LTE UE receiver performance measurements

White Paper

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LTE user equipment (UE) receiver performance has significant impact to cellular radio network coverage and capacity. It determines the maximum data throughput across the air interface between the LTE base station (eNB, evolved node B) and the mobile network subscriber UE, thus it determines the total capacity across the air interface. Therefore, it is one of the most important measurements to verify the actual receiver performance of individual devices, and a key metric to compare different devices, in particular.

This paper shall give an introduction to receiver performance measurements and discusses the measurement metrics as well as the challenges of over the air (OTA) measurements.

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White Paper
Heinz Mellein
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1 Introduction

LTE user equipment (UE) receiver performance has significant impact to cellular radio network coverage and capacity. It determines the maximum data throughput across the air interface between the LTE base station (eNB, evolved node B) and the mobile network subscriber UE, thus it determines the total capacity across the air interface. Therefore, it is one of the most important measurements to verify the actual receiver performance of individual devices, and a key metric to compare different devices, in particular.

There are minimum performance requirements specified by 3GPP (3rd Generation Partnership Project, *www.3gpp.org*) which shall be met by any UE before it gets approved by appropriate certified bodies (e.g. GCF, Global Certification Forum, *www.globalcertificationforum.org*). Manufacturers are free to outperform such minimum performance requirements in order to beat competitors in that field or to meet enhanced network operator specific requirements, for instance.

This paper shall give an introduction to receiver performance measurements. It discusses the measurement metrics and the challenges of over the air measurements, in particular.

LTE UE(s) receiver performance is specified with respect to their antenna connector(s). For UE(s) with an integral antenna only (i.e. no antenna connectors are exposed for measurements), ideal omni-directional reference antenna(s) with a gain of 0 dBi towards each direction are assumed for each antenna port. Furthermore, all receiver requirements assume that UE(s) are equipped with two Rx antenna ports as a baseline. Therefore, [1] and [2] assumes that for UEs with more than one receive antenna connector, identical signals shall be applied to each receiver port. Chapter 2 will discuss conducted receiver performance metrics and measurements as they are specified by 3GPP for LTE UE(s).

To improve receiver performance, and thus air interface capacity, there is a selection of diversity algorithms suggested by 3GPP. They aim to increase either the transmission quality and thus the radio cell coverage range or the peak data rate by spatial multiplexing. All diversity methods are based on either multiple transmit antennas or multiple receive antennas, or even both at the same time. Furthermore, it is up to the UE vendor to implement advanced receive diversity algorithms on top, such as switched diversity (SD), equal gain combining (EGC) or maximum ratio combining (MRC). Chapter 3 will focus on such receive diversity options to improve the performance and will provide conducted measurement results.

Now, in real operation the UE(s) performance including its antennas does matter. Therefore, a number of non-conducted, i.e. over-the-air (OTA) measurement methods have been specified by wireless industry recognized standardization bodies, e.g. 3GPP or CTIA (www.ctia.org). However, as soon as the antennas get into the scene, measurement reference points are no more as obvious as while measuring at the antenna connector. Furthermore, real antennas do not have ideal omni-directional radiation patterns. Finally, correlation between multiple receive paths can no more be ignored. This is why chapter 4 will focus on OTA performance measurements and the very specific challenges there.

Finally, chapter 5 will summarize the key aspects regarding LTE receiver performance assessment and will attempt an outlook towards the next generation of mobile communication, known as “5G”.

2 Receiver performance

2.1 Reference and true receiver sensitivity

According to [2] and [5] receiver sensitivity measurements are using data **throughput** rate R (i.e. bits per second, bps) as the **performance measurement metric**. Therefore, the UE's receiver sensitivity is defined as the minimum receive power level required to provide a data throughput rate greater than or equal to 95% of the maximum possible throughput of a given reference measurement channel.

The assumption that all subscriber UEs in the field meet this minimum performance requirement is the basis to radio network planning, i.e. the determination of the effective coverage area for each radio base station. Consequently, minimum performance conformance measurements are done by measuring the throughput at the 3GPP [1] specified **reference sensitivity level** $\mathbf{P_{REFSENS}}$, using well defined reference channel configurations in order to ensure traceability, repeatability and comparability of the measurements. The UE is conform to the specification as long as the measured throughput is ≥ 95% of the maximum possible throughput while receiving data at the reference sensitivity level.

On the other hand, to determine the UE's **true receiver sensitivity**, the downlink level shall be lowered during the measurement as long as the throughput stays above the 95% threshold. The minimum RF level $\mathbf{P_{SENS}}$ where the throughput is only just ≥ 95 % is the true receiver sensitivity of this device, which may differ more or less from the required minimum reference sensitivity level.

In any case the requirement is: $\mathbf{P_{SENS} \leq P_{REFSENS}}$.

The reference measurement channels (RMC) are composed of the modulation and coding scheme (MCS) used for user data transmission and the LTE CP-OFDM physical resource block (PRB) allocation which includes the channel bandwidth (CBW) available. The MCS index value summarizes the modulation type and the coding rate that is used in a given PRB. Typically, a higher MCS index offers a higher spectral efficiency (which translates to a higher potential data rate) but requires a higher SNR for a given transmission quality. Generally speaking, higher throughput comes not for free, but with the cost of less coverage range.

2.2 Reference sensitivity determination

The sensitivity level of a radio receiver is determined by its **noise power** $\mathrm{P_{noise}}$ at the output of the receivers low noise amplifier (LNA).

$$\mathrm{P_{noise}} = 10\,\mathrm{lg}(\mathrm{k}\cdot\mathrm{T}\cdot\mathrm{BW}\cdot\mathrm{NF}) = -174\frac{\mathrm{dBm}}{\mathrm{Hz}} + 10\mathrm{lg}\,\mathrm{BW} + \mathrm{NF_{dB}}$$

Equation 2-1: Receiver output noise power

k = Boltzmann constant (1.38 · 10-23 J/K)
T = System temperature (typical assumption is 290 Kelvin)
BW = signal bandwidth
NF = noise figure
lg(x) represents the common logarithm, i.e. logarithm with base 10.

The factor $10\,lg(\mathrm{k}\cdot\mathrm{T})$, known as the **spectral noise power density** $\mathrm{N_0}$ is typically set to $-174\frac{\mathrm{dBm}}{\mathrm{Hz}}$, which assumes a system temperature of T = 290 K. The bandwidth factor $10\,lg(\mathrm{BW})$ integrates the noise power density across the channel bandwidth of interest. For instance, 10 MHz bandwidth contributes a bandwidth factor of 70 dB which results in noise power N = -104 dBm within a 10 MHz channel. The noise figure NF is implementation specific, i.e. if finally determines the quality of the actual receiver.

