306[8] show the UE categories and the data they will support in each 1 ms transmission time interval (TTI).

Table 5. FDD downlink physical layer parameter values set by UE category (TS 36.306 Table 4.3-1)

UE category	Max # of DL-SCH transport block bits received in TTI	Max # of bits of a DL-SCH transport block received in TTI	Max # of supported layers for spatial multiplexing in DL
1	10040	10040	1
2	50000	50000	2
3	100000	75056	2
4	150112	75056	TBD
5	300064	150032	4

Table 6. FDD uplink physical layer parameter values set by UE category (TS 36.306 Table 4.3-2)

UE category	Max # of bits of a DL-SCH transport block transmitted in TTI	Support for 64QAM
1	5032	No
2	25008	TBD
3	50000	TBD
4	50000	TBD
5	75056	Yes

Terms used in these tables are defined as follows:

Maximum number of DL-SCH transport block bits received within a TTI – The maximum number of downlink shared channel (DL-SCH) transport block bits that the UE is capable of receiving within a DL-SCH TTI. In the case of spatial multiplexing, it is the sum of the number of bits delivered in each of the two transport blocks. This number does not include the bits of a DL-SCH transport block carrying broadcast control channel (BCCH) in the same sub-frame.

Maximum number of bits of a DL-SCH transport block within a TTI – The maximum number of DL-SCH transport block bits that the UE is capable of receiving in a single transport block within a DL-SCH TTI.

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 5 taken from TS 36.892[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.

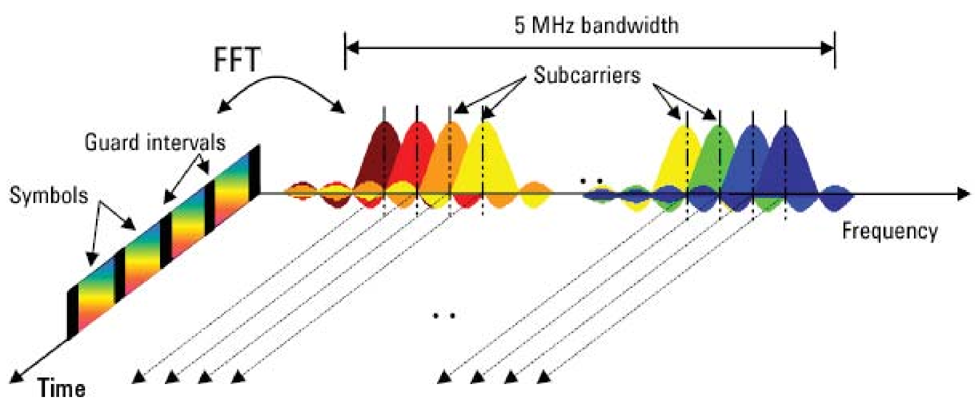

Figure 5. OFDM signal represented in frequency and time (TS 25.892 V6.0.0 Figure 1)

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 pre-coding 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 6 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.

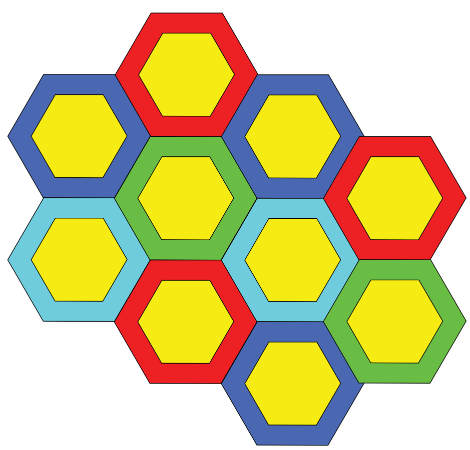

Figure 6. Example of frequency planning to avoid inter-cell interference at the cell edges

The main differences between CDMA and OFDM are summarized in Table 7.

Table 7. Comparison of CDMA and OFDM

Attribute	CDMA	OFDM
Transmission bandwidth	Full system bandwidth	Variable up to full system bandwidth
Symbol period	Very short – inverse of the system bandwidth	Very long – defined by subcarrier spacing and independent of system bandwidth
Separation of users	Orthogonal spreading codes	Frequency and time

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 7. 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 multi-path fading.

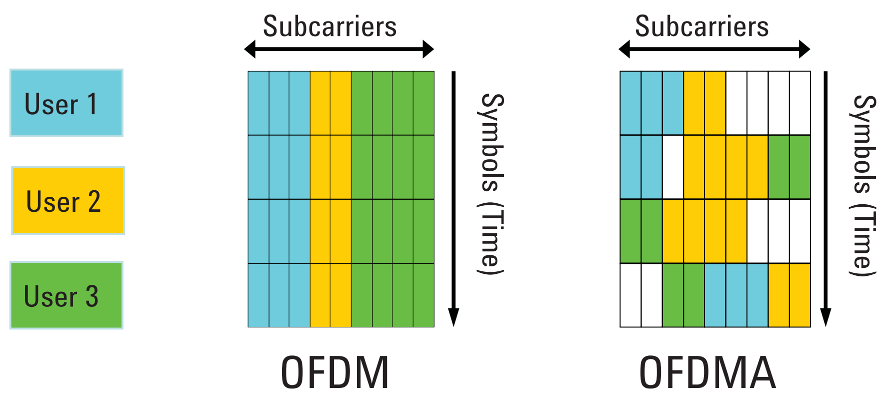

Figure 7. OFDM and OFDMA subcarrier allocation

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 TS 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 8 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.

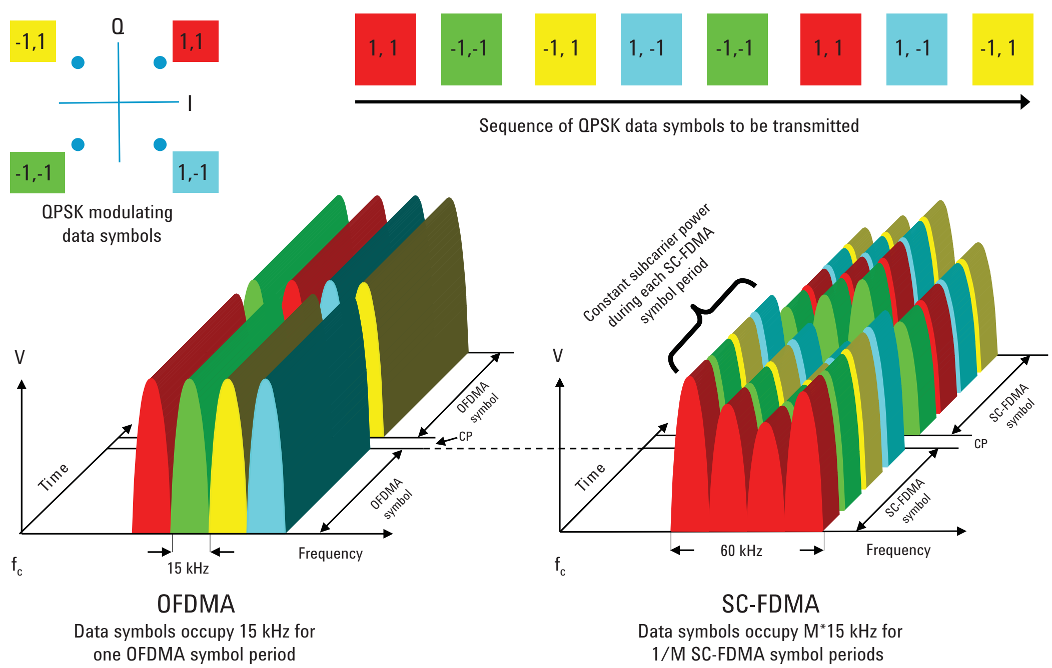

Figure 8. Comparison of OFDMA and SC-FDMA transmitting a series of QPSK data symbols

On the left side of Figure 8, 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 pre-coding 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 8. 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 pre-coding process. Figure 9 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 8, 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.

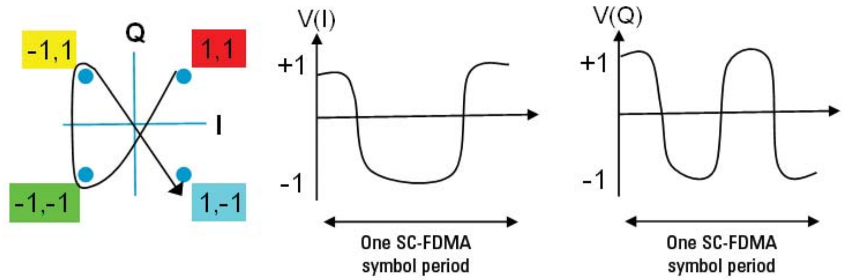

Figure 9. Creating the time-domain waveform of an SC-FDMA symbol

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 10. 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.

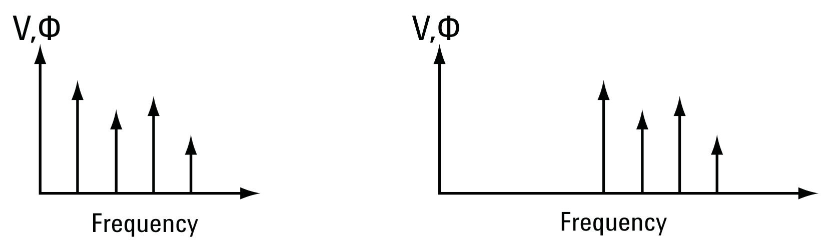

Figure 10. Baseband and frequency shifted DFT representations of an SC-FDMA symbol

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 10 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 11.

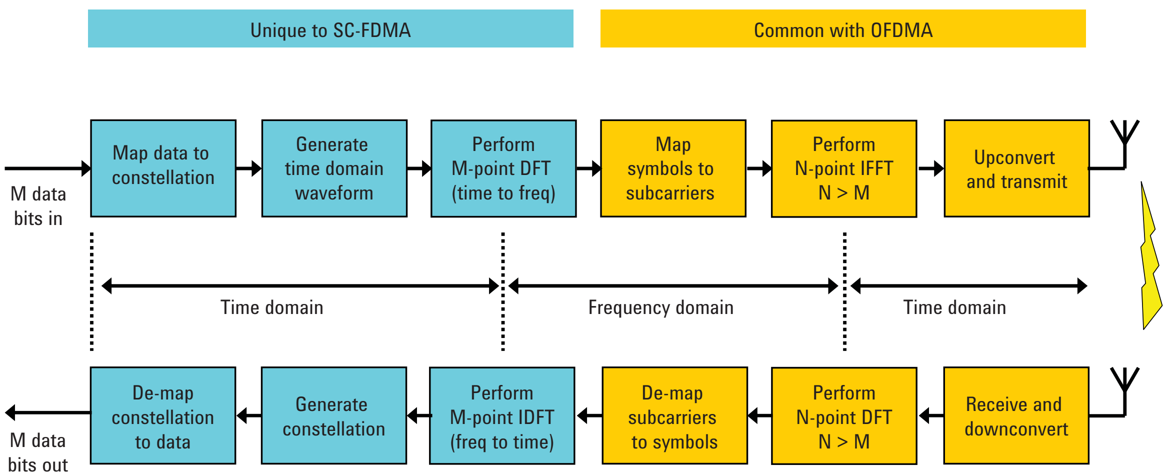

Figure 11. Simplified model of SC-FDMA and OFDMA signal generation and reception

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 8 and Figure 10, 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 counterintuitive 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 8 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 8. Analysis of OFDMA and SC-FDMA at different bandwidths

Modulation format	OFDMA		SC-FDMA	
Analysis bandwidth	15 kHz	Signal bandwidth (M x 15 kHz)	15 kHz	Signal bandwidth (M x 15 kHz)
Peak-to-average power ratio	Same as data symbol	High PAR (Gaussian)	< Data symbol (not meaningful)	Same as data symbol
Observable IQ constellation	Same as data symbol at 66.7 μs rate	Not meaningful (Gaussian)	Not meaningful (Gaussian)	Same as data symbol at M X 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 12.

