LTE Quality of Experience

Modulation and MIMO
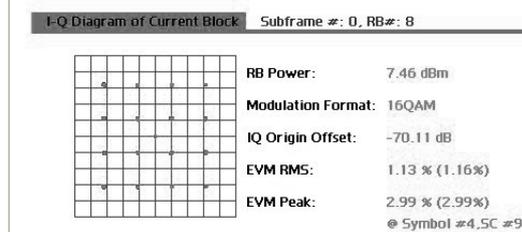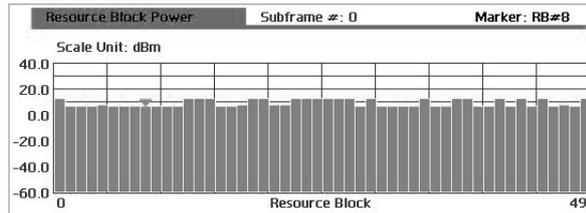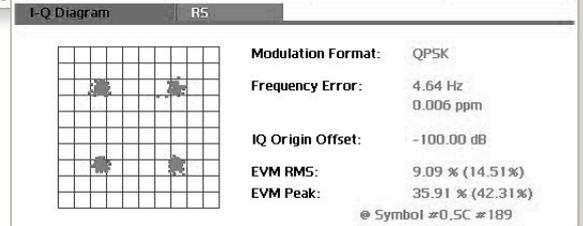
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Introduction

Long term evolution (LTE) is the fourth-generation wireless technology specified by 3rd Generation Partnership Project (3GPP). Different factors motivated the creation of LTE. From a mobile user's perspective, increased throughput was needed to support demand for rich content and real-time applications. From a mobile operator's perspective, a less-complex and more-efficient network with lower-operational costs became advantageous by leveraging the simplicity of an all-IP backbone.

Improved connectivity with lower complexity in the network was achieved with better signaling management, adding more intelligence into cell sites, thereby reducing the time for connection setups and handovers between cells.

Perhaps one of the most important achievements of LTE relates to using the spectrum to properly serve the increasing demand for throughput while maintaining similar spectrum allocations and without compromising service quality.

This spectrum or radio resource management considers different aspects, including:

- LTE Signal Format — implementing a new transmission format of cell sites based on orthogonal frequency division multiple access (OFDMA), composed of 15 KHz resource elements across different channel bandwidths from 1.4 MHz to 20 MHz
- LTE Scheduler — incorporating the ability to dynamically adapt the number of bits transmitted on the link between the cell site and mobile devices in which different modulation types (QPSK, 16 QAM, and 64 QAM) are scheduled based on the signal quality received by the mobile device
- LTE Multiple Input Multiple Output (MIMO) — allowing multiple transmission streams between the cell site and mobile devices with the adoption of MIMO arrays, from a dual reception and transmission, or MIMO 2 x 2 to multipliers up to MIMO 8 x 8 (considered in LTE Advanced)

LTE Signal Format

The signal format of LTE is based on OFDMA in the transmission of cell sites or downlinks and single carrier FDMA (SC-FDMA) in the transmission of mobile devices or uplinks.

The most critical transmission in terms of available resources or bandwidth is the downlink because it provides bandwidth to mobile users. The minimum bandwidth that can be assigned to a user in LTE is defined as the resource block (RB), which consists of a group of 84 resource elements (12 subcarriers of 15 KHz in frequency x 7 symbols) and these RB are transmitted in a time-slot every 0.5 ms.
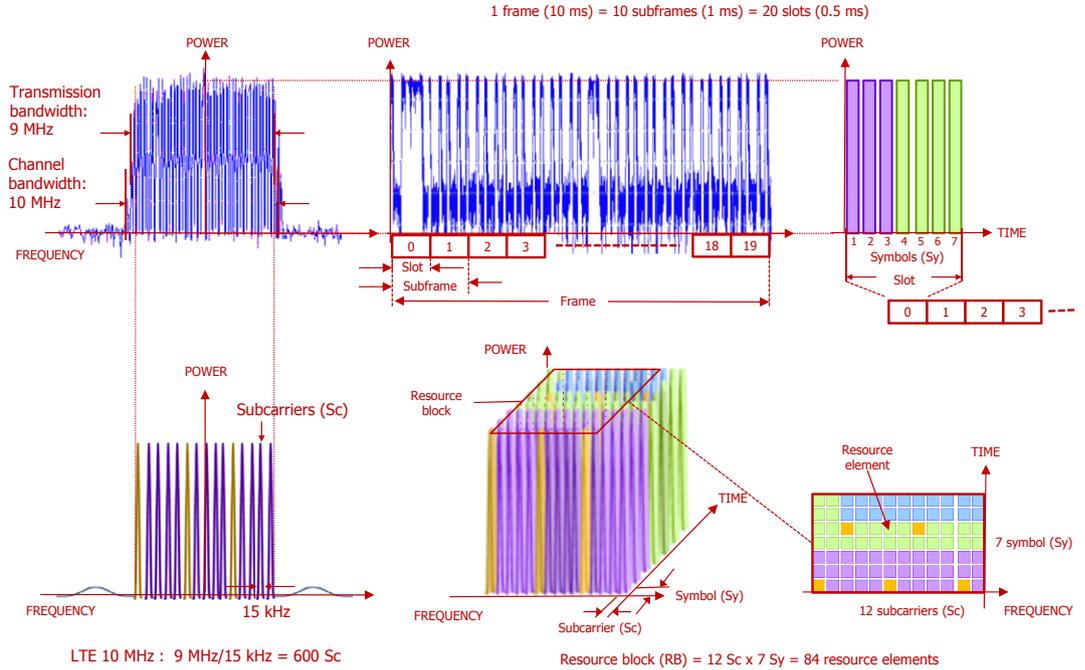
Figure 1. LTE signal format

LTE enables spectrum flexibility where the transmission bandwidth can be selected between 1.4 MHz and 20 MHz depending on the available spectrum. Therefore, the maximum number of users that can be served at every 0.5 ms is 800 considering a 20 MHz channel with 8 simultaneous transmitter branches.

