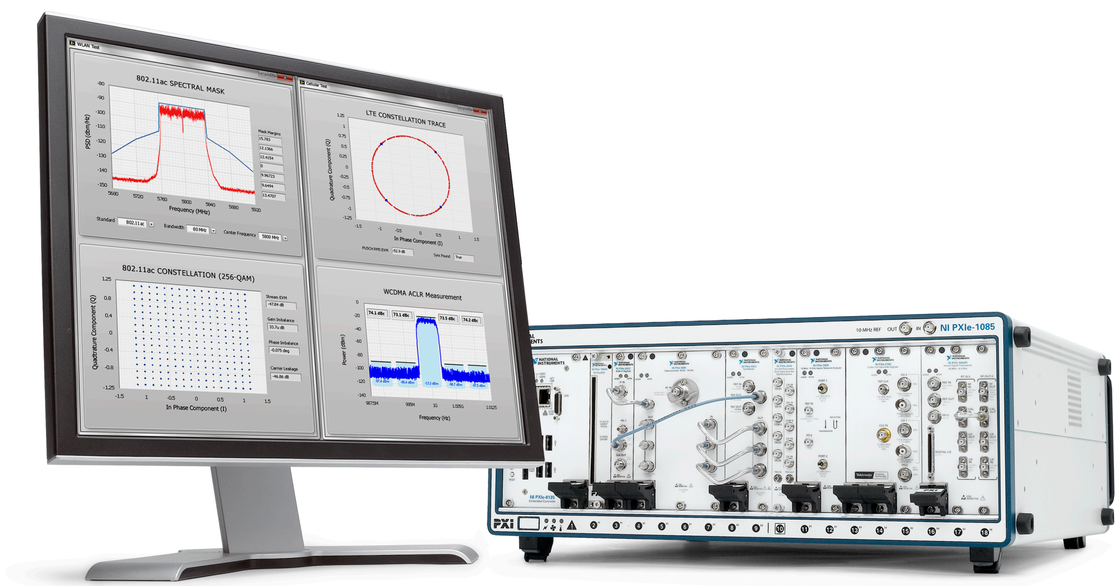
Introduction to LTE Device Testing

From Theory To Transmitter and Receiver Measurements



Visit www.ni.com/rf-academy

Table of Contents

1. LTE and LTE Advanced

Long Term Evolution (LTE) is an evolution of the GSM and UMTS standards, which are also referred to as 2G and 3G standards respectively. Although LTE is marketed as a 4G standard, it does not strictly satisfy the technical requirements prescribed by the International Telecommunication Union (ITU). The ITU requirements are, however, satisfied by LTE-A. The major goals of the LTE standard are increased network capacity and higher user data transfer speeds. Because the LTE physical layer uses bandwidth allocations that are different from the 2G and 3G standards, LTE needs a separate spectrum for its operation.

LTE Signal Structure

LTE was first introduced as part of 3GPP release 8, with additional enhancements in 3GPP release 9 and later. LTE uses a combination of wide channel bandwidths of up to 20 MHz and MIMO technology to offer theoretical data rates of up to 300 Mbps. LTE is also significant because it was the first broadly-adopted cellular standard to use OFDMA technology – a multicarrier technique that better exploits wider channel bandwidths than traditional narrowband systems such as GSM.

Starting with 3GPP release 10 and later, the 3GPP specifications formalized the evolution of LTE - which is LTE Advanced. LTE Advanced employs several key technologies, including downlink features such as the utilization of up to 8x8 MIMO and aggregation of up to five carriers to further increase data throughput. As a result, the theoretical data throughput offered by LTE Advanced is up to 3 Gbps data rates - a significant improvement over LTE. **Table 1.1** compares key characteristics of LTE and LTE Advanced.

	LTE (Release 8)	LTE Advanced (Release 10)
Peak Downlink Data Rate	300 Mb/s	3 Gb/s
Peak Uplink Data Rate	75 Mb/s	1500 Mb/s
Peak DL Spectrum Efficiency	15 bps/Hz	30 bps/Hz
Peak UL Spectrum Efficiency	3.75 bps/Hz	15 bps/Hz
Bandwidth	Up to 20 MHz	Up to 100 MHz
Modulation Schemes	QPSK, 16-QAM, 64-QAM	QPSK, 16-QAM, 64-QAM
Carrier Aggregation	No	Yes
MIMO Support	Up to 4x4	Up to 8x8

Table 1.1. Comparison of LTE Versus LTE Advanced

As we observe in **Table 1.1**, the LTE standard supports downlink peak data rates of 300 Mbits/s and uplink peak rates of 75 Mbits/s. The standard also supports scalable carrier bandwidths from 1.4 MHz to 20 MHz, and supports both frequency-division duplexing (FDD) and time-division duplexing (TDD). TDD uses the same spectrum for uplink and downlink in time-duplexed mode, thus reducing the spectrum usage by half. This makes TDD ideal for countries where spectrum is scarce.

LTE Advanced not only offers major theoretical enhancements over LTE in terms of wider bandwidths and more sophisticated MIMO schemes, but also offers other practical improvements to improve performance in field use.

For example, one of the features offered by LTE Advanced is the ability to beam-steer specific downlink subcarriers to a specific handset. As a result, this handset will receive a relatively higher power of its own resource blocks, and a relatively lower power of other UE's resource blocks. This effective increase in receive signal strength can improve throughput in scenarios where the SNR is low.

OFDM

Unlike GSM and WCDMA standards, which are based on single-carrier modulation schemes, the LTE physical layer is based on Orthogonal Frequency Division Multiplexing (OFDM) technology. The fundamental principle of OFDM is to use a large number of narrowband, orthogonal subcarriers to carry data transmissions instead of using a single, wideband carrier. Not only does the multicarrier approach allow for better spectral efficiency, but it also reduces the impact of multipath reflections on the receiver's ability to demodulate the signal.

The modulation of each orthogonal subcarrier is accomplished through an Inverse Discrete Fourier Transform (IDFT). As illustrated in **Figure 1.1**, a bitstream is first de-serialized into parallel bitstream. Each parallel bitstream is then mapped onto symbols and then fed into the IFFT.

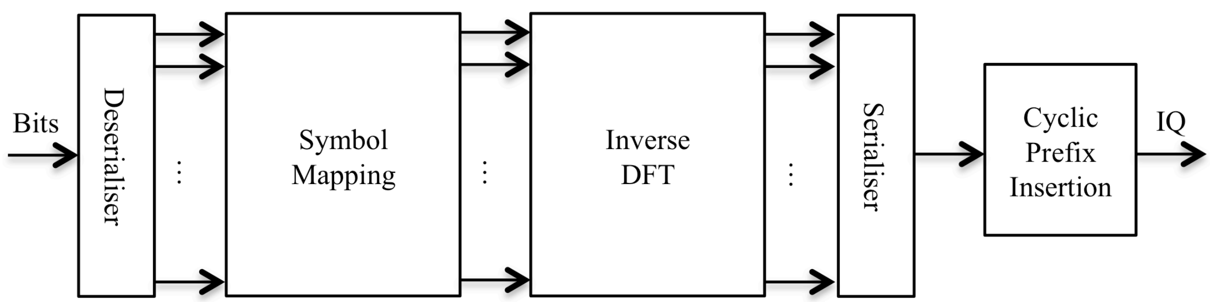


Figure 1.1. Block Diagram of a Basic OFDM Transmission.

Note in **Figure 1.1** that a cyclic prefix is inserted after the inverse DFT. The cyclic prefix operates as a guard interval – but with dummy data – to ensure phase continuity of the transmission. One should also note that because each subcarrier is independently modulated in an OFDM transmission, it is possible for each subcarrier to use a different modulation scheme. In LTE transmissions, data subcarriers can be modulated using the QPSK, 16-QAM, or 64-QAM modulation schemes.

OFDM transmissions have a unique signature in the frequency domain because the waveform visually resembles a signal that has been filtered by a brick-wall filter. In fact, you can visualize an OFDM signal as a combination of multiple subcarriers as shown in **Figure 1.2**.

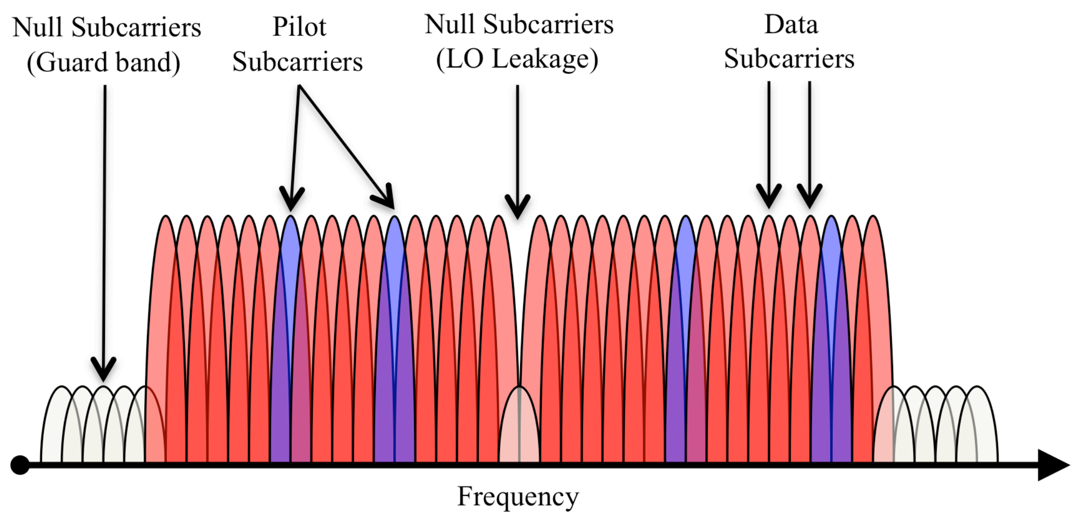


Figure 1.2. OFDM Signal in the Frequency Domain.

In **Figure 1.2**, observe that each subcarrier in an OFDM transmission is both orthogonal and overlapping. The orthogonality of the subcarriers is achieved through the use of the IDFT. Moreover, the overlapping nature of the subcarriers allows for better spectral efficiency than single-carrier modulation schemes. Note in **Figure 1.2** that not all subcarriers are used to carry data or control information. Instead, a significant number of subcarriers at the band edge are kept null as a guard band. In addition, the center subcarrier is kept null due to the probability of LO leakage at the center frequency of the transmitter.

One of the most significant benefits of OFDM technology for mobile wireless communications systems is the reduction of intersymbol interference (ISI) in wide bandwidth transmissions. It is important to note that as the channel bandwidth of a single-carrier modulation scheme increases, the symbol period also decreases. In mobile communications environments, lower symbol periods increase the length of intersymbol interference (ISI), because multipath reflections can potentially arrive at a receiver after different delays as compared to the signal arriving from the direct path.

OFDM mitigates the challenge of ISI in wideband channels through its use of a cyclic prefix. The cyclic prefix is prepended to the beginning of each IFFT block and then thrown away at the receiver in order to eliminate the overlapping portion between symbols - which would otherwise result in ISI. In addition, due to the channelization of the subcarriers, frequency domain equalization may be performed, greatly simplifying the receiver design. In fact, an OFDM receiver's equalizer is typically a single-tap design versus the multi-tap design in an UMTS receiver.

OFDM Applied to LTE

Although the design of the LTE downlink and uplink channels is based on OFDM technology – the LTE standard uses two variants of OFDM as appropriate for mobile communications. For example, the LTE downlink signal is to use Orthogonal Frequency Division Multiple Access (OFDMA). Although this multiple access scheme borrows the underlying subcarrier design of OFDM, it is specifically designed for multi-user access. In the OFDMA scheme, the multiple subcarriers are grouped into resource blocks that can be dedicated to individual users.

The combination of 12 subcarriers make up one resource block, and the number of available subcarriers and resource blocks that can be allocated for users varies according to bandwidth configuration. As we observe in **Table 1.2**, the 20 MHz bandwidth option offers up to 100 allocable resource blocks for data transmission.

	Channel Bandwidth Configuration					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Frame Duration (ms)	10 ms					
Subcarrier Spacing (kHz)	15	15	15	15	15	15
Sampling Frequency (MS/s)	1.92	3.84	7.58	15.36	23.04	30.72
FFT Size	128	256	512	1024	1526	2048
Resource Blocks	6	15	25	50	75	100
Data Subcarriers	72	180	300	600	900	1200

Table 1.2 Theoretical Maximum Data Rate for LTE Downlink per Channel Bandwidth

By contrast to the downlink, the fundamental LTE uplink signal design uses Single-Carrier Frequency Division Multiple Access (SC-FDMA). SC-FDMA borrows much of the fundamental design of OFDM systems, but with one essential modification. In SC-FDMA, a transmitter applies FFT "pre-coding" before symbols are modulated onto subcarriers. As discussed in a later section in this document, the use of FFT pre-coding reduces the peak-to-average power ratio (PAPR) of the transmission – an essential requirement in uplink transmission. The result of the FFT pre-coding is that the modulation symbols are in time domain (in contrast to their presence in frequency domain in OFDMA) with a PAPR that is substantially smaller than the PAPR of a standard OFDM signal. Thus, although both the LTE uplink and downlink signals do not directly use "simple OFDM," it is important to understand OFDM technology in order to understand the design of each of these signals.

MIMO

A second important technology featured in the LTE is the use of multiple-input-multiple-output (MIMO) antennas for both transmission and reception. MIMO technology improves the reliability and the throughput of communication over wireless channels through its use of multiple spatial streams.

The fundamental principle of MIMO technology is that multiple data streams can be transmitted at the same time and into the same channel using multiple antennas. These data streams can either be redundant to improve reliability or they can be different to improve data rates. The process by which a single data stream is multiplexed into multiple data streams and transmitted at the same is called spatial multiplexing.

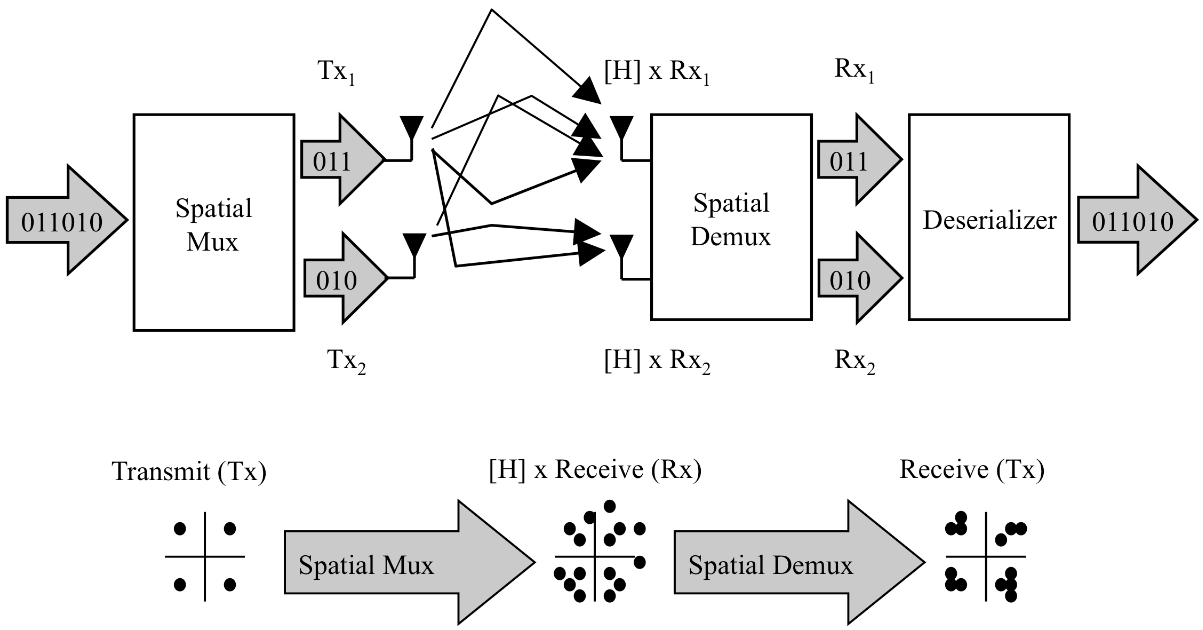


Figure 1.3. MIMO System Uses Spatial Multiplexing to Increase Data Rate

As we observe in **Figure 1.3**, multiple antennas are used both for the transmission and reception of the individual spatial streams. The benefit of spatial multiplexing is that by using specialized signal processing to decode each stream independently, the effective data rate of a MIMO channel is increased such that it is greater than that of the traditional single-input-single-output (SISO) channel.

The data rate improvement of a MIMO link over a SISO link is a linear function of the number of independent spatial streams. For example, a 2x2 transmission can support up to two spatial streams and is theoretically capable of data rates that are twice that of a 1x1 SISO link. By contrast, a 8x8 transmission can support up to eight spatial streams and yields up to an 8x improvement in data rate.

However, the number of independent spatial streams that can practically be used in a given scenario is greatly dependent on the channel characteristics. Typically, line-of-sight channels can support two independent spatial streams through the use of antenna polarization. By contrast, non line-of-sight channels can often support more than two spatial streams through a combination of antenna polarization and multipath diversity.

MIMO Modes in LTE

The LTE standard allows for devices to use a wide range of MIMO configurations. In the first generation of LTE, defined in 3GPP Release 8, devices were able to use MIMO configurations of up to 4x4 on the downlink and 1X1 on the uplink. By contrast, the LTE Advanced specifications defined by 3GPP Release 10 allow for MIMO configurations of up to 8x8 on the downlink and 4X4 on the uplink.

LTE downlink transmission supports both single-user MIMO (SU-MIMO) and multi-user MIMO (MU-MIMO). In SU-MIMO, one or more data streams are transmitted to a single UE through space-time processing. By contrast, in MU-MIMO, data streams are transmitted to different UEs using the same time-frequency resource.

LTE uplink transmission also supports MU-MIMO – a scheme that allows the eNodeB to allocate the same time and frequency resources to two UEs with each UE transmitting on a single antenna. In this scenario, only one transmit antenna is required for each UE. In this scheme, the eNodeB requires channel state information in order to separate streams for each UE. The channel state information is obtained through uplink reference signals that are orthogonal between UEs. Note that uplink MU-MIMO also requires each UE to exercise precise power control to ensure that UE's nearer to the eNodeB do not drown out transmissions from UE's that are farther away.

LTE Modulation Schemes

LTE supports three modulation schemes in both the downlink and the uplink: QPSK, 16-QAM, and 64-QAM. The constellation diagram of each modulation scheme is illustrated in **Figure 1.4**. As the figure illustrates, 16-QAM has 16 discrete combinations of phase and amplitude, while 64-QAM has 64. As a result, LTE transmissions achieve the highest data rate when using 64-QAM.

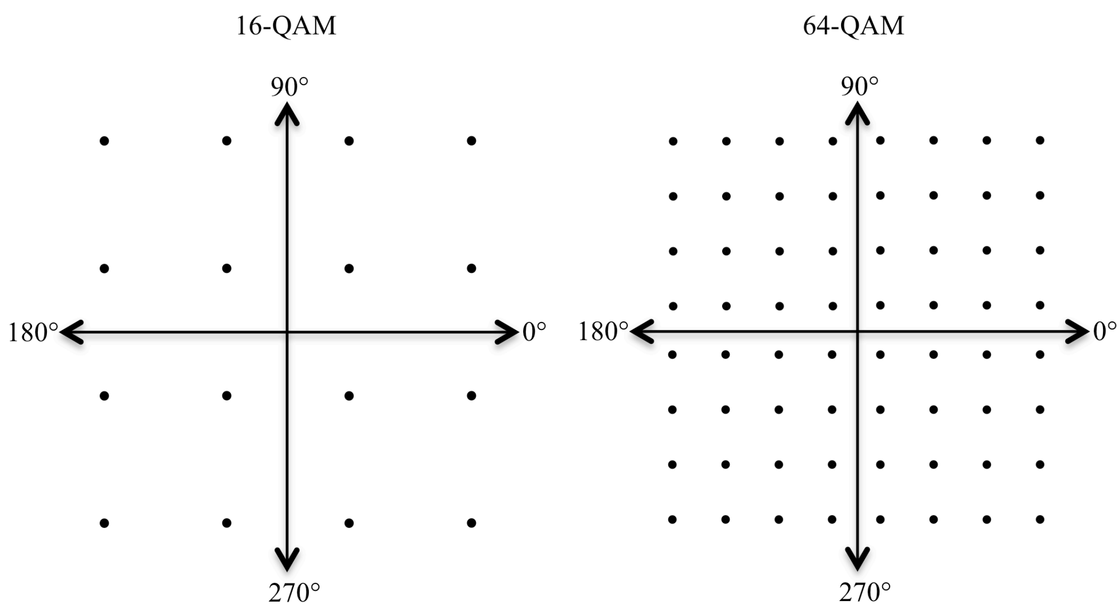


Figure 1.4. 16-QAM and 64-QAM Symbol Map

It is worth noting that the LTE standard uses adaptive modulation techniques – which allow the eNodeB to choose the specific modulation scheme depending on the channel conditions. Depending on channel conditions, some UEs might receive a more robust transmission (QPSK), and others might receive higher data-rate transmissions (64-QAM or 16-QAM). Similarly, each UE can use a different modulation scheme in the uplink transmission. Again, good channel conditions would result in the usage of the 64-QAM or 16-QAM modulation scheme, while poor channel conditions cause the selection of the more robust but less efficient QPSK constellation.

Carrier Aggregation

Unlike UMTS where the evolution to HSPA and HSPA+ relied heavily on higher order modulation schemes to achieve higher data rates, LTE advanced improves data rates over LTE through additional features such as carrier aggregation and more spatial streams. Carrier aggregation is one of the most straightforward mechanisms to improve data rates to an individual user, although it does not improve spectral efficiency. LTE Advanced allows for up to five aggregated carriers, called component carriers, to be combined for transmission to a single user. Each of these carriers can either be contiguous or non-contiguous, as illustrated in **Figure 1.5**.

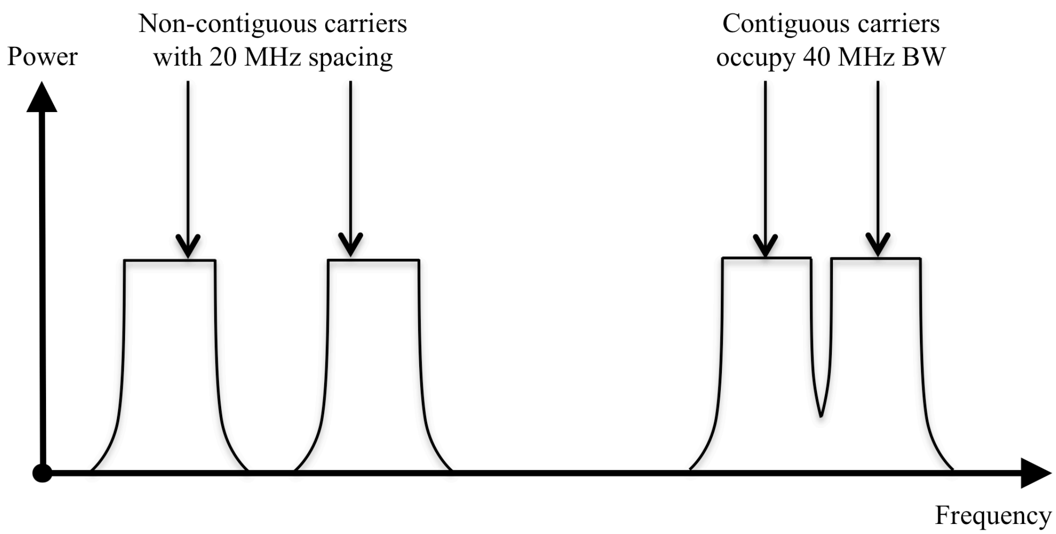


Figure 1.5. Contiguous Versus Non-contiguous Aggregated Carriers for LTE Advanced

Through the use of channel aggregation, LTE supports an incredibly wide range of channel bandwidth configurations. For example, a LTE transmission can range from as small as 1.4 MHz in the smallest configuration to up to a 100 MHz with 5 aggregated carriers.