Now, for each MCS there is a minimum signal-to-noise (SNR) ratio required in order to ensure the minimum required performance (i.e. 95% of the maximum possible throughput at given MCS). Thus, the reference sensitivity level $\mathrm{P_{REFSENS}}$ of a receiver at a certain MCS is given as

$$\mathrm{P_{REFSENS}} = \mathrm{P_{noise}} + \mathrm{SNR_{min}}(MCS)$$

Equation 2-2: Reference sensitivity level

The reference sensitivity power is illustrated in Fig. 2-1.

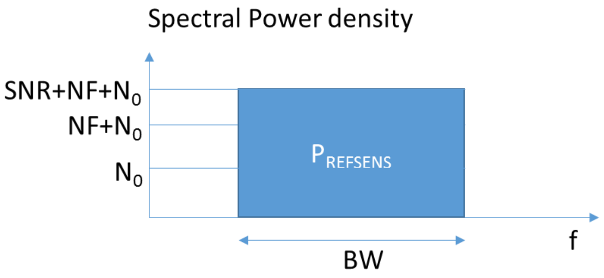


Fig. 2-1: Reference sensitivity power illustration

3GPP assumes certain NF values, depending on frequency bands and bandwidth in order to specify reference sensitivity levels. [2] provides all $\mathrm{P_{REFSENS}}$ values for different frequency ranges, bandwidths and modulation schemes. As an example Table 2-1 shows an excerpt of the requirements for QPSK modulation schemes.

E-UTRA Band (DL frequency range)	5 MHz	10 MHz	15 MHz	20 MHz
1 (2110- 2170 MHz)	-100	-97	-95.2	-94
3 (1805 – 1880 MHz)	-97	-94	-92.2	-91
7 (2620 – 2690 MHz)	-98	-95	-93.2	-92
13 (746 – 756 MHz)	-97	-94	-	-

Table 2-1: Example PREFSENS values for QPSK modulation

2.2.1 Reference power considerations

The power of the LTE downlink signal is derived from the RS EPRE (Reference Symbol Energy Per Resource Element), i.e. the energy of a single resource element of 15 kHz bandwidth bearing a known reference symbol. To calculate the reference sensitivity power across the entire bandwidth assuming full physical resource block allocation, Table 2-2 applies.

Bandwidth	Spectral power	
15 kHz (EPRE)	-124.8 dBm/15 kHz	
180 kHz (PRB)	-114 dBm/180 kHz	= -124.8 dBm + 10lg(12)
10 MHz (full RPB allocation)	-97 dBm/10 MHz	= -114 dBm + 10lg(50)
20 MHz (full PRB allocation)	-94 dBm/20 MHz	= -114 dBm + 10lg(100)

Table 2-2: Example reference power calculations

Note: A physical resource block (PRB) includes 12 OFDM sub carriers of 15 kHz bandwidth, each. Furthermore, a 10 MHz LTE channel holds up to 50 PRBs, while a 20 MHz channel includes up to 100 PRBs.

2.2.2 Throughput and Block Error Rate vs. SNR

To measure the true sensitivity, the device specific reference sensitivity is measured by lowering the receive power until a certain throughput threshold is reached, which in turn is similar to measuring the block error rate vs. the receive power or available signal to noise ratio SNR when keeping the MCS unchanged throughout the test. LTE FEC channel coding schemes perform typically according to Fig. 2-2. For AWGN (Additive White Gaussian Noise) only channels, there is a sharp slope of decreasing BER along with increasing SNR, while in multipath fading environments the performance becomes worse with a less steep slope.

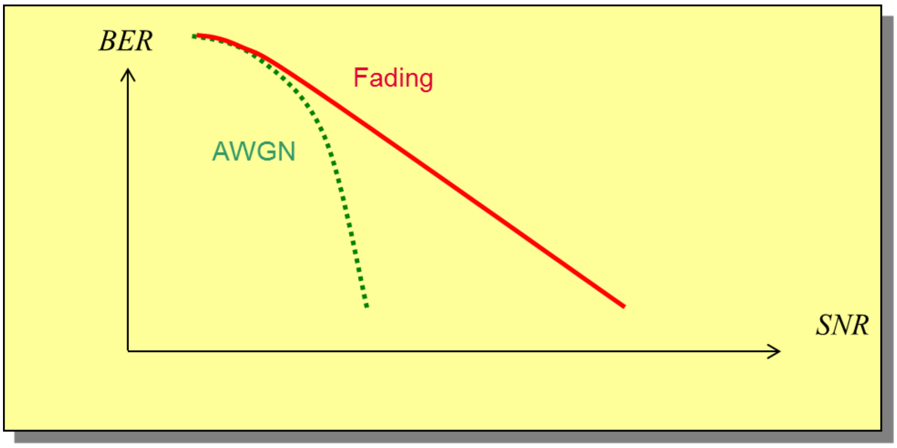


Fig. 2-2: **Error rate vs. SNR**

According to [2] the measured information (user data) bit throughput R is defined as the sum of information bit payloads successfully received during the test interval, divided by the duration of the test interval [in seconds]. During receiver performance measurements the UE indicates successfully received information bit payload block-wise by signaling an acknowledgement (ACK) indicator to the eNB emulator (e.g. R&S®CMW500). If a payload block is received, but damaged and cannot be decoded (block check failure), the UE returns a non-acknowledgement (NACK) indicator. So, for measuring purposes, only the ACKs and NACKs are known to the eNB emulator. Thus, the number of payload bits sent with each block must be stored by the test equipment. Furthermore, when no acknowledgement at all occurs for a transmission block, the related block is regarded as some irregular discontinuous transmission (DTX) and an appropriate block counter is incremented by the test instrument, known as statDTX.

Thus, the block error ratio (BLER) is defined as

$$\mathrm{BLER} = \frac{\mathrm{NACKs} + \mathrm{statDTXs}}{\mathrm{ACKs} + \mathrm{NACKs} + \mathrm{statDTXs}}$$

Equation 2-3: **Block Error Rate definition**

with (N)ACKs as the counted number of block (N)ACKnowledgements and statDTXs as the counted number of missed block receptions. The sum of all block counters gives the total number of subsequent blocks involved during the test. With the number of bits per block BitsPerBlock and the transmission time per block TxTimePerBlock, the throughput R can be calculated as

$$\mathrm{R} = \frac{\mathrm{ACKs} \cdot \mathrm{BitsPerBlock}}{(\mathrm{ACKs} + \mathrm{NACKs} + \mathrm{statDTXs}) \cdot \mathrm{TxTimePerBlock}}$$

Equation 2-4: **Throughput definition**

which gives the important correspondence between BLER and R as

$$R = (1 - \mathrm{BLER})\frac{\mathrm{BitsPerBlock}}{\mathrm{TxTimePerBlock}}.$$

Equation 2-5: BLER and Throughput correspondence

Thus, block error measurements are equivalent to **normalized throughput measurements**. The requirement to stay ≥ 95% of the maximum throughput corresponds to an upper BLER limit of 5%. To simplify comparison, all measurement results presented in this white paper are of type BLER.