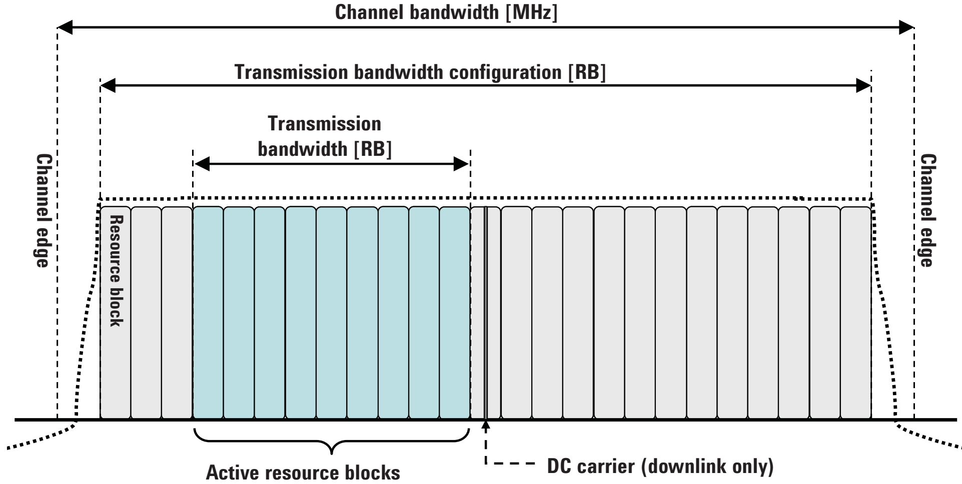

Figure 12. Definition of channel bandwidth and transmission bandwidth configuration (TS 36.101 Table 5.4-1)

Figure 13 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.

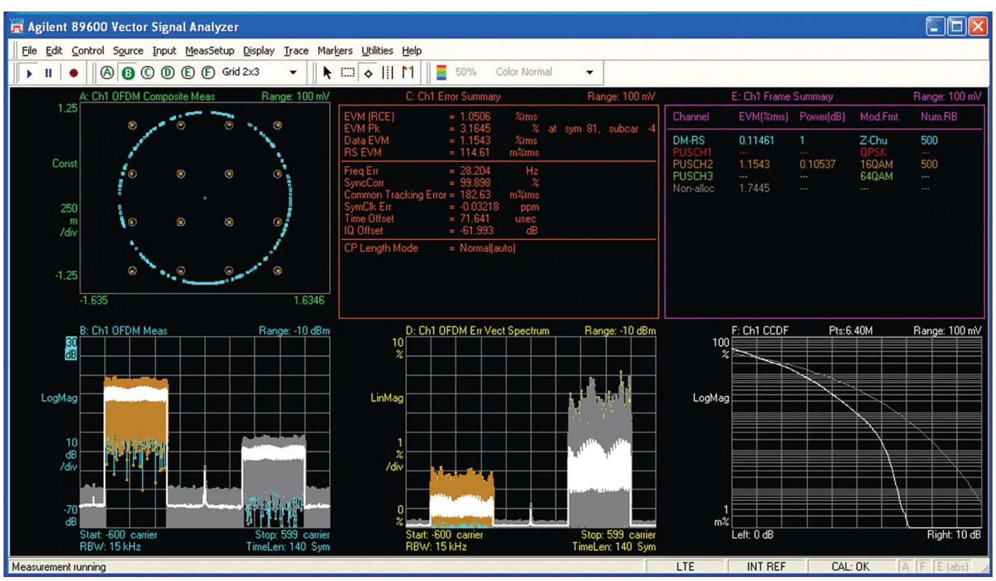

Figure 13. Analysis of a 16QAM SC-FDMA signal

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 will be 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 this impairment will be 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 by 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—often loosely referred to as MIMO—which take advantage of spatial diversity in the radio channel. Multiple antenna techniques are of three main types: diversity, MIMO, and beamforming. These techniques are used to improve signal robustness and to increase system capacity and single-user data rates. Each technique has its own performance benefits and costs.

Figure 14 illustrates the range of possible antenna techniques from simplest to most complex, indicating how the radio channel is accessed by the system's transmitters and receivers.

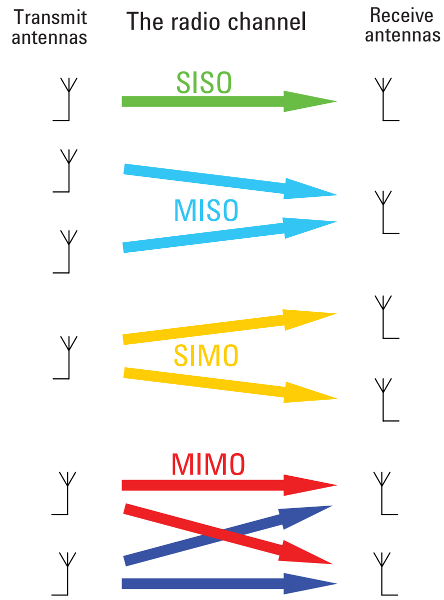

Figure 14. Radio-channel access modes

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 Multiple input single output

Slightly more complex than SISO is multiple input single output (MISO) mode, which uses two or more transmitters and one receiver. (Figure 14 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 signal-to-noise ratio (SNR) conditions; however, it does not increase data rates as such, but rather supports the same data rates using less power. Transmit diversity can be enhanced with closed loop feedback from the receiver to indicate the balance of phase and power used for each antenna.

2.7.3 Single input multiple output

The third mode shown in Figure 14 is single input multiple output (SIMO), which—in contrast to MISO—uses one transmitter and two or more receivers. SIMO is often referred to as receive diversity. Similar to transmit diversity, it is particularly well suited for low SNR conditions in which a theoretical gain of 3 dB is possible when two receivers are used. As with transmit diversity, 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.

2.7.4 Multiple input multiple output

The final mode is full MIMO, which requires two or more transmitters and two or more receivers. This mode is not just a superposition of SIMO and MISO since multiple data streams are now transmitted 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 into MIMO, even though there are now two Tx and two Rx antennas involved. 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 crosstalk and noise in the radio channel are low enough.

One other 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 15.

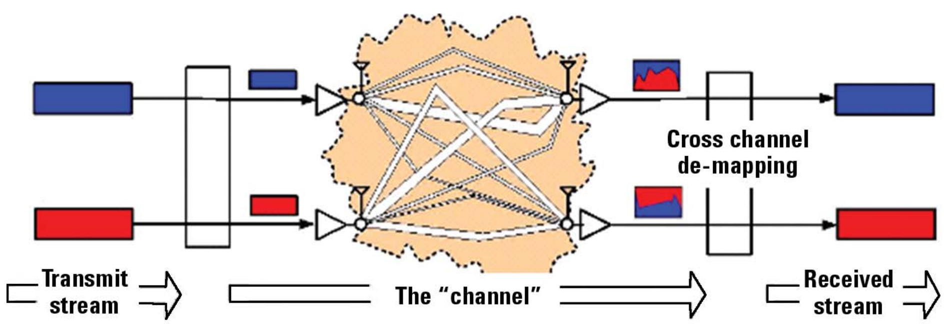

Figure 15. Non-precoded 2x2 MIMO

In this form, one data stream is uniquely assigned to one antenna. 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 pre-coding 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. Pre-coding 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 channel crosstalk 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.

2.7.5 Single user, multiple user, and cooperative MIMO

It is important to note that Figure 14 does not make explicit whether the multiple transmitters or receivers belong to the same base station or UE. This leads to a further elaboration of MIMO that is presented in Figure 16.

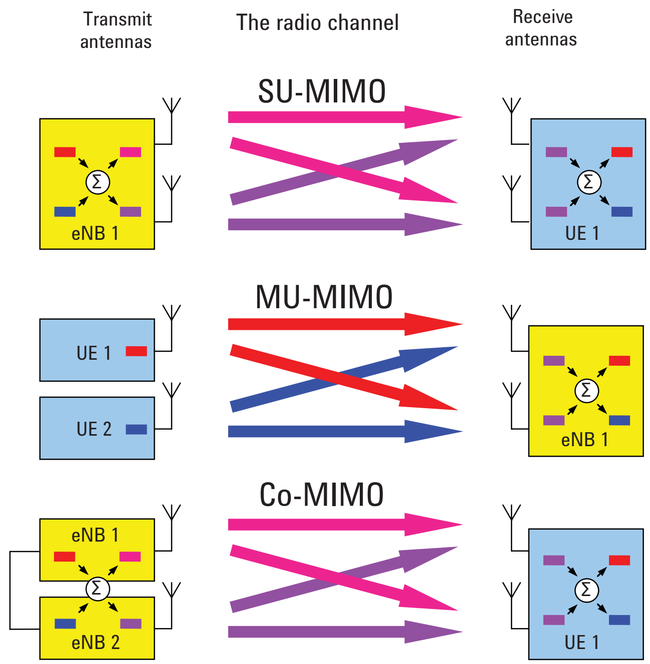

Figure 16. Single user, multiple user, and cooperative MIMO

The first case is single user MIMO (SU-MIMO), which is the most common form of MIMO and can be applied in the uplink or downlink. The primary purpose of SU-MIMO is to increase the data rate to one user. There is also a corresponding increase in the capacity of the cell. Figure 16 shows the downlink form of 2x2 SU-MIMO in which two data streams are allocated to one UE. The data streams in the example are coded red and blue, and in this case are further pre-coded in such a way that each stream is represented at a different power and phase on each antenna. The colors of the data streams change at the transmit antennas, which is meant to signify the mixing of the data streams. The transmitted signals are further mixed by the channel. The purpose of the pre-coding is to optimize the transmissions to the characteristics of the radio channel so that when the signals are received, they can be more easily separated back into the original data streams.

The second case shows 2x2 multiple user MIMO (MU-MIMO), which is used only in the uplink. (MU-MIMO is described in the WiMAX™ specifications as collaborative spatial multiplexing or collaborative MIMO). MU-MIMO does not increase an individual user's data rate but it does offer cell capacity gains that are similar to, or better than, those provided by SU-MIMO. In the figure, 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 pre-coded 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.

The third case shown in Figure 16 is cooperative MIMO (Co-MIMO). This term should not be confused with the WiMAX term "collaborative MIMO" described earlier. The essential element of Co-MIMO is that two separate entities are involved at the transmission end. The example here is a downlink case in which two eNB "collaborate" by sharing data streams to pre-code the spatially separate antennas for optimal communication with at least one UE. When this technique is applied in the downlink it is sometimes called network MIMO. The most advantageous use of downlink Co-MIMO occurs when the UE is at the cell edge. Here the SNR will be at its worst but the radio paths will be uncorrelated, which offers significant potential for increased performance. Co-MIMO is also possible in the uplink but is fundamentally more difficult to implement as no physical connection exists between the UE to share the data streams. Uplink Co-MIMO without a connection between the UE collapses into MU-MIMO, which as we have seen does not use pre-coding. Uplink Co-MIMO is also known as virtual MIMO. Co-MIMO is not currently part of the Release 8 LTE specifications but is being studied as a possible enhancement to LTE in Release 9 or Release 10 to meet the goals of the ITU's IMT-Advanced 4G initiative.

2.7.6 Beamforming

Beamforming uses the same signal processing and antenna techniques as MIMO but rather than exploit de-correlation in the radio path, beamforming aims to exploit correlation so that the radiation pattern from the transmitter is directed towards the receiver. This is done by applying small time delays to a calibrated phase array of antennas. The effectiveness of beamforming varies with the number of antennas. With just two antennas little gain is seen, but with four antennas the gains are more useful. Obtaining the initial antenna timing calibration and maintaining it in the field are challenge.

Turning a MIMO system into a beamforming system is simply a matter of changing the pre-coding matrices. In practical systems, however, antenna design has to be taken into account and things are not so simple. It is possible to design antennas to be correlated or uncorrelated; for example, by changing the polarization. However, switching between correlated and uncorrelated patterns can be problematic if the physical design of the antennas has been optimized for one or the other.

Since beamforming is related to the physical position of the UE, the required update rate for the antenna phasing is much lower than the rates needed to support MIMO pre-coding. Thus beamforming has a lower signaling overhead than MIMO.

2.7.7 Combining beamforming and MIMO

The most advanced form of multiple antenna techniques is probably the combination of beamforming with MIMO. In this mode MIMO techniques could be used on sets of antennas, each of which comprises a beamforming array. Given that beamforming with only two antennas has limited gains, the advantage of combining beamforming and MIMO will not be realized unless there are many antennas. This limits the practical use of the technique on cost grounds.

2.8 LTE multiple antenna schemes

Having described the basics of multiple antenna techniques we now look at what LTE has specified.

2.8.1 LTE downlink multiple antenna schemes

For the LTE downlink, three of the multiple antenna schemes previously described are supported: Tx diversity (MISO), Rx diversity (SIMO), and spatial multiplexing (MIMO). The first and simplest downlink LTE multiple antenna scheme is open-loop Tx diversity. It is identical in concept to the scheme 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. Figure 17 shows 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 second downlink scheme, Rx diversity, is mandatory for the UE. It is the baseline receiver capability for which performance requirements will be defined. A typical use of Rx diversity is maximum ratio combining of the received streams to improve the SNR in poor conditions. Rx diversity provides little gain in good conditions.