Theoretical Data Rates

Although LTE does not officially meet the 4G requirements issued by the International Telecommunications Union (ITU) in the definition for International Mobile Telecommunications-Advanced (IMT-Advanced), the data rates available in LTE (up to 300 Mbps) are substantially higher than previous generations of cellular standards. It is worth noting that the maximum theoretical data rates of LTE Advanced (up to 3.08 Gbps) are compliant with the '4G' definition of the IMT-Advanced requirements.

Throughput of digital wireless communications channels is defined by several factors, including: symbol period utilization, symbol rate, modulation scheme, code rate, number of resource blocks, and number of spatial streams. Throughput for LTE transmissions can be calculated as a function of all of these factors, as shown in **Equation 1.1**.

$$Throughput = Data\ Subcarriers \times Slots\ per\ second \times Symbols\ per\ Slot \times Bits\ per\ Symbol\ \times Code\ Rate \times Spatial\ Streams$$

Equation 1.1. Throughput calculation for MIMO OFDM transmissions

With LTE, the maximum throughput in a 1x1 SISO channel occurs when the eNodeB allocates all resource blocks (1200 subcarriers) for a 20 MHz signal bandwidth using the 64-QAM modulation scheme. In this case, the estimated theoretical throughput is 76.8 Mbps.

$$Throughput = 1200\ data\ subcarriers \times 2000\ slots \times 7\ symbols \times 6\ bits\ \times \frac{4}{5}\ code\ rate \times 1\ spatial\ stream = 76.9\ Mbps$$

Equation 1.2. Throughput calculation for LTE SISO Link

Using MIMO technology, maximum data rates scale according to the number of spatial streams. Thus, a 4x4 MIMO system, which has up to four spatial streams, would have a data rate of 308 Mbps and an 8x8 LTE Advanced MIMO system would have a data rate of 612 Mbps.

In addition to more sophisticated MIMO schemes, the addition of carrier aggregation increases the theoretical data rates of LTE Advanced further. For example, while a 20 MHz channel bandwidth allows for 1,200 data subcarriers, the use of five aggregated carriers would increase the number of data subcarriers to 6,000. For LTE Advanced downlink, the maximum data rate can be calculated as follows:

$$DL\ Throughput = 6000\ data\ subcarriers \times 2000\ slots \times 7\ symbols \times 6\ bits\ \times \frac{4}{5}\ code\ rate \times 8\ spatial\ stream = 3.08\ Gbps$$

Equation 1.3. Throughput calculation for LTE Advanced 8x8 MIMO Link

By offering peak theoretical data rates of 3.08 Gbps, LTE Advanced is the first commercial wireless standard that exceeds the IMT-Advanced requirements for 4G cellular systems.

LTE Frame Structure

Because LTE supports both time (TDD) and frequency (FDD) division duplexing modes, the LTE standard defines two types of frame structures. LTE FDD systems use frame structure ‘type 1,’ where radio frames are divided into sub-frames, times slots, and eventually symbols. TDD systems use a frame design similar to ‘type 1’, but are referred to as having frame structure ‘type 2’in which both the uplink and downlink share timeslots in a common block of allocated bandwidth.

The waveform sample rates of LTE waveforms are explicitly designed to ensure compatibility with WCDMA/UMTS systems. Although LTE uses scalable bandwidths ranging from 1.4 MHz to 20 MHz, the required sample rates are designed to be a multiple or fraction of the WCDMA chip rate of 3.84 Mcps. As we observe in **Table 1.3**, the sample rate for each LTE bandwidth configuration is either a fraction or multiple of 3.84 Mcps.

	Channel Bandwidth Configuration					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Sample Rates (MS/s)	1.92	3.84	7.68	15.68	23.03	30.72
FFT Size	128	256	512	1024	1536	2048

Table 1.3. Sample Rates and FFT Sizes for Each LTE Bandwidth Configuration.

Because the sampling frequency of LTE signals is a multiple or sub-multiple of the WCDMA chip rate, multimode UTRA/HSPA/LTE terminals can be implemented with a single clock source.

It is worthwhile to note that the LTE standard defines the size of elements in the time domain as a function of time units. Time units are defined as T = 1/(15000 * 2048) seconds. Because the normal subcarrier spacing is defined as Δf = 15 kHz, T can be considered as the sampling time of an FFT-based OFDM transmitter and receiver implementation with FFT size, N=2048.

FDD Frame Structure

Frame structure type 1 supports both full-duplex and half-duplex FDD. By definition, the UE can transmit and receive simultaneously in full-duplex FDD and cannot transmit and receive at the same time in half-duplex FDD. The smallest unit of the LTE frame structure is called slot and has a duration of 0.5 ms (15360T). Two consecutive slots are defined as a 1 ms subframe and 20 slots comprise a 10 ms radio frame. Channel-dependent scheduling and link adaptation operate on the 1 ms subframe allowing for fast adaptation and better channel-dependent scheduling than HSPA. The division of frames, subframes, and slots is illustrated in **Figure 1.6**.

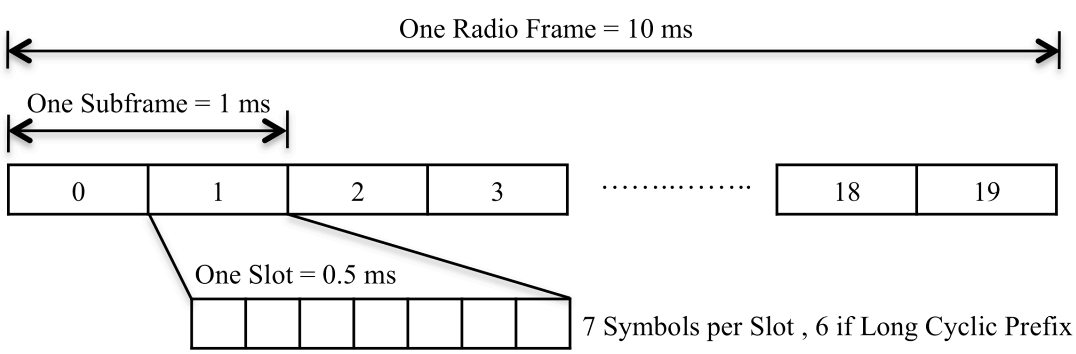


Figure 1.6: LTE Frame Structure Type 1

For the 15 kHz subcarrier spacing signal, each time slot consists of six or seven OFDM symbols including cyclic prefixes. The cyclic prefix is a guard interval to handle inter-OFDM-symbol interference and is designed to be larger than the channel delay spread. When the subcarrier spacing is 15 kHz, the OFDM symbol time is 1/15 kHz ≈ 66.7 µs (i.e., 2048T).

LTE defines two different cylic prefix lengths: a normal length and an extended length, corresponding to six and seven OFDM symbols per slot, respectively. The extended cyclic prefix is designed for multicell multicast/broadcast, which uses very large cell areas. In these scenarios, the larger cyclic prefix can mitigate larger delay spread. By contrast, the normal length is suitable for urban environments and high data rate applications. For normal lengths, the cyclic prefix in the first OFDM symbol has a different length compared to subsequent symbols to ensure full 0.5 ms occupancy.

TDD Frame Structure

LTE's frame structure 'type 2' supports Time Division Duplex (TDD) mode. LTE TDD is designed to co-exist with 3GPP TD-SCDMA, and as a result, uses the same frequency bands and frame structure. Thus, by properly configuring the timeslots, interference between TD-SCDMA and LTE TDD can be avoided. In TDD, both transmission and reception take place in the same frequency band with sufficiently large guard intervals for the equipment to switch between transmission and reception.

As we observe in **Figure 1.7**, each radio frame of frame structure type 2 has a duration of 10 ms and consists of two half-frames that are of 5ms duration. Each half-frame is divided into 5 subframes of 1ms duration each.

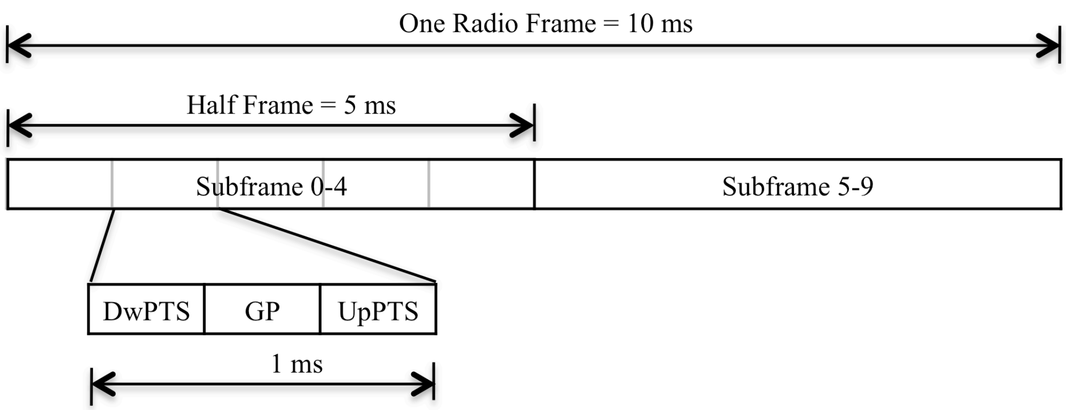


Figure 1.7 LTE Frame Structure Type 2

In addition to standard data subframes, frame structure type 2 supports "special" subframes. A special subframe is designed to facilitate the transition from the downlink to the uplink, and consists of three fields: a Downlink Pilot Time Slot (DwPTS), a Guard Period (GP), and an Uplink Pilot Time Slot (UpPTS). The downlink portion of the special subframe – the DwPTS – contains 3 to 12 data symbols. The uplink portion - the UpPTS – consists of one or two symbols that contain sounding reference signals and random access preambles. The special subframe also provides for a guard period between the DwPTS and the UpPTS. The GP can contain 2 to 10 OFDM symbols. The total length of these three special fields is 1ms.

In TDD mode, sub-frames within the LTE radio frame are dedicated for either uplink or downlink transmissions. The LTE standard defines seven unique configurations of sub-frame allocations, with downlink to uplink switch point periodicity of either 5 ms or 10 ms. These configuration options are illustrated in **Table 1.4**.

Uplink-Downlink Configuration	Switch Point Periodicity	Subframe Number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

Table 1.4: Uplink-downlink Configurations for the LTE TDD Mode

As we observe in **Table 1.4**, the LTE TDD mode supports seven uplink-downlink configurations with either 5 ms or 10 ms downlink-to-uplink switch-point periodicity. In this table, “D” and “U” denote subframes reserved for downlink and uplink, respectively, and “S” denotes the special subframe.

LTE Downlink Channel Structure

The fundamental design of the LTE downlink signal is orthogonal frequency division multiple access (OFDMA), and is based on multicarrier frequency division multiple access (FDMA), where users are assigned orthogonal sets of subcarriers. OFDMA (Orthogonal Frequency Division Multiple Access) enables the OFDM transmission to benefit from multi-user diversity. Based on feedback information about the frequency-selective channel conditions from each user, the eNodeB allocates users to subcarriers adaptively, enhancing considerably the total system spectral efficiency compared to single-user OFDM systems.

OFDMA can also be used in combination with time division multiple access (TDMA) such that the resources are partitioned in the time-frequency plane - into groups of subcarriers for a specific time duration. In LTE, such time-frequency blocks are known as resource blocks (RBs). As we observe in **Figure 1.8**, an LTE eNodeB allocates specific resource blocks for each user. As a result, data for each user is allocated both according to time and frequency.

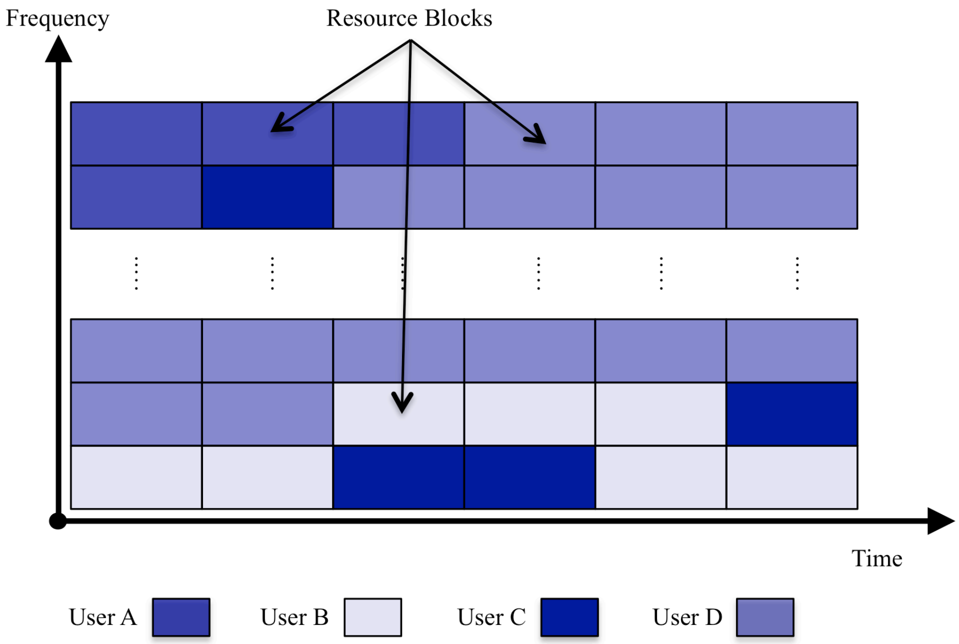


Figure 1.8: Allocation of Resource Blocks to Various Users in the LTE Time-Frequency Grid

Figure 1.9 illustrates more detailed time-frequency grid, which displays each resource block as a collection of 12 OFDM subcarriers. The smallest unit of the resource grid, corresponding to one OFDM symbol and one OFDM subcarrier, is called a resource element. For downlink transmission with normal cyclic prefix, a block of twelve resource elements in frequency and seven symbols in time (spanning one slot) make up one resource block (RB).

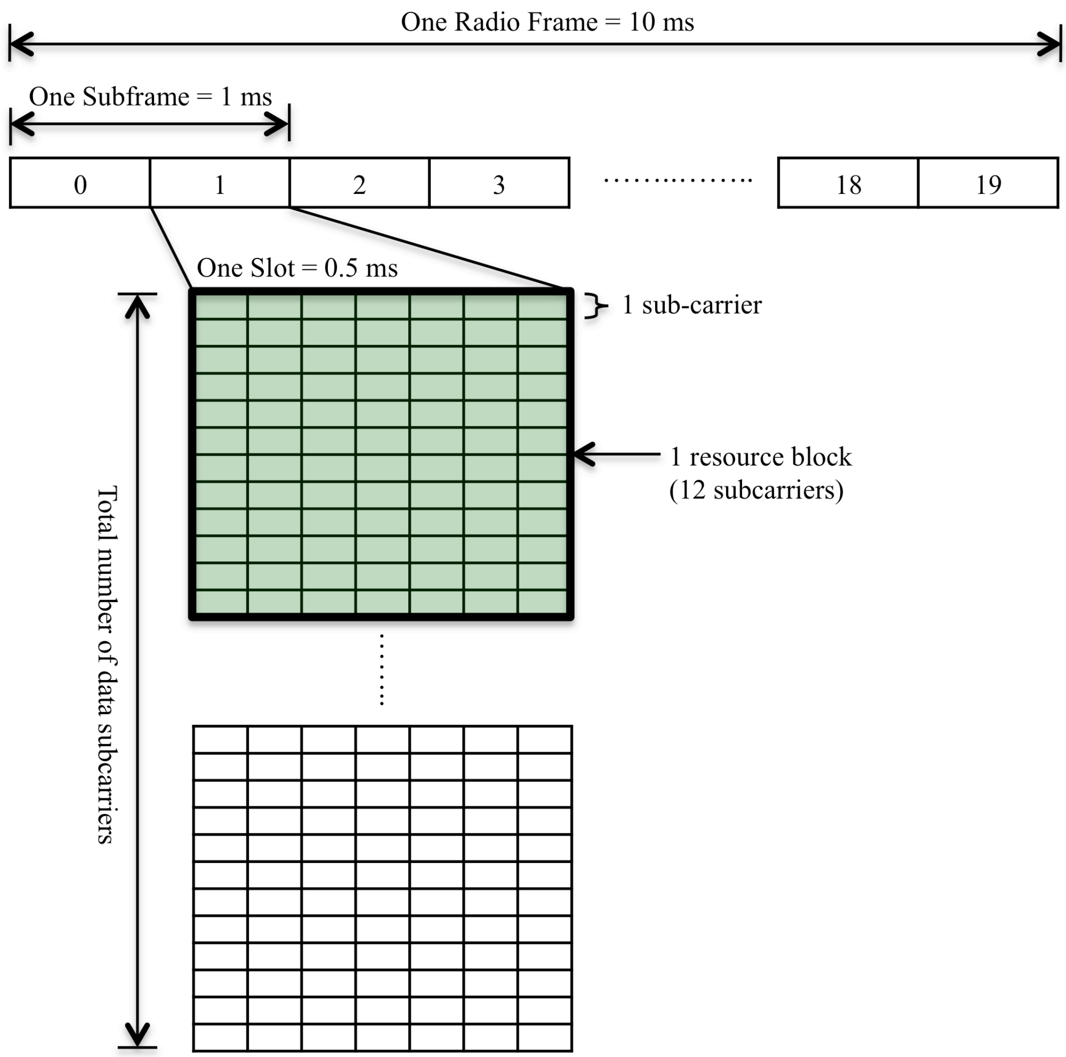


Figure 1.9. Resource Blocks (RBs) in the Time-frequency Grid for the LTE Downlink

Each resource grid can be completely described by the following parameters: the number of downlink resource blocks, the number of subcarriers in each resource block, and the number of OFDM symbols in each block. In **Figure 9**, each resource block contains seven symbols when the normal cyclic prefix is used. By contrast, when the extended cyclic prefix is used, a resource block contains six symbols.

Note that in the special case where the subcarrier spacing is 7.5 kHz, a resource block contains only 3 time slots. The reduced subcarrier spacing of 7.5 kHz supports Multicast-Broadcast Single-Frequency Network (MBSFN) services, such as mobile television, in which the larger OFDM symbol duration is able to handle the large delay associated with MBSFN.

LTE Uplink Channel Structure

A notable difference between the LTE uplink and the LTE downlink is the difference between their implementation of orthogonal subcarriers, that is, OFDM technology. Although the LTE downlink uses OFDMA, the uplink uses single carrier-frequency division multiple access (SC-FDMA). SC-FDMA is a unique OFDM-like multi-carrier scheme that applies specialized signal processing to reduce the peak-to-average power ratio (PAPR) of the signal. A sufficiently low PAPR of the transmitted waveform is especially important in UE, where transmitter power consumption and battery life are more critical.

Similar to LTE downlink transmission, LTE uplink transmission uses a multiple access scheme where each UE uses a pre-allocated set of uplink resource blocks, as illustrated in **Figure 1.10**. Using this scheme, the eNodeB allocates channel resources to UEs in the form of time-frequency blocks based on UE requests and on the channel quality measured on the uplink sounding reference signals.

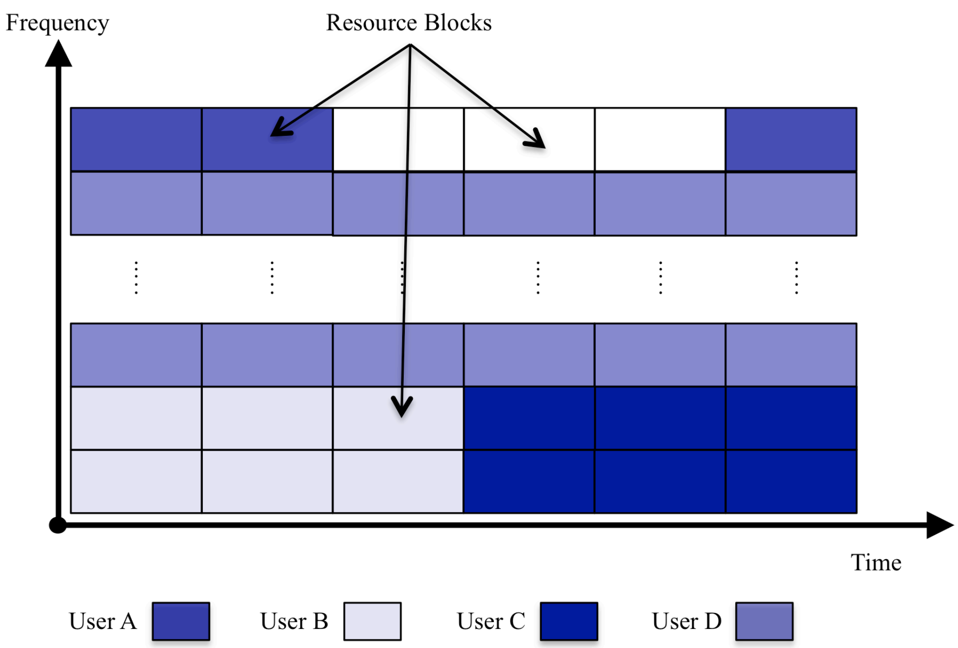


Figure 1.10: Figure Describing UL Allocation for Each Resource Block

Orthogonality between uplink subcarriers is achieved at the eNodeB by synchronizing the reception of uplink signals of each UE. Synchronization of each UE is facilitated through the use of timing advance at each UE transmitter which allows different UEs in a cell to be time-aligned at the eNodeB receiver. This alignment in time for each UE counters the different propagation delays between the different UEs scattered across a cell. It is important to note that by contrast, UMTS uplink transmission is not completely orthogonal and is significantly interference limited, thus reducing its coverage and capacity.

In general, LTE uses two methods of resource allocation to assign UEs to a particular resource block. Distributed resource allocation describes allocation that is performed randomly, that is, without the knowledge of which resource blocks constitute the highest performance channels. Localized resource allocation, by contrast, describes allocation that is based on knowledge of which resource blocks are the highest performance channels, which are discovered through sounding reference signals. Although the LTE downlink uses both distributed and localized resource allocation, the LTE uplink uses only localized resource allocation. Because distributed resource allocation requires more stringent time and frequency alignment between the UEs, it is much harder to implement in the uplink, and is therefore not used.

SC-FDMA in Uplink Transmission

SC-FDMA is a unique innovation of LTE, allowing for most of the benefits of OFDM but with a lower PAPR. In OFDM systems, a large number of subcarriers periodically (and somewhat randomly) add to or subtract from one another, thus creating waveforms with a nearly Gaussian distribution of power variation. As a result, OFDM signals tend to have a PAPR ranging from 10 to 13 dB.

Although a PAPR of 10 to 13 dB might be acceptable for downlink generation where available power is higher, having a lower PAPR is more important in uplink transmission. In practical use, because peak power levels of wireless devices are highly regulated, a higher PAPR for uplink generation limits the average output power of the transmission device. Moreover, even at nominal transmit power levels, signals with a higher PAPR also require higher current consumption of the radios used to transmit the signal.

In general, OFDM signals have a much higher PAPR than the modulation types used in other standards. For example, the Gaussian Minimum Shift Keying (GMSK) signal in GSM has a theoretical PAPR of 0 dB, as illustrated in **Table 1.5**.