2.3 Conducted LTE receiver performance with static MCS

LTE offers great flexibility in terms of modulation and coding schemes. In the downlink there is the choice of QPSK, 16-QAM, 64-QAM and 256-QAM along with adaptive FEC (forward error correction) rates.

Fig. 2-3 depicts the general LTE downlink data processing chain, incl. a 24 bit CRC (cyclic redundancy check) block coding stage and the FEC channel encoding stage. A rate matching stage aligns the encoded bit blocks to the target CP-OFDM physical resource block (PRB) size, followed by baseband modulation mapper. A real number example is given in the right hand chain in Fig. 2-3, which depicts the case of QPSK modulation with approximate coding rate 1/3.

Information (or user data) are encoded block wise and the size of the block corresponds to the transmission time intervals (TTI) which may vary depending on the application.

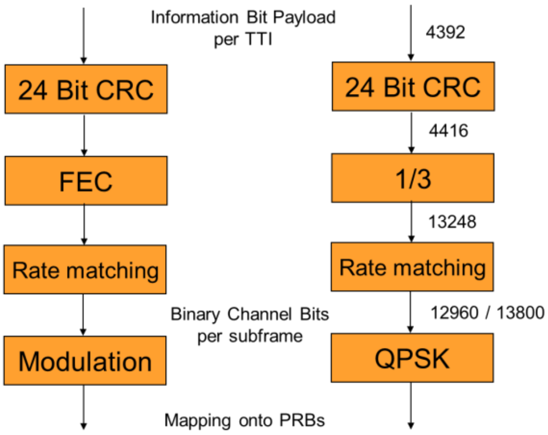


Fig. 2-3: Example of LTE downlink QPSK1/3 reference channel data processing

The LTE modulation and coding schemes are identified by an integer index MCSI. The coding rates are selected in a way that two successive modulation and coding schemes perform with approximately 1 dB difference, i.e. the performance can be adapted to actual channel conditions with a resolution of approximately 1 dB.

As an example, MCS index 7 outperforms MCS index 8 by 1 dB in terms of sensitivity, however, MCS index 8 offers a higher peak data rate when the available SNR is sufficient. As the UEs indicate their current receive quality to the network with an appropriate channel quality indicator (CQI), the network scheduler can respond to decreasing or increasing reception quality for individual UEs by modifying the applied downlink modulation and coding scheme accordingly.

The reference sensitivity power level $P_{REFSENS}$ is the minimum mean power applied to each of the UE antenna ports for all UE categories, at which the throughput shall meet or exceed a certain minimum that is determined by the modulation and coding scheme in operation as well as the propagation characteristics of interest (e.g. AWGN or fading channel).

Parameter	Unit	Value					
Channel bandwidth	MHz	1.4	3	5	10	15	20
Allocated resource blocks		6	15	25	50	75	100
Subcarriers per resource block		12	12	12	12	12	12
Allocated subframes per Radio Frame		9	9	9	9	9	9
Modulation		QPSK	QPSK	QPSK	QPSK	QPSK	QPSK
Target Coding Rate		1/3	1/3	1/3	1/3	1/3	1/3
Information Bit Payload per Sub-Frame							
For Sub-Frames 1,2,3,4,6,7,8,9	Bits	408	1320	2216	4392	6712	8760
For Sub-Frame 5	Bits	n/a	n/a	n/a	n/a	n/a	n/a
For Sub-Frame 0	Bits	152	872	1800	4392	6712	8760
Transport block CRC	Bits	24	24	24	24	24	24
Number of Code Blocks per Sub-Frame							
For Sub-Frames 0,1,2,3,4,6,7,8,9	Bits	1	1	1	1	2	2
For Sub-Frame 5	Bits	n/a	n/a	n/a	n/a	n/a	n/a
Binary Channel Bits Per Sub-Frame							
For Sub-Frames 1,2,3,4,6,7,8,9	Bits	1368	3780	6300	13800	20700	27600
For Sub-Frame 5	Bits	n/a	n/a	n/a	n/a	n/a	n/a
For Sub-Frame 0	Bits	528	2940	5460	12960	19860	26760
Max Throughput averaged over 1 frame	kbps	341.6	1143.2	1952.8	3952.8	6040.8	7884

Table 2-3: Fixed reference channel for FDD receiver requirements

Receiver characteristics measured based on fixed reference channels for receiver requirements according to [1], to ensure traceability, repeatability and comparability. Fixed reference channels are clearly specified downlink signals incl. the following parameters:

- channel bandwidth
- number of allocated resource blocks and subcarriers per resource block
- allocated sub frames per radio frame
- transmission mode
- single or multi antenna transmission scheme
- modulation and coding scheme (MCS)

Most important for the performance quality evaluation is the modulation and coding scheme parameter. As an example, Table 2-3 shows the QPSK fixed reference channel for FDD receiver measurements with full resource block allocation.

[2] specifies a huge number of downlink fixed reference measurement channels for all types UE categories, duplex schemes (FDD, TDD and H-FDD) and measurement applications. Please refer to [2] for more details.

MCSI	Modulation	Coding rate	Max FDD throughput per frame	MCSI	Modulation	Coding rate	Max FDD throughput per frame
0	QPSK	0,109	1.374 Mbps	15	16-QAM	0.548	14.054 Mbps
1	QPSK	0.141	1.794 Mpbs	16	16-QAM	0.593	15.206 Mbps
2	QPSK	0.173	2.203 Mbps	17	64-QAM	0.395	15.206 Mbps
3	QPSK	0.222	2.843 Mbps	18	64-QAM	0.425	16.301 Mbps
4	QPSK	0.282	3.598 Mbps	19	64-QAM	0.474	18.202 Mbps
5	QPSK	0.341	4.366 Mbps	20	64-QAM	0.514	19.697 Mbps
6	QPSK	0.400	5.141 Mbps	21	64-QAM	0.553	21.307 Mbps
7	QPSK	0.484	6.154 Mbps	22	64-QAM	0.593	22.843 Mbps
8	QPSK	0.543	6.917 Mbps	23	64-QAM	0.658	25.279 Mbps
9	QPSK	0.622	7.941 Mbps	24	64-QAM	0.708	27.184 Mbps
10	16-QAM	0.311	7.941 Mbps	25	64-QAM	0.733	28.240 Mbps
11	16-QAM	0.341	8.709 Mbps	26	64-QAM	0.790	30.352 Mbps
12	16-QAM	0.385	9.874 Mbps	27	64-QAM	0.820	31.463 Mbps
13	16-QAM	0.444	11.371 Mbps	28	64-QAM	0.948	36.542 Mbps
14	16-QAM	0.504	12.886 Mbps				