Channel bandwidth (MHz)	1.40	3.00	5.00	10.00	15.00	20.00
Transmission bandwidth (MHz)	1.08	2.70	4.50	9.00	13.50	18.00
Resource blocks (0.5 ms)	6	15	25	50	75	100
Resource blocks (MIMO 2x2)	12	30	50	100	150	200
Resource blocks (MIMO 4x4)	24	60	100	200	300	400
Resource blocks (MIMO 8x8)	48	12	200	400	600	800

Table 1. LTE channels and user connections

LTE signals can be transmitted in relative narrowband channels or broadband channels, however the size of the channel bandwidth doesn't improve resiliency against interference (external or internal) nor spurious noise or noise generated by the cell site. Instead, the channel bandwidth has a direct relationship with the number of connections or data throughput it can provide to mobile users via resource blocks.

Any deficiency in the signal format can affect the transmission of resource blocks and have a direct impact on quality of experience. For example, interference signals within an LTE downlink will affect the RB assigned to a user which might get distorted and unreadable by the mobile device.
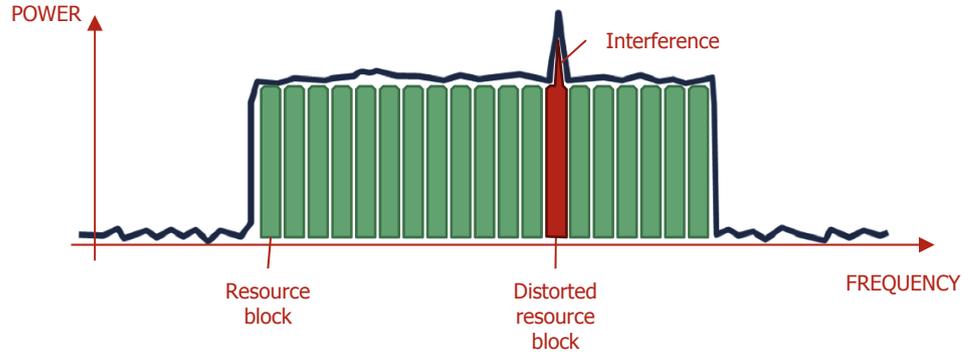
Figure 2. LTE signal distorted by interference

LTE Bandwidth						
Channel bandwidth (MHz)	1.4	3.0	5.0	10.0	15.0	20.0
TX bandwidth (MHz)	1.1	2.7	4.5	9.0	13.5	18.0
RB per timeslot (0.5 ms)	6	15	25	50	75	100
64 QAM MIMO 2x (Mbps)	12.1	30.2	50.4	100.8	151.2	201.6
LTE Bandwidth (1 distorted RB)						
RB per timeslot (0.5 ms)	5	14	24	49	74	99
64 QAM MIMO 2x (Mbps)	10.1	28.2	48.4	98.8	149.2	199.6
Bandwidth reduction	−16.7%	−6.7%	−4.0%	−2.0%	−1.3%	−1.0%

Note: Bandwidth estimates consider all resource elements (REs) transmitting user data.

Table 2. LTE bandwidth reduction (1 distorted RB)

Similarly, a problem with linearity in the amplifier or filter of the cell site might affect the power level of a group of RBs, significantly reducing the number of RBs available for service.
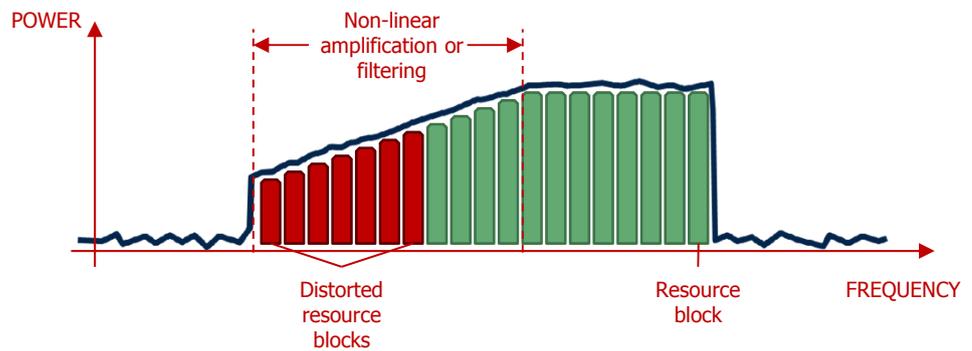

Figure 3. LTE signal distorted by non-linear amplification or filtering

LTE Bandwidth						
Channel bandwidth (MHz)	1.4	3.0	5.0	10.0	15.0	20.0
TX bandwidth (MHz)	1.1	2.7	4.5	9.0	13.5	18.0
RB per timeslot (0.5 ms)	6	15	25	50	75	100
64 QAM MIMO 2x (Mbps)	12.1	30.2	50.4	100.8	151.2	201.6
LTE Bandwidth (7 distorted RBs)						
RB per timeslot (0.5 ms)	0	8	18	43	68	93
64 QAM MIMO 2x (Mbps)	—	15.8	35.4	84.7	133.9	187.5
Bandwidth reduction	−100%	−46.7%	−28.0%	−14.0%	−9.3%	−7.0%

Note: Bandwidth estimates consider all REs transmitting user data.

Table 3. LTE bandwidth reduction (7 distorted RBs)

To ensure integrity of the LTE signal, 3GPP [4] has defined a series of RF performance requirements, including:

- Channel power
- Occupied bandwidth
- Frequency error in a subframe
- Time alignment between branches
- Unwanted emission
- Adjacent channel leakage power ratio
- Error vector magnitude in user data (PDSCH)

The following diagrams illustrate some of these performance tests on a 3GPP-compliant LTE 10 MHz signal.
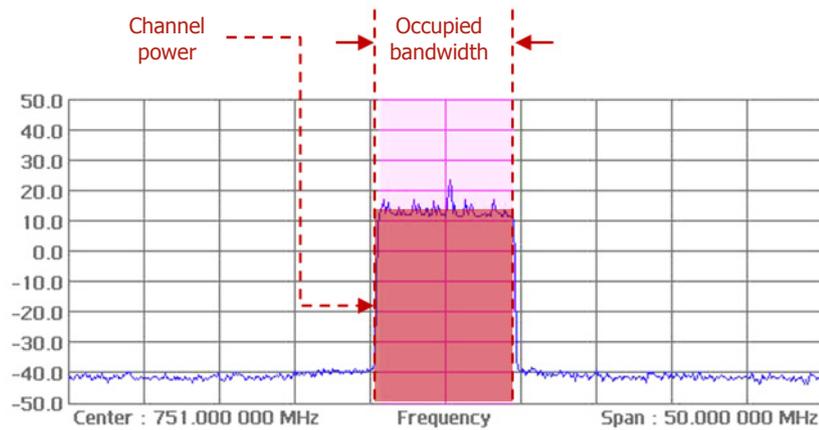