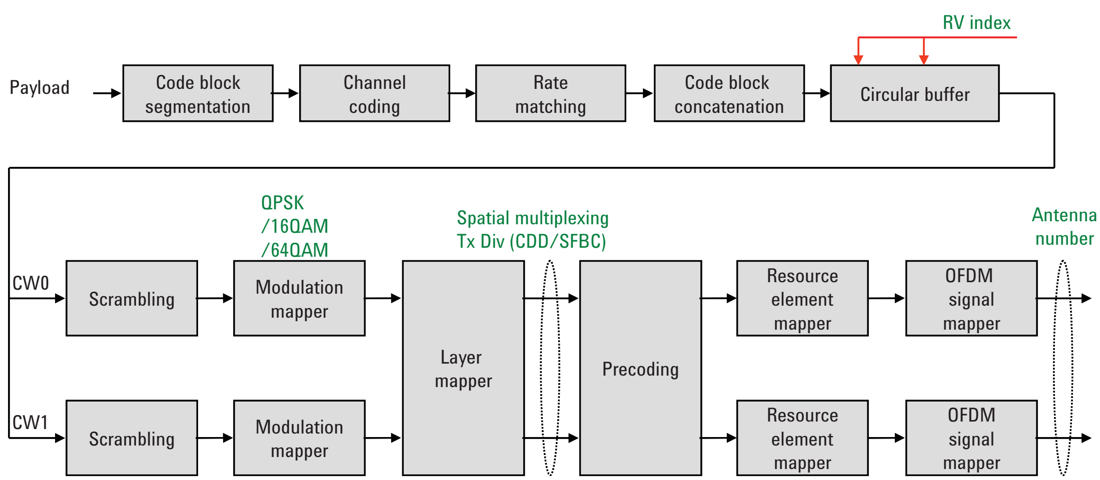

Figure 17. Signal processing for Tx diversity and spatial multiplexing

The third downlink scheme is spatial multiplexing, or MIMO, which is also 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 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 17.

Depending on the pre-coding used, each code word is represented at different powers and phases on both antennas. In addition, each antenna is uniquely identified by the position of the reference signals within the frame structure. This process is described later. LTE uses the closed loop form of MIMO with pre-coding of the streams, so for the FDD case the transmitter must have knowledge of the channel. Channel information is provided by the UE on the uplink control channel. The channel feedback uses a codebook approach to provide an index into a predetermined set of pre-coding matrices. Since the channel is continually changing, this information will be provided for multiple points across the channel bandwidth, at regular intervals, up to several hundred times a second. At the time of writing, the exact details are still to be specified. However, 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 pre-coding 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 pre-coding.

The pre-coding matrices for LTE support both MIMO and beamforming. There are four codebook entries for 2x2 SU-MIMO and 16 for 4x4 SU-MIMO.

In addition to MIMO pre-coding there is an additional option called cyclic delay diversity (CDD). This technique adds antenna-specific cyclic time shifts to artificially create multi-path on the received signal and prevents signal cancellation caused by the close spacing of the transmit antennas. Normally multipath would be 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. The CDD system works by adding the delay only to the data subcarriers while leaving the RS subcarriers alone. The UE uses the flat RS subcarriers to report the received channel flatness and the eNB schedules the UE to use the RB that it knows will benefit from the artificially induced frequency un-flatness. By not applying the CDD to the RS, the eNB can choose to apply the CDD on a per-UE basis.

When the CDD is enabled there is a choice of small or large delay. The large delay is approximately half a symbol, which creates significant ripple in the channel, whereas the small delay is defined by channel bandwidth and varies from 65 ns for the 20 MHz channel to just over 1 μs for the 1.4 MHz channel. For the widest channels using the small delay will be a challenge because the required time shift is very close to the limits of antenna timing calibration.

It is possible to apply a small delay CDD to the entire cell, including the RS. Doing so would make the CDD transparent to the UE but worsen the performance of channel quality indicator (CQI) reporting for those UE that would otherwise provide frequency-selective CQI reports.

2.8.2 LTE uplink multiple antenna schemes

The baseline configuration of the UE has one transmitter. This configuration was chosen to save cost and battery power, and with this configuration the system can support MU-MIMO—that is, two different UE transmitting in the same frequency and time to the eNB. This configuration has the potential to double uplink capacity (in ideal conditions) without incurring extra cost to the UE.

An optional configuration of the UE is a second transmit antenna, which allows the possibility of uplink Tx diversity and SU-MIMO. The latter offers the possibility of increased data rates depending on the channel conditions.

For the eNB, receive diversity is a baseline capability and the system will support either two or four receive antennas.

3 LTE Air Interface Protocol Aspects

Figure 18 from TS 36.201[11] shows the overall radio interface protocol architecture. Layer 1 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 provides logical channels to the Layer 2 RLC sub-layer. Transport channels are characterized by how the information is transferred over the radio interface, whereas logical information is characterized by the information type. The circles in the diagram between different layers or sub-layers indicate service access points (SAPs). The physical layer also interfaces to the Layer 3 RRC layer.

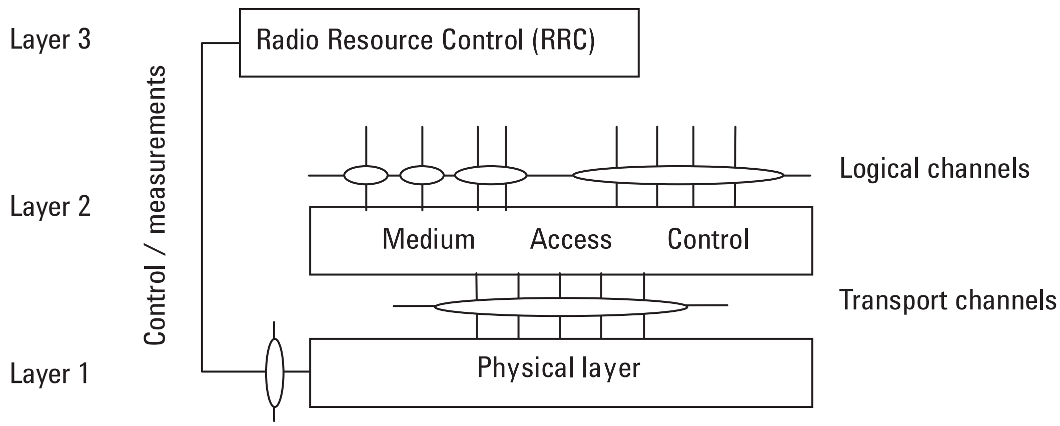

Figure 18. Radio interface protocol architecture around the physical layer (TS 36.201 V8.1.0 Figure 1)

The physical layer performs a series of functions that enable data transport service. These include:

- Error detection on the transport channels
- Encoding/decoding of the transport channels
- Hybrid automatic repeat request (HARQ) soft-combining
- Rate matching and mapping of coded transport channels to physical channels
- Modulation and demodulation of physical channels
- Frequency and time synchronization
- Radio characteristics measurements
- MIMO antenna processing
- Transmit diversity
- Beamforming
- RF processing

3.1 Physical layer overview

The physical layer specifications are split into four main sections as shown in Figure 19.

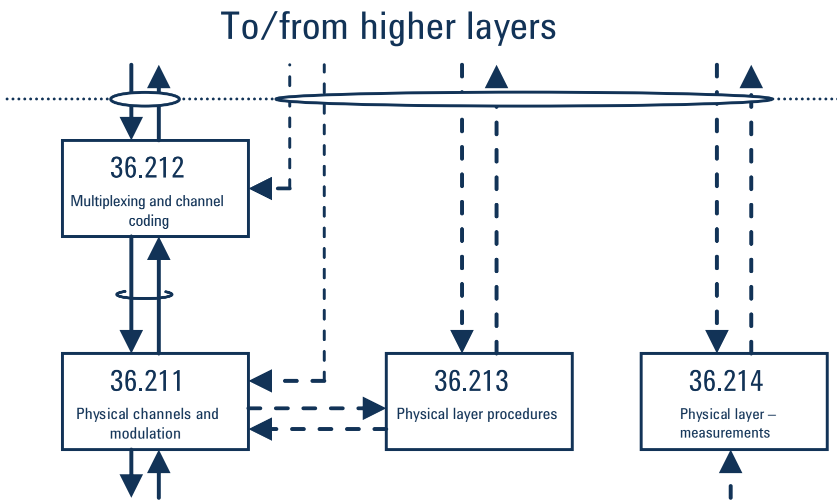

Figure 19. Relation between physical layer specifications (TS 36.201 V8.1.0 Figure 2)

TS36.211 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.

TS 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 L1 and L2 control information, interleaving, and rate matching.

TS 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.

TS 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.

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

3.2 Physical channels and modulation (TS 36.211)

The LTE air interface consists of physical signals and physical channels, which are defined in TS 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 9. 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 RSs, 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 9. LTE physical signals

DL signals	Full name	Purpose
P-SCH*	Primary synchronization signal	Used for cell search and identification by the UE. Carries part of the cell ID (one of three orthogonal sequences)
S-SCH*	Secondary synchronization signal	Used for cell search and identification by the UE. Carries the remainder of the cell ID (one of 168 binary sequences)
RS	Reference signal (Pilot)	Used for DL channel estimation. Exact sequence derived from cell ID (one of 3 X 168 = 504 pseudo random sequences)
UL signals	**Full name**	**Purpose**
RS	Reference signal (Demodulation and sounding)	Used for synchronization to the UE and UL channel estimation

*Note: There are no formal acronyms to describe the primary and secondary synchronization signals; the terms PSCH and S-SCH come from earlier technical reports but are still used informally despite suggesting "channel" rather than "signal."

Alongside the physical signals are physical channels, which carry the user and system information. These are summarized in Table 10. Notice the absence of dedicated channels, which is a characteristic of packet-only systems. The channel structure of LTE is closer to HSPA than it is to the original W-CDMA, which is based on channels dedicated to single users.

Table 10. 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 sub-frame (1, 2, or 3)
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

There are two radio frame structures for LTE: frame structure type 1 (FS1) for full duplex and half duplex FDD, and frame structure type 2 (FS2) for TDD. These frame structures are shown in Figures 20 and 21.

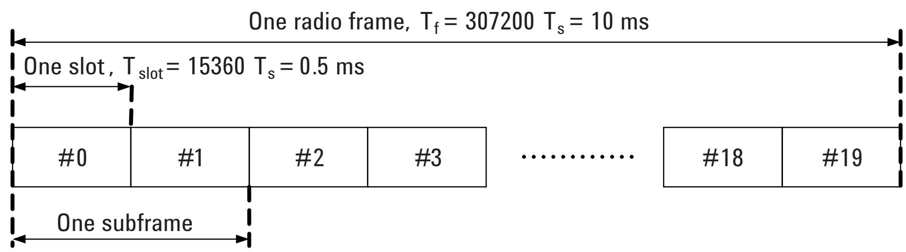

Figure 20. LTE frame structure type 1 (TS 36.211 V8.2.0 Figure 4.1-1)

FS1 is optimized to co-exist with 3.84 Mbps UMTS systems. This structure consists of ten 1 ms sub-frames, each composed of two 0.5 ms slots, for a total duration of 10 ms. The FS1 is the same in the uplink and downlink in terms of frame, sub-frame, and slot duration although the allocation of the physical signals and channels is quite different. Uplink and downlink transmissions are separated in the frequency domain.

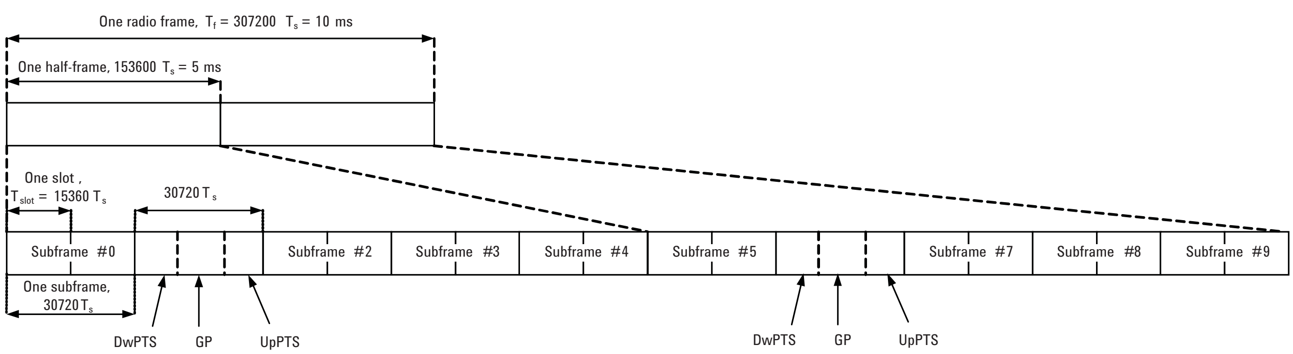

Figure 21. LTE frame structure type 2 (5 ms switch-point periodicity) (TS 36.211 V8.2.0 Figure 4.2-1)

The structure of FS2 is much more flexible than the structure of FS1. An example of an FS2 structure is shown in Figure 21. This example is for 5 ms switch-point periodicity and consists of two 5 ms half-frames for a total duration of 10 ms. Sub-frames consist of either an uplink or downlink transmission or a special sub-frame containing the downlink and uplink pilot timeslots (DwPTS and UpPTS) separated by a transmission gap guard period (GP). The allocation of the sub-frames for the uplink, downlink, and special sub-frames is determined by one of seven different configurations. Sub-frames 0 and 5 are always downlink transmissions and sub-frame 1 is always a special sub-frame, but the composition of the other sub-frames varies depending on the frame configuration. For a 5 ms switch-point configuration, sub-frame 6 is always a special sub-frame as shown in Figure 5. With 10 ms switch-point periodicity, there is only one special sub-frame per 10 ms frame.