Table 2-4: MCS index 0 – 28 mapping to modulation and channel encoding rate

Table 2-4 lists the maximum FDD downlink throughput per frame (10 ms) for the 10 MHz channel bandwidth with full resource block allocation. Please note that the actual coding rate depends on the number of available resource elements for information bits, which does not simply increase linearly with the number of PRBs. Thus, the coding rate change when changing the bandwidth. All details on LTE channel coding is available in [4]. [1] and [2] specify the MCS dependent reference sensitivity values for all E-UTRA bands, supported channel bandwidths and duplex modes FDD, H-FDD and TDD.

2.4 Conducted receiver performance measurements

To measure the receiver performance in terms of BLER vs. SNR the test setup according to Fig. 2-4 applies. Assuming the UE under test is equipped with two antenna connectors, one hybrid transmit and receive antenna connector (TX/RX1) and one receive only antenna connector (RX2), the test environment includes an eNB simulator and two uncorrelated noise sources (AWGN 1 and AWGN 2).

To maintain a known total input power S at the UE, the downlink signal power is splitted in a way that equal power $S_1 = S_2 = S/2$ is supplied to each UE receiver port. Prior to the UE receiver antenna connectors the AWGN sources add equal but uncorrelated noise power N = AWGN1 = AWGN2 to create a known signal to noise ratio SNR at the UE antenna connectors.

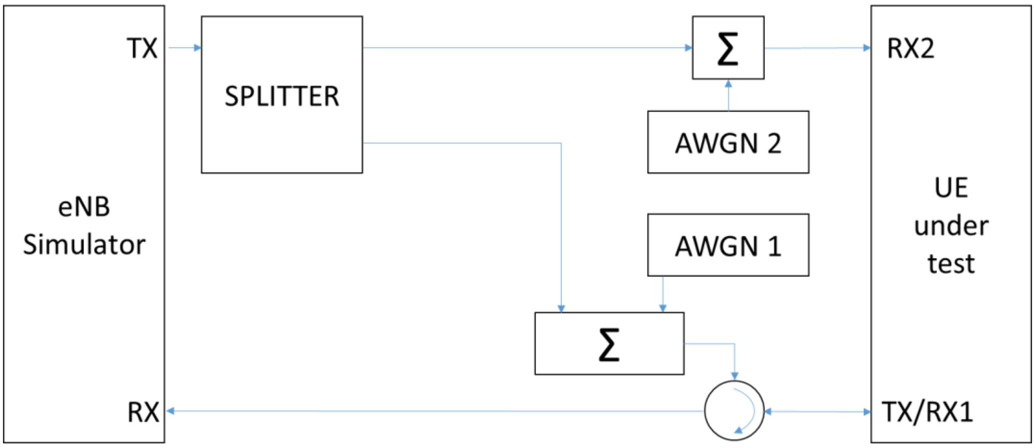


Fig. 2-4: Conducted receiver performance measurement setup suggestion according to [2]

To emulate the measurement setup according to Fig. 2-4 a single R&S®CMW500 is sufficient, as it provides the eNB simulation as well as the uncorrelated downlink AWGN sources, which is also the basic measurement instrument used for all measurements presented in this paper.

Fig. 2-5 depicts a FDD band 1 conducted BLER vs. SNR measurement for various modulation and coding schemes MCS 7, MCS 8, MCS9 and MCS 10 (according to Table 2-4 and 10 MHz channel bandwidth.

Note: All measurement results presented in this white paper are manually post-processed for suitable graphical presentation.

The measured SNR range of { -3 .. +1 } dB has been created by a fixed AWGN level and a changing downlink signal level S in steps of 0.1 dB. LTE transmission mode 1 was applied during the measurement, i.e. no transmit diversity scheme to improve the performance. Thus, the result provides the pure UE receive performance for the case of one downlink transmit antenna.

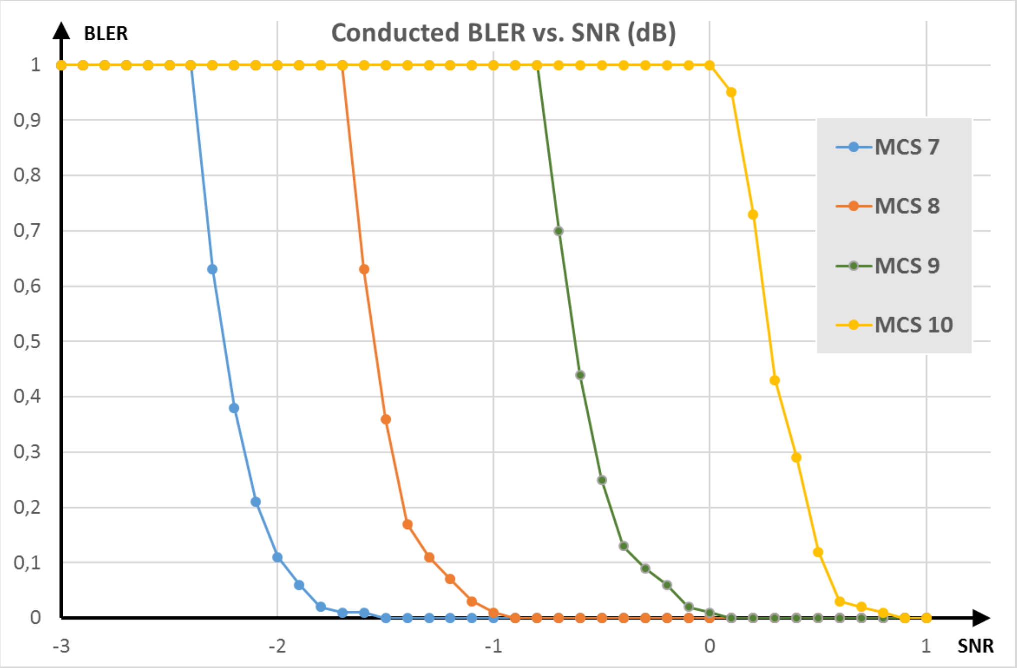


Fig. 2-5: **Conducted measurement results BLER vs. SNR for various MCS indices**

As explained in the previous chapter, the subsequent modulation and coding schemes are designed in a way that the performance increase by approximately 1 dB when decreasing the MCS index by one. The measurement results for 4 subsequent MCS confirm this design goal very clearly.