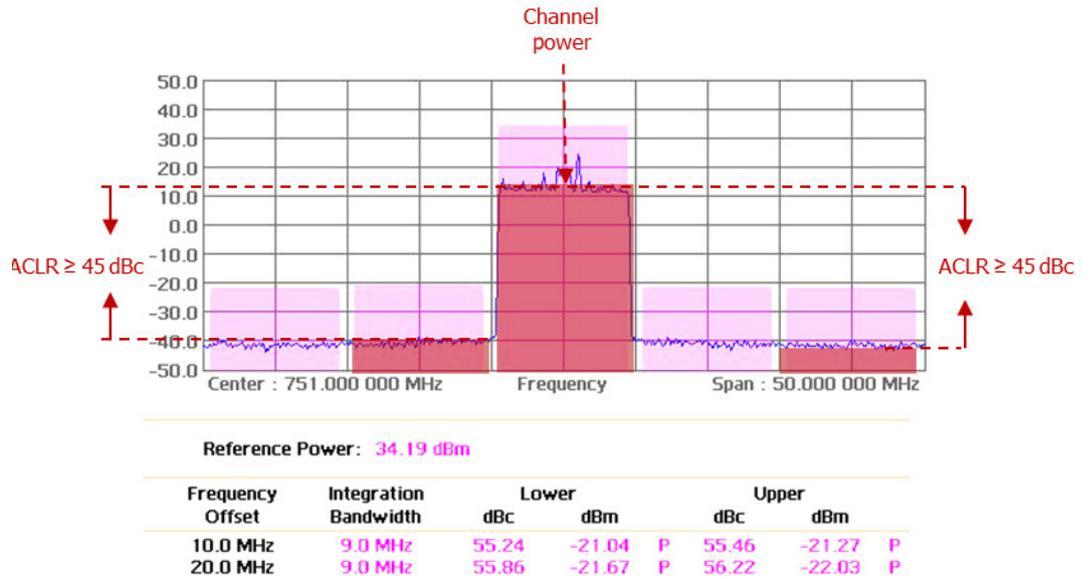Figure 4. LTE channel power and occupied bandwidth

Figure 5. LTE adjacent channel leakage power ratio

LTE Scheduler

The assignment of RBs to mobile users and the modulation scheme to transmit user data is done by the LTE scheduler. It is not a fixed assignment; it can be dynamically adjusted based on the signal quality received by the mobile user. This ability to adapt the link according to the RF conditions is defined as link adaptation.

The radio resources assigned to mobile users are transmitted in physical downlink shared channels (PDSCH). These are based on bandwidth requirements, and can be one or multiple RBs. In addition, the user data transmitted can have different modulation schemes (QPSK, 16 QAM, 64 QAM) as defined by the LTE scheduler. The higher the modulation (such as 64 QAM), the higher the number of bits (6 bits per symbol) transmitted by the RB.
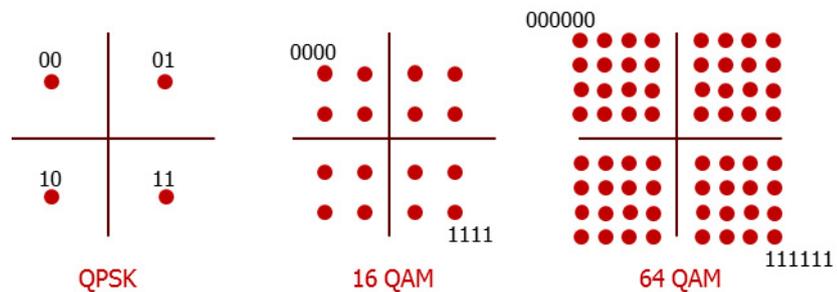

Figure 6. User data (PDSCH) modulation types

RF Environment and Throughput

The scheduler's decision on the modulation format to be used for each mobile user at a specific moment in time is derived by the RF environment experienced by the mobile user. This RF environment is measured by the mobile device based on the signal quality of the reference signal (RS) received from each antenna; and, in turn, the mobile device sends a signal-quality level to the cell site via the channel quality indicator (CQI). The scheduler uses the received CQI level to assign the corresponding modulation scheme that the mobile user will be able to receive according to its RF environment.

CQI	PDSCH Modulation
0	Out of range
1 to 6	QPSK
7 to 9	16 QAM
10 to 15	64 QAM

Figure 7. RF environment assessment (via reference signals) and CQI

RSs are used by the mobile device to assess the RF environment because they are always transmitted by the cell site in every RB at a constant power level and with the same modulation scheme. Therefore, it is a reliable reference to periodically measure the mobile's RF environment and adjust the modulation accordingly.

In addition, unique RSs are transmitted by each branch or antenna of the cell site. For example, in dual transmission, the cell site will be sending two RS: RS0 from antenna 1, and RS1 from antenna 2. This will allow the mobile device to make independent assessments of the signal quality received from each transmitting antenna. This characteristic is further described in the LTE MIMO section.
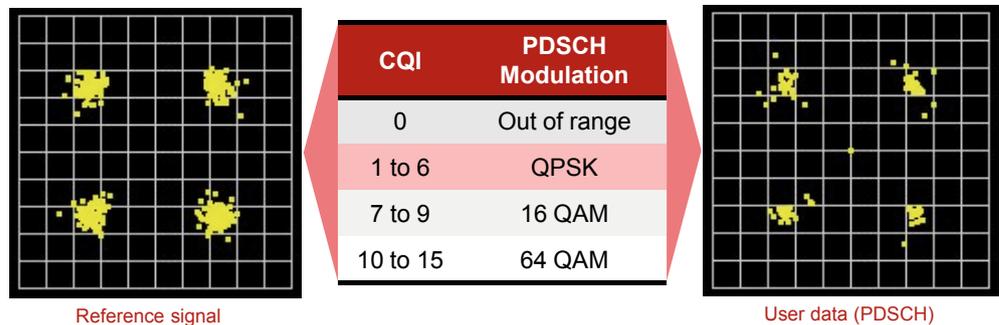

