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11

MIMO OTA Testing

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11.1 Topical Working Group on Multiple-Input Multiple-Output (MIMO) Over-The-Air (OTA)

The main goal of the Topical Working Group on MIMO OTA is to gather all the relevant research across the Working Groups in the IC1004 Action for backing-up choices to be made in standardisation on technologies for OTA testing of multi-antenna devices. As no standards are conceived in European cooperation in science and technology (COST) IC1004, discussions are generally held in an easier atmosphere than in standardisation bodies. Contributions to a broader understanding of OTA testing of multi-antenna systems and its implications are welcomed as much as investigations of particular technologies or concepts. Such contributions come from industry and academia. Compared to earlier work in, for instance in COST Action 2100, the focus has shifted from RF performance (the present OTA standard) to overall device performance as seen by the user, without regarding any specific hardware/subsystem performance. This also means not primarily finding out why a certain terminal in a particular radio environment behaves the way it does, the focus is on how it performs w.r.t. to exchanging information (data, speech, images). The impetus comes from, among others, mobile service providers that want to rank UE for their portfolio. The targeted application of MIMO OTA in standardisation is the conformance testing cycle, currently targeting RF performance only and not production testing. In this Chapter, contributions over the project duration are documented and resumed in a coherent way.

11.1.1 The Organisation of This Chapter

Originally, four methods for OTA testing of MIMO terminals were under discussion for standardisation and an appreciable part of the research within

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the Topical Working Group is devoted to these particular methods which are multi-probe anechoic, reverberation, two-stage, and decomposition. At the time of writing this book, 3rd generation partnership project (3GPP) is continuing to develop standards for three of the methods but has stopped work on the decomposition method. Of the three remaining methods, international association for the wireless telecommunications industry (CTIA) has selected two for the first draft of its MIMO OTA test plan and is considering the third method for a future release. However, independently from any decisions taken by 3GPP and CTIA, results for all the methods are presented here as part of the research within COST IC1004.

In addition, research into MIMO OTA in a broader sense was also undertaken. Therefore, after this introduction we will first give some general underlying concepts of the present state of the art of MIMO OTA and will then describe the concepts behind the four proposed technologies. In the succeeding sections, this structure will be repeated by first presenting research results that are relevant for all OTA technologies and then successively treating contributions to each of the particular technologies. A summary and outlook conclude this chapter.

11.2 OTA Lab Testing: Models and Assumptions

11.2.1 General Considerations of OTA Testing

The main reason for OTA-testing is the interaction between device antenna and EM environment. Simply put, the more directive the wavefields produced by the environment, the more the directivity of the antennas matters. As preceding COST Actions have gone a long way modelling the non-isotropic directionality of the mobile radio channel, its polarisation state, and its time variance, accounting for the effects these properties have on reception through the antennas of a specific terminal is a logical consequence. The first standard on single-input single-output (SISO) OTA concentrated on capturing the power received or transmitted by a system through its antennas and RF subsystems [3GPP12, CTIA14], as the amount of transmitted/received power determines the achievable throughput (TP). For MIMO systems, it is of importance to know how much power is received in or transmitted into the available independent channels as provided by the radio environment. Scattering richness of the channel determines how many of these links exist, with their number indicated by the channel rank. How much of this channel rank is available to the transmission system depends on both the antenna array constellation, the respective radiation patterns of the individual antenna elements, and the signal-to-noise ratio (SNR). Also, orientation of the device antennas with respect to the environment plays an additional role through their directivity, as mentioned above. Because device orientation generally will differ from user to user, measurements have to be performed with different device orientations in order to properly describe these orientation influences. The channel models prescribed in standardisation are adaptations of 3GPP spatial channel model extended (SCME) [BHdG$^+$05] effectively modelling two-dimensional (2-D) incident fields with static angular distributions, that are run in "drops", i.e., without temporal evolutions of large-scale effects.

11.2.2 Anechoic Chamber or Multi-Probe Method

This method is the one that attempts to physically recreate the radio environment of the device under test (DuT) by emulating the important features of the incident wave fields. For this, the DuT is encircled in an anechoic chamber by a set of OTA antennas, typically in an annular array. The individual antennas are excited with signals that are jointly optimised to produce, by superposition, a wave-field that represents the radio environment. A characteristic of this method is that the size of the test area with good field quality (the "test zone" or "sweet spot") scales linearly with the number of OTA antennas and wavelength, see Section 11.4. As the annular set-up intrinsically is 2-D, projections onto the azimuthal plane are necessary when emulating three-dimensional (3-D) environments, which is still realistic under perfect power control [LGP$^+$13], as long as both polarisations are emulated. Pirkl and Remley [PR12] reached similar conclusions without mentioning power control.

Advantages of multi-probe method are:

- No access to antenna ports is needed, as no conducted tests are needed.
- The method allows for emulating virtually any radio environment, not only the ones modelled in standardisation.
- Spatial channel characteristics, e.g., for MIMO operation, can be emulated with great accuracy.