3.2.2 Downlink physical resource elements

The smallest time-frequency unit used for downlink transmission is called a resource element, defined as one symbol on one subcarrier. A group of 12 subcarriers contiguous in frequency and one slot in time form a RB, discussed earlier and shown here in Figure 22. Transmissions are allocated in units of RB.

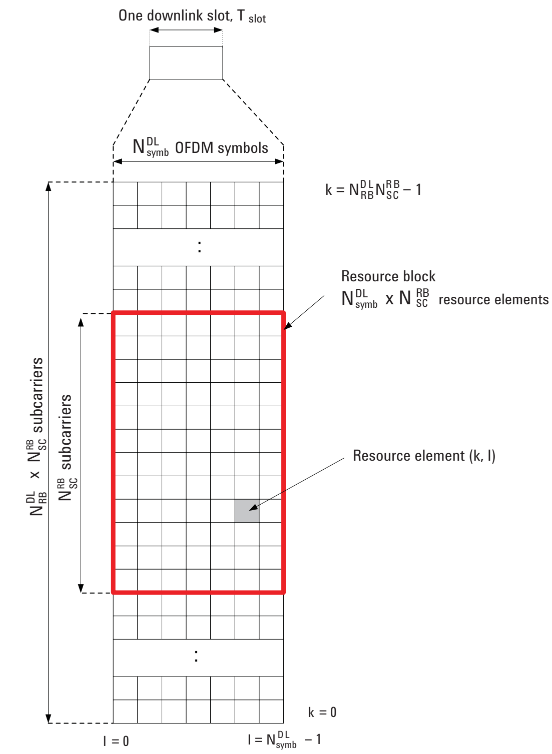

Figure 22. Downlink resource grid (TS 36.211. V8.2.0 Figure 6.2.2-1)

One downlink slot using the normal CP length contains seven symbols. Variations on this configuration for FS1 are summarized in Table 11. The CP is chosen to be slightly longer than the longest expected delay spread in the radio channel. For LTE, the normal CP length has been set at 4.69 μs, enabling the system to cope with path delay variations up to about 1.4 km. Note that this figure represents the difference in path length due to reflections, not the size of the cell. Longer CP lengths are available for use in larger cells and for specialist multi-cell broadcast applications. This provides protection for up to 10 km delay spread but with a proportional reduction in the achievable data rates. Inserting a CP between every symbol reduces the data handling capacity of the system by the ratio of the CP to the symbol length. For LTE, the symbol length is 66.7 μs, which gives a small but not insignificant seven percent loss of capacity when using the normal CP.

Table 11. Physical resource block parameters (TS 36.211 V8.2.0 Table 6.2.3-1)

Configuration		N^{BR}_{BW}	N^{DL}_{symb} Frame structure type 1
Normal cyclic prefix	Δf = 15 kHz	12	7
Extended cyclic prefix	Δf = 15 kHz		6
	Δf = 7.5 kHz	24	3

3.2.3 Downlink physical resources and mapping

Figure 23 gives a more detailed view of FS1 for the downlink, showing the downlink slot structure and color coded for the different signals and channels. As the diagram shows, an entire 10 ms frame is required for the control channels to repeat. The frame structure is referenced to Ts which is the shortest time interval of the system defined as 1/(15000x2048) seconds or 32.552 ns.

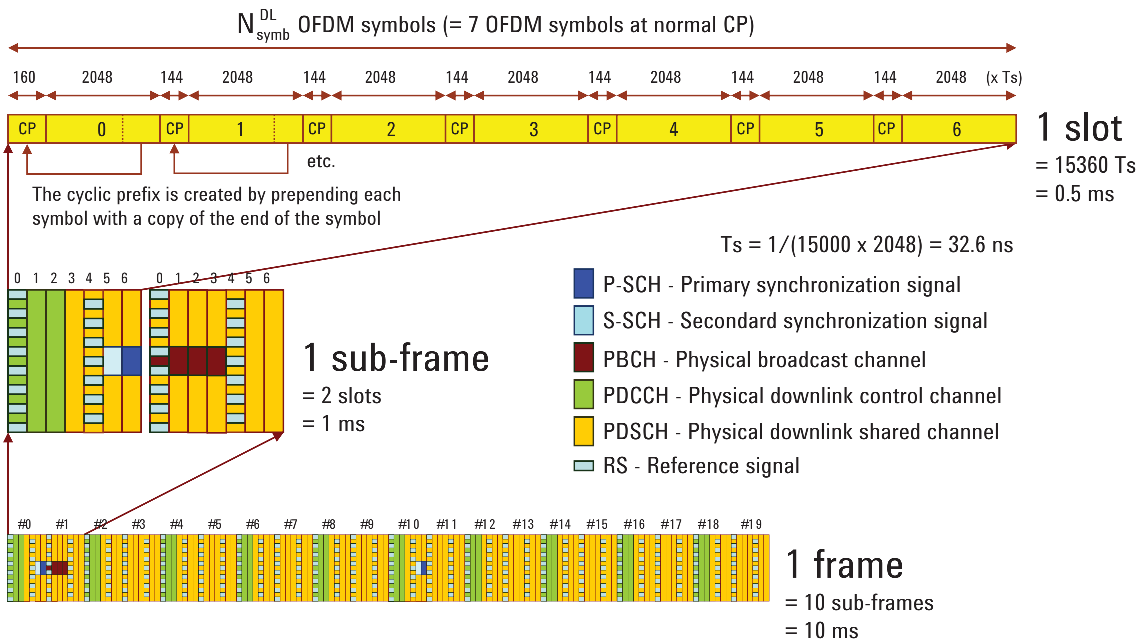

Figure 23. FS1 for downlink

For this example, the physical mapping of the DL physical signals is as follows:

- RS are transmitted at OFDMA symbol 0 of the first subcarrier and symbol 4 of the fourth subcarrier of each slot. This is the simplest case for single antenna use. The position of the RS varies with the antenna port number and the CP length.
- P-SCH is transmitted on symbol 6 of slots 0 and 10 of each radio frame; it occupies 62 subcarriers, centered around the DC subcarrier.
- S-SCH is transmitted on symbol 5 of slots 0 and 10 of each radio frame; it occupies 62 subcarriers centered around the DC subcarrier.
- PBCH is transmitted on symbols 0 to 3 of slot 1; it occupies 72 subcarriers centered around the DC subcarrier.

Note that the PMCH, PCFICH, and PHICH are not shown in this example.

The control channels are contained within the central 1.08 MHz of the signal so that the system operation can be independent of the channel bandwidth. The length 72 for the P-SCH and S-SCH gives high correlation when an allocation of 6 RB (72 subcarriers) is used, whereas the length 62 for the PBCH means that it can be detected using an FFT of length 64, which helps minimize the complexity for the UE.

Figure 24 shows the downlink mapping across frequency and time. The central sub-carrier of the downlink channel is not used for transmission but is reserved for energy generated due to LO feed through in the signal generation process.

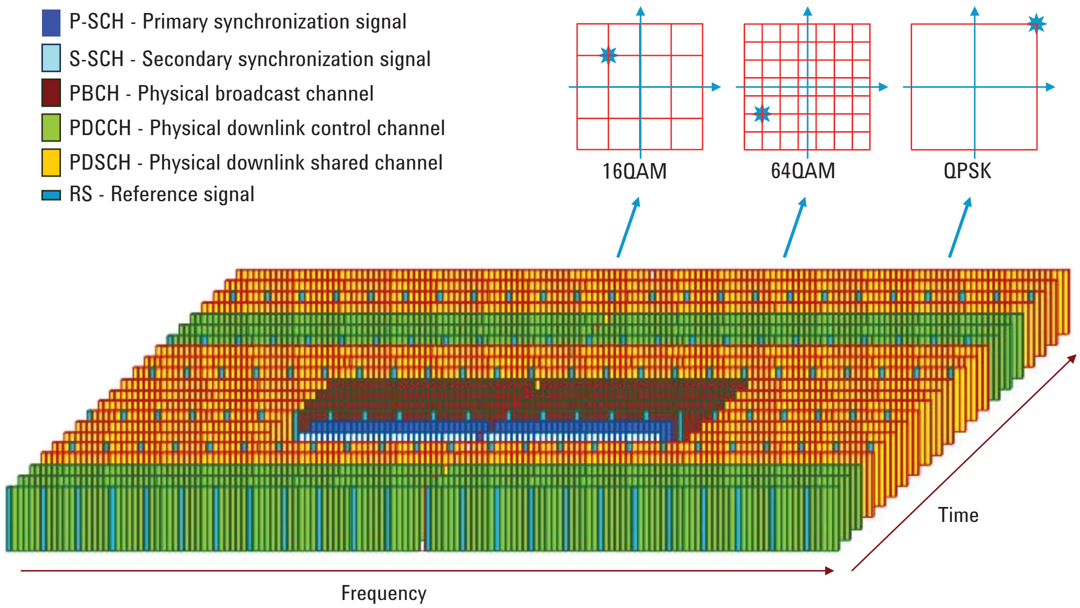

Figure 24. FS1 for downlink showing one subframe versus frequency

Table 12 shows the normal and extended CP lengths by symbol number. For the normal CP configuration, the subcarrier spacing is 15 kHz and the CP length is 160 x Tx (for OFDMA symbol number 0) and 144 (for OFDMA symbols numbered 1 to 6). The extended CP lengths also are used to cope with the longer path delays in large cells or for eMBMS in which multiple cells are combined.

Table 12. Cyclic prefix configurations for downlink FS1

CP configuration		CP in Ts by symbol number 0	1	2	3	4	5	6
Normal	Δf = 15 kHz	160	144	144	144	144	144	144
Extended	Δf = 15 kHz	512	512	512	512	512	512	—
	Δf = 7.5 kHz	1024	1024	1024	—	—	—	—

3.2.4 Uplink physical resources and mapping

As previously described, the uplink FS1 is the same as the downlink structure in terms of frame, slot, and sub-frame length. Example mappings for the PDSCH and PUCCH are shown in detail in Figures 25 and 26 respectively. The number of symbols in a slot depends on the CP length. For a normal CP, there are seven SC-FDMA symbols per slot. For an extended CP there are six SC-FDMA symbols per slot.

Demodulation reference signals are transmitted in the fourth symbol of the slot on all subcarriers of allocated PUSCH resource blocks. These are used for uplink channel estimation to enable the eNB to demodulate the signal. CP configurations are shown in Table 13.