CQI	PDSCH Modulation
0	Out of range
1 to 6	QPSK
7 to 9	16 QAM
10 to 15	64 QAM

Reference signal

User data (PDSCH)

Figure 8. Reference signal and user data (QPSK)

LTE Bandwidth					
Channel bandwidth (MHz)	1.4	3.0	5.0	10.0	15.0	20.0
TX bandwidth (MHz)	1.1	2.7	4.5	9.0	13.5	18.0
RB per timeslot (0.5 ms)	6	15	25	50	75	100
64 QAM MIMO 2x (Mbps)	12.1	30.2	50.4	100.8	151.2	201.6
LTE Bandwidth (QPSK MIMO 2x)					
QPSK MIMO 2x (Mbps)	4.0	10.1	16.8	33.6	50.4	67.2
Bandwidth reduction	−66.7%	−66.7%	−66.7%	−66.7%	−66.7%	−66.7%

Note: Bandwidth estimates consider all RE transmitting user data.
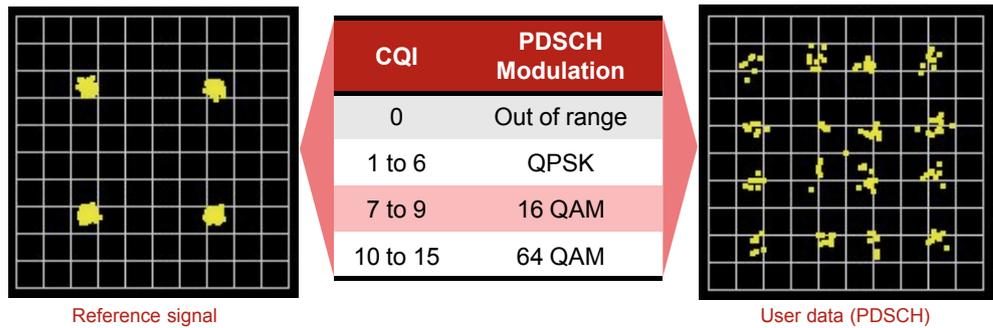
Table 4. LTE bandwidth QPSK

CQI	PDSCH Modulation
0	Out of range
1 to 6	QPSK
7 to 9	16 QAM
10 to 15	64 QAM

Reference signal   User data (PDSCH)

Figure 9. Reference signal and user data (16 QAM)

LTE Bandwidth					
Channel bandwidth (MHz)	1.4	3.0	5.0	10.0	15.0	20.0
TX bandwidth (MHz)	1.1	2.7	4.5	9.0	13.5	18.0
RB per timeslot (0.5 ms)	6	15	25	50	75	100
64 QAM MIMO 2x (Mbps)	12.1	30.2	50.4	100.8	151.2	201.6
LTE Bandwidth (16 QAM MIMO 2x)					
16 QAM MIMO 2x (Mbps)	8.1	20.2	33.6	67.2	100.8	134.4
Bandwidth reduction	−33.3%	−33.3%	−33.3%	−33.3%	−33.3%	−33.3%

Note: Bandwidth estimates consider all RE transmitting user data.
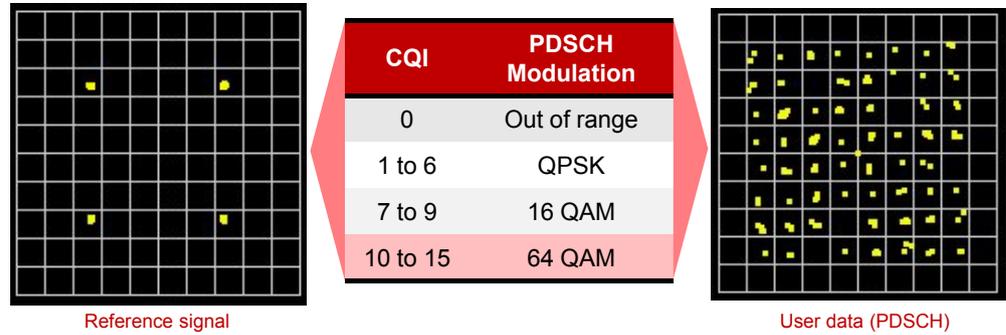
Table 5. LTE bandwidth 16 QAM

CQI	PDSCH Modulation
0	Out of range
1 to 6	QPSK
7 to 9	16 QAM
10 to 15	64 QAM

Reference signal   User data (PDSCH)

Figure 10. Reference signal and user data (64 QAM)

LTE Bandwidth						
Channel bandwidth (MHz)	1.4	3.0	5.0	10.0	15.0	20.0
TX bandwidth (MHz)	1.1	2.7	4.5	9.0	13.5	18.0
RB per timeslot (0.5 ms)	6	15	25	50	75	100
64 QAM MIMO 2x (Mbps)	12.1	30.2	50.4	100.8	151.2	201.6

Note: Bandwidth estimates consider all RE transmitting user data.

Table 6. LTE bandwidth 64 QAM

Mobile operators are constantly monitoring the signal quality of transmitted RSs in order to allocate 64 QAM to mobile users and achieve two main objectives: first, to efficiently utilize the spectrum, maximizing capacity; and second, to deliver high throughput providing a high quality of experience to its mobile users.