Now, when removing the artificial noise sources from the test setup according to Fig. 2-4, the true absolute sensitivity can be measured in terms of BLER vs. receive power, i.e. BLER vs. EPRE (energy per resource element). In that case the effective SNR is determined by the UEs own noise power only, which is very much depending on the quality of its implementation, i.e. its noise figure NF in particular as explained in subclause 2.2.

According to Table 2-4 MCS 9 applies QPSK, while MCS 10 applies 16-QAM. When analysing the MCS 9 measurements in more detail, it can be seen that the measured true reference sensitivity level for QPSK is approx. -125.1 dBm/15 kHz, where still the performance requirement of < 5 % BLER is met, while the true reference sensitivity level for MCS 10 is -124,4 dBm/15 kHz. The measurements have been performed with 10 MHz channel bandwidth and full resource block allocation, i.e. the true reference sensitivity level across the 10 MHz bandwidth calculates to -97.3 dBm for MCS 9 and -96.6 dBm for MCS 10 according to Table 2-2. Thus, this UE implementation meets the required $P_{REFSENS}$ of –97 dBm for QPSK and 10 MHz for the most sensitive QPSK based MCS as specified in Table 2-1.

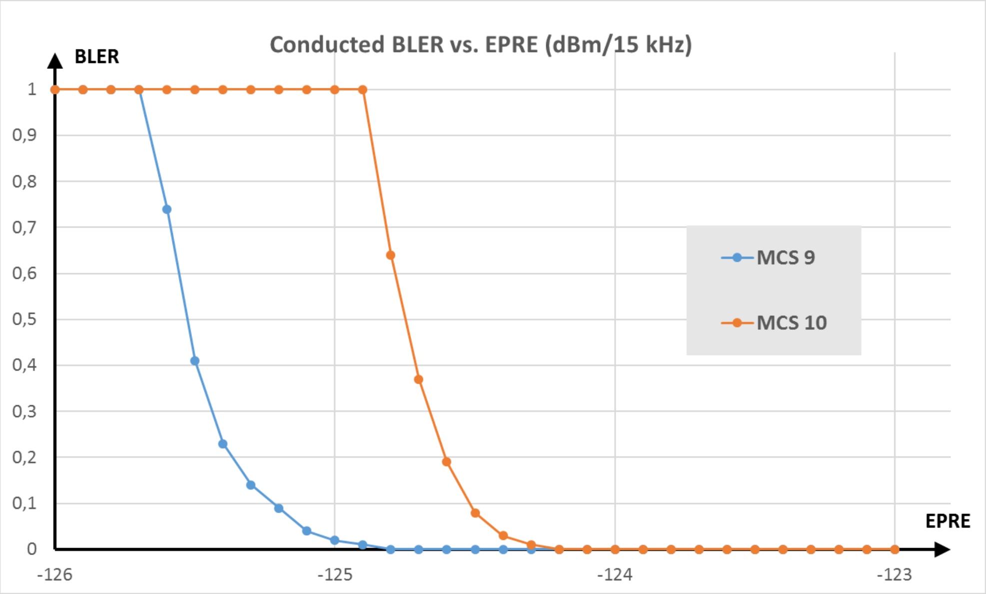


Fig. 2-6: Conducted BLER vs. EPRE

3 Receive diversity

Receive diversity combining devotes the entire resources of multiple receive antennas to service a single user. Receive diversity schemes enhance reliability by minimizing the channel fluctuations due to fading caused by multipath propagation and receive signal time variance. The simple principle of diversity is that multiple receive antennas receive different copies of the same signal. The chances of all these copies being in a deep fade is small. These schemes therefore make most sense when the fading is independent from element to element and are of limited use if perfectly correlated. Independent fading is most typical in dense urban areas where the potential multipath components add up very differently at each receive element. However, correlation of multiple receive signals is also a matter of the mutual correlation of the receiving components, in particular the receiving antennas. The latter one becomes particularly important when measuring over the air, rather than conducted.

3.1 Receive diversity schemes

Basically, there are three popular receive diversity schemes with one of them implemented in the vast majority of mobile user equipment today. Those shall be discussed briefly in this chapter, with the focus on their principle approach rather than their mathematical background.

3.1.1 Selection combining or switched diversity

The receiver monitors each available radio input instantaneous receive power and switches to the strongest one, i.e. it selects the input with the greatest SNR for further processing. This algorithm is known as selection combining or switched diversity. Thus, the output SNR of the selection diversity scheme is max $\{SNR_n\}$ with
n = { 1 ... Number of receive antennas} . Since selection combining needs a signal power measurement only, it is a low complex approach to improve the resulting SNR. The resulting SNR improvement is obvious when comparing the average SNR at the selection combining output versus the average SNR at each input element. In a Rayleigh Fading environment the gain of SNR over that of a single element is of order of ln(N).

3.1.2 Maximum ratio combining

The approach of maximum ratio combining MRC is to maximize the output SNR of the receiver, i.e. it is optimal in terms of SNR, at the cost of high complexity. MRC does weight each input based on channel estimations - just as a matched filter does - to gain the best possible combined SNR, which increases linear with the number of input elements N. This clearly outperforms selection combining which increases with the natural logarithm of N only.

3.1.3 Equal gain combining

The equal gain combiner is a very similar approach as MRC, however, it overcomes the problem of strong signal magnitude fluctuation by setting unit gain at each input element. Thus, the equal gain combiner results in an improvement in SNR that is comparable to that of MRC combiner, i.e. the effective SNR and thus the receiver performance increases linearly with N as well.

Both, the maximum ratio and equal gain combiners require phase information. The maximum ratio combiner requires accurate measurement of the gain too. This is clearly more complex to implement, as the dynamic range of a Rayleigh fading signal may be quite large.

In any case, it is up to the vendors which kind of receive diversity they implement, as it is not required by the standards. Nevertheless, it will have an influence on receiver performance measurement results.

3.2 Conducted receive diversity measurements

As the default LTE UE is equipped with two receive antenna ports to support receive diversity, the maximum SNR gain compared to single antenna port receiver becomes 3 dB for MRC and EGC implementations. In a conducted setup according to Fig. 2-4 this can be measured, assuming non-correlated noise and/or fading at both inputs. Fig. 3-1 provides a measured comparison of a single input receiver (no diversity) and dual input receiver (diversity), while the total power supplied to the mobile phone stays unchanged. As the measurement shows a performance improvement of 3 dB it is obvious that the receiver applies either MRC or EGC as receive diversity scheme.