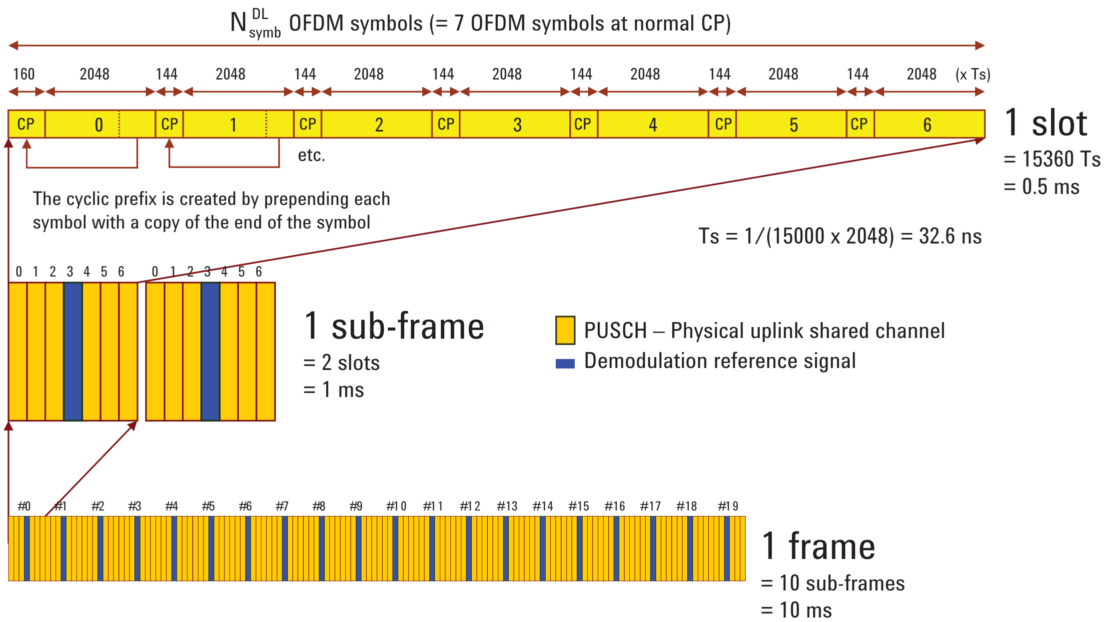

Figure 25. FS1 for uplink showing mapping for PUSCH

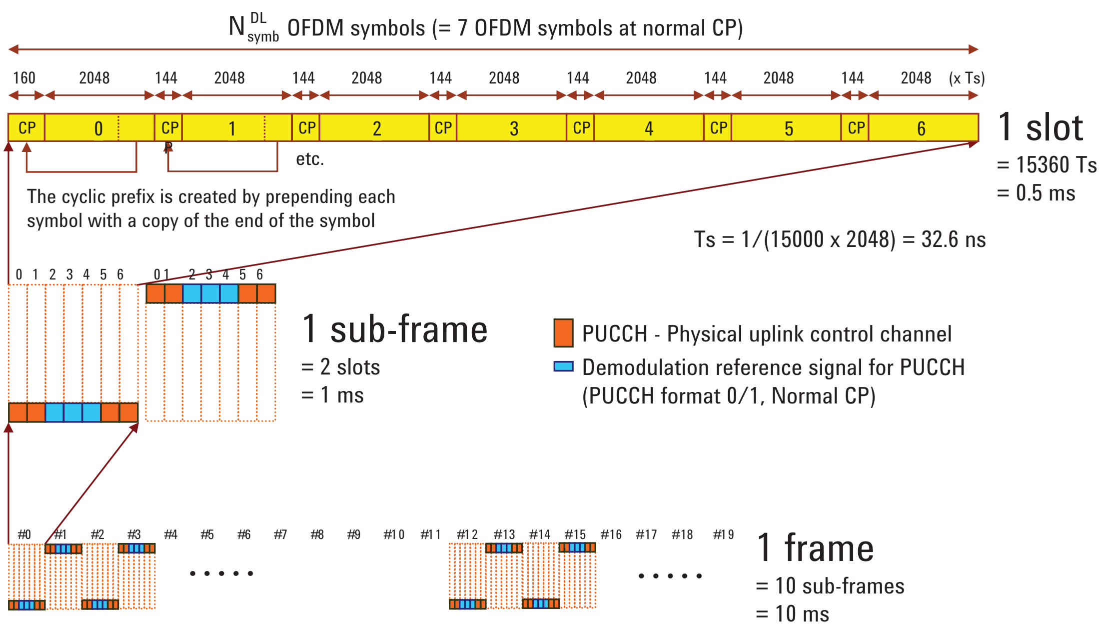

Figure 26. FS1 for uplink showing mapping for PUCCH format 0 or 1

Table 13. CP configurations for FS1 for uplink

CP configuration		CP in Ts by symbol number						
		0	1	2	3	4	5	6
Normal	Δf = 15 kHz	160	144	144	144	144	144	144
Extended	Δf = 15 kHz	512	512	512	512	512	512	—

Figure 27 shows the FS1 physical uplink mapping for one UE assuming a constant allocation. Because the uplink is shared by multiple users and the data rate is directly linked to the bandwidth, the allocation for one UE will almost always be much less than the channel bandwidth. The demodulation reference signal in the uplink is not transmitted beyond the allocation of each UE, unlike the reference signal in the downlink, which is always transmitted across the entire operating bandwidth, even if the downlink channel is not fully allocated. This allows any UE to make channel measurements in the downlink to optimize scheduling opportunities; however, for the uplink transmitting RS at the maximum system bandwidth would be impractical for reasons of battery consumption and coordination with other UE. When no PUCCH or PUSCH is scheduled in the uplink, the eNB can request transmission of the sounding reference signal (SRS), which allows the eNB to estimate the uplink channel characteristics.

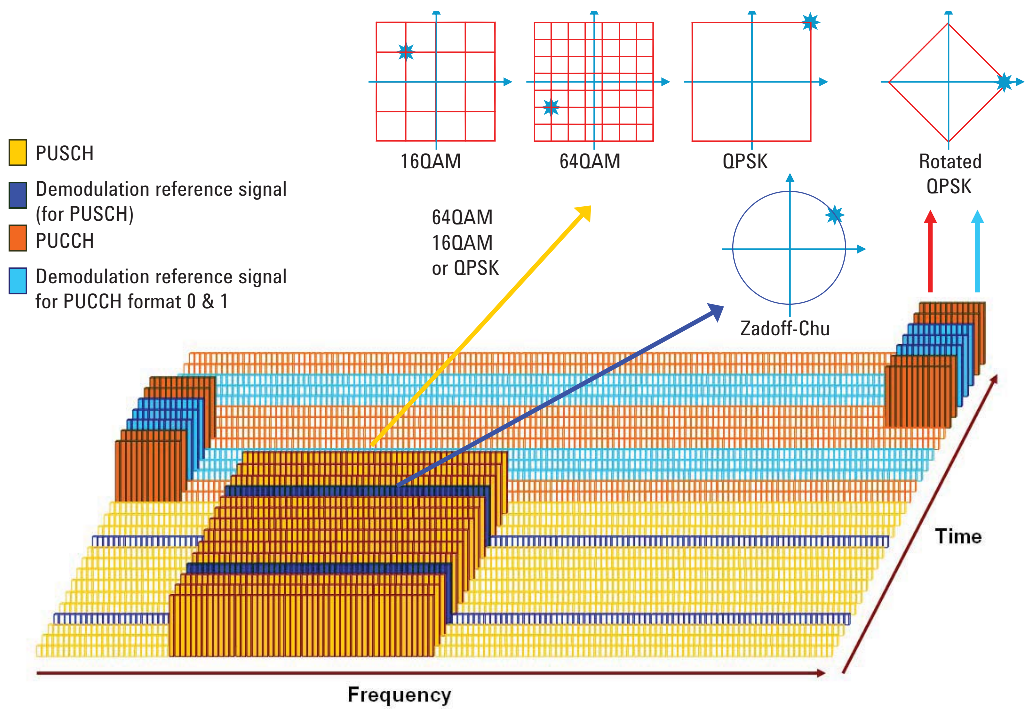

Figure 27. FS1 for uplink showing one sub-frame versus frequency

3.2.5 Modulation

The allowed signal and channel modulation schemes for the downlink and uplink are shown in Table 14. Detailed specifications for the physical signals and channels, along with their modulation and mapping, are documented throughout TS 36.211.[10]

Table 14. Modulation schemes for the LTE downlink and uplink (TS 36.211 V8.2.0)

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
P-SCH	One of three Zadoff-Chu sequences
S-SCH	Two 31-bit BPSK M-sequence

Uplink

Physical channels	Modulation scheme
PUCCH	BPSK, QPSK
PUSCH	QPSK, 16QAM, 64QAM
PRACH	u^{th} root Zadoff-Chu
Physical signals	**Modulation scheme**
Demodulation RS	Zadoff-Chu
Sounding RS	Based on Zadoff-Chu

3.3 Multiplexing and channel coding (TS 36.212)

The physical channels defined in TS 36.211[10] are mapped to transport channels (TrCH) that carry information between the physical layer and the MAC and higher layers. Table 15 lists the types of downlink and uplink TrCH described in TS 36.300 V8.3.0.[5] The TrCH specifications are documented in TS 36.212.[12]

Table 15. 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

The following control information is also specified:

Table 16. Control information

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

The TrCH and control information is mapped to the LTE physical channels as described in Table 17.

Table 17. Mapping to physical channels (TS 36.212 V8.2.0)

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

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 combines error detection, error correcting, rate matching, interleaving, and transport channel or control information mapping onto or splitting from physical channels.

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, and various control rates. The precise details of the physical layer processing for the TrCH vary by TrCH type and are specified throughout TS 36.212.

3.4 Physical layer procedures (TS 36.213)

Several physical layer procedures are associated with LTE operation. These are specified in 3GPP TS 36.213.[13]

LTE uses HARQ processing and link adaptation similar to HSPA. Adaptive modulation and coding (AMC) is used as the mechanism 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 such problems 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.

Not all the physical layer procedures have been fully defined but the general principles of the main procedures are outlined here.

3.4.1 Cell search

This 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 RS, P-SCH, and S-SCH. Because the synchronization signals are located in the central part of the channel, one LTE cell search procedure supports a scalable overall transmission bandwidth from 6 RB up to the maximum of 100 RB.

3.4.2 Power control

This procedure includes 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 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 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 sub-frame or set of consecutive sub-frames 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.

The next procedures define how the UE reports the CQI, the pre-coding 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 sub-band CQI, can be created by splitting the channel into several sub-bands. The number of sub-bands depends on the channel bandwidth and is shown in Table 18. Alternatively the entire channel can be reported once as wideband CQI.

Table 18. Sub-band size versus downlink system bandwidth

System bandwidth (resource blocks)	Sub-band size
6 - 7	(wideband CQI only)
8 - 10	4
11 - 26	4
27 - 64	6
64 - 110	4, 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 sub-band selection and periodic reporting of different 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 pre-coding matrices would result in the best performance. The PMI can be a single value or multiple values configured by the network for specific RBs. The PMI carries an index to a codebook of predetermined pre-coding matrices. For the simplest downlink configuration of 2x2 SU-MIMO there are four matrices. For the most complex 4x4 configuration there are 32 matrices that combine MIMO and beamforming.

The rank feedback defines the preferred number of parallel MIMO data streams and is always reported as a single value for the channel. It is a simplification that significantly reduces the amount of feedback data since the rank affects the CQI and PMI. Rank feedback is needed about once per frame (10 ms), which is slower than CQI and PMI reporting that can be done at the sub-frame 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 when no PUCCH or PUSCH are scheduled is not yet fully specified at the time of this writing. Parameters provided by the upper layers will include SRS periodicity and duration, symbol location in the sub-frame, 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 sub-frame 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 sub-frame n, the associated ACK/NACK messages are transmitted in sub-frame n+4. This delay is a key parameter in determining the overall latency for retransmission, which is eight sub-frames (8 ms).

3.5 Physical layer measurements (TS 36.214)

The UE and the eNB are required to make physical layer measurements of the radio characteristics. These requirements are specified in TS 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 measurements for RRM.

Tables 19 and 20 summarize the currently defined physical layer measurements. The applicable states define the RRC states from which the measurement must be possible.