Synchronization and Throughput

Another important aspect of the LTE scheduler is synchronization, since it is the base from which a cell site modulates the signal. For example, if a primary synchronization reference derived from a global positioning system (GPS) is lost, a cell site will continue its operation based on its internal time base. However, due to its wander characteristics, it will start drifting its frequency. In this case, the modulation will be affected by this frequency drift in terms of phase shift, and in turn, will create transmission problems in user-data-degrading throughput.
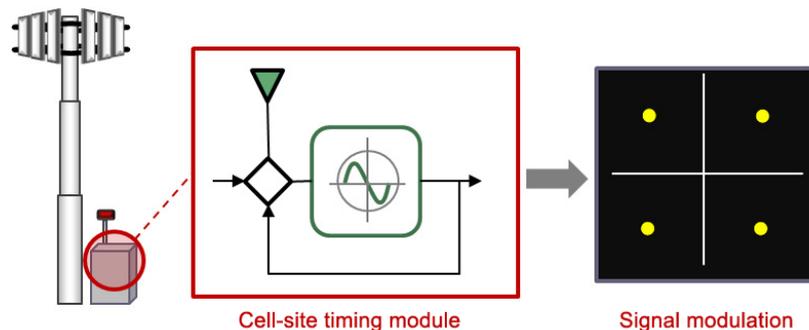

Cell-site timing module   Signal modulation

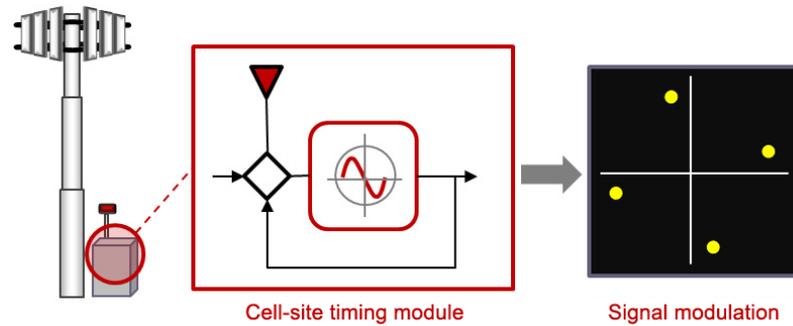Figure 11. Cell site synchronized with GPS

Figure 12. Cell site in free run

LTE MIMO

The principle of MIMO is to establish different communication paths between a cell site and a mobile user by providing multiple antennas into each entity. For example, the most common deployment of LTE links is with MIMO 2x2, which implies that the cell site and the mobile user have two antennas for transmission and reception.

The main benefits of MIMO are transmission diversity and spatial multiplexing. The first is to improve reception for a mobile device influenced by fading or located where the received signal might be weak. In this case, the same data is transmitted from multiple paths.

Figure 13. MIMO 2x2 transmission diversity

The second benefit, spatial multiplexing, is where the transmitted paths from each antenna contain different user data, effectively multiplying cell-site bandwidth capacity.

Figure 14. MIMO 2x2 spatial multiplexing

Similar to the case of adaptive modulation based on CQI, the operation mode of MIMO is continuously adapted based on the RF conditions of the mobile device.

LTE Bandwidth						
Channel bandwidth (MHz)	1.4	3.0	5.0	10.0	15.0	20.0
TX bandwidth (MHz)	1.1	2.7	4.5	9.0	13.5	18.0
RB per timeslot (0.5 ms)	6	15	25	50	75	100
64 QAM MIMO 2x (Mbps)	12.1	30.2	50.4	100.8	151.2	201.6
64 QAM MIMO 4x (Mbps)	24.2	60.5	100.8	201.6	302.4	403.2
64 QAM MIMO 8x (Mbps)	48.4	121.0	201.6	403.2	604.8	806.4

Note: Bandwidth estimates consider all RE transmitting user data.

Table 7. Downlink peak rates for LTE

In the case of good reception conditions at the mobile device, MIMO adapts its mode of operation as does spatial multiplexing, which in the case of MIMO 2x2 will be transmitting different user data from each antenna. This effectively doubles the capacity or bandwidth.

The ability to differentiate the path from each antenna is based on the cell-specific reference signals which occupy different positions in the resource blocks.
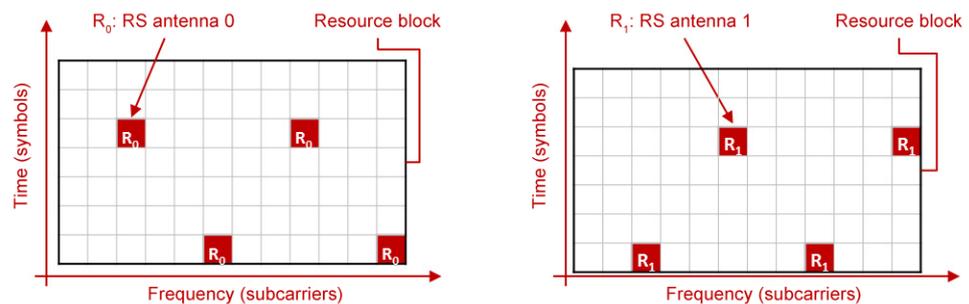

Figure 15. Cell-specific RS for antennas 0 and 1 in an RB

Two conditions are required for proper MIMO operation:

1. The power levels transmitted by antennas should be similar so that mobile devices effectively receive data from each antenna. In the case of a power imbalance, the mobile user will discard the low-power signal and only receive the data transmitted from one path.
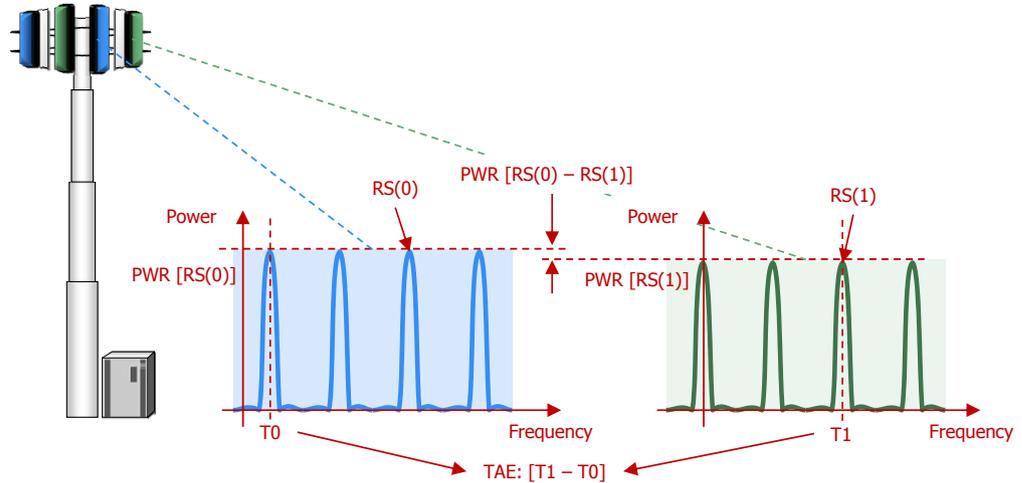