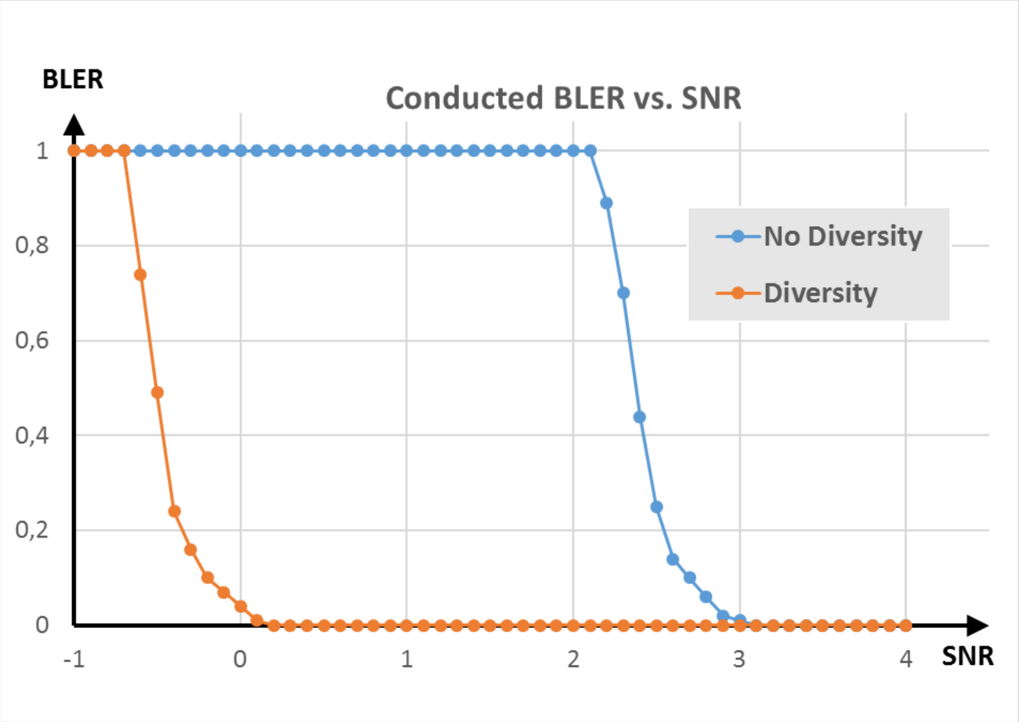


Fig. 3-1: **Conducted receiver diversity performance for MCS 9**

4 Radiated performance

Finally, the radiated performance is the one that counts in real operation. Thus, OTA (over-the-air) rather than conducted receiver performance measurements are required, too. Unfortunately, it is not very simple to compare OTA with conducted measurement results. As discussed before, in the conducted measurement domain it is assumed that the antennas have ideal omni-directional radiation characteristics, which is never true for real implementations. The non-ideal radiation pattern of real antenna deployments result in a spatial selectivity of the receiver performance. In other words, the receiver performance becomes directional, i.e. its reference sensitivity level is not the same from all directions. By extending Equation 2-2 this attribute can be expressed by the following model:

$$P_{REFSENS}(\boldsymbol{\Theta},\boldsymbol{\Phi}) = P_{noise} + SNR_{min}(MCS) - \boldsymbol{G}(\boldsymbol{\Theta},\boldsymbol{\Phi})$$

Equation 4-1: OTA reference sensitivity

where $G(\Theta,\Phi)$ represents the spatial selective receive antenna gain. Θ is the elevation angle and Φ the azimuth angle from the antennas perspective.

4.1.1 Radiation pattern and antenna gain

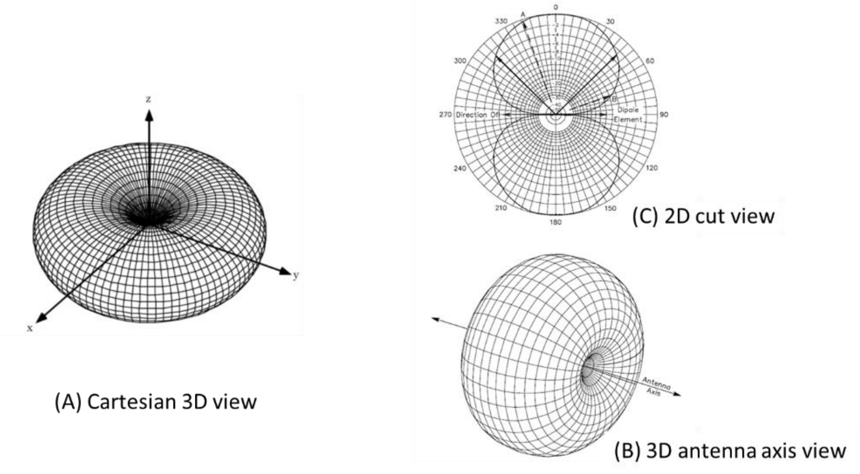
The most popular metrics to describe antenna characteristics - including the antenna gain in particular - are refering to an isotropic radiator with an ideal omni-directional radiation pattern. Such an isotropic antenna is nothing but a theoretical model of an infinitesimal point source of electromagnetic waves that creates the same spatial power density towards all possible directions. In other words, an isotropic antenna has no directivity and thus no isotropic gain at all. The **isotropic antenna gain** $\boldsymbol{G}(\boldsymbol{\Theta},\boldsymbol{\Phi})$ - which is equal to the antenna's directivity multiplied by the antenna's efficiency according to [6] - of a real antenna is defined as the ratio of the spatial power density, also known as intensity $\boldsymbol{I}$, beyond a minimum distance from the antenna (far field distance) and the theoretical **isotropic intensity** $\boldsymbol{I_{iso}}$. The isotropic intensity $\boldsymbol{I_{iso}}$ at a certain distance r is given by $\boldsymbol{P_R}/_{\boldsymbol{4\pi r^2}}$, with $\boldsymbol{P_R}$ representing the **total radiated power**. Thus, it is simply the uniform spread of the total radiated power across the full surface of a theoretical sphere with radius r around the antenna's phase center. An antenna provides a gain when the ratio $\boldsymbol{I}/_{\boldsymbol{I_{iso}}} > \boldsymbol{1}$, or in common logarithmic scale $\boldsymbol{10\lg\left(I/_{I_{iso}}\right) > 0\ dBi}$. The postfix $\boldsymbol{i}$ indicates its reference to the isotropic antenna. Consequently, the gain of an isotropic antenna is $\boldsymbol{0\ dBi}$ in any direction, which turns equation (3) back to equation (2), as equation (2) was based on the assumption of omni-directional antenna characteristics.