Standard	Modulation Type	Typical Uplink PAPR
GSM	GMSK	0 dB
EDGE	8-PSK	3 – 4 dB
UMTS	QPSK	3 – 5 dB
HSUPA	16-QAM and 64-QAM	5 – 7 dB
LTE	Various (SC-FDMA)	6 – 8 dB
General OFDM	*Various (OFDM)*	*10 – 13 dB*

Table 1.5. Peak-to-Average Power Ratio (PAPR) for Various Cellular Technologies

As we observe in **Table 1.5**, a PAPR range of 10-13 dB for OFDM signals is substantially higher than the PAPR of modulation types used in other uplink transmissions. Given the need to reduce PAPR of the transmitted waveform, LTE uses SC-FDMA – a variation of standard OFDM. SC-FDMA employs a Discrete Fourier Transform (DFT) to reduce the PAPR of the OFDM signal. As we observe in **Figure 1.11**, the block diagram of an SC-FDMA signal closely resembles that of an OFDM transmission. Here, we observe that a DFT is performed before the IDFT (Inverse Discrete Fourier Transform).

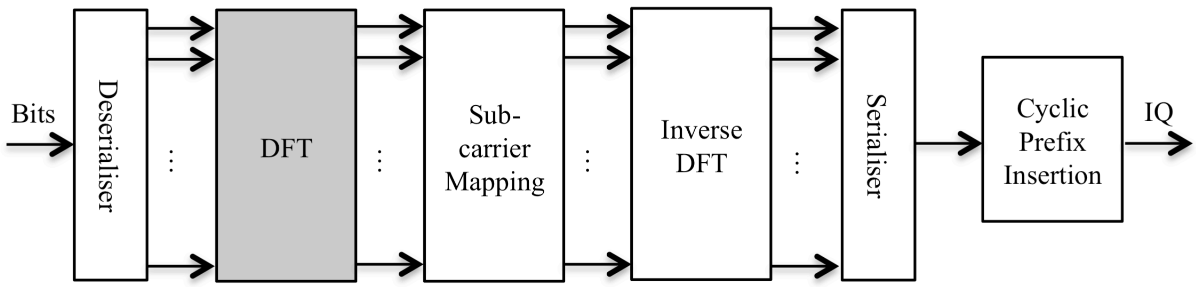


Figure 1.11. Block Diagram of an SC-FDMA Signal Transmission

By performing the DFT before the IDFT, the SC-FDMA modulated symbols are essentially transmitted in the time-domain, instead of the frequency-domain . As a result, the PAPR is generally reduced by up to 5 to 6 dB to produce waveforms with a PAPR range of 6 to 8 dB.

Physical and Logical Channels

Similar to UMTS, LTE supports the notion of physical channels, transport channels, and logical channels. A physical channel can be thought of recurring classification of information that is generated on precise set of subcarriers and at specific symbol intervals. By contrast, one can think of the notion of transport channels and logical channels merely as a classification of the type of information contained within the physical channel.

Similar to GSM and UMTS, physical channels map to transport and logical channels in a hierarchical manner. As we observe in **Figure 1.12**, which illustrates channels in the LTE downlink, there are six different classifications of downlink physical channels. Note that it is useful to consider the relationship between physical and logical channels before explaining the naming conventions of the physical channels.

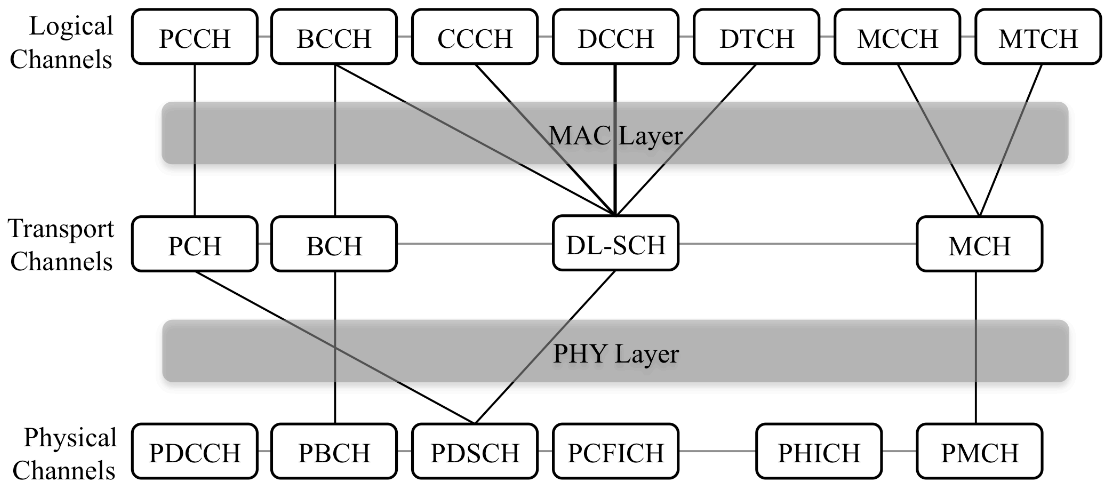


Figure 1.12. Logical, Transport, and Physical Channels of LTE Downlink

By contrast, the LTE uplink has a simpler channel structure, as illustrated in **Figure 1.12**. Again, although we will not explain the naming convention of each channel yet, observe that the LTE uplink contains 3 physical channels.

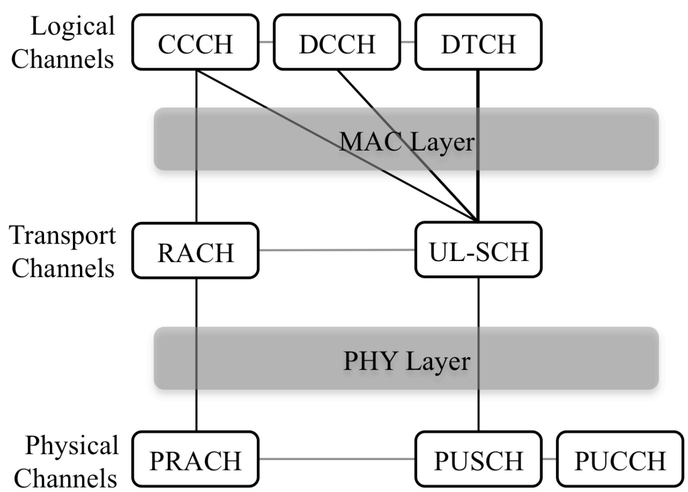


Figure 1.13. Logical, Transport, and Physical Channels of LTE Uplink

Physical Channels of LTE

Although GSM separates physical channels by slot, and UMTS separates physical channels by scrambling/spreading code, LTE separates physical channels by subcarrier and symbol offset. Physical channels are named according to their function and both uplink and downlink transmissions contain multiple physical channels. In addition, each of these channels can be either dedicated to one particular user or shared between multiple users.

In the downlink, there are physical channels that can be dedicated either to data or control, and some of the most common are described below:

- **Physical Broadcast Channel (PBCH):** The PBCH carries the broadcast control information of the transport-level broadcast control channel (BCH). PBCH always appears in the center of the channel occupying 6 RB and uses the QPSK modulation scheme.
- **Physical Downlink Shared Channel (PDSCH):** The PDSCH carries the downlink data to each user. It is important to note that the PDSCH can support modulation schemes such as QPSK, 16-QAM, and 64-QAM – depending on the channel conditions between the eNodeB and a specific user.
- **Physical Downlink Control Channel (PDCCH):** The PDCCH carries control information related to channel allocation.
- **Physical Multicast Channel (PMCH):** The PMCH channel is similar to the PDSCH channel in that it contains downlink data and can support the QPSK, 16-QAM, or 64-QAM modulation scheme. However, unlike the PDSCH, it is designed for broadcast services which have a point to multi-point orientation.
- **Physical Hybrid ARQ Indicator Channel (PHICH):** The PHICH is used to report the hybrid ARQ status. The eNodeB uses this channel to notify the user that is has successfully or unsuccessfully received uplink data.

Note that in addition to the downlink physical channels, the downlink signal also contains a number of reference and synchronization signals. Reference and synchronization signals allow the user to synchronize to the downlink burst, and enable effective demodulation of the transmissions. The location of the synchronization and reference signals, in addition to the downlink physical channels, are illustrated in **Figure 1.14**.

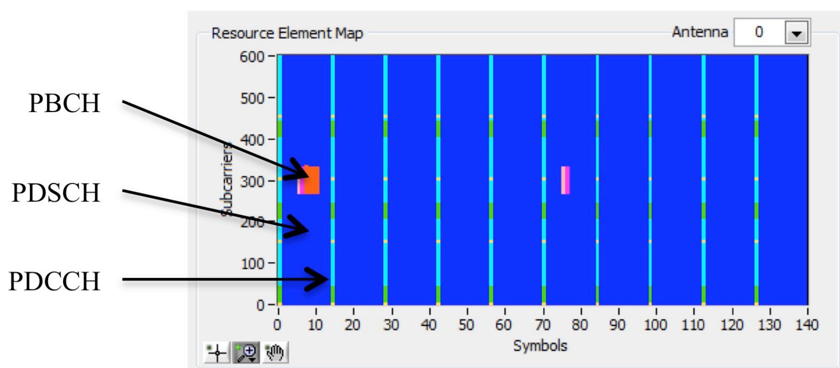


Figure 1.14. Physical Channel Allocation in a Typical LTE Downlink Transmission

The structure of physical channels in the uplink is simpler than that of the downlink. LTE contains three uplink channels that are designed to handle control or data information. These channels are described below:

- **Physical Uplink Control Channel (PUCCH):** The PUCCH caries uplink control information such as scheduling requests.
- **Physical Uplink Shared Channel (PUSCH):** The PUSCH carries the uplink data to each user. It is important to note that the PUSCH can support modulation schemes such as QPSK, 16-QAM, and 64-QAM – depending on the channel conditions between the eNodeB and a specific user.
- **Physical Random Access Channel (PRACH):** The PRACH carries control information related to synchronization and timing between the user and the eNodeB.

2. LTE Transmitter Measurements

The LTE uplink transmitter measurements are generally designed to ensure interoperability with other cellular and general wireless devices. For example, measurements such as minimum output power and spectrum measurements characterize the amount of unintended interference an LTE transmitter might produce during transmission. In addition, modulation quality is important because its measures the presence of signal impairments that might prevent a base station receiver from demodulating the transmissions.

While the full suite of LTE transmitter measurements are essential to characterize the performance of a handset, only a subset of these measurements are relevant when testing RF components such as power amplifiers (PAs) or diplexers. In general, only modulation quality (generally error vector) and spectral measurements (generally adjacent channel leakage ratio) are the primary figures of merit for RF components. Because these measurements describe the influence of non-ideal component behaviors - such as nonlinearity – on the quality of a transmitted signal, they are excellent metrics of component performance.

LTE transmitters measurements are defined by Section 6 of the 3GPP TS 36.521 specifications, and include requirements on transmit power, spectrum emissions, and modulation quality as illustrated in **Table 2.1**.

		Measurement Description	3GPP TS 36.521 Section
Power Measurements	Transmit Power	Maximum Output Power	6.2.2
		Maximum Power Reduction	6.2.3
		Additional Maximum Power Reduction	6.2.4
		Configured Transmitted Output Power	6.2.5
	Output Power Dynamics	Minimum Output Power	6.3.2
		Transmit OFF Power	6.3.3
		ON/OFF Time Mask	6.3.4
		Power Control	6.3.5
Signal Quality Measurements	Frequency Error	Frequency Error	6.5.1
	Transmit Modulation	Error Vector Magnitude (EVM)	6.5.2.1
		Carrier Leakage	6.5.2.2
		In-Band Emissions	6.5.2.3
		Spectral Flatness	6.5.2.4
Spectrum Measurements	Occupied Bandwidth		6.6.1
	Out-of-band Emissions	Spectrum Emissions Mask	6.6.2.1
		Adjacent Channel Leakage Ratio	6.6.2.3
	Spurious Emissions		6.6.3
	Transmit Intermodulation		6.7

Table 2.1. 3GPP TS 36.521 Transmitter Measurements

Test Setup Configuration

Test and measurement of fully integrated LTE handsets generally require a combination of a vector signal generator (VSG) and vector signal analyzer (VSA). When characterizing an LTE transmitter, a vector signal analyzer (VSA) is the preferred instrument. This instrument is ideal because of its ability not only to make modulation quality measurements, but also to make accurate power and spectrum measurements. Note that LTE transmit measurements are often performed in the characterization of discrete components such as diplexers or power amplifiers. When testing these devices, a vector signal generator (VSG) is also required to source the modulated signal to the device under test. Two example transmitter test setups are illustrated in **Figure 2.1**.

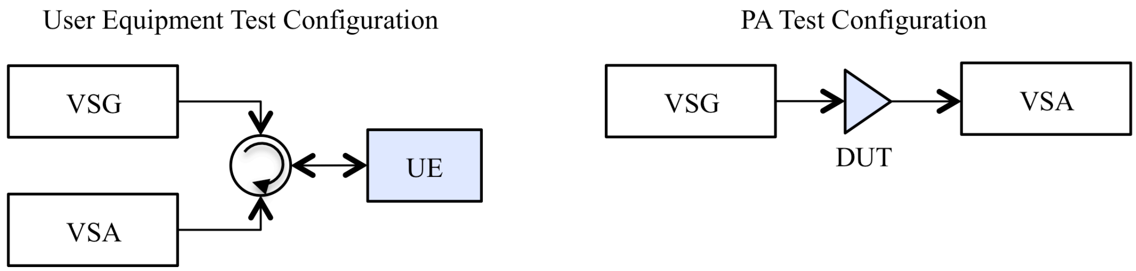


Figure 2.1. Test Setup Configuration for Handset and PA

As we observe in Figure 2.1, only a vector signal analyzer is required for the majority of LTE transmitter measurements on a handset – since the handset itself produces the stimulus. By contrast, one requires both a VSG and VSA to characterize components such as a PA or diplexer.

Power Measurements

LTE power measurements are generally designed to ensure that the transmitter is able to produce the appropriate range of power levels required for interoperability with an eNodeB. We can generally divide power measurements into two categories: transmit power measurements and output power dynamics measurements. Note that the transmit power specifications are designed to ensure that device is capable of producing an output power that is within a specific power tolerance. By contrast, the output power dynamics measurements characterize issues such as emissions when the radio is not transmitting.

Transmit Power

Transmit power measurements for LTE user equipment are specified by section 6.2 of the 3GPP TS 36.521 specifications and include: Maximum Output Power, Maximum Power Reduction (MPR), Additional Maximum Power Reduction (A-MPR), and Configured Transmitted Output Power.

LTE devices are designed to operate at a power range from -40 dBm to +23 dBm for Power Class 3 UE devices. The maximum output power test is designed to ensure that the UE does not interfere with neighboring cells or other handsets – and is defined for a wide range operating scenarios. An RF vector signal analyzer (VSA) can measure power either in the frequency domain or in the time domain. In the time domain, a VSA can measure power as a part of the power versus time (PVT) measurement trace - shown in **Figure 2.2** for a 10 MHz LTE signal.

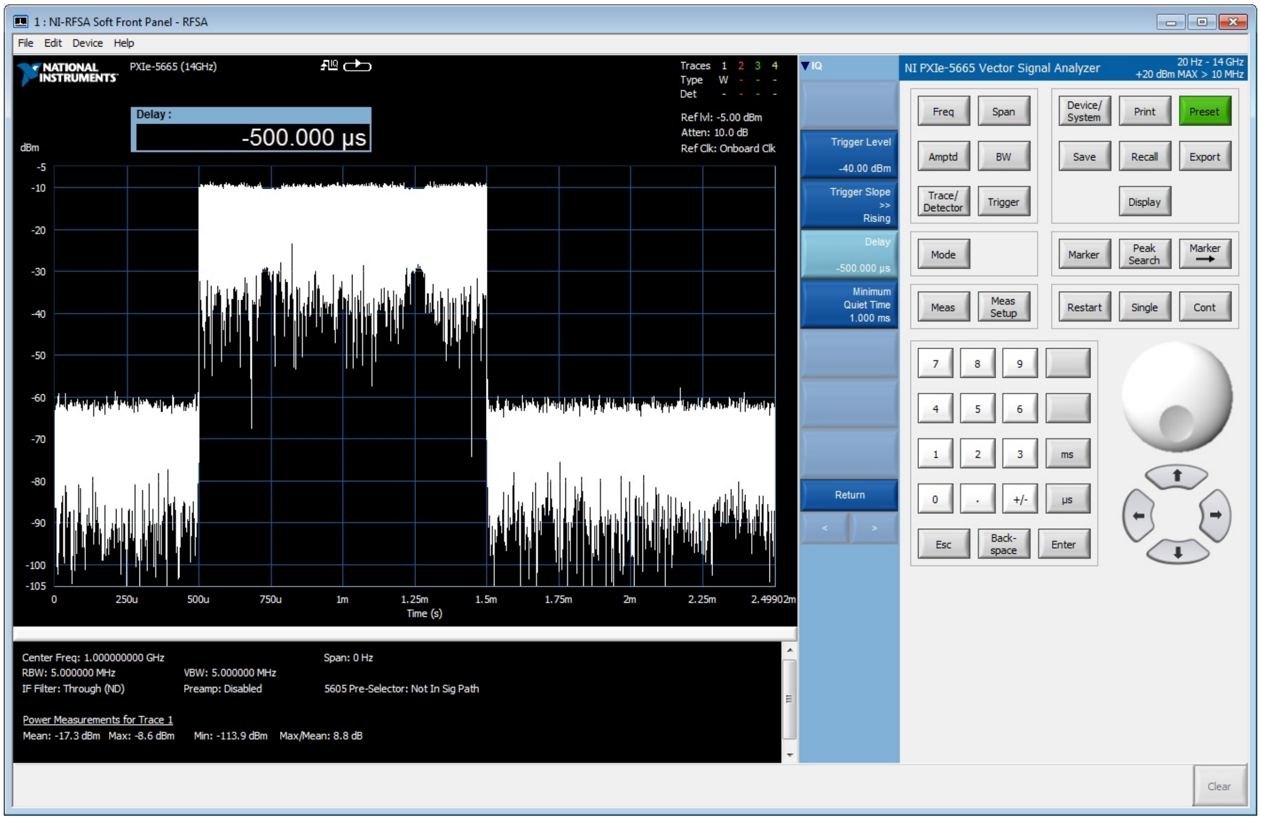


Figure 2.2. Power Versus Time Measurement

In the frequency domain, an LTE transmit power measurement is referred to as the channel power measurement, and is measured as an integrated power from a gated spectrum. Note that the measurement bandwidth for the channel power measurement is dependent on the channel bandwidth configuration – illustrated in **Table 2.2**.

	Channel Bandwidth Configuration					
	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Measurement Bandwidth (MHz)	1.08	2.7	4.5	9.0	13.5	18

Table 2.2. Measurement Bandwidth for Maximum Output Power

As we observe in **Table 2.2**, the measurement bandwidths defined for channel power measurements are notably smaller than allocated bandwidth for the channel. In practice, the occupied bandwidth of an LTE signal is less than the channel spacing or specified bandwidth. **Figure 2.3** illustrates an LTE channel power measurement for a 10 MHz channel configuration. In this channel configuration, the measurement bandwidth is 9 MHz.

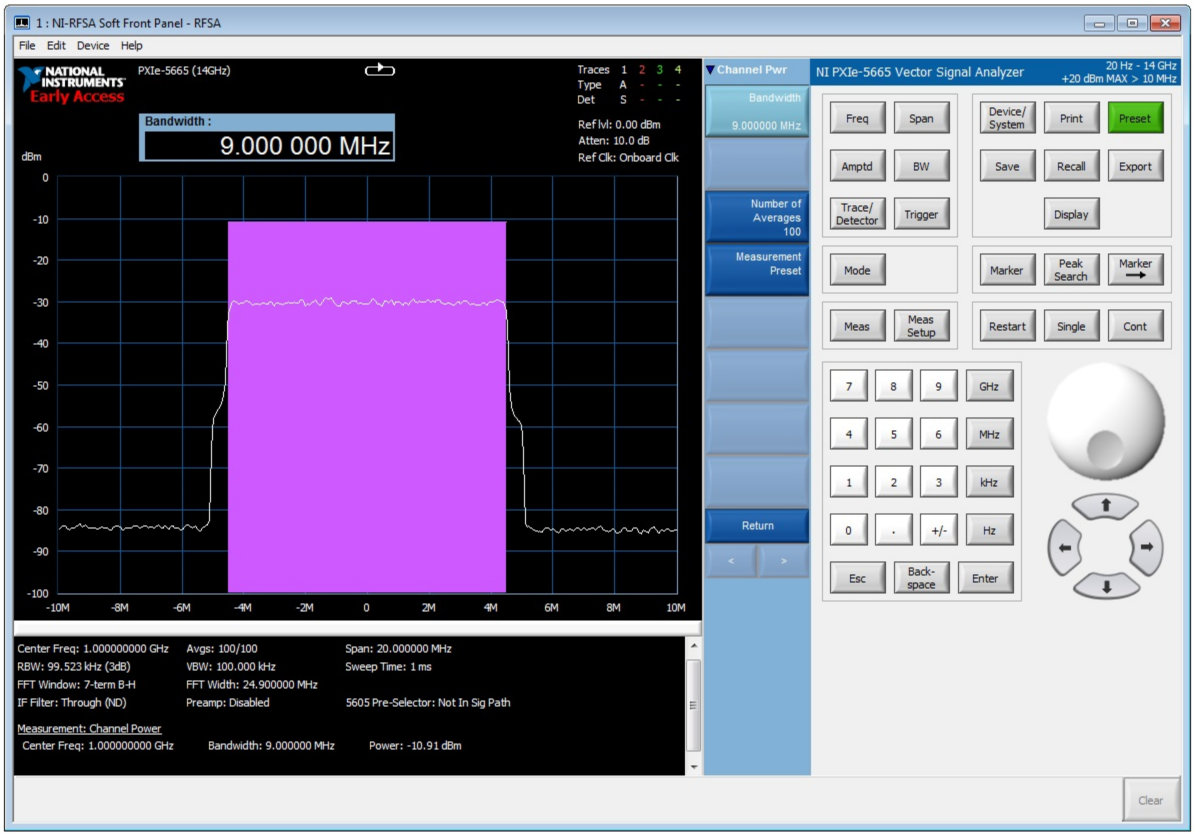


Figure 2.3 Channel Power Measurement of 10 MHz LTE Signal

UE Maximum Output Power

The maximum output power requirements for LTE user equipment is specified by section 6.2.2 of the 3GPP TS 36.521 specifications and contains requirements for both the maximum output power as well as the output power tolerance. For class 3 devices, the maximum output power is +23 dBm for all bands with the nominal power tolerance of ± 2.0 dB for most E-UTRA bands. As we observe in **Table 2.3**, the specific tolerance depends on the E-UTRA band of operation.

E-UTRA Bands	Class 3 Power (dBm)	Tolerance (dB)
1-14	+ 23	± 2.0
…		
17-21	+ 23	± 2.0
22	+ 23	+2.0 / -3.5
23-27	+ 23	± 2.0
28	+ 23	+2.0 / -2.5
…		
33-41	+ 23	± 2.0
42-43	+ 23	+2.0 / -3.0

Table 2.3. UE Maximum Output Power and Nominal Tolerance[1]

Power tolerance can be defined as the acceptable power range over which a transmitter can operate at when configured to output at its maximum output power. For example, the maximum output criteria for E-UTRA band 1 is such that a device configured to transmit at its maximum output power must produce a power level that is between +21 dBm and +25 dBm (+23 dBm ± 2 dB).
According to the 3GPP specifications, UE maximum output power must be measured using the QPSK modulation scheme. In addition, the device must meet these specifications over a range of allocated resource blocks (RBs). As we observe in **Table 2.4**, the LTE transmitter signal is tested with various RB allocations that can be as low as 1 and as high as 18 for FDD and TDD, with QPSK modulated symbols for all bandwidths. Thus, the signal is tested at less than full occupancy for all bandwidths.