Figure 16. MIMO power imbalance

MIMO power imbalance can be caused by different factors internal and external to the cell site. Examples include reflection on the feed lines, different attenuation from each antenna, and different RF conditions such as fading due to multipaths at the location of the mobile user.
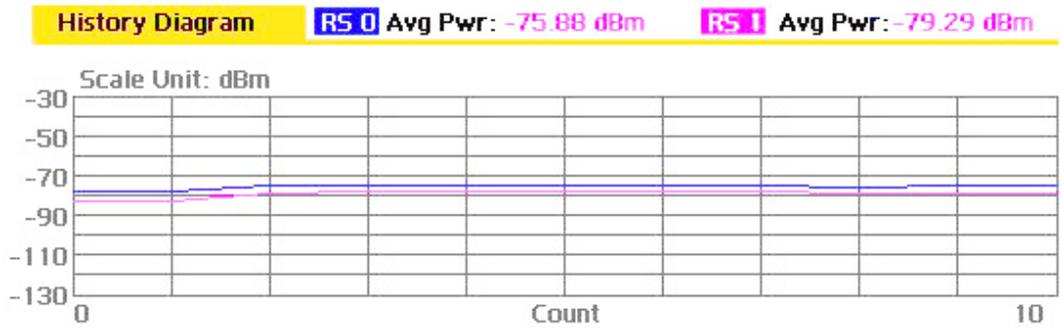

Figure 17. MIMO power difference from antenna 0 (RS0) and antenna 1 (RS1)

Regardless of the cause, MIMO power imbalance should be avoided in order capitalize on its benefits of diversity and perhaps, more importantly, to transmit different paths multiplying bandwidth with spatial multiplexing.

2. Time alignment, which is the time difference between the reference signals of two transmitting antennas should be minimal. If the time alignment difference of both arriving signals is excessive, then a mobile device won't be able to synchronize data received from both paths. The maximum time alignment difference or error between antennas should be no greater than 65 ns [4].
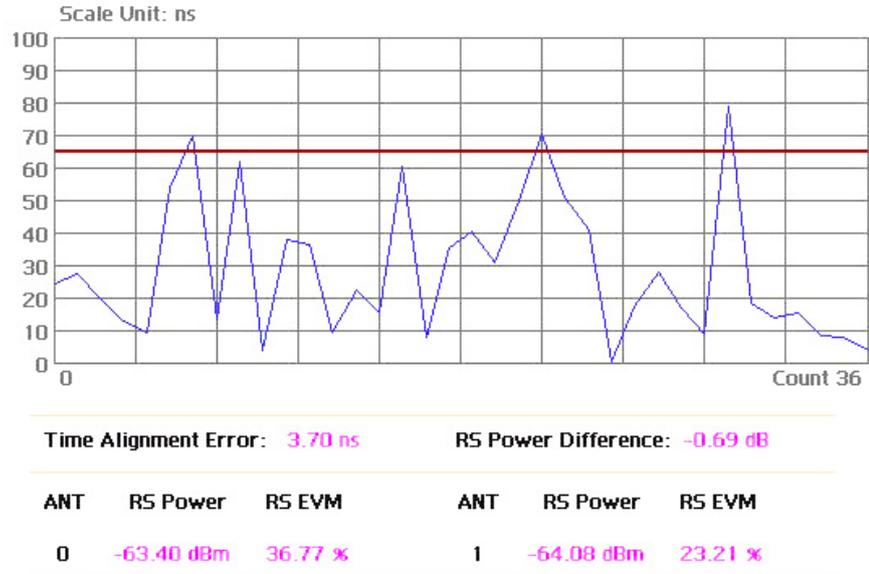
Figure 18. MIMO time alignment error antenna 0 (RS0) and antenna 1 (RS1)

In addition to power and time alignment between MIMO branches, it is common practice to assess the modulation quality of each transmitted antenna in order to promptly identify and correct transmission impairments.
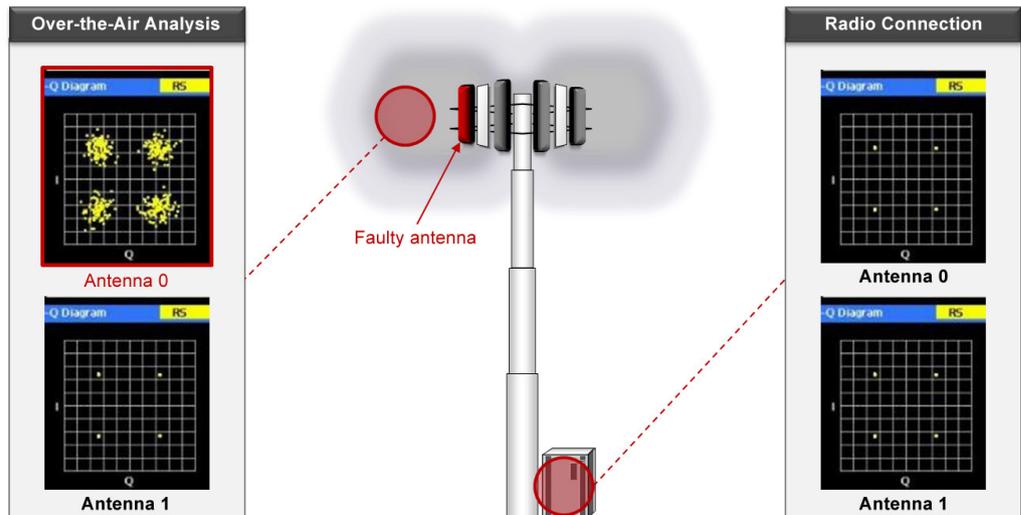