Assuming perfectly matched feeding of the transmit power into the antenna connector, the ratio of the total radiated power and the power accepted by the antenna P_O is known as the radiation or antenna efficiency [6]. For simplification we are assuming perfect efficiency, i.e. the total power fed into the antenna connector is equal to the total radiated power, i.e. the power at the antenna connector is equal to the total transmit power. As reciprocity is a fundamental property of (passive) antennas, the radiation pattern and the antenna gain are the same whether the antenna is transmitting or receiving. Thus, the total power collected by a perfectly efficient receive antenna from all directions is fully available at the receive antenna output connector, accordingly.

When talking about the gain of an antenna, typically we mean the maximum isotropic gain the antenna can provide, no matter whether its transmitting or receiving. For instance, a standard gain horn antenna typically offers 20 dBi gain. However, that maximum gain only applies towards a certain direction. For a horn antenna the gain can even be calculated based on its dimensions and the wavelength of the radiated electromagnetic wave. However, for most antenna geometries in commercial products such as mobile phones the calculation of the gain might not be that simple or even impossible, which requires appropriate measurements according to [5] and [6].

To measure the radiation pattern of a transmit antenna, an appropriate scan is done with a suitable power sensor over the surface of a fictive sphere with a given radius. The power measurements of each sample provides the EIRP$(\Theta,\Phi) = P_R + \boldsymbol{G}(\boldsymbol{\Theta},\boldsymbol{\Phi})$, i.e the equivalent isotropic radiated power towards the related spatial direction. To measure radiation patterns anechoic environments are required, typically chambers covered with dedicated absorbers such as R&S®TS7124, R&S®DST200 or R&S®ATS1000.

The most basic antenna element, a free space dipole, creates a certain non-omnidirectional radiation pattern, as depicted in Fig. 4-1 in three different views. In the 2D cut view it can be seen that the maximum gain is towards the boresight of the dipole element, while there is no radiation at all towards the direction of the dipole element.



(A) Cartesian 3D view

(C) 2D cut view

(B) 3D antenna axis view

Fig. 4-1: Free space dipole radiation characteristics

Fig. 4-2 depicts the Cartesian view of a measured transmit radiation pattern based on EIRP measurements of a LTE FDD band 1 (i.e. in the range of 2.1 GHz) mobile phone according to [6], using R&S OTA test system incl. R&S©AMS32 OTA test measurement software, R&S©DST200 anechoic chamber and R&S©CMW500.

By integrating and averaging all EIRP measurements across the surface of the fictive sphere we get the total radiated power. This provides us the link between conducted measurements and radiated measurements. For the transmit antenna this is known as the total radiated power TRP which is equal to the antenna feed power at the antenna connector, assuming perfect transmission line match and antenna efficiency.

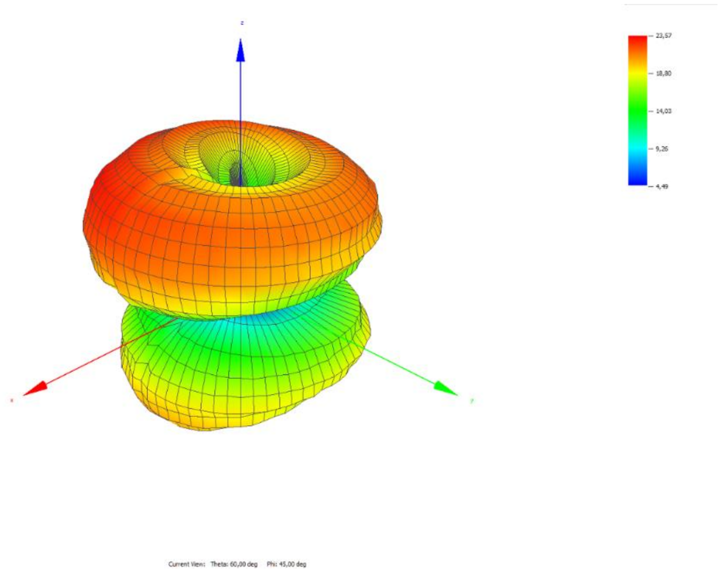


Fig. 4-2: EIRP radiation pattern of a sample LTE band 1 FDD mobile phone

4.1.2 Total isotropic sensitivity TRS

As we are interested in the receiver performance, we are looking for the OTA parameter that corresponds to the conducted receiver sensitivity. Therefore, [6] defines the **total radiated sensitivity TRS**, which is based on the integration and average of individual equivalent isotropic sensitivity (EIS) measurements. EIS measurements are OTA receiver performance measurements from a given direction (Θ,Φ), e.g. directive BLER or throughput measurements. Thus, equivalent to EIRP based transmit radiation pattern measurements, there is an EIS based receive radiation pattern measurement possible. Fig. 4-3 depicts such a pattern measurement for the same device as for the transmit pattern measurement and the conducted measurements using MCS 10. The total isotropic sensitivity was calculated as -96.3 dBm, which corresponds to the conducted true sensitivity measurement result of -96.6 dBm provided in 2.4.

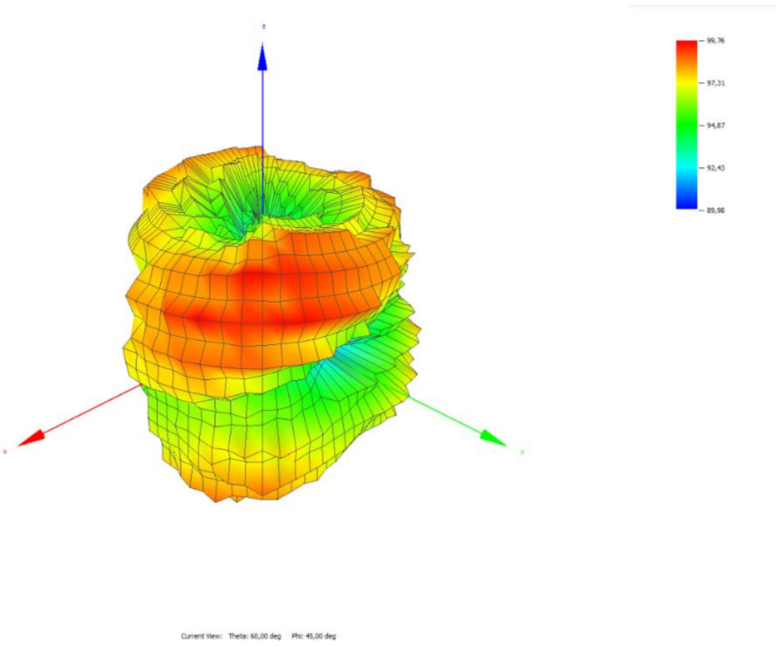


Fig. 4-3: EIS radiation pattern of a LTE band 1 FDD mobile phone

4.1.3 Relation of OTA and conducted measurement results

Thus, to compare conducted and radiated receiver sensitivity measurements, the total isotropic sensitivity TIS radiated measurement value that corresponds to the conducted measurement value. Thus, a single measurement in the conducted domain compares to a full sphere measurement series in the radiated domain. For certification purposes according to [6] the TIS measurement requires BLER measurement samples at data points taken every 30 degrees in the Θ and Φ axis, which accounts for a total of 60 measurements for each of two orthogonal polarizations. [6] defines all measurement parameter details and the algorithms to calculate TIS from all taken EIS samples. It is obvious that OTA measurements are very time consuming compared to conducted domain measurements, despite the fact that OTA measurements required much more efforts in terms of measurement setup calibration.