Table 19. E-UTRA (UE) physical layer measurements

Measurement name	Definition	Applicable states
Reference signal receive power (RSRP)	The linear average (in watts) over the power contributions of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth. If receiver diversity is in use by the UE, the reported value shall be equivalent to the linear average of the power values of all diversity branches.	RRC_IDLE intra-frequency, RRC_IDLE inter-frequency, RRC_CONNECTED intra-frequency, RRC_CONNECTED inter-frequency
E-UTRA carrier Received signal strength indicator (RSSI)	The total received wideband power observed by the UE from all sources, including co-channel serving and non-serving cells, adjacent channel interference, thermal noise, etc.	TBD
Reference signal received quality (RSRQ)	The ratio N×RSRP/(E-UTRA carrier RSSI), where N is the number of RBs of the E-UTRA carrier RSSI measurement bandwidth. The measurements in the numerator and denominator shall be made over the same set of resource blocks.	RRC_IDLE intra-frequency, RRC_IDLE inter-frequency, RRC_CONNECTED intra-frequency, RRC_CONNECTED inter-frequency
UTRA FDD CPICH received signal code power (RSCP)	The received power on one code measured on the primary CPICH. The reference point for the RSCP shall be the antenna connector of the UE. If Tx diversity is applied on the primary CPICH, the sum from each antenna is reported. If receiver diversity is in use by the UE, the linear average of all diversity branches is reported.	RRC_IDLE inter-frequency, RRC_CONNECTED inter-frequency
UTRA FDD carrier RSSI	The received wideband power, including thermal noise and noise generated in the receiver, within the bandwidth defined by the receiver pulse shaping filter. If receiver diversity is in use by the UE, the linear average of all diversity branches is reported.	RRC_IDLE inter-frequency, RRC_CONNECTED inter-frequency
UTRA FDD CPICH Ec/No	The received energy per chip or the primary CPICH divided by the power density in the band. The CPICH Ec/No is identical to CPICH RSCP/UTRA carrier RSSI. If Tx diversity is applied on the primary CPICH, the sum from each antenna is reported. If receiver diversity is in use by the UE, the linear average of all diversity branches is reported.	RRC_IDLE inter-frequency, RRC_CONNECTED inter-frequency
GSM carrier RSSI	The wideband received power within the relevant channel bandwidth. Measurement shall be performed on a GSM BCCH carrier.	RRC_IDLE inter-frequency, RRC_CONNECTED inter-frequency
UTRA TDD carrier RSSI	The received wideband power, including thermal noise and noise generated in the receiver, within the bandwidth defined by the receiver pulse shaping filter, for TDD within a specified timeslot.	RRC_IDLE inter-frequency, RRC_CONNECTED inter-frequency
UTRA TDD P-CCPCH RSCP	The received power on P-CCPCH of a neighbor UTRA TDD cell.	RRC_IDLE inter-frequency, RRC_CONNECTED inter-frequency

Table 20. UE (E-UTRA) physical layer measurements

Measurement name	Definition	Applicable states
DL RS Tx power	The linear average in watts over the power contributions of the resource elements that carry cell-specific reference signals, which are transmitted by the eNode B within its operating system bandwidth.	TBD

3.6 Radio resource management (TS 36.133)

The requirements for RRM are defined in TS 36.133.[15] RRM covers the procedures and performance requirements that are used to make effective use of the radio resources. The most basic requirements in the E-UTRAN_RRC_IDLE state cover initial cell selection and cell reselection procedures including those between different radio access technologies (RAT). Additional procedures are defined in the E-UTRAN_RRC_CONNECTED state related to handover and measurement performance.

A summary of current RRM requirements is as follows:

Procedures during E-UTRAN RRC_IDLE state mobility
Cell selection
Cell re-selection
- E-UTRAN intra-frequency, E-UTRAN inter-frequency, UTRAN FDD
- UTRAN TDD, GSM

Procedures during E-UTRAN RRC_CONNECTED state mobility
Handover delay and interruption requirements for
- E-UTRAN FDD – FDD, E-UTRAN FDD – TDD, E-UTRAN TDD – FDD
- E-UTRAN TDD – TDD, E-UTRAN – UTRAN FDD, E-UTRAN – UTRAN TDD
- E-UTRAN – GSM

Procedures for RRC connection mobility control
- RRC re-establishment
- Random access

Timing and signaling characteristics
- UE transmit timing
- UE timer accuracy

Procedures for UE measurements in RRC_CONNECTED state
E-UTRA UE measurements
- E-UTRAN FDD intra frequency measurements
- E-UTRAN TDD intra frequency measurements
- E-UTRAN FDD – FDD inter frequency measurements
- E-UTRAN FDD – TDD inter frequency measurements
- E-UTRAN TDD – FDD inter frequency measurements
- E-UTRAN TDD – TDD inter frequency measurements

Inter-RAT measurements
- E-UTRAN FDD – UTRAN FDD measurements
- E-UTRAN TDD – UTRAN FDD measurements
- E-UTRAN FDD – UTRAN TDD measurements
- E-UTRAN TDD – UTRAN TDD measurements
- E-UTRAN FDD – GSM measurements
- E-UTRAN TDD – GSM measurements

Performance requirements for UE measurements
- Absolute RSRP accuracy
- Relative accuracy of RSRP
- Inter-frequency RSRP accuracy requirements
- UTRAN FDD CPICH RSCP
- UTRAN FDD carrier RSSI
- UTRAN FDD CPICH Ec/No
- UTRAN TDD P-CCPCH RSCP
- UTRAN TDD carrier RSSI
- UTRAN TDD P-CCPCH RSCP
- GSM carrier RSSI

Performance requirements for E-UTRAN measurements
- DL RS Tx power

4 RF Conformance Tests

4.1 eNB RF conformance tests

The eNB RF conformance test specifications are at an early stage and are being defined in TS 36.141.[16] These tests are based on the core requirements for eNB radio transmission and reception in TS 36.104.[7] The scope of the current work is split into transmitter, receiver, and performance sections. Although LTE is using an OFDMA downlink, the scope and structure of the tests are very similar to UMTS. The current tests are listed in the next three paragraphs:

4.1.1 Transmitter characteristics

Base station output power
Output power dynamics
Transmit ON/OFF power
Transmitted signal quality

- Frequency error
- EVM
- Time alignment between transmitter branches

Unwanted emissions

- Occupied bandwidth
- Adjacent channel leakage power ratio (ACLR)
- Operating band unwanted emissions
- Transmitter spurious emissions

Transmitter intermodulation

4.1.2 Receiver characteristics

Reference sensitivity level
Dynamic range
In-channel selectivity
Adjacent channel selectivity (ACS) and narrow-band blocking
Blocking
Receiver spurious emissions
Receiver intermodulation

4.1.3 Performance requirements

Demodulation of PUSCH
Demodulation of PUCCH
PRACH performance

4.1.4 Transmitter test signals (test models)

LTE transmitter tests will be performed with specific signals known as test models. These test models will be similar in approach to what was used for UMTS, but at the time of this writing they have not yet been defined. The OFDMA air interface presents many more RF variables than was the case with UMTS. There are six supported channel bandwidths from 1.4 to 20 MHz, and the allocation granularity is an RB of 180 kHz. There are three supported modulation depths of QPSK, 16QAM, and 64QAM and the ability of the eNB to transmit the RB varies depending on the position of the RB in the channel. It is expected that the RB towards the edge of the channel will suffer from effects of the transmit filter, which is necessary to limit the out-of-channel unwanted emissions. As such, the outer RBs are unlikely to support 64QAM. Another complexity is that out-of-channel performance depends on the bandwidth of the adjacent channel, which can no longer be assumed to be the same as the interfering channel. The relationship between in-channel and out-of-channel performance is further complicated by the fact that there is no transmit filter definition, which means that it is up to eNB manufacturers to shape the signal as they see fit in order to trade off in-channel and out-of-channel performance. This was not the case in UMTS, which defined an RRC filter for transmission, reception, and measurements. With this filter being proprietary for LTE, how the choice of different test models will impact eNB performance is less well understood.

As a result of these factors, there exists a great number of transmitter configurations that could be used to test performance, and there is no agreement yet on a practical set of test vectors that will enable conformance tests to be developed.

4.1.5 Receiver reference measurement channels

The eNB receiver tests make use of reference measurement channels (RMCs) that define attributes of the uplink test signals. The structure of the RMC is given in Figure 28.

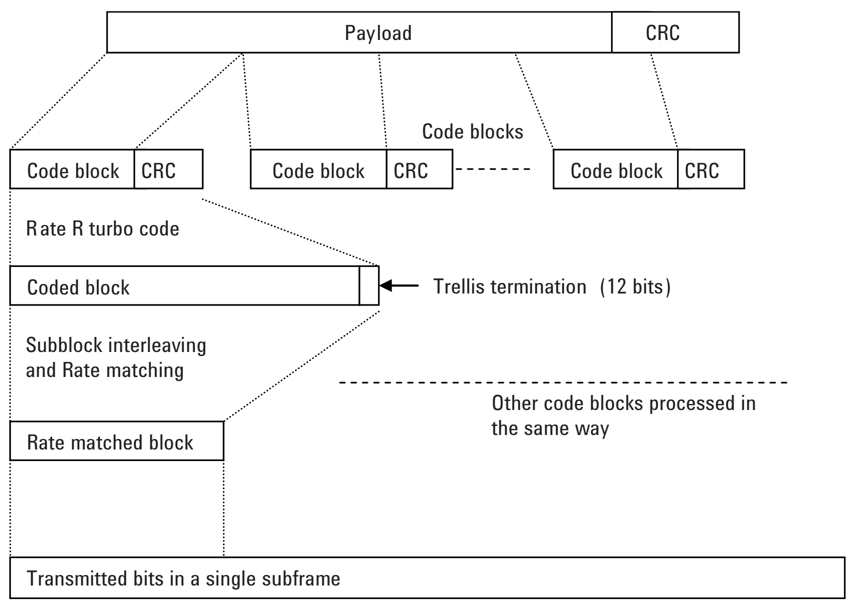

Figure 28. Schematic overview of the encoding process (TS 36.141 Figure A0-1)

Two RMC examples are shown in Tables 21 and 22. They cover the reference sensitivity, in-channel selectivity, and dynamic range tests. Additional fixed reference channels (FRC) will be defined as the tests are developed.

Table 21. FRC parameters for reference sensitivity and in-channel selectivity TS 36.141 V0.3 Table A.1-1

Reference channel	A1-1	A1-2	A1-3	A1-4	A1-5	A1-6	A1-7	A1-8
Allocated resource blocks	6	15	25	7	16	25	3	9
DFT-OFDM symbols per sub-frame	12	12	12	8	8	8	12	12
Modulation	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK
Code rate	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3
Payload size (bits)	568	1416	2344	448	1000	1576	288	856
Transport block CRC (bits)	24	24	24	24	24	24	24	24
Code block CRC size (bits)	0	0	0	0	0	0	0	0
Number of code blocks – C	1	1	1	1	1	1	1	1
Coded block size including 12 bits trellis termination (bits)	1788	4332	7116	1428	3084	4812	948	2652
Total number of bits per sub-frame	1728	4320	7200	1344	3072	4800	864	2592
Total symbols per sub-frame	864	2160	3600	672	1536	2400	432	1296
Maximum throughput (kbps)	568	1416	2344	448	1000	1576	288	856

Table 22. FRC parameters for dynamic range TS 36.141 V0.3 Table A.2-1

Reference channel	A2-1	A2-2	A2-3	A2-4	A2-5	A2-6
Allocated resource blocks	6	15	25	7	16	25
DFT-OFDM symbols per sub-frame	12	12	12	8	8	8
Modulation	16QAM	16QAM	16QAM	16QAM	16QAM	16QAM
Code rate	2/3	2/3	2/3	2/3	2/3	2/3
Payload size (bits)	2280	5736	9528	1768	4072	6328
Transport block CRC (bits)	24	24	24	24	24	24
Code block CRC size (bits)	0	0	24	0	0	24
Number of code blocks – C	1	1	2	1	1	2
Coded block size including 12 bits trellis termination (bits)	6924	17292	14412	5388	12300	9612
Total number of bits per sub-frame	3456	8640	14400	2688	6144	9600
Total symbols per sub-frame	864	2160	3600	672	1536	2400
Maximum throughput (kbps)	2280	5736	9528	1768	4072	6328

4.2 UE RF conformance tests

The UE RF conformance test specifications will be defined towards the end of 2008 in TS 36.521-1.[17] These tests are based on the core requirements for UE radio transmission and reception in TS 36.101[6] and the requirements for RRM in TS 36.133.[15]

The major topics that will be covered by the UE RF conformance tests have been determined and follow the same general headings used for UMTS. They are transmitter characteristics, receiver characteristics, performance requirements, and radio resource management.

4.2.1 Transmitter characteristics

The current list of transmitter test is as follows:

Maximum output power (MOP)
Maximum power reduction (MPR)
Additional maximum power reduction (A-MPR)
Minimum output power
Transmission ON/OFF power
Out-of-synchronization handling of output power
Frequency error
EVM
IQ-component
In-band emissions for non-allocated RB
Occupied bandwidth
Spectrum emission mask
Adjacent channel leakage ratio (ACLR)
Additional ACLR requirements
Spurious emissions
Transmit intermodulation

Most of the transmitter tests are similar in scope and purpose to those for UMTS. The in-channel measurements obviously vary to take into account the SC-FDMA modulation scheme, while the out-of-channel measurements should be familiar. There is significant emphasis on the maximum power requirements and in particular the MPR and A-MPR tests, which check that the UE reduces its maximum power when it transmits certain combinations of RB and modulation. These methods are used to fine-tune the UE so that it can operate at high data rates in deployments with higher spurious emissions and then scale back its maximum power; for example, at the cell edge where the UE is more sensitive to out-of-channel emissions.