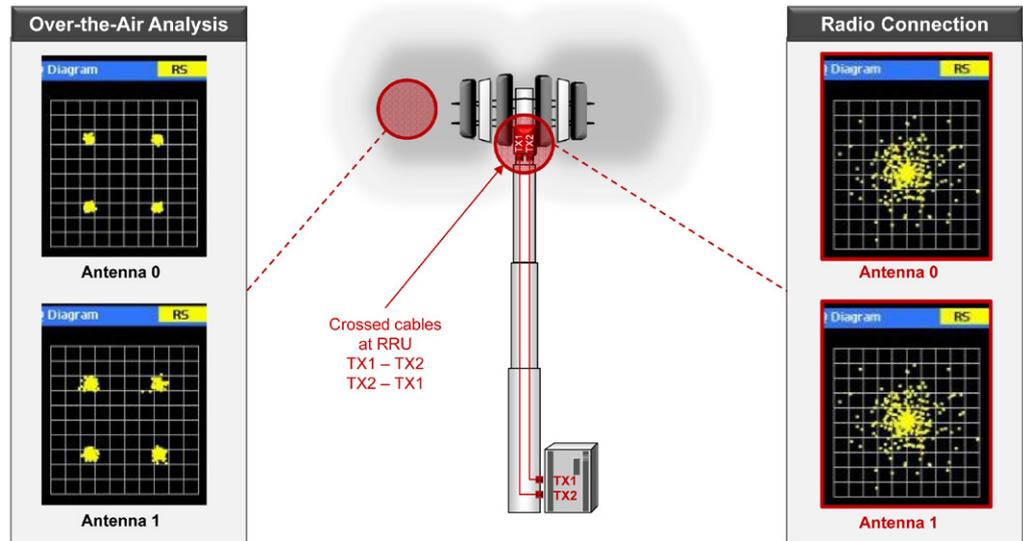Figure 19. MIMO failure due to antenna 0

Figure 20. MIMO failure due to cross cabling

LTE Quality Assessment Over the Air

The variety of cell-site types, from conventional radios with coaxial feed-lines to distributed radios with baseband units and remote units connected via fiber, as well as the different terrain conditions and environments where cell-sites are installed, creates the need to make performance measurements over the air (OTA).

However, OTA measurements are affected by several conditions that need to be carefully considered in order to perform reliable measurements. Perhaps the most important conditions to consider include the following:

- **Interference** — The presence of other signals at the same frequency from those transmitted by the cell-site might distort the performance characterization of the cell site. Therefore, measurement techniques must be applied to minimize the presence of interference by using directional antennas with limited beam width and having a direct line-of-sight to the cell site under test.
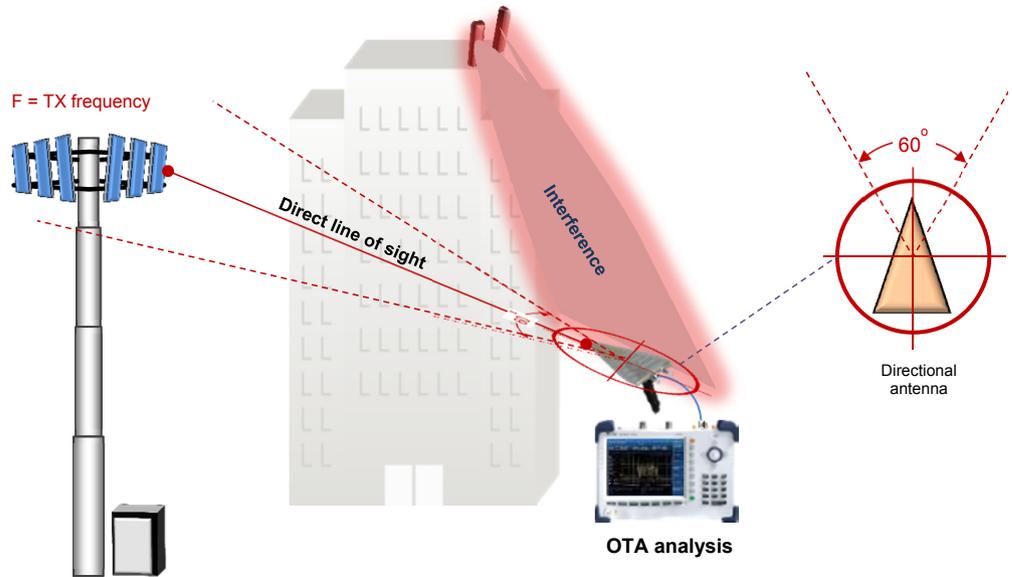
Figure 21. Interference effects in OTA measurements

- **Multipath** — Similar to the effects of interference from other transmitters, in certain environments the signal transmitted by the cell site is reflected by different elements in the environment. This creates multiple paths that reach the receiver, altering the performance profile of the signal transmitted by the cell site; in which case, the use of a directional antenna with a direct line-of-sight to the cell site under test will minimize the effect of multipath.
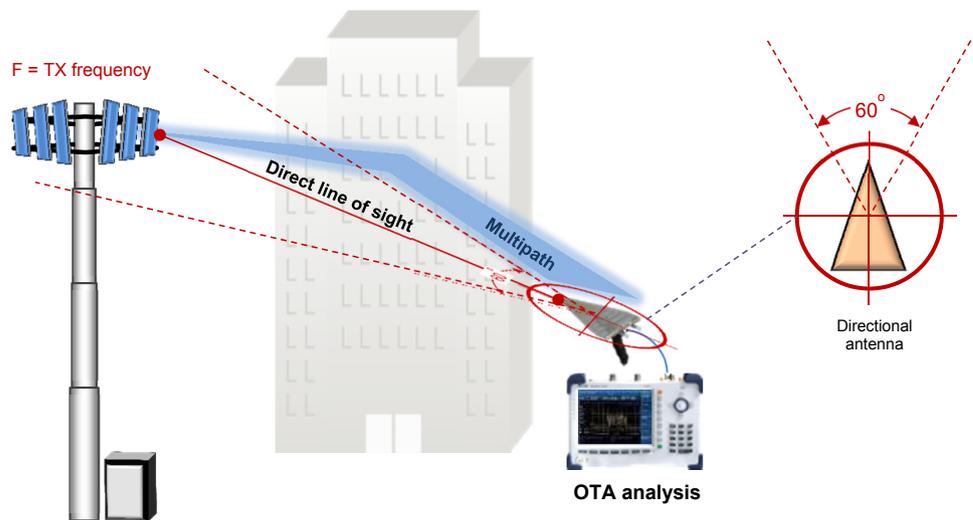

Figure 22. Multipath effect in OTA measurements

- **Path Loss** — This characterizes the decrease in power experienced by the transmitted signal when it is propagated over the air which has a direct relationship with the traveled distance, and takes into consideration the signal's properties such as frequency and transmitted power.