In particular, when trying to compare different devices in a OTA environment requires much more efforts than in the conducted domain. To compare the receiver performance with a single figure of merit, you need to compare TIS values. Comparing single EIS values does not make any sense at all, except you want to compare radiation patterns in detail.

4.1.4 Position matters

It has been shown that single direction OTA measurement results are not telling the full truth, an integration of measurement results over a full sphere around the device under test is needed. Thus, the receiver performance comparison of different devices based on single direction measurements is not valid at all, in particular comparing OTA throughput measurements for only one direction (i.e. UE position relative to eNB emulator antennas).

As an example, Fig. 4-4 depicts the results of two measurements with the same device and test signal MCS 9. However, the positon of the device within the anechoic chamber and relative to the eNB emulator antennas has been changed between the measurements: it was simply turned by 90 degrees. The results clearly show that “position matters” for OTA measurements, as the performance differs in this simple example by approx. 0.5 dB.

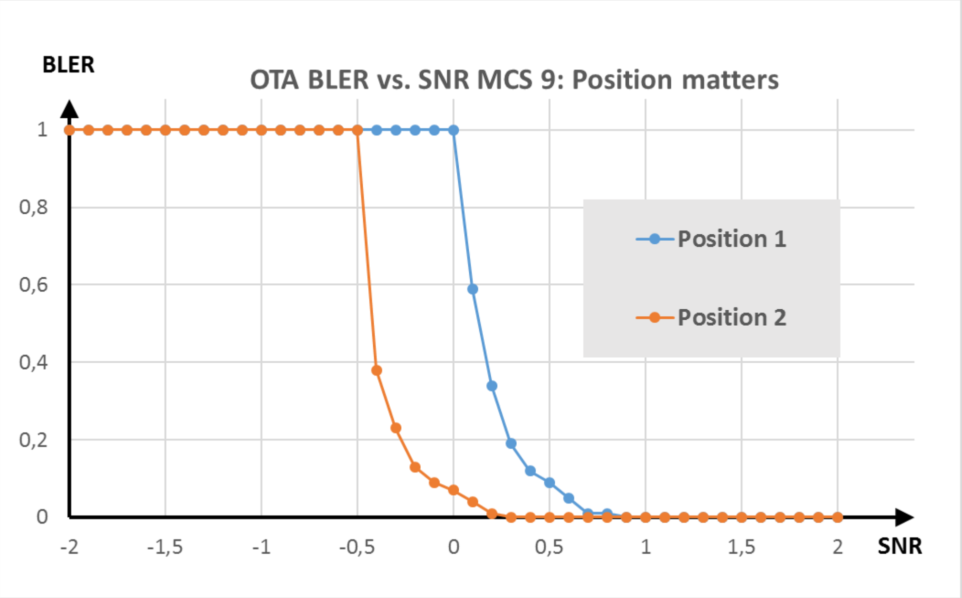


Fig. 4-4: **OTA BLER vs. SNR measurements - Position matters**

Thus, comparing devices in OTA measurement environment requires either great care with respect to the positioning of the devices or ideally the use of anechoic environments with appropriate positioning systems (e.g. R&S©DST200 or R&S®ATS1000) to enable full sphere measurements.

5 Outlook

This white paper explains the metric and test methodology of LTE UE receiver performance measurements. A number of measurement results are provided to confirm the theoretical background of receiver performance. It was emphasized that OTA measurements are not easy compare with conducted measurements, as real UE antenna radiation patterns are never omni-directional. While a single conducted measurement can provide the true sensitivity of a LTE UE receiver, a series of OTA measurements over the whole sphere around the UE under test is needed to gain the same information.

Up to the fourth generation of mobile communication, commonly known as LTE, conformance measurements – including receiver performance assessment – are based on conducted measurements, assuming the availability of appropriate connectors. Only a very few measurements, namely TRP and TIS, are specified for OTA measurement environments, too.

This might change dramatically when looking towards the next, i.e. the 5th generation of mobile communications. According to the standardization body 3GPP, which has just started the specification of the next generation “new radio” (NR), frequencies far beyond the spectrum that has been used so far for mobile communications are considered seriously. Basically, no frequency up to 100 GHz shall be precluded. In particular operating frequencies in the 28 GHz range are of vital interest and are ready to be deployed for initial “5G” services for the 2018 Olympic Winter games in South Korea, for instance.

Such high operating frequencies require high gain antenna implementations to overcome the increased free space path loss. For instance, the path loss for a 30 GHz signal is 20 dB higher than for a 3 GHz signal according to the Friis equation. Consequently, we will see antenna array deployments, rather than single antenna elements, in the new generation of mobile devices. This will make it impossible to perform conducted measurements as we have been used to so far. All measurements need to be performed over the air, which creates new challenges for everybody involved. 3GPP has just started with the work on specifying OTA conformance requirements and measurements for 5G. And R&S is actively involved in that process.

6 Literature

[1] Technical Specification 3GPP TS 36.101 V14.4.0 (2017-06)
“E-UTRA; UE radio transmission and reception”

[2] Technical Specification 3GPP TS 36.521-1 V14.3.0 (2017-06)
“E-UTRA; UE conformance specification; Radio transmission and reception; Part 1: Conformance Testing” (Release 14)

[3] Technical Specification 3GPP TS 36.211 V14.3.0 (2017-06)
“E-UTRA; Physical Channels and modulation”

[4] Technical Specification 3GPP TS 36.213 V14.3.0 (2017-06)
“E-UTRA; Physical layer procedures”

[5] CTIA Test Plan for Wireless Device Over-the-Air Performance, Version 3.6.1

[6] IEEE Std. 145-2013 - IEEE Standard for Definition of Terms for Antennas

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Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

Asia Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

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Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | 81671 Munich, Germany
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com