[1] Recreated from Table 6.2.2.3.1 of the 3GPP TS 36.521 Specifications

Channel Bandwidth (MHz)	Modulation	RB allocation	
		FDD	TDD
1.4	QPSK	1	1
1.4	QPSK	5	5
3	QPSK	1	1
3	QPSK	4	4
5	QPSK	1	1
5	QPSK	8	8
10	QPSK	1	1
10	QPSK	12	12
15	QPSK	1	1
15	QPSK	16	16
20	QPSK	1	1
20	QPSK	18	18

Table 2.4. Resource Block Allocation for UE Maximum Output Power Measurement[2]

UE maximum output power test measures the power transmitted by the UE in the channel bandwidth. Although Table 2.4 provides nominal tolerance requirements for the measurement, **Table 2.5** provides wider and enforceable tolerance requirements for the same measurement for the subset of configurations.

E-UTRA Bands	Class 3 Power (dBm)	Tolerance (dB)
1-14	+ 23	± 2.7
…		
17-21	+ 23	± 2.7
22	+ 23	+3.0 / -4.5
23-27	+ 23	± 2.0
28	+ 23	+2.7 / -3.2
…		
33-41	+ 23	± 2.7
42-43	+ 23	+3.0 / -4.0
44	+23	+2.7 / [-3.7]

Table 2.5. Relaxed and Enforceable Maximum Power Test Tolerances[3]

---

[2] Recreated from Table 6.2.2.4.1-1 of 3GPP TS 36.521 Specifications

[3] Recreated from Table 6.2.2.5.1 of the 3GPP TS 36.521 Specifications

Maximum Power Reduction

Maximum Power Reduction (MPR) specifies the allowed decrease in the maximum power transmitted in order to enable the device to pass transmitter adjacent channel leakage ratio (ACLR) requirements. This requirement is specified for various modulation schemes and LTE transmission bandwidths. The MPR specification is important because although a handset is capable of operating at power levels as high as +23 dBm, device components such as the transmit power amplifier (PA) often operate in their nonlinear region at maximum power output, thus occasionally violating the LTE ACLR requirements at these power levels, it. Hence, it is useful to reduce the transmit power slightly so that the PA operates in a more linear region. MPR specification defines the maximum power reduction that is allowable in order to meet the LTE standard's transmitter ACLR requirements.

It is important to note that while the LTE uplink SC-FDMA signal has a lower peak to average power ratio (PAPR) than the LTE downlink signal of OFDMA, the uplink SC-FDMA signal still has a much higher PAPR than that of the uplink WCDMA signal. Higher PAPR increases the required back-off of output power and makes the PA of the handset more expensive and less efficient. To ease the design of the PA, MPR is an important parameter for both LTE and WCDMA.

Because the PAPR of the SC-FDMA LTE uplink signal is dependent on the modulation scheme and number of resource blocks used in transmission, the LTE specifications provide MPR requirements for various signal configurations. **Table 2.6** provides the transmission resource block allocations and modulation schemes for the maximum power reductions.

Modulation	Channel Bandwidth Configuration						MPR (dB)
	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz	
QPSK	> 5	> 4	> 8	> 12	> 16	> 18	≤ 1
16-QAM	≤ 5	≤ 8	≤ 12	≤ 12	≤ 16	≤ 18	≤ 1
16-QAM	> 5	> 4	> 12	> 16	> 16	> 18	≤ 2

***Table 2.6. Maximum Power Reduction for Power Class 3 Devices*[4]**

As a result of the MPR requirements, test configurations for power measurements can include additional modulation schemes and resource block allocations. Thus, although **Tables 2.3 and 2.4** describe measurement criteria and limits with the QPSK modulation scheme with one RB and less-than-full RB allocations, **Table 2.7** provides more detailed configurations of the remaining RB allocations. These three tables together describe the test configurations for both partial and full RB allocations for all bandwidths, duplex schemes, and the QPSK and 16-QAM modulation schemes and are captured in a single table in **Table 2.7**.

[4] Recreated from Table 6.2.3.3.1 of the 3GPP TS 36.521 Specifications

Bandwidth Configuration	Modulation Scheme	Resource Blocks
1.4 MHz	QPSK	5
1.4 MHz	QPSK	6
1.4 MHz	16-QAM	5
1.4 MHz	16-QAM	6
3 MHz	QPSK	4
3 MHz	QPSK	15
3 MHz	16-QAM	4
3 MHz	16-QAM	15
5 MHz	QPSK	8
5 MHz	QPSK	25
5 MHz	16-QAM	8
5 MHz	16-QAM	25
10 MHz	QPSK	12
10 MHz	QPSK	50
10 MHz	16-QAM	12
10 MHz	16-QAM	50
15 MHz	QPSK	16
15 MHz	QPSK	75
15 MHz	16-QAM	16
15 MHz	16-QAM	75
20 MHz	QPSK	18
20 MHz	QPSK	100
20 MHz	16-QAM	18
20 MHz	16-QAM	100

Table 2.7. Expanded Test Configurations for Power Measurements[5]

Note from **Table 2.7** that the one must test the UE for the lowest bandwidth configuration, the 5 MHz and 10 MHz bandwidth configurations, and the highest bandwidth configuration.

The addition of more complex signal configurations with a wide range of combinations of modulation schemes and number of allocated resource blocks also leads to a greatly expanded specification for maximum output power tolerance. As we observe in **Table 2.8,** the upper and lower tolerances of the maximum output power can be derived

[5] Recreated from Table 6.2.3.4.1-1 of the 3GPP TS 136.521 Specifications

using the maximum power reduction for various transmission configurations. The maximum power reduction is thus an extension of the maximum output power measurement with the tolerances for various configurations illustrated here.

E-UTRA Bands	Class 3 Power (dBm)	QPSK Partial RB Allocation Tolerance (dB)	QPSK Full RB Allocation Tolerance (dB)	16-QAM Partial RB Allocation Tolerance (dB)	16-QAM Full RB Allocation Tolerance (dB)
1-21	+ 23	± 2.7	+2.7 / -3.7	+2.7 / -3.7	+2.7 / -4.7
22	+ 23	+3.0 / -4.5	+3.0 / -5.5	+3.0 / -5.5	+3.0 / -6.5
23-27	+ 23	± 2.7	+2.7 / -3.7	+2.7 / -3.7	+2.7 / -4.7
28	+ 23	+2.7 / -3.2	+2.7 / -4.2	+2.7 / -4.2	+2.7 / -5.2
…					
33-41	+ 23	± 2.7	+2.7 / -3.7	+2.7 / -3.7	+2.7 / -4.7
42-43	+ 23	+3.0 / -4.0	+3.0 / -5.0	+3.0 / -5.0	+3.0 / -6.0

***Table 2.8: UE Power Class Test Requirements*[6]**

Additional Maximum Power Reduction

Additional maximum power reduction (A-MPR) is an extension of the tolerances applicable to the maximum output power test in specific deployment scenarios. These specific deployment scenarios are signaled through the Network Signaling Values (NS_x) that are communicated to the UE during cell handover or broadcast message. The default value for all bands is NS_01.

These A-MPR requirements help enforce region-specific spurious emissions requirements. For example, network signal values NS_03, NS_04 or NS_06 are designed to ensure transmitters satisfy FCC requirements in the US. By contrast, network signal value NS_05 adheres to Personal Handy-Phone System (PHS) band requirements in Japan.

Due to the highly varied requirements, the specification mandates only a subset of values for channel bandwidths, resource block allocations and additional maximum power reduction for a particular E-UTRA band.

Note that the 3GPP TS 36.151 specifications specify 18 unique network signaling values for A-MPR. Each network signaling value is applicable to specific E-UTRA bands, channel bandwidths, number of resource blocks. An example of a subset of network signaling values is shown in **Table 2.9**.

[6] Recreated from Table 6.2.3.5-1 of 3GPP TS 36.151 Specifications

Network Signaling Value	Requirements (sub-clause)	E-Utra band	Channel Bandwidth (10 MHz)	Resource Blocks	A-MPR (dB)
NS_01	6.6.2.1.1	Table 5.2-1	1.4, 3, 5, 10, 15, 20	Table 5.4.2-1	N/A
NS_03	6.6.2.2.3.1	2, 4, 10, 23, 25, 35, 36	3	> 5	≤ 1
			5	> 6	≤ 1
			10	> 6	≤ 1
			15	> 8	≤ 1
			20	> 10	≤ 1
NS_04	6.6.2.2.3.2	41	5	> 6	≤ 1
			10, 15, 20	Table 6.2.4.3-4	
NS_05	6.6.3.3.3.1	1	10, 15, 20	≥ 50	≤ 1
NS_06	6.6.2.2.3.3	12, 13, 14, 17	1.4, 3, 5, 10	Table 5.4.2-1	N/A

Table 2.9. A-MPR and Corresponding Spectrum Emissions Requirements[7]

In addition to providing a limit on the addition maximum power reduction (in dB), each network signaling value also prescribes a specific spectrum emissions subclause. As we observe in **Table 2.9**, the transmitter must meet the additional "special case" spectrum emissions requirement (there are several) for each network signaling value - rather than merely meeting the general spectrum emissions requirement. As we observe in the "requirements" column in **Table 2.9**, the additional spectrum emissions requirements are specified by an additional table in the 3GPP TS 36.151 specifications.

Configured Transmitted Output Power

Unlike the transmit power measurement, which defies output power tolerances for operation at the maximum output power (+23 dBm for LTE Class 3 devices), the configured transmitted output power specification defines output power tolerances for specific output power operating points. As a result, this specification verifies that the UE does not exceed the tolerances for a partially-configured LTE-transmitted signal at a range of nominal power values. As we observe in **Table 2.10,** the 3GPP 36.521 specifications define fairly wide power tolerances for transmitters operating at power levels ranging from -10 dBm to +15 dBm.

[7] Recreated from Table 6.2.4.3-1 of the 3GPP 35.151 Specifications

Test Point	Channel Bandwidth Configuration					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
UE Output Power Test Point 1 (-10 dBm)	For carrier frequency f ≤ 3.0 GHz: -10 dBm ± 7.7 dB For carrier frequency 3.0 GHz < f ≤ 4.2 GHz: -10 dBm ± 8.0 dB					
UE Output Power Test Point 2 (+10 dBm)	For carrier frequency f ≤ 3.0 GHz: +10 dBm ± 6.7 dB For carrier frequency 3.0 GHz < f ≤ 4.2 GHz: +10 dBm ± 7.0 dB					
UE Output Power Test Point 3 (+15 dBm)	For carrier frequency f ≤ 3.0 GHz: +15 dBm ± 5.7 dB For carrier frequency 3.0 GHz < f ≤ 4.2 GHz: _15 dBm ± 6.0 dB					

Table 2.10. Configured UE Output Power[8]

When testing configured transmitted output power, the device can be configured to generate a partially-filled LTE signal, which is QPSK modulated. **Table 2.10** describes three specific operating points for the device at output powers of -10, +10, and +15 dBm.

Output Power Dynamics

Output power dynamics characterize the ability of the handset to control its output power – particularly in scenarios where it is turned off. These measurements apply only to the handset – and not to discrete components – because the output power dynamics measurements are determined by the intelligence that the device applies to control its own behavior. Output power dynamics includes the following measurements: Minimum Output Power, Transmit OFF Power, Transmit ON/OFF Power, and Power Control

Minimum Output Power

When the transmitter is configured to the minimum power control value, the UE must transmit at the specified limit (-40 dBm) or below this value. The minimum output power test measures the power generated by the UE when the UE power is set to the smallest possible value. This measurement can be made by measuring the power in the measurement bandwidths on the spectrum of the signal.

When measuring minimum output power, the RF signal analyzer is configured to perform a power-in-band measurement for the appropriate measurement bandwidth as specified in **Table 2.11**. The measurement bandwidths are slightly smaller than the channel bandwidths because the edges of the channel bandwidths contain null subcarriers that do not contain data. The minimum output power test is performed at maximum resource block allocation. Because the resource block allocation is maximum, the measurement bandwidth for 1.4 MHz and 20 MHz signal configurations are illustrated in **Equations 2.1 and 2.2**.

[8] Recreated from Table 6.2.5.5.1 of the 3GPP TS 36.521 Specifications

$$Signal\ Bandwidth_{1.4\ MHz\ Channel} = 6\ RB \times 12\ subcarriers \times 15\ kHz = 1.08\ MHz$$

$$Signal\ Bandwidth_{20\ MHz\ Channel} = 100\ RB \times 12\ subcarriers \times 15\ kHz = 18\ MHz$$

Equations 2.1 and 2.2. Signal bandwidth calculations for 1.4 MHz and 20 MHz LTE channels

While one can intuitively calculate the expected occupied bandwidth of as signal in each configuration, **Table 2.11** illustrates the measurement bandwidth for minimum output power.

	Channel Bandwidth Configuration					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Minimum Output Power (dBm)	- 40					
Transmission Bandwidth (MHz)	1.08	2.7	4.5	9.0	13.5	18

***Table 2.11. Measurement Bandwidth Settings for Minimum Output Power*[9]**

Table 4 thus sets the maximum threshold for the minimum power transmitted by the UE. The exact thresholds for the UE minimum output power are outlined in **Table 2.12**. Power can be measured in the frequency domain by using either a swept spectrum analyzer or an FFT-based spectrum analyzer.

	Channel Bandwidth Configuration					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Minimum Output Power (dBm)	For carrier frequency f ≤ 3.0 GHz: ≤ -39 For carrier frequency 3.0 GHz < f ≤ 4.2 GHz: ≤ -38.7					
Transmission Bandwidth (MHz)	1.08	2.7	4.5	9.0	13.5	18

***Table 2.12. Minimum Output Power Requirements*[10]**

Note that both the maximum transmitted output power and minimum output power tests ensure that the transmitted UE power is below a prescribed threshold. The threshold specified for the maximum power test is +23 dBm and that specified for the minimum power test is -40 dBm. Transmission at excess power causes increased interference for the other UEs in the cell and reduces their cell coverage areas.

Transmit OFF Power

A handset transmits residual output power even when it is not actively sending data. The transmit OFF power measurement is used to characterize these transmissions. Unlike the minimum output power specification, which ensures that a UE can produce an LTE uplink signal at a relatively lower output power during data transmission, the

---

[9] Recreated from Table 6.3.2.31-1 of the 3GPP TS 36.521 Specifications

[10] Recreated from Table 6.3.2.5-1 of the 3GPP TS 36.521 Specifications

transmit OFF power prescribes a requirement for the maximum power a UE can emit during periods when the UE is not allowed to transmit or during periods when the UE is not transmitting a sub-frame. During discontinuous transmission and measurement gaps, the UE is not considered to be OFF.

Transmit OFF power is defined as the mean power in a duration of at least one sub-frame (1ms) excluding any transient periods. The residual power transmitted during off periods must be ≤-50 dBm. The measurement bandwidths are shown in **Table 2.13**. Similar to the minimum output power measurement, the measurement bandwidth is slightly smaller than the channel bandwidths because the edges of the channel bandwidths are not occupied by any subcarriers.

	Channel Bandwidth Configuration					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Minimum Output Power (dBm)	-50					
Transmission Bandwidth (MHz)	1.08	2.7	4.5	9.0	13.5	18

Table 2.13 Measurement Bandwidth Settings for Transmit OFF Power[11]

ON/OFF Time Mask

The transmitter ON/OFF mask measurement, defined by Section 6.3.4 of the 3GPP 35.521 specification, specifies the maximum ramp-up time for a transmitted signal when transitioning from the OFF state to the ON state, and vice versa. This test ensures that the transition from one state to another is adequately controlled. If the UE transmits more power than prescribed, it increases interference in other channels or introduces errors in the uplink channel. There are two types of ON/OFF time mask measurements: the General ON/OFF time mask and the PRACH and SRS time mask.

The General ON/OFF time mask defines the observation period between Transmit OFF and ON power and between Transmit ON and OFF power. ON/OFF scenarios include the beginning or end of transmission (DTX) measurement gap and contiguous and non-contiguous transmission.

The OFF power measurement period is defined in a duration of at least one sub-frame excluding any transient periods. ON power is defined as the mean power over one sub-frame excluding any transient period. As we observe in Figure 3, the mask requires that the transition from OFF power to ON power must occur in a transient time of 20 µs or less. Thus, the start of ON power for the purpose of measurement is 20µs after the start of the sub-frame as seen in **Figure 2.4** while the end of the ON power is at the end of the sub-frame.

[11] Recreated from Table 6.3.3.1-1 in the 3GPP 36.521 Specifications

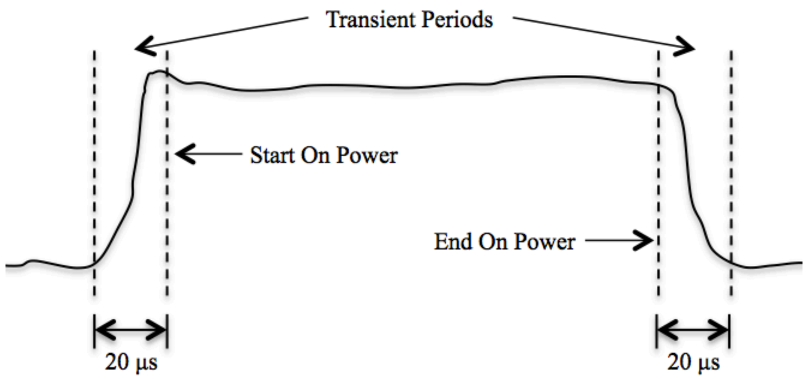


Figure 2.4 General ON/OFF Time Mask Measurement)[12]

To measure the ON-OFF time mask measurement, simply acquire a power-versus-time (PvT) trace of an LTE burst. As we observe in **Figure 2.5**, a time-domain PvT measurement provides a full power profile of the burst.

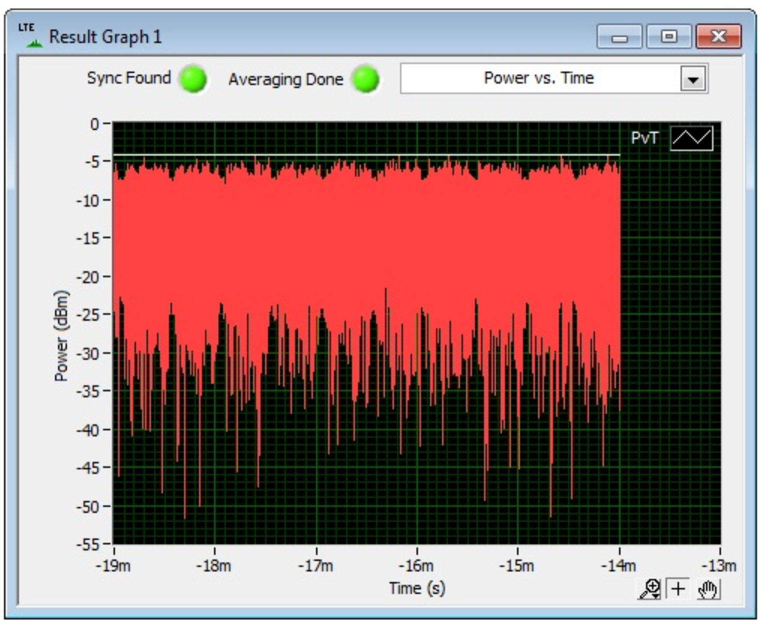


Figure 2.5 Power Versus Time Measurement

[12] Recreated from Figure 6.3.4.1.3-1 in the 3GPP TS 36.521 Specifications

ON/OFF Time Mask Settings

When measuring the ON-OFF time mask, one must configure the transmitter with full RB allocation and with QPSK-modulated symbols. In addition, the transmitter is configured to transmit on sub-frame 2 of every radio frame. As a result, the signal has three parts: the OFF sub-frame prior to the PUSCH sub-frame, the ON sub-frame during the UE PUSCH transmission excluding a transient period of 20us at the beginning of the sub-frame, and the OFF sub-frame following the PUSCH sub-frame excluding a transient period of 20us at the beginning of the sub-frame. The ON-OFF time mask measurement can be recorded by calculating the power in the PvT capture of the transmitted signal.

The limits of the ON/OFF time mask measurement are specified in three parts of the frame as described in the **Table 2.14.** The transmission OFF powers are similar to those in the Transmit OFF power test. Note that the transmission ON powers are derived such that the power per unit bandwidth (also known as power spectral density) is the same for all the signal bandwidths. Thus if the expected ON power is -2.6 dBm for a measurement bandwidth of 18 MHz, the expected ON power for a measurement bandwidth of 9 MHz is 3 dB lower (in this case -5.6 dBm).

	Channel Bandwidth Configuration					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Minimum Output Power (dBm)	For carrier frequency f ≤ 3.0 GHz: ≤ -48.5 For carrier frequency 3.0 GHz < f ≤ 4.2 GHz: ≤ -48.2					
Transmission OFF Measurement Bandwidth (MHz)	1.08	2.7	4.5	9.0	13.5	18
Expeted Transmission ON Measured Power (dBm)	-14.8	-10.8	-8.6	-5.6	-3.9	-2.6
ON power tolerance (dB) f ≤ 3.0 GHz 3.0 GHz < f ≤ 4.2 GHz	 ± 7.5 ± 7.8	 ± 7.5 ± 7.8	 ± 7.5 ± 7.8	 ± 7.5 ± 7.8	 ± 7.5 ± 7.8	 ± 7.5 ± 7.8

Table 2.14. General ON/OFF Time Mask Measurement Requirements[13]

In addition to the general ON/OFF time mask requirements, Section 6.3.4.2 of the 3GPP TS 36.531 specifications also prescribes Physical Random Access Channel (PRACH) and Sounding Reference Signals (SRS) time mask measurements, which have similar qualitative requirements as the General ON/OFF time masks, for the transmitted signals of PRACH and SRS. Given the similarity of these measurements, the PRACH and SRS time mask measurements are not discussed in this document.

Power Control

An LTE handset must be able to regulate its transmitted output power for a variety of reasons. When the UE is closer to the eNodeB, it is useful to generate at a lower output power to minimize potential interference with handsets closer to the cell edge. By contrast, a UE closer to the band edge might be required to generate at a higher

[13] Recreated from Table 6.3.4.1.5-1 the 3GPP TS 36.521 Specifications

output power to ensure the eNodeB can demodulate the uplink signal without incurring significant bit errors. The power control measurements are used to characterize a transmitter's ability to control its output power. This measurement category actually contains three distinct, though interrelated, measurements. These include the following:

- Absolute Power Tolerance
- Relative Power Tolerance
- Aggregate Power Tolerance

Absolute Power Tolerance

Absolute power tolerance is the ability of the UE transmitter to set its initial output power to a precise value for the first sub-frame at the start of a contiguous transmission or non-contiguous transmission, with a transmission gap larger than 20ms. As we observe in **Table 2.15**, the absolute power tolerance requirements are ±9 dB for normal conditions and ±12 dB for extreme conditions.

Conditions	Tolerance (dB)
Normal Conditions	± 9.0
Extreme Conditions	± 12.0

Table 2.15. Minimum Requirements for Absolute Power Control for the LTE Transmitted Signal[14]

In addition to having general tolerances for absolute power control, LTE transmitters also have absolute power control tolerances at specific power levels. These specific power tolerances at each operating point are illustrated in **Table 2.16**, which is recreated from Tables 6.3.5.1.5-1 and 6.3.5.1.5-2 of the 3GPP TS 36.251 specifications. The absolute power tolerance measurement must be made with a maximum resource block allocation using the QPSK modulation scheme.