The fact that SC-FDMA does not require allocation of the entire channel bandwidth has led to the specification of a new class of in-channel measurements known as the in-band emissions for non-allocated RB. These measurements are a bit like in-channel ACLR measurements in which the power of the allocated RB is compared to the power of the unallocated RB. The exact details of the requirement are still to be finalized. Also, the LO leakage is specified separately rather than being included as part of EVM. The LO energy falls in between the two central subcarriers of the uplink channel bandwidth since the SC-FDMA definition includes a 7.5 kHz shift.

The additional ACLR requirements apply to the second (alternate) 5 MHz universal terrestrial radio access (UTRA) channel when signaled by the network. They are similar to A-MPR requirements in which the UE is expected to reduce its maximum output power. Under these lower power conditions the UE has to meet tighter ACLR requirements for deployment in particular bands in which interference to UMTS is a problem.

4.2.2 Receiver characteristics

The current list of transmitter test is as follows:

Reference sensitivity level
Maximum input level
Adjacent channel selectivity (ACS)
In-band blocking
Out of-band blocking
Narrowband blocking
Spurious response
Wideband intermodulation
Narrow band intermodulation
Spurious emissions

The receiver tests are similar to those of UMTS. One key difference in LTE, however, is the baseline UE capability requiring diversity reception, which is an option for UMTS.

4.2.3 Performance requirements

These requirements are still at an early stage, but they will define performance targets for reception of the various channels under fading conditions.

The current list is:

Demodulation of FDD PDSCH (fixed reference channel)
Demodulation of FDD PCFICH/PDCCH (fixed reference channel)

4.2.4 Radio resource management

The RRM tests will cover the dynamic aspects related to mobility and timing. At this time there are no details although most of the principles from UMTS will be repeated for LTE. Because of the desire to support inter-RAT capabilities, the LTE RRM tests will be more complicated as they will involve an increasing number of alternative technologies and frequency bands than now exist.

The current list is:

E-UTRAN cell selection
E-UTRAN FDD - FDD cell re-selection intra frequency case
E-UTRAN TDD - TDD cell re-selection intra frequency case
E-UTRAN FDD - FDD cell re-selection inter frequency case
E-UTRAN FDD - TDD cell re-selection inter frequency case
E-UTRAN TDD - FDD cell re-selection inter frequency case
E-UTRAN TDD - TDD cell re-selection inter frequency case
E-UTRAN FDD - UTRAN FDD cell re-selection
E-UTRAN FDD - UTRAN TDD cell re-selection
E-UTRAN TDD - UTRAN FDD cell re-selection
E-UTRAN TDD - UTRAN TDD cell re-selection
E-UTRAN FDD - GSM cell re-selection
E-UTRAN TDD - GSM cell re-selection
E-UTRAN FDD - FDD handover
E-UTRAN FDD - TDD handover
E-UTRAN TDD - FDD handover
E-UTRAN TDD - TDD handover
E-UTRAN FDD - UTRAN FDD handover
E-UTRAN FDD - UTRAN TDD handover
E-UTRAN TDD - UTRAN FDD handover
E-UTRAN TDD - UTRAN TDD handover
E-UTRAN FDD - GSM handover
E-UTRAN TDD - GSM handover
UTRAN - E-UTRAN handover
GSM - E-UTRAN handover
UE transmit timing
UE measurement procedures
Measurement performance requirement

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 have been reported, test calls have been made using LTE, and organizations such as the GSM Association are backing the technology as the mobile broadband standard to supersede HSPA.

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 a new uplink modulation scheme, SC-FDMA. It may be some time before the "real-world" behavior of these enhancements is well understood and products can be optimized accordingly.

The six channel bandwidths specified for LTE increase the flexibility and capability of the system but at the same time add to its overall complexity. Moreover, there is an expectation that LTE devices will incorporate GSM and UMTS systems—and possibly with other emerging formats as well. At the time of this writing, 3GPP has just completed the Stage 2 technical report for LTE WiMAX interworking and will soon start on the Stage 3 specifications.

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 can 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.

Agilent's Advanced Design System (ADS) is a powerful electronic design automation (EDA) solution that meets these criteria. It tackles the challenges of LTE design simulation by providing a comprehensive set of models, including standards-based models, so that engineers can quickly construct a top-level design. Additional capabilities allow co-simulation of baseband and RF circuit designs so that system-level performance can be verified in this single simulation environment. ADS is at the heart of Agilent's connected solutions for LTE, which provide seamless integration of design and test capability for verifying system-level performance with real device component hardware in the simulation path. The use of these solutions is illustrated in Figure 29.

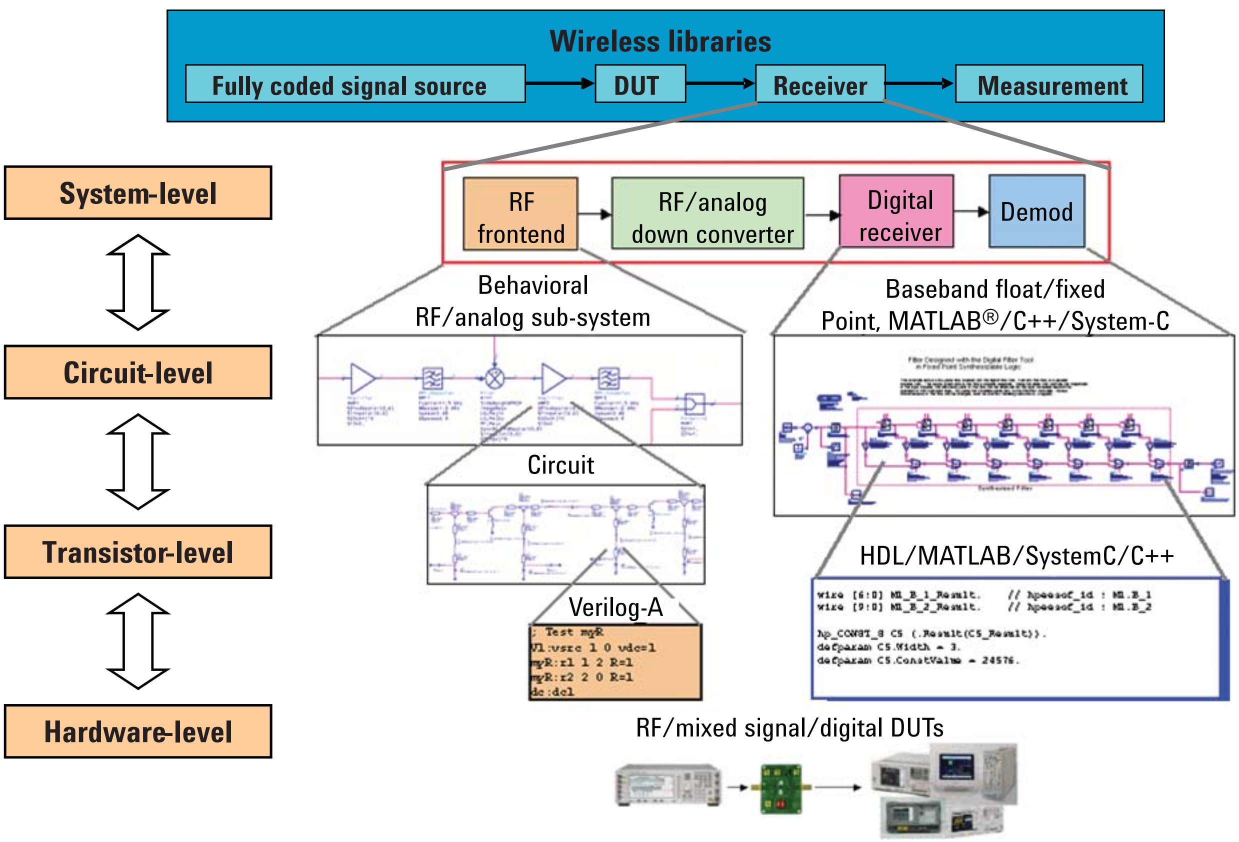

Figure 29. Overview of ADS and connected solutions

For system and circuit design verification, ADS provides a library that contains wireless simulation signal sources, receivers, and measurements. An RF system design can be constructed using behavioral models for blocks such as amplifiers, filters, and mixers. Parameters can be set for these models and they can be adjusted and easily varied until the top-level design meets the requirements. Once parameters have been set, they can be used also as circuit-design requirements for the individual blocks. Individual RF circuits can be designed with the ADS circuit simulators, and these circuits inserted back into the top-level system design. Floating-point and fixed-point behavioral models are available for constructing baseband designs, and support is available for writing algorithms (using HDL code, for example), which can be co-simulated with the RF designs to verify overall system-level performance.

At the hardware level ADS combines with Agilent test solutions to verify performance with actual device components added to the simulated model. For example, a simulated signal from 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 ADS for simulation post-processing.

Using this approach, engineers can perform typical measurements such as coded bit error ratio and coded packet error ratio on the RF device hardware using the simulated baseband coding and decoding capability to represent the missing baseband hardware functionality.

The E8895 ADS LTE Wireless Library includes signal sources and receivers for both the OFDMA downlink and the SC-FDMA uplink. The library can be used for top-down design, including RF and baseband performance budgeting, and for detailed verification of RF and baseband performance. System measurements required by the specifications are supported, with examples and templates provided to help jumpstart design activities. Also, the LTE Wireless Library can be imported into Agilent's RF Design Environment (RFDE). This allows RFIC designers to access 3GPP LTE test benches within the Cadence Virtuo Custom IC platform.

Waveforms created with the LTE Wireless Library comply with the latest LTE specifications. They can be used, for example, to measure EVM, peak-to-average power ratio (PAPR), and ACLR performance of system RF components such as power amplifiers, antennas, and filters.

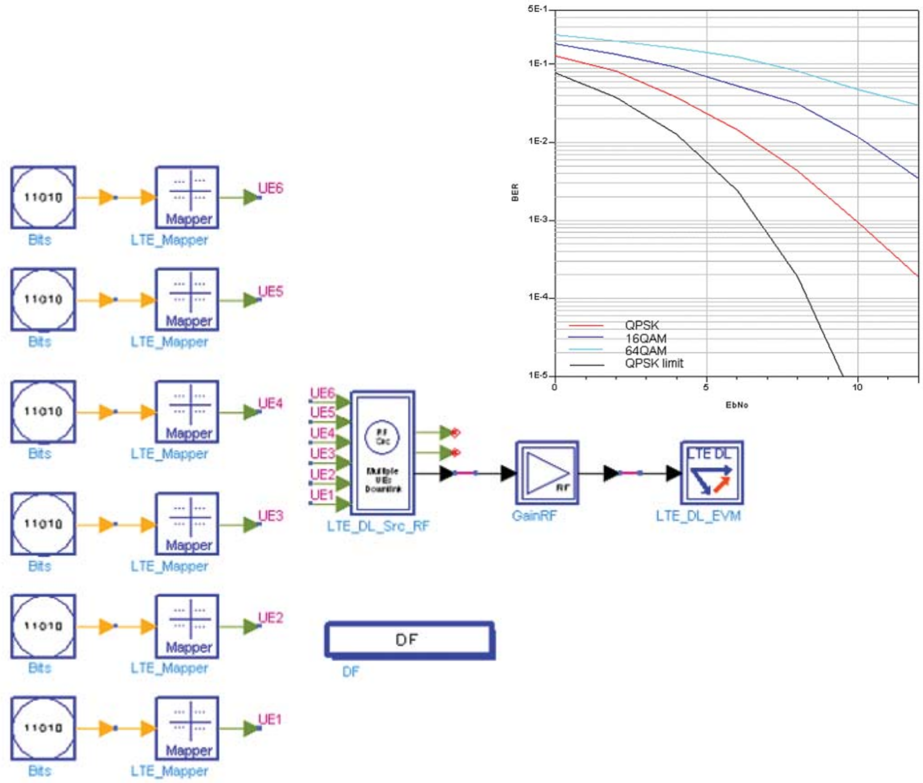

Figure 30. Waveforms created with the Agilent E8895 LTE Wireless Library used for downlink and uplink measurements

5.2 LTE test solutions

Similar to other 3.9G technologies, LTE requires new capabilities in test equipment. The latest generations of base stations rely heavily on "software radio" architecture with digital serial interfaces such as common public radio interface (CPRI) and open base station architecture interface (OBSAI), which replace traditional analog test interfaces. Now UE design is moving in the same direction with standards such as DigRF and MIPI D-PHY. The changing block diagram of both the base station and UE means that test equipment, too, will have to cross the analog-to-digital divide. Agilent is providing the necessary capability to meet these cross-domain testing challenges. See Figure 31.