The following propagation model is used by 3GPP 36.942 for urban and suburban areas:

$$\text{Path loss} (F, D, BS) = 39.84 \times BS \times Log(D) - 18 \times Log(BS) + 21 \times Log(F) + 80$$

Where,

- F is the frequency of the transmitted signal
- D is the distance between the transmitting and receiving antennas
- BS is the height of the cell-site's transmitting antenna

Therefore, considering a typical cell site with transmitting antennas at 30 m (98.4 ft) of height and the accessible measurement distance between 100 m (328 ft) and 500 m (1,640 ft), then the path loss for a 751 MHz signal transmitted at 43 dBm is as follows:

Path loss (751, 0.1, 30) = 78.6 dB (if TXPWR = 43 dBm then RXPWR = –35.6 dBm)
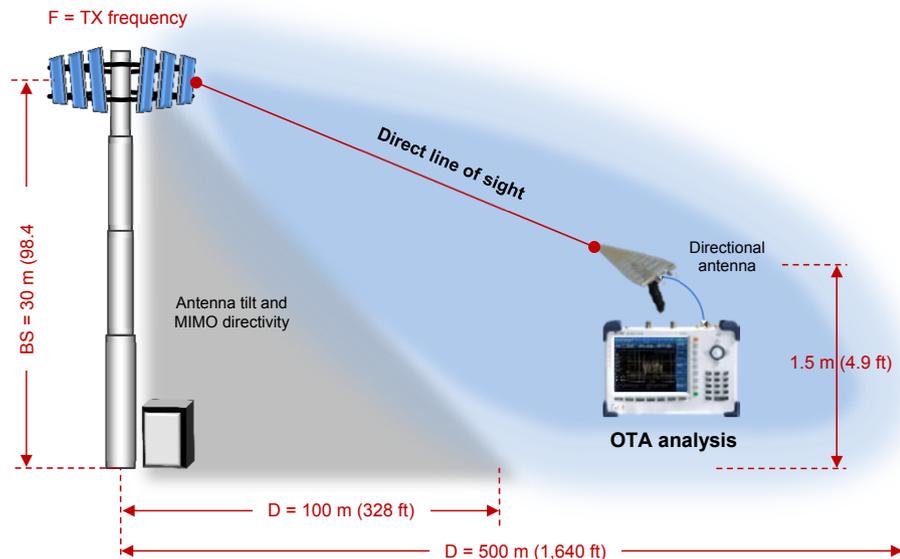Path loss (751, 0.5, 30) = 103.2 dB (if TXPWR = 43 dBm then RXPWR = –60.2 dBm)

Figure 23. Path loss effects in OTA measurements

Taking into account the above conditions of interference, multipath, and path loss, OTA measurements can be performed with the following criteria:

Measurement Conditions	Modulation Quality	MIMO Performance
Channel power >-35dBm (100 m)	Antenna 1 (RS0) EVM <10%	RS0(P) − RS1(P) < 10 dB
Channel power <-60dBm (500 m)	Antenna 2 (RS1) EVM <10%	RS0(T) − RS(T) < 65 ns
Directional antenna 60o beam		

Table 8. Conditions and LTE indicators for OTA measurements

Conclusions

LTE networks provide significant benefits over previous-generation networks such as CDMA2000 and WCDMA. These benefits include a better utilization of the spectrum due to a more flexible and dynamic signal format based on OFDMA and a capacity to dynamically adapt modulation to mobile users based on their RF environment. In addition, multiple transmission paths improve coverage to ultimately improve transmission bandwidth.

These benefits are achieved with proper communication conditions, but impairments such as interference, RF leakage, and spurious noise will negatively affect the communication of one or several regions of the LTE signal and therefore lower available bandwidth.

Furthermore, problems with modulation and multiple transmissions can severely affect the delivery capacity for which LTE was created. For instance, in the case of low signal quality for which basic QPSK modulation is used and if multiple transmissions in a MIMO 2x2 communication are affected for which the mobile user discards one branch, then bandwidth is reduced by 83%.

LTE Bandwidth						
Channel bandwidth (MHz)	1.4	3.0	5.0	10.0	15.0	20.0
TX bandwidth (MHz)	1.1	2.7	4.5	9.0	13.5	18.0
RB per timeslot (0.5 ms)	6	15	25	50	75	100
64 QAM MIMO 2x (Mbps)	12.1	30.2	50.4	100.8	151.2	201.6
LTE Bandwidth (QPSK MISO 1x)						
QPSK MISO 1x (Mbps)	2.0	5.0	8.4	16.8	25.2	33.6
Bandwidth reduction	−83.3%	−83.3%	−83.3%	−83.3%	−83.3%	−83.3%

Note: Bandwidth estimates consider all REs transmitting user data.

Table 9. LTE bandwidth QPSK MISO 1x

For these reasons, it is vital to conduct regular tests on all LTE factors of RF transmission, modulation quality, and MIMO performance. Proper testing ensures optimal bandwidth to all users. And, it helps monetize the mobile network while increasing quality of experience.

Acronyms

3GPP	3rd Generation Partnership Project
16 QAM	16-symbol quadrature amplitude modulation
64 QAM	64-symbol quadrature amplitude modulation
ACLR	Adjacent channel leakage power ratio
CQI	Channel quality indicator
GPS	Global positioning system
LTE	Long term evolution
MIMO	Multiple input multiple output
OFDMA	Orthogonal frequency division multiple access
PDSCH	Physical downlink shared channel
QPSK	Quadrature phase-shift keying
RB	Resource block
RF	Radio frequency
RS	Reference signal
SC-FDMA	Single carrier frequency division multiple access

References

[1] 3GPP TR 25.912. V11.0.0.3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Feasibility study for evolved Universal Terrestrial Radio Access (UTRA) and Universal Terrestrial Radio Access Network (UTRAN) (Release 11).

[2] 3GPP TR 25.913. V8.0.0.3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Requirements for Evolved UTRA (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN) (Release 8).

[3] 3GPP TR 36.211. V11.3.0.3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation.

[4] 3GPP TS 36.104. V10.5.0. . .3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Requirements for Evolved UTRA (E-UTRA); Base Station (BS) radio transmission and reception.

[5] LTE and the Evolution to 4G Wireless. Design and Measurement Challenges. (Second Edition). Editor Moray Rumney.

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