[14] Recreated from Table 6.3.5.1.5-1 of the 3GPP TS 36.521 Specifications

	Channel Bandwidth Configuration					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Expected Measured Power - Normal Conditions (dBm)	-14.8	-10.8	-8.6	-5.6	-3.9	-2.6
Power Tolerance (dB) f ≤ 3.0 GHz 3.0 GHz < f ≤ 4.2 GHz	 ± 10.0 ± 10.4	 ± 10.0 ± 10.4	 ± 10.0 ± 10.4	 ± 10.0 ± 10.4	 ± 10.0 ± 10.4	 ± 10.0 ± 10.4
Expected Measured Power - Extreme Conditions (dBm)	-14.8	-10.8	-8.6	-5.6	-3.9	-2.6
Power Tolerance (dB) f ≤ 3.0 GHz 3.0 GHz < f ≤ 4.2 GHz	 ± 13.0 ± 13.4	 ± 13.0 ± 13.4	 ± 13.0 ± 13.4	 ± 13.0 ± 13.4	 ± 13.0 ± 13.4	 ± 13.0 ± 13.4
Expected Measured Power - Normal Conditions (dBm)	-2.8	+1.2	+3.4	+6.4	+8.2	+9.4
Power Tolerance (dB) f ≤ 3.0 GHz 3.0 GHz < f ≤ 4.2 GHz	 ± 10.0 ± 10.4	 ± 10.0 ± 10.4	 ± 10.0 ± 10.4	 ± 10.0 ± 10.4	 ± 10.0 ± 10.4	 ± 10.0 ± 10.4
Expected Measured Power - Extreme Conditions (dBm)	-2.8	+1.2	+3.4	+6.4	+8.2	+9.4
Power Tolerance (dB) f ≤ 3.0 GHz 3.0 GHz < f ≤ 4.2 GHz	 ± 13.0 ± 13.4	 ± 13.0 ± 13.4	 ± 13.0 ± 13.4	 ± 13.0 ± 13.4	 ± 13.0 ± 13.4	 ± 13.0 ± 13.4

Table 2.16. Absolute Power Control Requirements for LTE Transmissions[15]

Relative Power Tolerance

By contrast to the absolute power tolerance measurement, relative power tolerance characterizes the ability of the UE transmitter to set its output power relative to the power of the most recently transmitted sub-frame. This specification requires that the transmission gap between these sub-frames is ≤ 20 ms, and is a metric of the maximum error between the desired change in power level and the actual change in power level. The measurement limits for relative power tolerance are described in **Table 2.17**.

[15] Recreated from Tables 6.3.5.1.5-1 and 6.3.5.1.5-2 from the 3GPP TS 36.251 Specifications

Power Step ΔP - Up or Down (dB)	All Combinations of PUSCH and PUCCH Transitions (dB)	All Combinations of PUSCH/PUCCH and SRS Transitions Between Subframes (dB)	PRACH (dB)
ΔP < 2	± 2.5	± 3.0	± 2.5
2 ≤ ΔP < 3	± 3.0	± 4.0	± 3.0
3 ≤ ΔP < 4	± 3.5	± 5.0	± 3.5
4 ≤ ΔP ≤ 10	± 4.0	± 6.0	± 4.0
10 ≤ ΔP < 15	± 5.0	± 8.0	± 5.0
15 ≤ ΔP	± 6.0	± 9.0	± 6.0

Table 2.17. Relative Power Tolerance Limits for LTE User Equipment[16]

Aggregate Power Control Tolerance
Aggregate power control tolerance describes the ability of a UE to maintain its power in a non-contiguous transmission mode. This measurement defines the allowable power variation within a 21 ms interval in response to 0 dB Transmitter Power Control (TPC) commands. As we observe in **Table 2.18**, the allowable aggregate power control tolerance is up to ± 2.5 dB or ± 3.5 dB, depending on the uplink channel.

TPC Command	UL Channel	Aggregate Power Tolerance Within 21ms
0 dB	PUCCH	± 2.5 dB
0 dB	PUSCH	± 3.5 dB

Table 2.18. Aggregate power tolerance limits for LTE user equipment[17]

The aggregate power tolerance limits are defined for the full output power range of the device. For class 3 devices, these tolerances must be adhered to from -40 dBm to 23dBm. When performing aggregate power tolerance measurement, the transmitter is configured to have partially-allocated resource blocks using the QPSK modulation scheme as shown in **Table 2.19** for an uplink PUSCH transmission.

[16] Recreated from Table 6.3.5.2.3-1 of the 3GPP TS 36.251 Specifications

[17] Recreated from Table 6.3.5.3.3-1 of the 3GPP TS 36.251 Specifications

Bandwidth Configuration	Modulation Scheme	RB Allocation	
		FDD	TDD
1.4 MHz	QPSK	1	1
3 MHz	QPSK	4	4
5 MHz	QPSK	8	8
10 MHz	QPSK	12	12
15 MHz	QPSK	16	16
20 MHz	QPSK	18	18

Table 2.19. Aggregate Power Tolerance Configuration for PUSCH LTE User Equipment[18]

Spectrum Measurements

LTE spectrum measurements are designed to characterize potential for emissions into both in-band and out-of-band EUTRA or UTRA channels. Because, electromagnetic spectrum is a valuable and expensive resource, it is important to be able to measure the usage of spectrum to ensure its fair and legal occupancy.

Section 6.6 of the 3GPP TS 36.521-1 specifications defines three specific LTE spectrum measurements including: occupied bandwidth, out-of-band (OOB) emissions, and spurious emissions. Out-of-band emissions requirements are probably the most common LTE spectrum measurement – as these requirements apply specifically to both handsets and discrete components such as power amplifiers. The out-of-band emissions requirements include the spectral emissions mask (SEM) and adjacent channel leakage ratio (ACLR) measurements.

Occupied Bandwidth

Occupied bandwidth is the most fundamental LTE spectral emissions measurement, and is defined as the bandwidth containing 99 % of the total integrated mean power of the transmitted spectrum on the assigned channel. Exceeding the bandwidth requirements will cause interference in adjacent channels leading to bit errors in adjacent channel transmissions. Excess spectral content is typically caused by impairments in the transmitter's DAC-to-antenna section.

Section 6.6 of the 3GPP TS 36.521-1 specifications prescribe the maximum bandwidth over which 99% of the channel power can be spread. These limits are illustrated in **Table 2.20**.

	Channel Bandwidth Configuration					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Channel Bandwidth (MHz)	1.4	3	5	10	15	20

Table 2.20. Occupied Bandwidth Measured Bandwidth is Equal to the Bandwidth Configuration[19]

[18] Recreated from a Subset of Information in Table 6.3.5.3.4.1-2 of the 3GPP 36.251 Specifications

The occupied bandwidth measurement is fundamentally a frequency domain measurement and it requires one to configure the RF signal analyzer to a span that is least two times the bandwidth of the transmitted signal. Note that when using swept-tuned spectrum analyzer, one must use a Gaussian filter. **Figure 2.6** shows a spectrum used to calculate the occupied bandwidth.

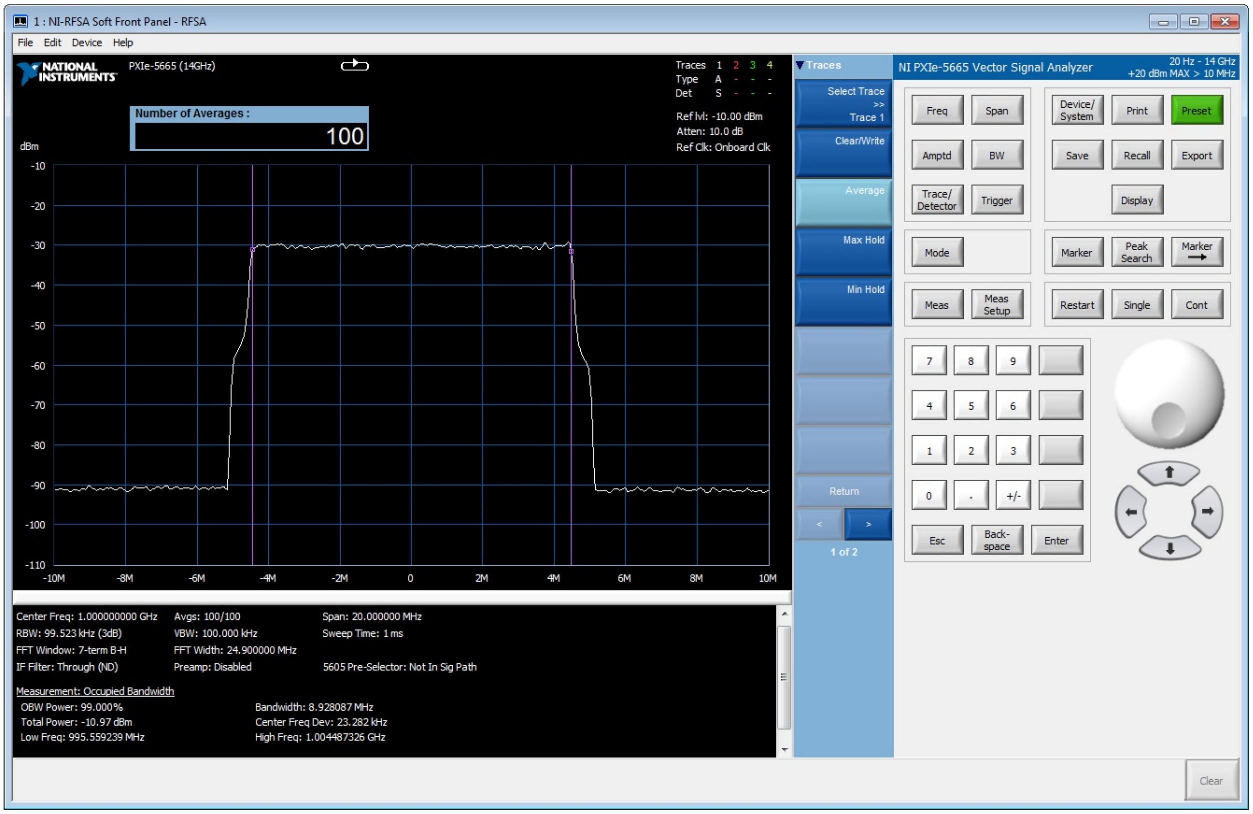


Figure 2.6. Occupied Bandwidth Measurement.

The occupied bandwidth measurement requires a measurement interval of one active subframe. The process for measuring occupied bandwidth begins with summing all power levels at each frequency bin (integrated power), including out-of-band content, to arrive at a result for the total power. The lower frequency bound is defined as the lower range of frequency bins that contain 0.5% of the total power. Similarly, the upper frequency bound is defined as the upper range of frequency bins that contain 0.5% of the total power. The difference between the upper and lower frequencies gives the occupied bandwidth.

---

[19] Recreated from Table 6.6 of the 3GPP TS 36.521 specifications

Out-of-band Emissions

The LTE out-of-band emissions specification characterizes both integrated and spurious emissions that a transmitter emits into adjacent bands. Section 6.6.32 of the 3GPP 36.251 specifications defines two specific measurements for the out-of-band emission requirements and includes:

- Spectrum Emissions Mask (SEM)
- Adjacent Channel Leakage Ratio (ACLR)

Although SEM and ACLR measurements are similar in that both measure power in adjacent bands, there are notable differences between the two measurements. In general, the SEM measurement characterizes emissions in relatively narrow bandwidths, while ACLR measures adjacent power in the bandwidth of a full channel. As a result SEM is more frequently used to identify spurious products, while ACLR is more frequently used to characterize the non-linearity of a transmitter. ACLR is considered the more difficult out-of-band emissions measurement and is usually limited by the linearity of the output power amplifier of the LTE transmitter.

Spectrum Emissions Mask

The spectrum emission mask defines maximum power that the transmitter can emit in a defined bandwidth at a range of frequency offsets from the center channel. Frequency offsets range from 0 MHz to 25 MHz away from the band edge of the in-use channel. The emissions mask is computed by comparing the output spectrum of the transmitter to a mask that is defined both by its frequency offset and its measurement bandwidth. As we observe in **Table 2.21**, the SEM measurement uses a measurement bandwidth of 30 kHz for close-in emissions.

Spectrum emission limit (dBm)/Channel bandwidth							
Δf_{OOB} (MHz)	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz	Measurement Bandwidth
±0-1	-10	-13	-15	-18	-20	-21	30 kHz
±1-2.5	-10	-10	-10	-10	-10	-10	1 MHz
±2.5-2.8	-25	-10	-10	-10	-10	-10	1 MHz
±2.8-5		-10	-10	-10	-10	-10	1 MHz
±5-6		-25	-13	-13	-13	-13	1 MHz
±6-10			-25	-13	-13	-13	1 MHz
±10-15				-25	-13	-13	1 MHz
±15-20					-25	-13	1 MHz
±20-25						-25	1 MHz

Table 2.21. Tabular form of LTE Spectrum Emissions Mask Measurement[20]

[20] Recreated from Table 6.6.2.1.1-1 of the 3GPP TS 36.521 Specifications

As we also observe in **Table 2.21**, for offsets ranging from 1 MHz to 25 MHz from the band edge, the SEM measurement uses a measurement bandwidth of 1 MHz.

In general, the SEM measurement is considered to be an easier metric when compared to ACLR. As we see in **Figure 2.7**, substantial spurs from the transmitted signal would be required to violate the SEM measurement.

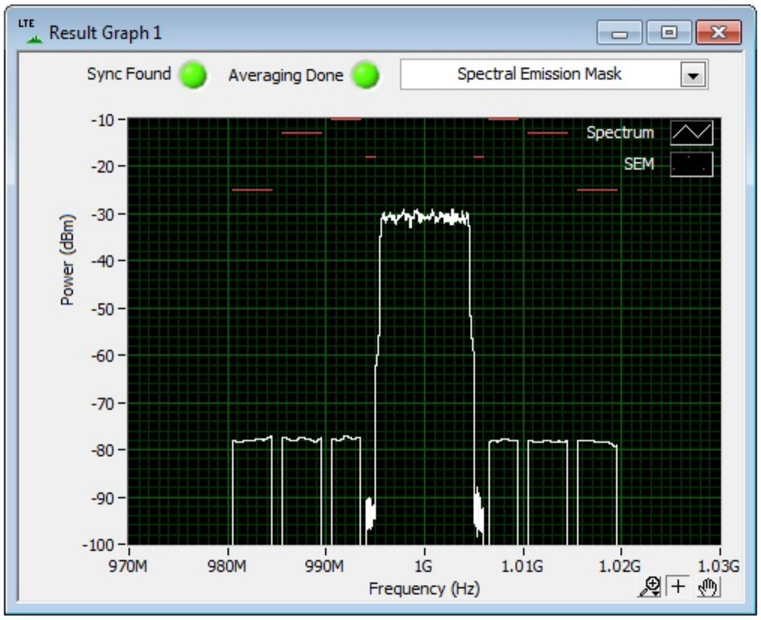


Figure 2.7. Spectrum Emissions Mask Measurement for a 10 MHz BW signal.

Adjacent Channel Leakage Ratio

The Adjacent Channel Leakage power Ratio (ACLR) measurement is the most widely used out-of-band emissions measurement – because it captures a wide range of transmitter impairments. This measurement is a metric of the emissions of a transmitter into the adjacent band. This measurement is important because it characterizes the non-linearity of the transmitting device. Because the ACLR performance of a device is heavily influenced by the non-linearity of the final stage power amplifier, (PA) ACLR is a key metric both of the handset and of the output PA. Additional LTE signal characteristics such as the high peak-to-average power-ratio (PAPR) of the signal intensify challenges such as meeting the ACLR requirements.

Whereas the SEM measurement measures the worst-case spectral content (per resolution bandwidth) in the adjoining spectral regions, the ACLR measurement measures the integrated power content in a given adjacent channel. The ACLR limit is a harder specification to meet than the SEM limit, with devices failing the SEM limit only due to unwanted spurious products at the output of the baseband transceiver.

ACLR is the ratio of the power measured within a specific E-UTRA bandwidth and the power measured on the adjacent E-UTRA or UTRA channel. ACLR requirements for LTE transmitters are specified for two scenarios - The specification for the E-UTRA channel is designed to predict potential interference with other LTE devices, and the specifications for the UTRA channel are designed to predict potential interference with WCDMA devices.

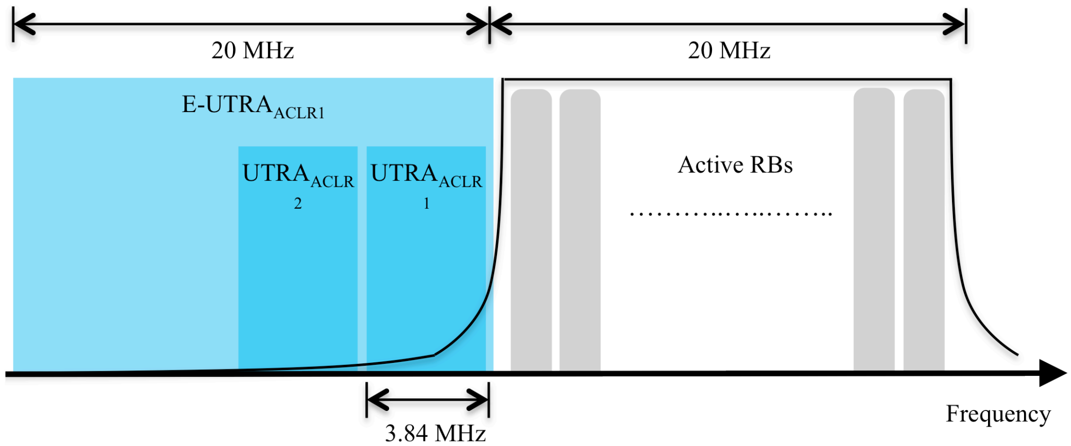


Figure 2.8. LTE ACLR Specifications Account for Interference into Adjacent LTE and WCDMA Channels[21]

In **Figure 2.8**, observe that the reference channel is an E-UTRA (LTE) channel, with a bandwidth corresponding to the LTE signal bandwidth. E-UTRA Adjacent Channel Leakage power ratio is defined as the ratio of the power in the center E-UTRA channel with the power in an adjacent E-UTRA channel. UTRA Adjacent Channel Leakage power ratio, by contrast, is defined as the ratio of power in the center E-UTRA channel and the power in the adjacent UTRA channel. The measurement bandwidth of the reference channel power is slightly smaller than the actual channel bandwidth, as illustrated in **Table 2.22**

	Channel Bandwidth					
	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz
E-UTRA$_{ACLR1}$	30 dB	30 dB	30 dB	30 dB	30 dB	30 dB
E-UTRA Channel Measurement BW	1.08 MHz	2.7 MHz	4.5 MHz	9.0 MHz	13.5 MHz	18 MHz

Table 2.22. Measurement Bandwidth for ACLR Channel[22]

[21] Recreated from Figure 6.6.2.3-1 of the 3GPP TS 36.521 Specifications

Section 6.6.2.3 of the 3GPP TS 36.521 specifications defines ACLR bandwidth requirements for each of the LTE bandwidth configurations. As we observe in **Table 2.23**, the E-UTRA adjacent channel measurement bandwidth is dependent on the LTE channel bandwidth. By contrast, the adjacent channel measurement bandwidth for UTRA ACLR measurements is determined by whether coexistence is desired with a 1.28 MHz WCDMA channel or with a 3.84 MHz WCDMA channel.

	Channel bandwidth					
	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz
$UTRA_{ACLR1}$	33 dB	33 dB	33 dB	33 dB	33 dB	33 dB
Adjacent channel centre frequency offset (in MHz)	$0.7+BW_{UTRA}/2$ / $-0.7-BW_{UTRA}/2$	$1.5+BW_{UTRA}/2$ / $-1.5-BW_{UTRA}/2$	$2.5+BW_{UTRA}/2$ / $-2.5-BW_{UTRA}/2$	$0.7+BW_{UTRA}/2$ / $-0.7-BW_{UTRA}/2$	$0.7+BW_{UTRA}/2$ / $-0.7-BW_{UTRA}/2$	$0.7+BW_{UTRA}/2$ / $-0.7-BW_{UTRA}/2$
$UTRA_{ACLR2}$	-	-	36 dB	36 dB	36 dB	36 dB
Adjacent channel centre frequency offset (in MHz)	-	-	$2.5 + 3*W_{UTRA}/2$ / $-2.5*3*BW_{UTRA}/2$	$5+3*W_{UTRA}/2$ / $-5*3*BW_{UTRA}/2$	$7.5 + 3*W_{UTRA}/2$ / $-7.5*3*BW_{UTRA}/2$	$10 + 3*W_{UTRA}/2$ / $-10*3*BW_{UTRA}/2$
E-UTRA channel Measurement bandwidth	1.08 MHz	2.7 MHz	4.5 MHz	9.0 MHz	13.5 MHz	18 MHz
UTRA 5MHz channel Measurement bandwidth[1]	3.84 MHz	3.84 MHz	3.84 MHz	3.84 MHz	3.84 MHz	3.84 MHz
UTRA 1.6MHz channel Measurement bandwidth[2]	1.28 MHz	1.28 MHz	1.28 MHz	1.28 MHz	1.28 MHz	1.28 MHz
Note 1: Applicable for E-UTRA FDD co-existence with UTRA FDD in paired spectrum Note 2: Applicable for E-UTRA FDD co-existence with UTRA TDD in unpaired spectrum						

Table 2.23. Measurement bandwidth for UTRA ACLR[23]

---

[22] Recreated from Table 6.6.2.3.3.2-1 of the 3GPP TS 36.521 specifications.

[23] Recreated from table 6.6.2.3.3.2-1 of the 3GPP TS 36.521 specifications

Note that the E-UTRA and UTRA ACLR test limits only apply when the adjacent channel power is greater than -50 dBm. For scenarios where the power in the adjacent channels is less than -50 dBm, the device is not required to achieve the ACLR requirements of 36 dB for E-UTRA channels and 33 dB for UTRA channels.

Spurious Emissions

Unlike the out-of band emissions measurements such as SEM and ACLR, which prescribe output emissions only in adjacent bandwidths, the spurious emission measurement prescribes emissions over the entire spectrum excluding the adjacent bandwidth region. Spurious emissions are generally caused by unwanted transmitter effects such as harmonics emission, parasitic emissions, intermodulation products, and frequency conversion products. As we observe in **Table 2.24**, the measurement or resolution bandwidth for spurious emissions increases from lower frequencies to higher frequencies, ranging from 1 kHz for low-frequency emissions to 1 MHz for high-frequency emissions.

Frequency Range	Maximum Level	Measurement Bandwidth
9 kHz $\leq f < 150$ kHz	-36 dBm	1 kHz
150 kHz $\leq f < 30$ MHz	-36 dBm	10 kHz
30 MHz $\leq f < 1$ GHz	-36 dBm	100 kHz
1 GHz $\leq f < 12.75$ GHz	-30 dBm	1 Mhz
12.75 GHz $\leq f < 5^{th}$ harmonic of the upper frequency edge of the UL operating band in GHz[1]	-30 dBm	1 Mhz
Note 1: Applies for Band 22, Band 42, and Band 43		

Table 2.24. Spurious Emissions Measurement Bandwidths and Limits[24]

Similar to SEM and ACLR measurements, the spurious emissions measurement is designed to evaluate a transmitter's ability to coexist with other wireless devices [2]. It is important to know that the spurious emission limits in **Table 2.24** in [1] apply for all transmitter bands, resource block (RB) configurations, and channel bandwidths.

In addition to general spurious emissions requirements, section 6.3.3.2 of the 3GPP TS 36.521 specifications also defines additional spurious emissions requirements that are designed to ensure LTE coexistence with UMTS tdevices in specified E-UTRA bands. Although we do not list the additional spurious emissions requirements for each of these bands in this document, (refer to Table 6.6.3.2-1 of the 3GPP TS 36.521 specifications [1]), most channels have a spurious emissions limit of -50 dBm measured in a 1 MHz bandwidth.