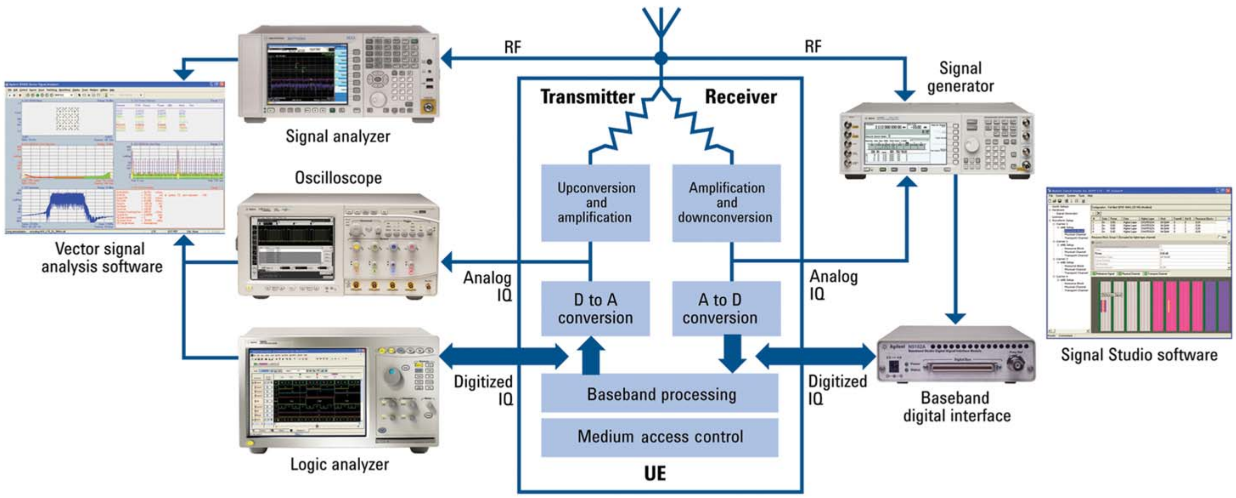

Figure 31. Agilent solutions cross the digital divide

In addition to ADS and the ADS Wireless LTE Library for design simulation and verification, Agilent has introduced a range of pattern generators, logic analyzers, signal generators, signal analyzers, and network emulation and protocol development tools. These offerings support early R&D in components, base station equipment, and UE with design automation tools and flexible instrumentation. As LTE products near commercial launch, Agilent intends to introduce further solutions for manufacturing and drive test.

The LTE test products described below are available today from Agilent. Updated product information is available at **www.agilent.com/find/lte**.

5.2.1 "Connected Solutions" for design simulation and verification

Unique to Agilent's offering are the LTE Connected Solutions, which combine test instrumentation with the ADS LTE Wireless Library simulation tools to provide early test access to the LTE product developer. A product developer can test a hardware device within a simulated design by downloading the LTE signals created using the ADS Wireless Library into an Agilent ESG or MXG vector signal generator, which produces the real-world, physical test signals. Output from the device under test can be captured with an Agilent MXA signal analyzer, PSA spectrum analyzer, or logic analyzer and then post-processed using the ADS LTE Wireless Library.

5.2.2 Uplink and downlink signal generation

Agilent Signal Studio is PC-based signal creation software that cuts the time spent on uplink and downlink signal generation. The software provides an Agilent-validated, performance-optimized, reference signal to better characterize, evaluate, and fine-tune designs under parametric and functional test conditions. Agilent Signal Studio software for 3GPP LTE configures coded physical layer LTE test signals to verify the RF performance of receivers and PA components. Signal Studio for LTE provides fully coded uplink and downlink signals with built-in fading profiles for eNB and UE receiver testing. Both RF and digital IQ connections are provided. When used with the Agilent MXG signal generator, Signal Studio provides the industry's best ACLR performance for the characterization and evaluation of base transceiver station (BTS) components such as multi-carrier power amplifiers as well as for UE PA components.

5.2.3 Uplink and downlink signal analysis

The complexity of LTE systems requires signal analysis with in-depth modulation analysis as well as RF power measurement. Agilent signal and spectrum analyzers measure complex LTE signals with world-class accuracy and repeatability. They can be used with the high-performance Agilent 89601A vector signal analysis (VSA) software, which provides RF and baseband engineers with the industry's most comprehensive, up-to-date LTE signal analysis based on the 3GPP standard. See Figure 32. The software provides downlink and uplink measurement capability in a single option; measures all LTE bandwidths and modulation schemes; and, with the PSA high performance spectrum analyzer, delivers industry-leading EVM of < –50 dB (< 0.35%). An example of how the 89601A software can be used to analyze an SC-FDMA signal is provided earlier in this application note.

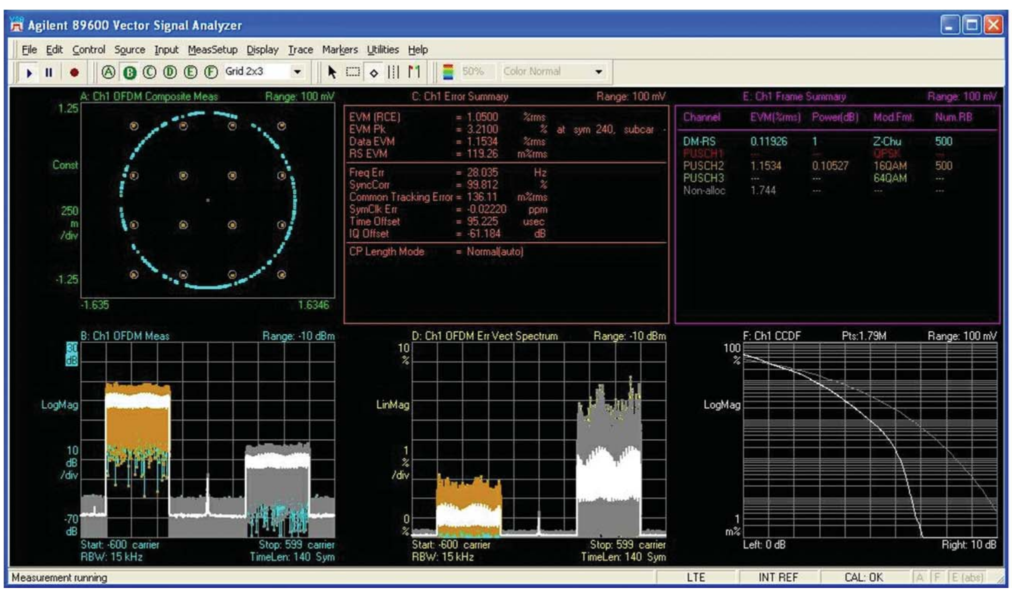

Figure 32. Comprehensive, up-to-date LTE signal analysis using Agilent signal analyzers with high-performance VSA software

5.2.4 Logic analyzers for baseband analysis

In LTE user equipment, communication between the RF front end and baseband processor occurs over a digital bus, which may be serial or parallel. Special signal analysis and signal generation tools are needed to properly characterize this digital interface. By combining an Agilent logic analyzer with signal analysis and signal generation tools, designers can comprehensively characterize the behavior of their systems from baseband to antenna. The logic analyzer provides a physical connection into the circuit, while the signal analysis software interprets the data from a wide range of measurements to be analyzed and displayed.

The logic analyzer also can be used with the 89601A VSA software, creating the industry’s only digital VSA (DVSA) package for digital baseband, IF, and RF signal analysis. With this software, digital signal processing (DSP) designers can design and debug interfaces that once were analog and now are digital. The VSA software performs functions such as I/Q analysis, EVM, and Fourier spectrum analysis on the decoded digital signal.

The Agilent N4850A digital acquisition probe and N4860A digital stimulus probe operate with Agilent 16800 and 16900 Series logic analyzers, providing digital acquisition and serial stimulus capabilities required for DigRF v3-based integrated circuit (IC) evaluation and integration. The integration of DigRF v3 logic analysis tools with the Agilent RF portfolio provides cross-domain solutions for rapid deployment of DigRF v3-based designs.

5.2.5 Oscilloscopes for real-time digital decode and debug

The Agilent Infiniium DSO90000A Series high performance real-time oscilloscope provides superior signal integrity and deep application analysis so that engineers can quickly debug and characterize digital systems. Applying Agilent’s RF design expertise, proprietary packaging technologies, and unique CMOS ADC architecture, the Infiniium scope offers the industry’s lowest noise floor. The InfiniiScan Plus event identification system is based on the world’s fastest hardware trigger system and can identify glitches faster than 250 ps. No other oscilloscope provides this level of trigger accuracy. With more than 29 applications, the Infiniium 90000A verifies application compliance and debugs the most difficult electronic designs in the shortest possible time.

5.3 UE development solutions platform

The Agilent E6620A wireless communications test set provides a scalable, advanced platform for developing LTE user equipment. As the specifications are released, the test set will support the development process from initial protocol development through RF and protocol conformance test, functional test, and interoperability test (IOT). The E6620A will use the same 3GPP-compliant LTE protocol stack across all solutions to provide consistency leading to shorter design cycles and the highest quality designs.

5.3.1 Protocol development

The complexity of LTE means that the importance of protocol development cannot be over-emphasized. New handset designs must meet the expectations of the consumer and the standards bodies, which mean carrying out earlier and more comprehensive development, design verification, and regression testing. Agilent has partnered with Anite to offer versatile but rigorous testing solutions.

The Anite SAT LTE development toolset (DT) using the Agilent E6620A, shown in Figure 33, is a comprehensive suite of tools that supports all phases of UE development—from pre-silicon protocol module development through to system integration and verification—helping to shorten development times and validate confidence in designs.

Figure 33. LTE UE protocol development solution from Agilent and Anite

5.3.2 UE signaling conformance test

In the wireless industry, Agilent and Anite offer proven conformance test solutions to ensure the performance of the protocol components of a handset. Today these solutions support a wide range of radio technologies including GSM, EDGE, W-CDMA, and HSPA. Anite's conformance toolset solutions for LTE, based on the Agilent E6620A, incorporate comprehensive campaign management and analysis tools to assess the quality of handsets under evaluation. They provide extensive automation and a remote-control interface to help maximize test throughput and are used throughout the product lifecycle for integration, conformance, and certification testing of handsets. When the LTE conformance specifications are published, Agilent and Anite will be ready with a standards-compliant solution.

5.3.3 RF conformance test

The RF conformance test specifications for LTE will be defined by 3GPP towards the end of 2008. They will cover the following measurement areas: transmitter requirements, receiver requirements, performance requirements, and radio resource management. Agilent will continue to evolve our portfolio of standards-compliant test components so that when the conformance specifications are finalized, Agilent will be ready with validated conformance test systems.

5.4 Network protocol signaling analysis

The Agilent network signaling analyzer software platform is adding LTE and SAE technology support. Together with a new high-density probing solution, the signaling analyzer software will enable passive probing and analysis of LTE network interfaces, including S1, X2, S3, S4, and S5. The powerful combination of distributable hardware pre-processing with scalable software architecture meets current and future performance needs to ensure a successful deployment of integrated LTE/SAE network systems.

5.5 Looking ahead

LTE has 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, plan to provide a broad, comprehensive portfolio of solutions that address the entire product development life cycle—from early design through to production test and deployment. LTE may have many challenges, but with early and powerful test equipment solutions, the LTE challenge can be met.

6 More Information

For more information about the 3GPP and LTE specifications visit
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

For more information about Agilent design and test products for LTE visit
http://www.agilent.com/find/lte

7 List of Acronyms

3G	3rd Generation
3GPP	3rd Generation Partnership Project
ACLR	Adjacent channel leakage ratio
ACPR	Adjacent channel power 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
CDD	Cyclic delay diversity
CCDF	Complementary cumulative distribution function
CDMA	Code division multiple access
CFI	Control format indicator
Co-MIMO	Cooperative MIMO
CP	Cyclic prefix
CPICH	Common pilot channel
CPRI	Common public radio interface
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
DT	Development toolset
DVSA	Digital vector signal analysis
EDA	Electronic design automation
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
HDL	Hardware description language
HI	HARQ indicator

7 List of Acronyms
(Continued)

HSDPA	High speed downlink packet access
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
MOP	Maximum output power
MPR	Maximum power reduction
MU-MIMO	Multiple user MIMO
NAS	Non-access stratum
OBSAI	Open base station architecture interface
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
P-SCH	Primary synchronization signal
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
RFDE	RF design environment
RLC	Radio link control
RMC	Reference measurement channel

7 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
S-SCH	Secondary synchronization 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
TTI	Transmission time interval
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

8 References

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17. 3GPP TS 36.521-1 V0.0.7 is currently unpublished but available at **ftp://ftp.3gpp.org/tsg_ran/WG5_Test_ex-T1/Working_documents/36_521-1/latest/** Once published it will be found at **http://www.3gpp.org/ftp/Specs/html-info/36521-1.htm**

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