[24] Recreated from Table 6.6.3.1.3-2 from the 3GPP TS 36.521 Specifications

Transmit Intermodulation

The transmit intermodulation test characterizes the linearity of the RF front end of an LTE transmitter. More precisely, this measurement describes the ability of the transmitter to avoid the creation of intermodulation when actively outputting an LTE signal – and can be used to troubleshoot issues with the transmitter's diplexer.

In practical use, all LTE handsets transmit an uplink signal simultaneously with other handsets. Thus, at the precise moment the transmitter is transmitting – a wide range of LTE transmission signals from other units have the potential to leak into the front-end of the transmitter. As a result, an LTE handset's transmitted signal can combine with incoming emissions from other transmitters to produce intermodulation products. Third order intermodulation products occur offset the center frequency of the transmitter at the difference frequency between the transmitted signal and the interference.

The transmit intermodulation measurement mimics the transmissions from another UE – except with a CW interferer. As illustrated in **Figure 2.9**, the CW interferer generated by a VSG will mix with the transmitted signal, producing small – though ideally nonexistent – intermodulation products offset from the center frequency of the transmitter.

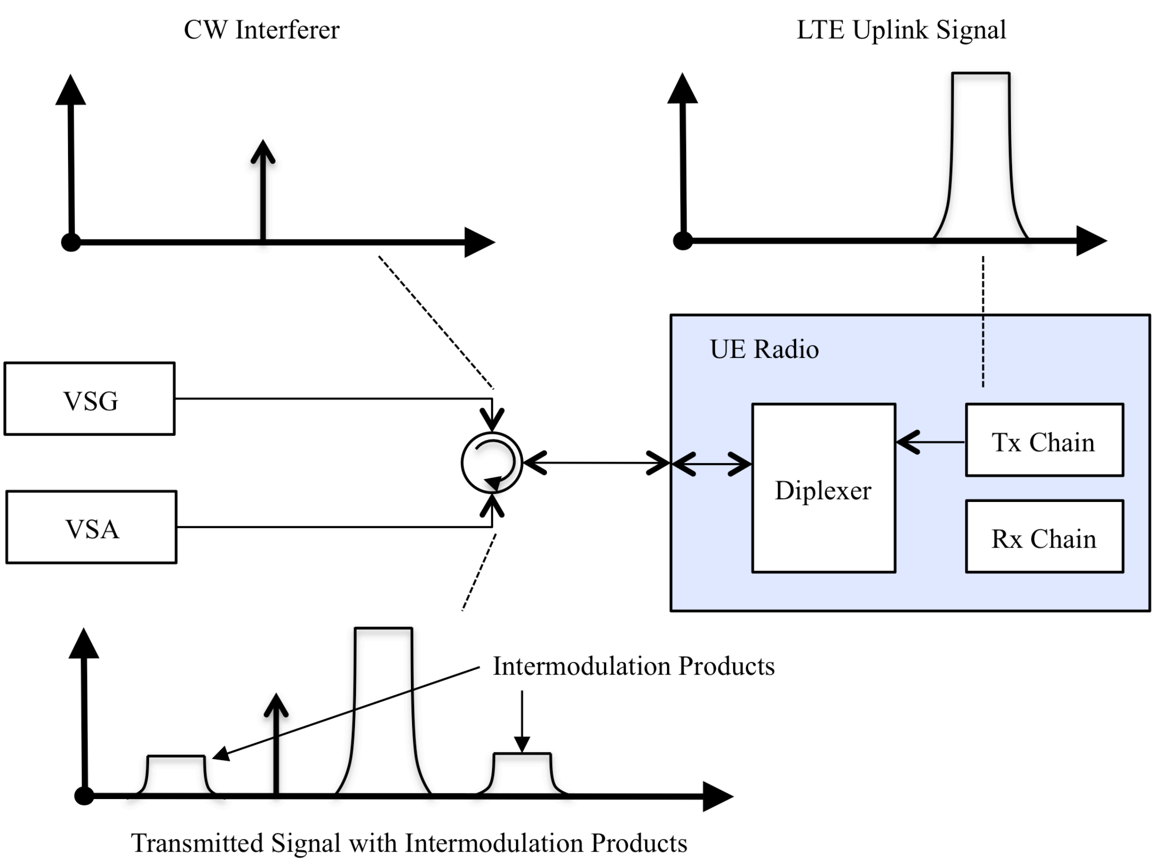


Figure 2.9. Block Diagram of Intermodulation Test Setup

Based on the configuration in **Figure 2.9**, the RF signal analyzer will observe both the transmitted LTE signal in addition to the intermodulation product, as shown in **Figure 2.10**. The intermodulation attenuation is strictly defined as the ratio of the LTE transmitted signal power to the power of the intermodulation product.

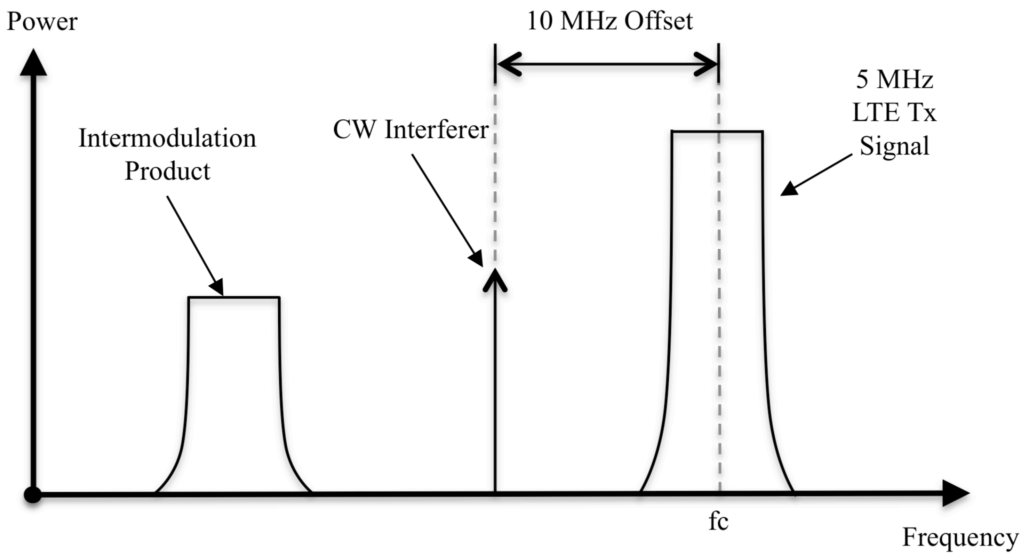


Figure 2.10. Conceptual view of spectral content at output of LTE transmitter

As we observe in **Figure 2.10**, the third order intermodulation product will appear as a modulated signal with a bandwidth that is equivalent to the original LTE uplink signal. Transmitters are subject to specific intermodulation requirements, as described in **Table 2.25**.

	Channel Bandwidth							
	5 MHz		10 MHz		15 MHz		20 MHz	
Interference Signal Frequency Offset	5MHz	10MHz	10 MHz	20MHz	15MHz	30MHz	20MHz	40MHz
Interference CW Signal Level	-40dBc							
Intermodulation Product	-29dBc	-35dBc	-29dBc	-35dBc	-29dBc	-35dBc	-29dBc	-35dBc
Measurement bandwidth	4.5MHz	4.5MHz	9.0MHz	9.0MHz	13.5MHz	13.5MHz	18MHz	18MHz

Table 2.25: Transmit Intermodulation Interferer Specifications[25]

[25] Recreated from Table 6.7.4.1-1 the 3GPP TS 36.521 Specifications

As we observe in **Table 2.25**, the VSG must generate a CW interferer that is -40 dBc relative to the transmit power of the uplink LTE signal. In addition, **Table 2.25** also describes specific power limits for interferers at two specific frequency offsets relative to the transmitted signal. Note that the transmit power for the uplink LTE transmissions is not strictly defined by the spec. This is because the worst-case transmit intermodulation products will occur at the maximum UE power. As a result, one should assume that the transmit intermodulation measurement should be performed with the transmitter operating at the maximum UE output power.

Transmit Signal Quality Measurements

The LTE transmit signal quality measurements are defined by section 6.5 of the 3GPP TS 36.521 specifications. These measurements, which include frequency error and transmit modulation quality, assess interoperability with the base station by measuring the ability of a signal to be demodulated by a base station receiver.

Frequency Error

Frequency error measurements are specified by section 6.5.1 of the 3GPP TS 36.101 and 36.521 specification documents. This specification ensures interoperability between the handset and the base station by minimizing the frequency error in a given transmission. Frequency error is defined as the difference between the RF modulated carrier frequency transmitted from the UE and the assigned frequency received from the eNodeB.

Frequency error can affect the system performance in many areas, such as handover performance, cell throughput and timing, and so on. To ensure that both the UE transmitter and the eNodeB receiver operate at the same frequency, the UE frequency error is a key metric of transmitter performance. Frequency error is specified in parts per million (ppm). The transmitter is required to have a frequency error of less ±0.1 ppm. As a result, the precise frequency accuracy requirements are dependent on the carrier frequency of the channel. For example, for a carrier frequency of 1800 MHz, the maximum frequency error would be ±180 Hz.

In high-mobility situations, the frequency offset between the UE and the Node B is also influenced by the velocity of the handset. The frequency offset caused by Doppler shift can occasionally be a significant portion of the overall frequency error. For example, assume that a UE is moving at a speed of 200 miles per hour, and is transmitting at a frequency of 1 GHz. Understanding that electromagnetic waves travel at the speed of light, the UE's mobility would produce a Doppler shift of 296 Hz. In this example, the frequency offset caused by Doppler shift (296 Hz), is greater than the transmitter frequency accuracy requirement of 100 Hz (0.1 ppm for a 1 GHz carrier). As a result, LTE systems are designed such that an eNodeB can correctly demodulate a signal in the presence of frequency error substantially greater than the frequency error that occurs in transmission – specifically to handle high Doppler shift conditions.

Frequency error is measured with both full and various partial RB allocations. The frequency error is measured along with other measurement parameters, namely, error vector magnitude (EVM), carrier leakage, unwanted emissions in the non-allocated RBs and EVM equalizer spectrum flatness. All these parameters are measured simultaneously by means of the global in-channel TX test. The global in-channel TX test compares the actual output signal of the transmitter under test received by an ideal receiver with a reference signal generated by the measuring equipment and representing an ideal error free signal. For both FDD and TDD, the measurement record is 10 subframes or 20 slots. However for TDD, special subframes and downlink subframes are excluded from the test and hence the 20 slots are derived from 3.25 frames.

Error Vector Magnitude

The Error Vector Magnitude (EVM) measurement is a comprehensive metric of modulation quality that encapsulates the effect of a wide range of transmitter impairments in the transmitter chain. In general, the EVM measurement can be used to identify impairments such as noise, I/Q amplitude and I/Q phase imbalances, residual I/Q origin offset, phase noise, and residual RF carrier frequency and sample timing offsets.

EVM is a metric of modulation quality that measures the phase and magnitude error of modulated symbols by comparing them to their measured phase and magnitude with the ideal "symbol location." When computing EVM, an error vector is first determined by comparing the measured and desired phase and magnitude of each symbol. EVM is simply the ratio of the magnitude of this "error vector" to the magnitude of the vector describing the ideal symbol location – as shown in **Figure 2.11**.

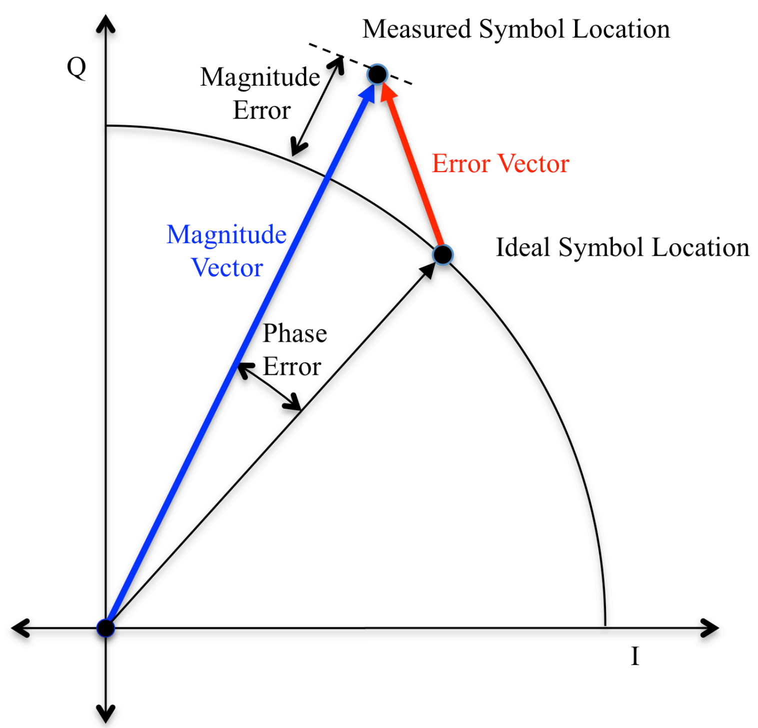


Figure 2.11. Graphical Representation of Error Vector Magnitude Measurement

It is important to note that measuring EVM is significantly more complex than measuring a ratio. In fact, before calculating EVM, the measurement algorithm must correct the sample timing offset and the RF frequency offset. The I/Q origin offset is then removed from the measured waveform. However, the estimation and removal of the timing offset, frequency offset, and I/Q origin offset have some error and their residual components affect the EVM calculation.

The measured waveform is further modified by selecting the absolute phase and absolute amplitude of the transmitter chain. The final EVM result is defined as given below.

$$EVM = \sqrt{\frac{Error\ Vector}{Magnitude\ Vector}}$$

This value can be expressed either as a percentage or in decibels. Conversion from percent to dB is expressed in **Equation 2.3**.

$$EVM_{dB} = 20\log(EMV_{\%})$$

Equation 2.3. Conversion of EVM in Percent to EVM in dB.

Section 6.5.2 of the 3GPP TS 36.521 specifications requires that 10 consecutive sub-frames be used for the RMS average for basic EVM measurements, and 60 consecutive sub-frames for the reference signal EVM. Additionally, as we observe in **Table 2.26**, the LTE specifications dictate a minimum EVM requirement that varies according to modulation scheme [1].

Modulation	EVM Limit
BPSK	17.5 %
QPSK	17.5 %
16-QAM	12.5 %

Table 2.26 Transmit EVM Limits[26]

When measuring EVM on LTE signals, results can be displayed in a number of ways for troubleshooting purposes. One of the most common EVM-related traces is the constellation graph, shows in **Figure 2.12**. The constellation plot not only displays the EVM, but also serves as an excellent tool to troubleshoot EVM measurements on RF test equipment. For example, when an RF signal analyzer is used to measure EVM on a highly-compressed LTE signal, the EVM result might appear reasonable (20% or less) even if the signal analyzer settings are not configured correctly. In this case, the constellation plot appears as a random pattern of recovered symbols. Thus, we can use the constellation plot to visually inspect the demodulated signals. If the recovered symbols are visually similar to the symbol map, we can be reasonably certain that the signal is being demodulated correctly. **Figure 2.12** shows the constellation plot of an LTE transmit signal with an EVM of -50 dB.

[26] Recreated from Table 6.5.2.1.1-1 of the 3GPP TS 36.521 Specifications

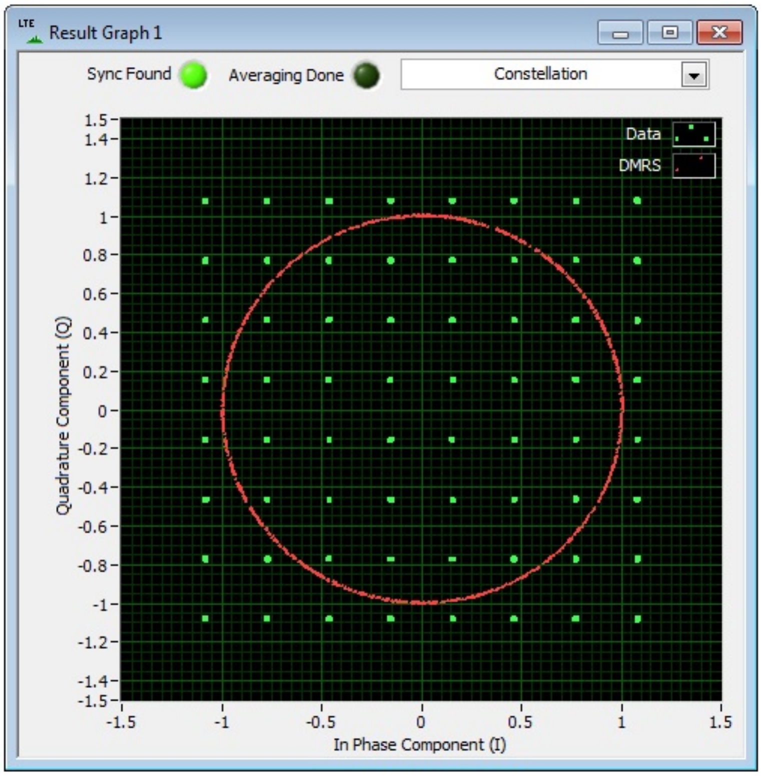


Figure 2.12. Constellation plot of a 64-QAM LTE Signal

Although section 6.5.2.1 of the 3GPP TS 36.521 specifications requires an EVM performance that is averaged over all subcarriers and a specific number of frames, EVM can also be displayed versus symbol or OFDM subcarrier. As we observe in **Figure 2.13**, the EVM versus subcarrier display shows the RMS EVM for each subcarrier, thus providing a frequency-dependent element to the EVM measurement. The EVM versus subcarrier plot is often used to identify issues, such as in-band spurs, with the transmitter design, or issues with filter designs.

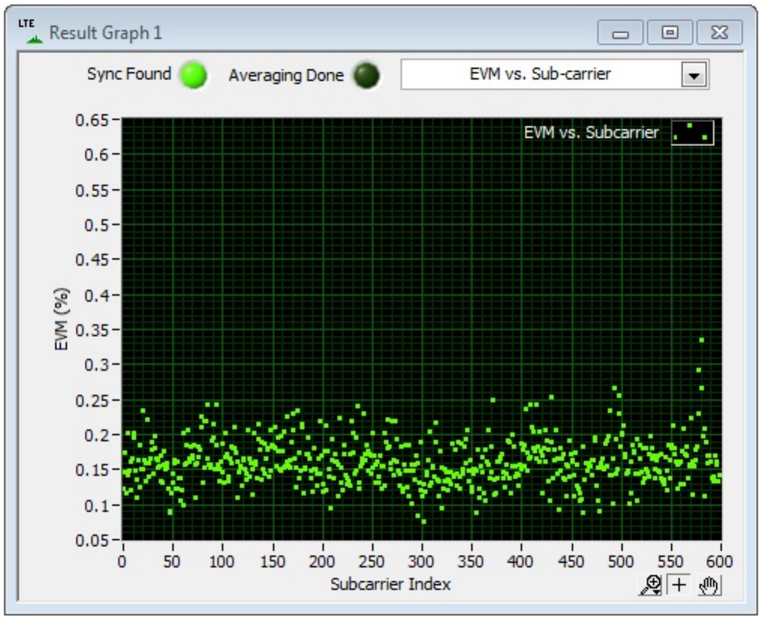


Figure 2.13. EVM Versus Subcarrier Measurement.

In addition to EVM versus subcarrier trace, another widely-used trace is the EVM versus symbol trace. The EVM versus symbol trace provides the time element of the modulation quality measurement. This plot is especially useful when troubleshooting timing or turn-on issues with the transmit power amplifier.

Carrier Leakage

The transmit carrier leakage measurement, also known as I/Q origin offset, is defined by section 6.5.2.2 of the 3GPP TS 36.521 specifications. Because most modern cellular device radios use direct upconversion architectures (quadrature modulator) to convert I/Q signals to RF signals, the radio itself is susceptible to quadrature impairments. Quadrature impairments define a range of impairments such as quadrature skew, I/Q gain imbalance, and I/Q DC offset. Each of these impairments can impair the modulation quality of a transmitted signal. DC offset of the I/Q signal paths within the radio manifests itself as a transmitter spur at the center frequency of the quadrature modulator. This spur is often referred to as LO (local oscillator) leakage or carrier leakage. Because carrier leakage is caused by DC offset of the I/Q signals, this measurement is also referred to as I/Q origin offset.

The effect of carrier leakage on the modulation quality of a transmitted signal is mitigated in LTE by configuring the center frequency to be a null subcarrier. As a result, the subcarrier at the center frequency of the radio does not carry data and is not included in calculating the RMS EVM measurement. Additionally, by keeping the center frequency subcarrier null, LO leakage can be measured by measuring the power of the null subcarrier.

The LO leakage requirements of LTE transmitters vary according to the transmitted output power, as illustrated in **Table 2.27**.

Output Power	LO Leakage Limit (dBc)
Output Power > 0 dBm	-25
-30 dBm ≤ Output Power ≤ 0 dBm	-20
-40 dBm ≤ Output Power ≤ -30 dBm	-10

Table 2.27. Carrier Leakage Requirements[27]

As we observe, in **Table 2.27**, the relative limit for LO leakage ranges from -10 dBc at low powers to -25 dBc at high powers. The absolute limit for LO leakage at the minimum transmit power is -50 dBm, which is equivalent to the transmitter OFF power requirement when data is not present during transmission.

In-band Emissions

The in-band emissions measurement is designed to characterize emissions that occur when the LTE transmitter uses only a partial allocation of resource blocks. During typical LTE transmission, the transmitter uses only a partial allocation of the available resource blocks, that is, less than 50 resource blocks for a 10 MHz channel bandwidth. In addition, because the multiple-access nature of LTE allows for simultaneous generation of multiple UEs at the same time, in-band emissions from UE have the potential to interfere with the allocated resource blocks of another UE.

In-band emissions are generally caused by quadrature impairments in direct upconversion modulators. Two specific impairments, I/Q gain imbalance and quadrature skew, of quadrature modulators are the direct cause of in-band emissions. Although the I and Q signal paths would have identical gain in an ideal modulator, variation in gain between these signal paths (I/Q gain imbalance) produces additional spectral content in the frequency domain. As we observe in **Figure 2.14**, resource blocks transmitted at + 1 MHz relative to the carrier frequency appear at -1 MHz relative to the carrier frequency because of I/Q gain imbalance.

[27] Recreated from Table 6.5.2.2.3-1 of the 3GPP TS 36.521 Specifications

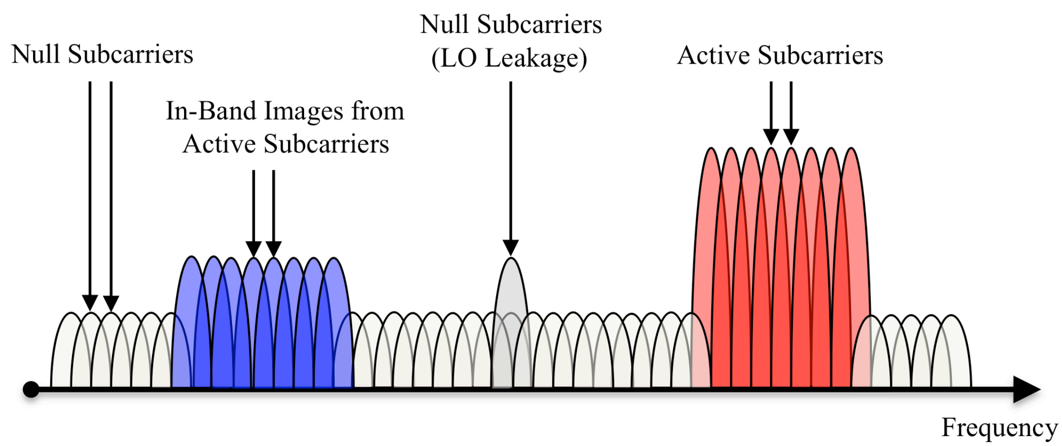


Figure 2.14. Quadrature Impairments Produce In-band Images that Mirror Across the Center Frequency

Quadrature skew, which describes the phase difference between the in-phase and quadrature-phase paths of the quadrature modulator, has a similar effect. While the in-phase and quadrature-phase components of the local oscillator would ideally be 90° out of phase, any variation from this value produces an effect similar to that caused by I/Q gain imbalance.

Because partial allocation of resource blocks is commonly used to enable multiple-user access to the uplink channel, the in-band emissions measurement is an important metric. This requirement ensures that multiple UEs do not interfere with one another's uplink transmissions.

Section 6.5.2.3 of the 3GPP TS 36.521 specifications defines in-band emissions requirements for each of the non-allocated transmitter resource blocks, as shown in **Table 2.28.**

Parameter Description	Unit	Limit	
General	dB	Max $\{-25-10\cdot\log_{10}(N_{RB}/L_{CRBs}), 20\cdot\log_{10} EVM-3-5\cdot(\Delta_{RB}\|1)/L_{CRBs}\cdot -57$ dBm/180kHz – $P_{RB}\}$	
IQ Image	dB	-25	
Carrier leakage	dBc	-25	Output power $>$ 0 dBm
		-20	-30 dBm $\leq$ Output power $\leq$ 0 dBm
		-10	-40 dBm $\leq$ Output power < -30 dBm

Table 2.28. In-band Emissions Requirements[28]

[28] Recreated from Table 6.5.2.3-1 of the 3GPP TS 36.521 specifications

In-band emissions are measured as the power ratio between the transmitted resource block and the integrated power in a given subcarrier. The in-band emissions measurement interval is defined over one slot in the time domain.

In **Figure 2.15**, we can observe a typical in-band emissions measurement for a 10 MHz LTE signal that occupies only the first 30 RBs out of the available 100 RBs. Note in Figure 2.15, we have applied 1 dB of IQ gain imbalance to artificially produce in-band emissions.

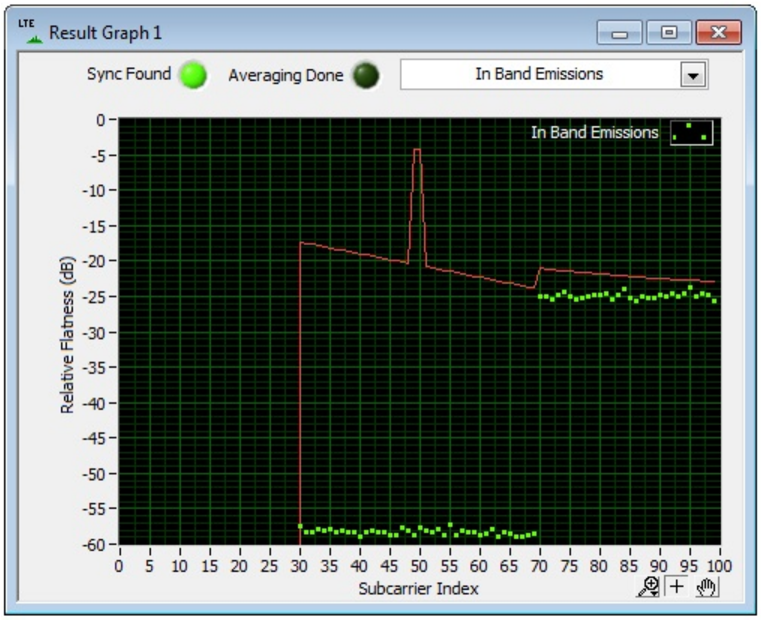


Figure 2.15. Spectral Flatness Measurement for Partially Allocated LTE Transmission.

As **Figure 2.15** illustrates, IQ gain imbalance produces an image that is mirrored across the center frequency of the transmission. Thus, the intentional spectral content in subcarriers 0 – 29 produces unwanted spectral content in subcarriers 70 – 99. Also, subcarriers 30 – 69 contain do not even approach the in-band emissions limit because the neither the resource blocks nor the blocks mirrored across the transmission center frequency contain transmitted energy.

Spectral Flatness

Spectral flatness is a measure of the flatness of the transmitter chain, including the power amplifier, and is measured in isolation to identify specific frequency-domain response issues in the transmitter. Spectral flatness measures the variation of subcarrier power in the frequency domain. The basic measurement interval is defined over one slot in the time domain. Typical results are shown in **Figure 2.16** for a 20 MHz LTE signal.

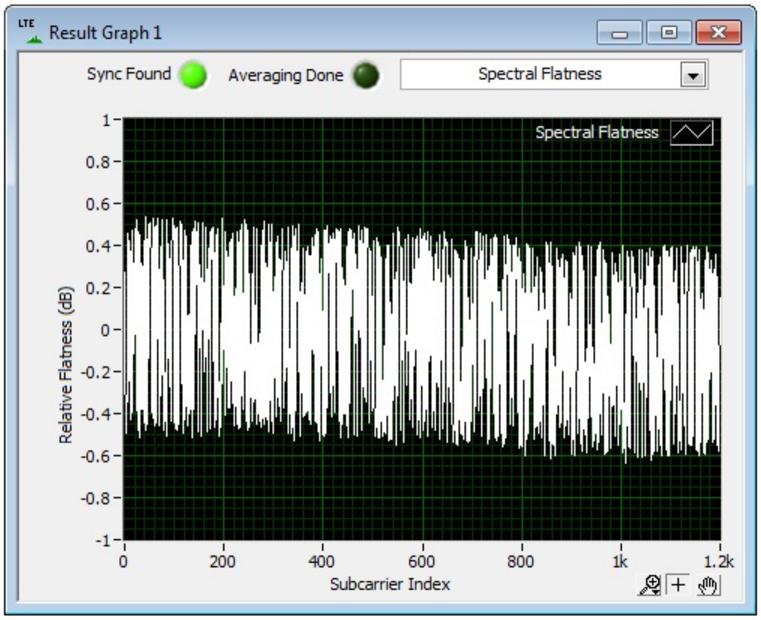


Figure 2.16. Spectral Flatness Measurement for Partially Allocated LTE Transmission.

Transmitter Measurement Optimizations

Improving measurement accuracy and repeatability first requires a working understanding of the instrumentation one might use for LTE transmitter measurements – the RF signal analyzer. RF signal analyzer is fundamental to sources of error including: finite power accuracy, phase noise, small degree's of non-linearity, and an inherent noise floor. Of these impairments, the effect of the signal analyzer's noise floor is one of the most interesting – because it can have a significant result on measurement repeatability – and can be mitigated through averaging.

Averaging and Repeatability

Averaging fundamentally improves the repeatability of a measurement – and to a lesser degree improves the accuracy by minimizing the error due to noise. In essence, averaging multiple measurements and averaging the results reduces the standard deviation of the measurement result. We know this from the central limit theorem, which suggests that averaging of a random process leads to a tighter distribution of measurement results. [3]. In general, one can apply averaging techniques to most transmitter measurements and this technique is commonly used in measurements such as power, EVM, and ACLR.

Although averaging measurement results is a common approach to improving the accuracy and repeatability of a measurement - it also results in longer measurement times. In some instances, one might desire to reduce measurement time – and even be willing to sacrifice accuracy or repeatability in the process. For transmit power and EVM measurements, one can improve measurement speed over the standard instrument settings by reducing the measurement interval. While this technique does reduce the measurement time, the tradeoff is worse repeatability.

Understanding VSA Settings

Outside of averaging, one can obtain the most accurate measurement results simply by choosing an appropriate reference level setting on the RF signal analyzer. For all measurements, including power, modulation quality, and especially spectrum, the signal to noise ratio of the analyzer has a significant impact on the measurement result. Averaging reduces the noise contribution to a certain extent – and it is particularly useful for measurements that push the capabilities of the instrumentation.

Because the "reference level" setting of an RF signal analyzer is directly tied to the instrument's front-end attenuator – reference level has a direct impact on the noise contribution of the instrument. Most signal analyzers are designed to have a power clipping level that is 6-8 dB above their reference level. Also, signal analyzers can obtain the most accurate power, EVM and ACLR results when the peak power of the transmitted signal is just below the clipping level of the instrument. Since the PAPR ranges from 6-8 dB for most LTE uplink transmissions – the ideal reference level is usually identical to the average power level of the transmitted signal.

EVM Measurement Optimizations

For specific measurements such as EVM, improving the SNR of the signal analyzer produces additional benefits. Because the type of channel estimation also affects the accuracy of an EVM measurement, one can improve the accuracy of the measurement result by improving channel estimation. LTE EVM measurements algorithms are generally designed such that one can use reference symbols, data symbols, or even both sets of symbols to estimate the channel. When the SNR of the received signal is high, using both the reference and data symbols to estimate the channel produces the most accurate result.

By contrast, when the SNR is low, one can achieve a more accurate measurement result by basing the channel estimation on the reference symbols alone. Using merely the reference symbols for channel estimation in low SNR conditions is more accurate because symbols are known. Since the data symbols are not known beforehand – channel estimation based on data symbols in low SNR conditions will be more inaccurate.

3. LTE Receiver Measurements

The LTE receiver measurement requirements are designed to ensure that a receiver is able to consistently demodulate over-the-air transmissions from the Node B. As a result, receiver performance must be measured over a range of conditions, including conditions where the transmitted signal has a high power, conditions where the signal has a lower power level, and in the presence of both in-band and out-of-band interferes. The receiver measurements specified by Section 7 of the 3GPP TS 36.521 specifications are as illustrated in **Table 3.1**.

Measurement	3GPP TS 36.521 Section
Reference Sensitivity Level	Section 7.3
Maximum Input Level	Section 7.4
Adjacent Channel Selectivity	Section 7.5
Blocking Characteristics	Section 7.6
Spurious Response	Section 7.7
Intermodulation Characteristics	Section 7.8
Spurious Emissions	Section 7.9

Table 3.1. Description of LTE Receiver Measurements

Receiver measurements apply only to the handset receiver, and do not apply to typical receiver components such as diplexers, LNAs, and power amplifiers. For receive chain components such as the low noise amplifier (LNA), there is a direct relationship between the noise figure of the LNA and the sensitivity of the device. As a result, metrics such as noise figure are most commonly used to characterize the behavior of the individual component, while metrics such as sensitivity are used to characterize the behavior of the receiver as a whole.

For the majority of receiver measurements, the primary receiver figure of merit is reviver throughput. Receiver metrics such as reference sensitivity level, ACS, and blocking characteristics, each require a receiver to achieve a minimum throughput in a wide range of signal and environmental conditions.

Reference Sensitivity Level

The reference sensitivity level is the most fundamental metric of receiver performance, and is intended to capture the receiver's ability to operate in low-power conditions. A receiver with excellent sensitivity is able to maintain sufficient throughput close to the band edges, while a receiver with poor sensitivity experiences diminished throughput close to the band edges.

Unlike GSM and WCDMA receivers that use bit error rate (BER) to define the sensitivity requirements, LTE defines minimum performance in terms of throughput. Sensitivity is therefore defined as the lowest average power level for which the receiver can achieve 95% of the maximum throughput, when using the QPSK modulation scheme.

The hardware configuration for LTE reference sensitivity level is nearly identical to that of WCDMA and requires a vector signal generator directly connected to the receiver. As illustrated in **Figure 3.1**, the VSG produces an LTE downlink signal, and the receiver reports its throughput through a digital interface.

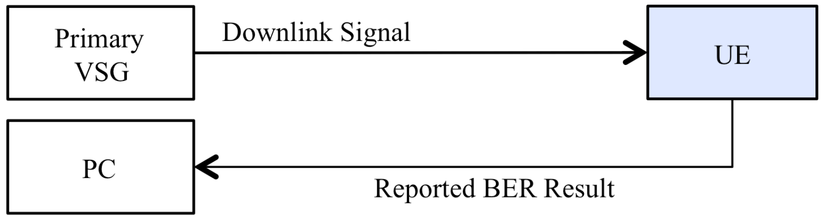


Figure 3.1. Connection for LTE Receiver Sensitivity

The LTE receiver reference sensitivity requirements, as specified by section 7.3 of the 3GPP TS 36.521 specifications, define a range of E-UTRA bands and channel bandwidths. For, each of these configurations, which are illustrated in **Table 3.2**, the receiver must achieve 95% or better of its maximum theoretical throughput

E-UTRA Band	Channel Bandwidth						Duplex Mode
	1.4 MHz (dBm)	3 MHz (dBm)	5 MHz (dBm)	10 MHz (dBm)	15 MHz (dBm)	20 MHz (dBm)	
1	-	-	-100	-97	-95.2	-94	FDD
2	-102.7	-99.7	-98	-95	-93.2	-92	FDD
3	-101.7	-98.7	-97	-94	-92.2	-91	FDD
4	-104.7	-101.7	-100	-97	-95.2	-94	FDD
5	-103.2	-100.2	-98	-95			FDD
6	-		-100	-97			FDD
7	-		-96	-95	-93.2	-92	FDD
8	-102.2	-99.2	-97	-94			FDD
9	-	-	-99	-96	-94.2	-93	FDD
10	-	-	-100	-97	-95.2	-94	FDD
11	-	-	-100	-97			FDD
12	-101.7	-98.7	-97	-94			FDD
13			-97	-94			FDD
14		-	-97	-94			FDD
…							
17	-	-	-94	-94			FDD
18	-	-	-97	-97	-95.2	-	FDD
19	-	-	-97	-97	-95.2	-	FDD
20			-94	-94	-91.2	-90	FDD
21			-97	-97	-95.2		FDD
22			-97	-94	-92.2	-91	FDD
23	-104.7	-101.7	-100	-97	-95.2	-94	FDD
24			-100	-97			FDD
25	-101.2	-98.2	-96.5	-93.5	-91.7	-90.5	FDD
26	-102.7	-99.7	-97.5	-94.5	-92.7		FDD
27	-103.2	-100.2	-98	-95			FDD
28		-100.2	-98.5	-95.5	-93.7	-91	FDD
…							
33	-	-	-100	-97	-95.2	-94	TDD

34	-	-	-100	-97	-95.2	-	TDD
35	-106.2	-102.2	-100	-97	-95.2	-94	TDD
36	-106.2	-102.2	-100	-97	-95.2	-94	TDD
37	-	-	-100	-97	-95.2	-94	TDD
38	-	-	-100	-97	-95.2	-94	TDD
39	-	-	-100	-97	-95.2	-94	TDD
40	-	-	-100	-97	-95.2	-94	TDD
41	-	-	-98	-95	-93.2	-92	TDD
42	-	-	-99	-96	-94.2	-93	TDD
43	-	-	-99	-96	-94.2	-93	TDD
44		[-100.2]	[-98]	[-95]	[-93.2]	[-92]	TDD

Table 3.2. Sensitivity Limits for LTE Receiver for Each E-UTRA Band [29]

Note that most receiver measurements use throughput as the primary metric of receiver performance – and achieving 95% of the theoretical maximum value is considered identical performance. Thus, for most receiver measurements, the receiver setup is identical to that of the sensitivity measurement. Similarly to sensitivity, the receiver will calculates the percentage of its theoretical throughput and reports the result to a PC through a digital interface.

Maximum Input Level

Similar to the reference sensitivity level measurement, the receiver maximum input level characterizes the receiver's ability to achieve minimum requirements for throughput under extreme signal level conditions. Receiver performance at relatively high power levels are primarily driven by the linearity of the front-end, which is usually dominated by components such as the first LNA in the receive chain.

The minimum conformance requirements for maximum input level necessitates that the receiver be able to achieve at least 95% of the maximum throughput in the presence of signal powers up to –25 dBm. The maximum input level requirement for LTE receivers is the same for all channel bandwidths, as illustrated in **Table 3.3**.

	Channel Bandwidth					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Power in Transmission Bandwidth Configuration	-25 dBm					

Table 3.3. Maximum Input Level Requirements for LTE Receivers for all Channel Bandwidths [30]

[29] Recreated from Table 7.3.3-1 of the 3GPP TS 36.521 Specifications

[30] Recreated from Table 7.4.3-1 of the 3GPP TS 36.521 Specifications

The test configuration for maximum input level is almost identical to that of reference sensitivity level. One minor difference between the two test configurations is that when testing maximum input level, it is not necessary to use substantial attenuation between the RF signal generator and the DUT. Instead, the signal generator is either connected directly to the DUT, or through a small attenuator used for impedance matching.

Adjacent Channel Selectivity

Adjacent Channel Selectivity (ACS) is a measure of a receiver's ability to achieve minimum throughput requirements in the presence of an adjacent channel signal at a specific frequency offset from the given channel. This measurement is particularly useful in determining the receiver's performance at the band edge, when higher power out-of-band signals from other base stations might be present. ACS can strictly be defined as the ratio (in dB) of the receiver filter's attenuation on the assigned channel frequency to the receive filter attenuation on the adjacent channels. The requirements for LTE receiver Adjacent Channel Selectivity (ACS) are defined in **Table 3.4** for each transmission bandwidth.

	Channel bandwidth					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
ACS (dB)	33.0	33.0	33.0	33.0	30	27

Table 3.4. Adjacent Channel Selectivity Requirements for LTE Receivers for All Channel Bandwidths[31]

The test configuration for ACS involves two signal generators connected to a power combiner. One signal generator produces the reference LTE signal, which is demodulated by the receiver. The other signal generator generates an interfering LTE signal, as illustrated in **Figure 3.2**.

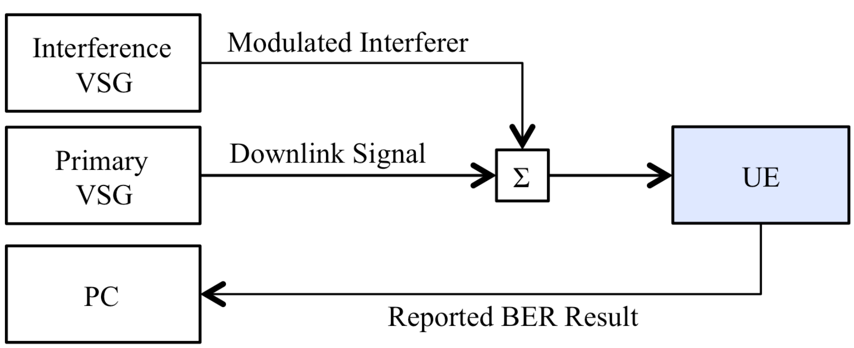


Figure 3.2. Test setup for adjacent channel selectivity measurement.

[31] Recreated from Table 7.5.3-1 of the 3GPP TS 36.521 Specifications

As we observe in **Figure 3.2**, the outputs of both the primary downlink signal generator and the interfering signal generator are combined using a combiner, and the output is introduced to the handset. For this configuration, it is important to calibrate for the insertion loss introduced in the combiner. Insertion losses in the range of 3 dB (ideal) to 3.5 dB (typical) are common when using a standard 2-port combiner. As a result, we must carefully calibrate the insertion loss of the combiner to compensate for it by adjusting the power level of the RF signal generators accordingly.

However, it is difficult to directly measure the receiver's absolute rejection of adjacent channels. As a result, the receiver is typically tested for its ACS performance by introducing a main channel and an interfering channel at both the upper and lower input power ranges of the LTE receiver.

When testing ACS at the lower end of the receiver input power range, the primary RF signal generator is used to generate a reference channel that is 14 dB above the receiver's sensitivity limits (refer to Table X). Next, the secondary RF signal generator, which produces the interfering LTE signal, is configured to an RF power level that is substantially higher than the reference channel power. The power level of the interfering channel is dependent on the bandwidth configuration and is described in **Table 3.5**.

	Channel Bandwidth					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Power in Transmission Bandwidth Configuration (dBm)	REFSENS + 14 dB					
$P_{interferer}$ (dBm)	REFSENS +45.5dB	REFSENS +45.5dB	REFSENS +45.5dB	REFSENS +45.5dB	REFSENS +45.5dB	REFSENS +45.5dB
$BW_{Interferer}$ (MHz)	1.4	3	5	5	5	5
$F_{interferer}$ (MHz)	1.4+0.0025 / -1.4-0.0025	3-0.0075 / -3-0.0075	5+0.0025 / -5-0.0025	7.5+0.0075 / -7.5-0.0075	10+0.0125 / -10-0.00125	12.5+0.00 / -12.5-0.0025

Table 3.5. Maximum Input Level Requirements for LTE Receivers for all Channel Bandwidths[32]

When testing ACS at the higher end of the receiver input power range, the second RF signal generator is used to produce an interferer at the maximum input level, that is, at -25 dBm, of an LTE transmission. Then, the primary RF signal generator is configured to produce a reference channel that is substantially lower than the interferer channel. The absolute power level of the reference channel is dependent on the channel bandwidth and is described in **Table 3.6**.

[32] Recreated from Table 7.5.3-2 of the 3GPP TS 36.521 Specifications

	Channel Bandwidth					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Power in Transmission Bandwidth Configuration (dBm)	-56.5	-56.5	-56.5	-56.5	-53.5	-50.5
$P_{interferer}$ (dBm)	-25					
$BW_{Interferer}$ (MHz)	1.4	3	5	5	5	5
$F_{interferer}$ (MHz)	1.4+0.0025 / -1.4-0.0025	3+0.0075 / -3-0.0075	5+0.0025 / -5-0.0025	7.5+0.0075 / -7.5-0.0075	10+0.0125 / -10-0.0125	12.5+0.0025 / -12.5-0.0025

Table 3.6. Maximum Input Level Requirements for LTE Receivers for all Channel Bandwidths[33]

Blocking Characteristics

The blocking characteristic is a measure of the receiver's ability to appropriately demodulate LTE signals in the presence of a wide range of interference signals. While blocking is similar to adjacent channel selectivity in some ways, the blocking characteristics are measured a more comprehensive range of interferers, including both continuous wave and modulated signals. Similar to WCDMA, LTE blocking characteristics are divided into three categories as illustrated below:

- In-band blocking: Specifies modulated blocking signals closer to the band of interest, as described in section 7.6.1 of the 3GPP TS 36.521 specifications
- Out-of band blocking: Specifies modulated blocking signals that are farther in frequency from the band of interest, as described in section 7.6.2 of the 3GPP TS 36.521 specifications
- Narrowband blocking: Specifies receiver performance in the presence of CW interference signals, as described in section 7.6.3 of the 3GPP TS 36.521 specifications

The blocking characteristics measurements specify a range of blocking signals that include: CW signals close to the band of interest (narrowband blocking), CW signals farther from the band of interest (out-of-band blocking), and modulated signals relatively close the band of interest (in-band blocking). **Figure 3.3** illustrates a visual representation of these blocking signals.

[33] Recreated from Table 7.5.3-3 of the 3GPP TS 36.521 Specifications.

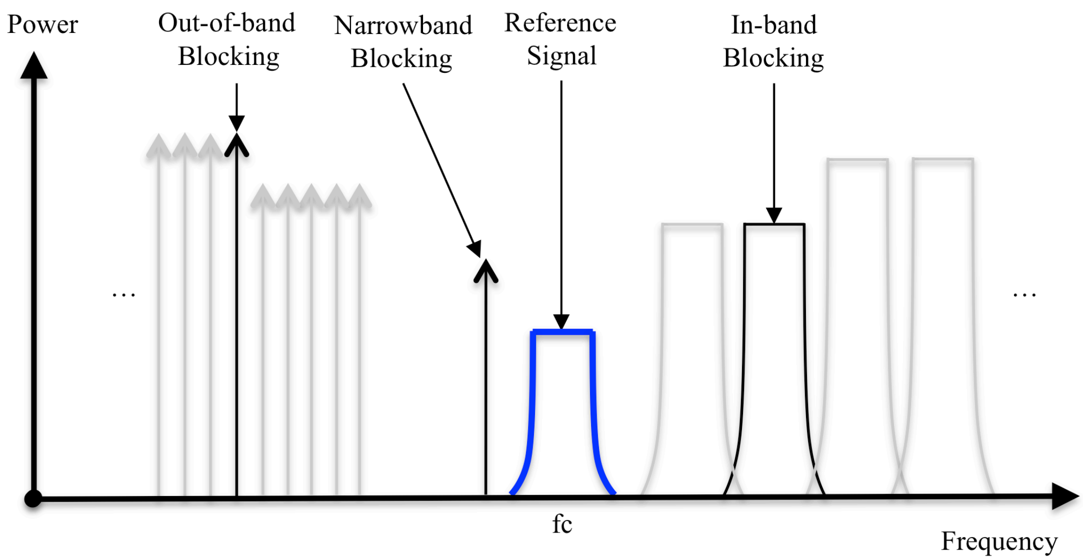


Figure 3.3. LTE Receiver Performance is Specified in the Presence of Three Types of Interference Signals.

When performing blocking characteristics measurements, you can use a measurement configuration similar to that of adjacent channel selectivity, with two RF signal generators connected to a combiner. **Figure 3.4** shows a typical test configuration setup for blocking characteristics.

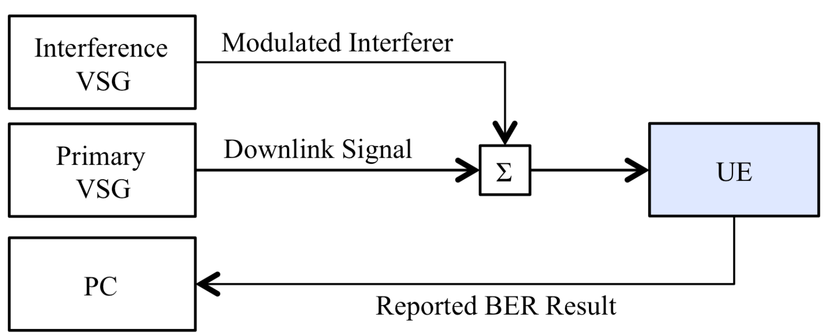


Figure 3.4. Connection for Receiver Tests with Interference or Additional CW Signal

The test setup in **Figure 3.4** illustrates the need for both a traditional vector signal generator (VSG) and a continuous wave (CW) signal generator to produce the interfering signal. In practice, most measurement configurations use only the VSG to produce the interfering signal, because most VSGs can operate in both a vector and CW mode. In **Figure 3.4**, configure the VSG to produce a CW blocking signal for narrowband blocking – and a modulated signal for both in-band and out-of-band blocking characteristics.

Similar to sensitivity and ACS, blocking characteristic measurements require a receiver to achieve a minimum throughput of 95% of its maximum throughput for each of the in-band, out-of-band, and narrowband blocking measurements.

In-Band Blocking

In-band blocking is a metric of receiver performance in the presence of unwanted interfering signal falling into the UE receive band, or into the first 15 MHz below or above the UE receive band. When performing this measurement, the primary vector signal generator is configured to produce an LTE signal at a relatively low power level that is 6-9 dB above the reference sensitivity limit, as specified in **Table 3.7.**

		Bandwidth Configuration					
		1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Power in Transmission Bandwidth		RFSENSE + 6 dB	RFSENSE + 6 dB	RFSENSE + 6 dB	RFSENSE + 6 dB	RFSENSE + 7 dB	RFSENSE + 7 dB
Interferer Bandwidth		1.4 MHz	3 MHz	5 MHz	5 MHz	5 MHz	5 MHz
Interferer Test Case 1	Interferer Power (dBm)	- 56 dBm					
	Interferer Frequency Offset (MHz)	–1.4125 & +1.4125	- 6.0075 & +6.0075	-10.0125 & +10.025	-12.5025 & +12.5025	- 15.0075 & +15.0075	-17.5125 & +17.5125
Interferer Test Case 2	Interferer Power	- 44 dBm					
	Interferer Frequency Offset (MHz)	-4.2075 & +4.2075	-9.0075 & +9.0075	-15.0075 & +15.0075	-17.5125 & +17.5125	-20.0025 & +20.0025	-22.5075 & +22.5075
Interferer Test Case 3	Interferer Power (dBm)	- 30 dBm					
	Interferer Frequency Offset (MHz)	-15.7 & -9.7	-16.5 & -10.5	-17.5 & -11.5	-20 & -14	-22.5 & -16.5	-25 & -19
Interferer Test Case 4	Interferer Power (dBm)	- 30 dBm					
	Interferer Frequency Offset (MHz)	-10.7	-11.5	-12.5	-15	-17.5	-20

Table 3.7. In-band blocking Signal Generator Power Configurations for All Bands Except Bands 12 and 13[34]

In addition, as we observe in **Table 3.7**, a modulated interference signal is configured at a range of frequency offsets and power levels relative to the primary test signal. Signals from both RF signal generators are combined using a combiner, and introduced to the receiver. **Figure 3.5** illustrates the a spectral view of the blocking signal at the input to an LTE reciever.

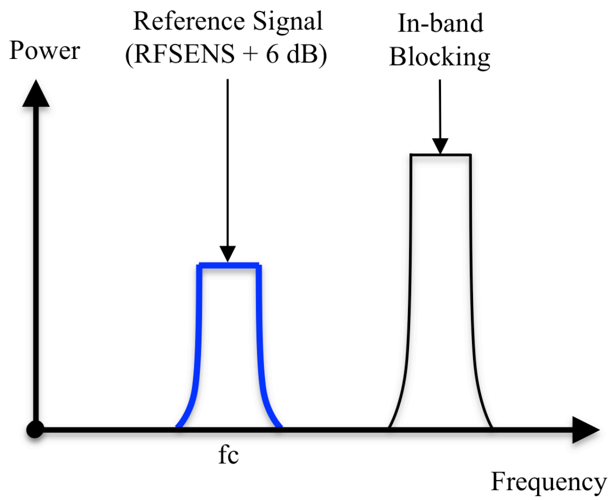


Figure 3.5. Spectrum at the Input of an LTE for In-Band Blocking

UEs are required to achieve a minimum of 95% of maximum theoretical throughput under the conditions described in **Table 3.7** in order to pass the in-band blocking requirements.

Out-of-Band Blocking

The LTE receiver out-of-band band blocking characteristics are designed as a metric to evaluate receiver performance in the presence of higher power out-of band signals. Unlike the in-band blocking characteristics that use a modulated signal, the out-of-band interfering signal is a continuous wave (CW) signal. Thus, this requirement is measured by connecting an RF vector signal generator and a CW signal generator to a power combiner. With this measurement, the primary VSG produces the reference signal for the receiver to demodulate.

When testing out-of-band blocking, the reference LTE signal is generated at a power level that is 6 – 9 dB above the reference sensitivity level of the receiver. The precise power level above the reference sensitivity is chosen based on the channel bandwidth, as illustrated in **Table 3.8**.

---

[34] Recreated from Tables 7.6.3-1 and 7.6.1.3-2 of the 3GPP TS 36.521 Specifications

	Channel Bandwidth					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Reference Signal VSG Power	Sensitivity + 6 dB	Sensitivity + 6 dB	Sensitivity + 6 dB	Sensitivity + 6 dB	Sensitivity + 7 dB	Sensitivity + 8 dB

Table 3.8. Power Requirements for Reference Signal Generator for Out-of-band Blocking Characteristics[35]

With the primary signal generator producing a reference signal, the interfering signal generator produces a blocking signal at a range of power levels and frequency offsets, as illustrated in **Figure 3.6**. As we observe in this figure, close-in interferers are lower in power than far-out interferers. **Figure 3.6** shows that in the 5 MHz bandwidth configuration in E-UTRA band 1, the reference sensitivity requirement is -100 dBm. Thus, the test signal for out-of-band blocking would be –94 dBm , that is 6 dB higher in power.

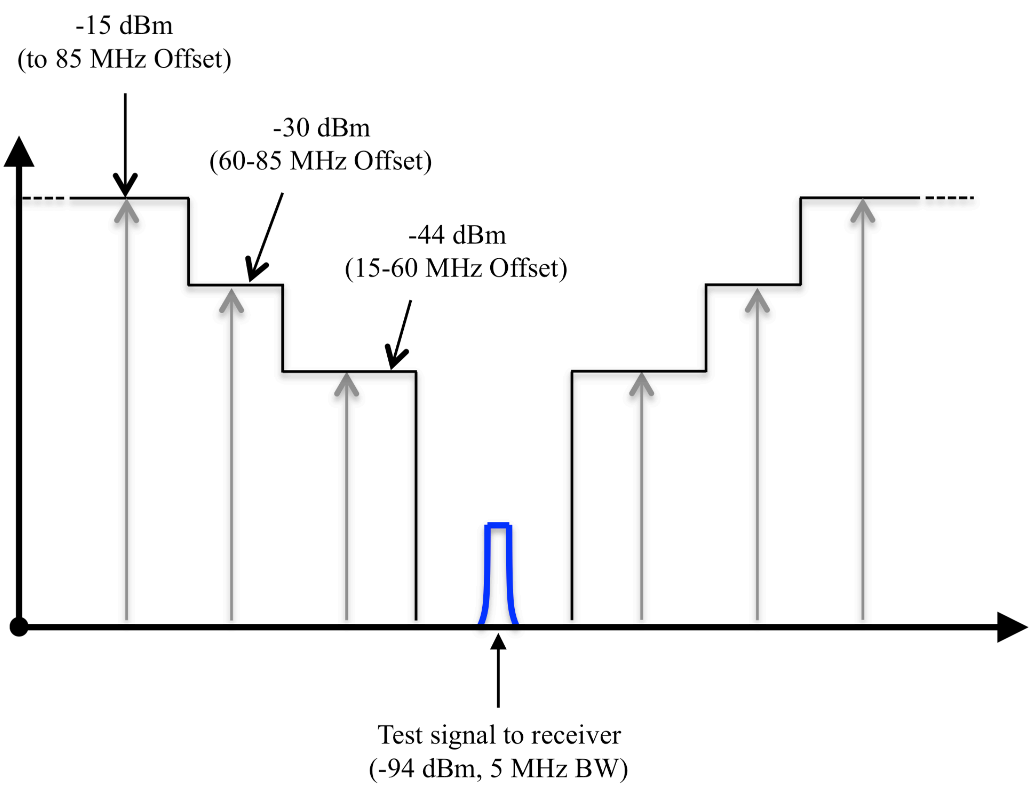


Figure 3.6. Visual Representation of Power Levels and Frequency Offsets For Out-of-band Blocking Characteristics

[35] Recreated from Table 7.6.2.3-1 of the 3GPP TS 36.521 Specifications

Table 3.9 shows the specific power specified for the interferer signal. As we observe from **Table 3.9**, LTE receivers must be able to achieve minimum throughput requirements for frequencies ranging from 1 MHz to 12.75 GHz.

E-UTRA Band	Parameter	Frequency			
		Range 1	Range 2	Range 3	Range 4
	$P_{interferer}$ (dBm)	-44	-30	-15	-15
1,2,3,4,5,6,7,8,9,10,11,12,13,14, 17,18,19,20,21,22,23,24,25,26, 27,33,34,35,36,37,38,39,40,41, 42,43,44	$F_{CW\ interferer}$ (MHz)	F_{DL_low} -15 to F_{DL_low} -60	F_{DL_low} -60 to F_{DL_low} -85	F_{DL_low} -85 to F_{DL_low} 1 MHz	-
		F_{DL_high} +15 to F_{DL_high} +60	F_{DL_high} +60 to F_{DL_high} +85	F_{DL_high} +85 to F_{DL_high} +12750 MHz	-
2,5,12,17	$F_{interferer}$	-	-	-	F_{DL_low} - F_{DL_high}

Table 3.9. Out-of-band Blocking Interferer Specifications[36]

Similar to the in-band blocking requirements, out-of-band blocking requires that the receiver must achieve 95% of maximum throughput.

Narrowband Blocking

Narrowband blocking is a metric of the LTE receiver's ability achieve minimum throughout in the presence of an unwanted narrow band interferer at a frequency offset that is less than the channel spacing. Similar to the out-of-band blocking characteristics, the narrowband blocking measurement requires a test configuration that uses both a vector signal generator and a CW signal generator.

When performing this measurement, the reference signal generator is configured to produce an LTE downlink signal, and the CW signal produces the interference tone. Because the interferer for narrowband blocking is close in frequency to the band of interest, the power level of the interferer is much closer to the power level of the reference signal. As we observe is **Table 3.10**, the reference LTE signal ranges from 16 dB to 22 dB above the sensitivity level of the receiver. Also, the interferer is generated at a power level of -55 dB for all bandwidth configurations, and is spaced at a frequency offset that is just over 200 kHz away from the band of interest.

[36] Recreated from Table 7.6.2.3-2 of the 3GPP 36.521 Specifications

	Channel bandwidth					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
P_W (dBm)	$P_{REFSENS}$ + channel-bandwidth specific value below					
	22	18	16	13	14	16
$P_{CW\ interferer}$(dBm)	-55	-55	-55	-55	-55	-55
$F_{cw\ Interferer\ Offset}$ (MHz)	0.9075	1.7025	2.7075	5.2125	7.7025	10.2075

Table 3.10. Reference Signal and Interferer Specifications for Narrow-band Blocking Requirements for General Case[37]

Similar to both in-band and out-of-band blocking characteristics, the narrow-band blocking measurement requires the LTE receiver to achieve greater than 95% throughput under the conditions described in **Table 3.10**.

Spurious Responses

Similar to the out-of-band blocking characteristics, the spurious responses measurement verifies the receiver's performance in the presence of a CW interferer. The spurious response measurement is designed to supplement the out-of-band blocking characteristics requirements by providing a looser specification requirement in cases where the receiver fails out-of-band blocking. The spurious responses measurement characteristics are defined in section 7.7 of the 3GPP TS 36.521 specifications.

Before testing for spurious responses, we must first test a receiver for out-of-band blocking characteristics and record the frequencies for which the receiver does not achieve 95% throughput. We must then test the receiver for spurious responses for these recorded frequencies.

The test hardware configuration for spurious responses is identical to out-of-band blocking and requires a vector signal generator, a CW signal generator, and a power combiner. The vector signal generator produces an LTE downlink signal. The CW signal generator is configured according to the power levels specified in **Table 3.11**.

[37] Recreated from Table 7.6.3.3-1 and Table 7.5.3-3 of the 3GPP TS 36.521 Specifications

	Channel Bandwidth					
	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Reference Signal VSG Power	Sensitivity + 6 dB	Sensitivity + 6 dB	Sensitivity + 6 dB	Sensitivity + 6 dB	Sensitivity + 7 dB	Sensitivity + 9 dB
CW Interferer Power	-44 dBm	-44 dBm	-44 dBm	-44 dBm	-44 dBm	-44 dBm
CW Interferer Frequency	CW interfer test frequencies are defined as frequencies for which the receiver failed out-of-band blocking characteristics					

Table 3.11. Power Levels of Both Reference and Interfering RF Signal Generator for Spurious Response[38]

Intermodulation Characteristics

Receiver intermodulation characteristics is a metric that describes the linearity of the receiver's front end. A receiver's resilience to intermodulation distortion is determined by injecting two interference signals in addition to a reference downlink LTE signal to the receiver. The frequency spacing of the two interfering signals is chosen such that they produce a third-order distortion product that directly interferes with the reference downlink signal. As we observe in **Figure 3.7**, the frequency offset between the CW interferer and the modulated interferer is equivalent to the frequency spacing between the CW interferer and the reference signal to the receiver. Thus, the resulting third-order distortion product directly interferes with the reference signal.

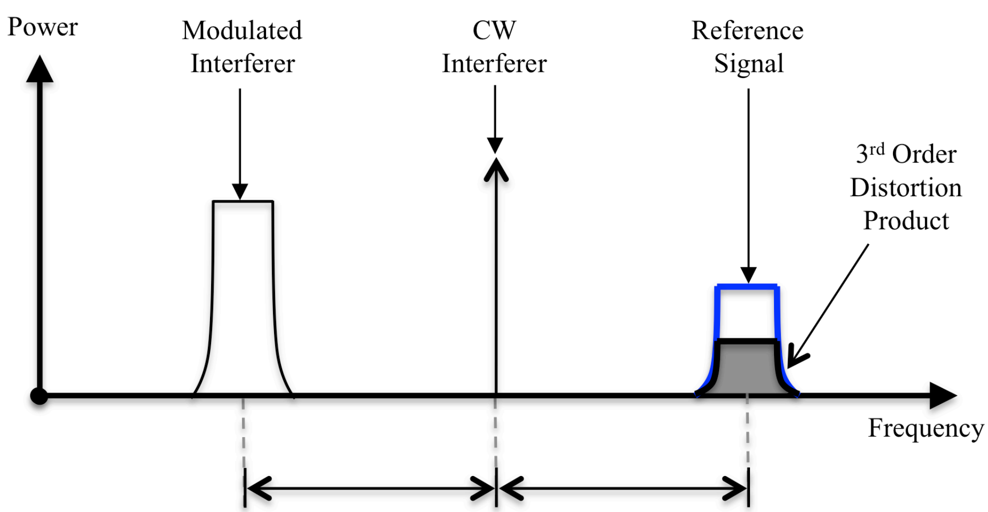


Figure 3.7. Interfering Signals are Spaced Such That the Third-order Distortion Product Interferes with the Reference Signal

[38] Recreated Tables 7.7.3-1 and Tables 7.7.3-2 of the 3GPP TS 36.521 Specifications

As **Figure 3.7** indicates, the test setup for intermodulation characteristics requires three RF signal generators and includes two VSGs and one CW signal generator. As a result, the hardware configuration requires a three-way RF power combiner. The combined output is then connected to the receiver, as shown in **Figure 3.8**.

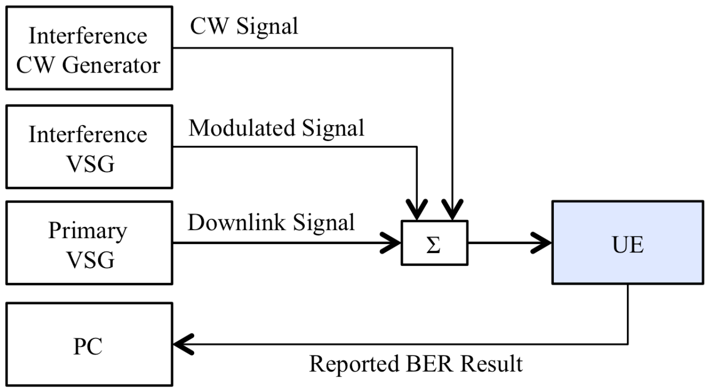


Figure 3.8. Hardware Configuration for Intermodulation Characteristics

As illustrated by **Figure 3.8**, the frequency spacing between interfering tones is precisely chosen in order to produce a third-order distortion product at the appropriate frequency. **Table 3.12** defines both the power levels and tone spacing for interfering signals.

		Channel Bandwidth					
		1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Reference Signal	Power Level	Sensitivity + 12 dB	Sensitivity + 8 dB	Sensitivity + 6 dB	Sensitivity + 6 dB	Sensitivity + 7 dB	Sensitivity + 9 dB
CW Interferer	Power Level	-46 dBm					
	Frequency Offset	-2.8 MHz & +2.8 MHz	-6.0 MHz & + 6.0 MHz	-10 MHz & +10 MHz	-12.5 MHz & +12.5 MHz	-15 MHz & +15 MHz	-17.5 MHz & +17.5 MHz
Modulated Interferer	Signal Bandwidth	1.4 MHz	3 MHz	5 MHz	5 MHz	5 MHz	5 MHz
	Power Level	-46 dBm					
	Frequency Offset	-5.6 MHz & +5.6 MHz	-12.0 MHz & +12.0 MHz	-20 MHz & +20 MHz	-25 MHz & +25 MHz	-30 MHz & +30 MHz	-35 MHz & +35 MHz

Table 3.12. Interferer Spacing and Power Levels for LTE Intermodulation Receiver Characteristics Measurements[39]

The receiver intermodulation measurement specifies two sets of interferer frequency offset for each measured center frequency. As we observe in Table 3.12, intermodulation requires one to test first with the two positive frequency offsets as interferes - and second with the two negative frequency offsets as interferers. Similar to other LTE receiver measurements, the criteria for passing intermodulation characteristics is 95% of maximum theoretical throughput.

Spurious Emissions

Unlike most receiver measurements, which define a receiver's ability to achieve a specified throughput under a range of signal conditions, the spurious emissions measurement is designed to characterize the receive port's radiated emissions. This measurement is defined in section 7.9 of the 3GPP TS 36.521 specifications.

The hardware requirements for spurious emissions specifies that we connect a spectrum analyzer to the receive port of the receiver. As we observe in **Figure 3.9**, the spectrum analyzer is connected to the receiver through a circulator.

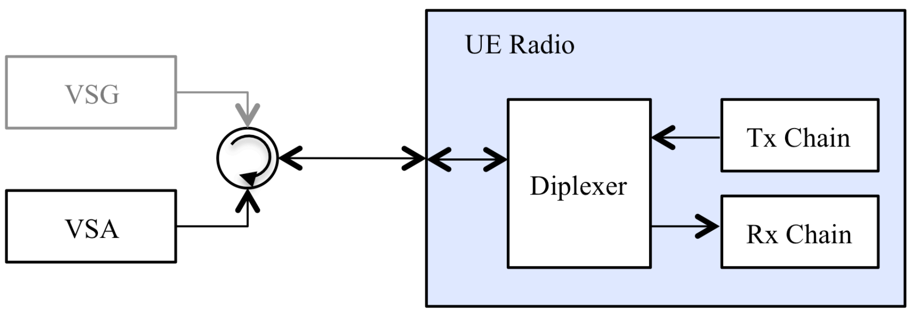


Figure 3.9. Hardware Configuration for Receiver Spurious Emissions Measurement[40]

Figure 3.9 illustrates that a vector signal generator is technically not required for the spurious emissions measurement. Instead, the spectrum analyzer measures emission in a range of signal bandwidths, as defined by **Table 3.13**.

[39] Recreated from Table 7.8.1.3-1 of the 3GPP TS 36.521 Specifications

[40] Recreated from figure A.8 of the 3GPP TS 36.508 specifications

Frequency Band	Measurement Bandwidth	Maximum Emissions	Note
30 MHz to 1 GHz	100 kHz	-57 dBm	
1 GHz to 12.75 GHz	1 MHz	-47 dBm	
12.75 GHz to 5th harmonic of upper frequency edge of DL operating band	1 MHz	-47 dBm	Applies to bands 22, 42, and 43 only

Table 3.13. Receiver Spurious Emissions Requirements[41]

As we observe in **Table 3.13**, the receiver emissions cannot exceed -57 dBm in a 100 kHz bandwidth when operating at center frequency less than 1 GHz. In addition, the emissions cannot exceed -47 dBm in a 1 MHz bandwidth at a center frequency greater than 1 GHz. These limits are established to ensure that the receiver does not interfere with other cellular and wireless devices. While the emissions requirements for LTE transmitters are rigidly defined, the only emissions requirement for LTE receivers is spurious emissions.

[41] Recreated from Table 7.9.3-1 of the 3GPP TS 36.521 specifications

4. References

[1] 3GPP TS 36.101 V8.5.0 (2009-03) Evolved Universal Terrestrial Radio Access (E-UTRA) User Equipment (UE) radio transmission and reception (Release 8)

[2] ITU-R Recommendation SM.329-10, "Unwanted emissions in the spurious domain"