Disadvantages are:

- Its cost, especially when emulating 3-D channel models. An anechoic chamber is needed, as are channel emulators (CEs) (with sufficient interconnectivity) for every separate antenna element, i.e. for testing a 2×2 setup in a dual-polarised 8-antenna ring (16 antenna ports) 16 dual-input CE are needed. Therefore, the size of the test zone cannot easily be made large.
- 2-D set-ups with annular OTA arrays tend to amplitude decay over the test zone.

- Of the proposed wave synthesis strategies, coherent synthesis demands coherent operation of all the CE channels with minimal drift. This, too, is expensive and creates a lot of overhead in terms of calibration. Pre-faded synthesis (PFS) is suited best for Non-line-of-sight (NLoS) situations, see Section 11.4.

11.2.3 Two-Stage Method

The philosophy behind the two-stage method is that communication hardware works on signals, not on fields. Therefore, imposing the correct signals at the device receivers will result in correct measurement. Consequently, cabled connections to the terminal are possible as long as the combined effect of the transmitting antenna array, the propagation channel, and the receiving antenna array is accurately emulated. For this, the antenna patterns of the DuT are measured in both polarisations and over 3-D (stage one). Then, the antenna patterns are embedded in the channel that is emulated, over cable connections (stage two). A recent enhancement is a radiated two-stage (RTS) method that avoids cabled connections thud relieving some of the disadvantages of the method, see Section 11.6.

The conducted two-stage method has the following advantages:

- No dedicated room (anechoic or reverberant chamber) needed for the second-stage throughput measurements. However, the device radiation patterns need to be determined in an anechoic antenna measurement chamber.
- Less emulation hardware resources needed than for wave-field synthesis; for instance, emulation of a 2×2 MIMO transmission will require emulating four independent links, meaning four CE channels, whereas a wave-field synthesis with eight dual-polarised antennas requires 16 dual-input CEs, see Section 11.2.2.
- No need for wave-field emulation to be restricted to 2-D.

The disadvantages are:

- In the conducted version, access to antenna ports is needed and the termination impedance mismatch must be considered.
- Devices with adaptive antennas cannot be tested properly, because of the variability of the patterns. This also applies to the radiated version.
- When connected by cable, it is not possible to measure device's radiated desensitisation caused by signals leaking from the DUT transmit antennas back into the DUT receiver as the antennas are disconnected by the cabled connections, see Section 11.6.3. The radiated two-stage method resolves this disadvantage.

11.2.4 Reverberant Chamber Method

As the name of the method already indicates, a reverberant chamber is used, creating a rich scattered wave field with large angular spreads. The fields are homogenised by continuously changing the geometric properties of the reflecting surfaces, by use of so-called stirrers and turn table rotations over time, see Section 11.5. These devices are historically mainly used for measuring power output irrespective of antenna directivity, by storing the energy in the reverberant field and spreading it angularly. Along similar lines, reception sensitivity can be measured too. As such, the use of reverberation chambers (RCs) is standardised as one of methods used for the SISO OTA test.

Advantages of the RC method are:

- No access to antenna ports is needed, as no conducted tests are needed.
- After installation (which includes properly loading the chamber, i.e., tuning the reverberation time), there is no need for extensive calibration.
- The size of the chamber can be made smaller than the anechoic chambers typically used for the anechoic chamber method.

Disadvantages are:

- Many important aspects of the emulated wave-field are fixed.
    - The fading profile typically is a Rayleigh distribution, related to the vast number of scattered field components, combined with the large angular spread. Other distributions are, therefore, difficult to generate.
    - Spatial correlation cannot be tuned because the angular distribution is random based on the stirrer positions.
    - The cross-polarisation power ratio (XPR) of the emulated fields is very close to 0 dB, meaning total depolarisation. This removes any effect of, e.g., polarisation diversity of the base station and DuT antennas.
    - However, in a variation of the RC method, some temporal characteristics can be added by the use of CEs:
        * Additional delay spread on top of that determined by the reverberation time of the chamber.
        * Additional Doppler profiles to those of fixed shape with relatively small spread determined by the rotation speed of the stirrers.
- Instantaneous angular distributions of the field are not isotropic, but are assumed isotropic only after sufficient averaging over time. Averaging

of measured TP has had considerable discussion due to the strongly non-linear behaviour of the measured TP with respect to received power.
- The evolution of the angular distribution over time is not typical of a cellular mobile radio channel. As a result, smart antenna adaptivity is not likely to develop its full potential.

11.2.5 Decomposition/Two-Channel Method

This method evolved during the project duration. At its start as the two-channel method, it deviated from the other methods described here as it considered component testing rather than testing device performance, in this way more or less continuing the line of thought that produced the first OTA standard. The main idea was to test OTA only the antenna with RF front-end, without any fading. All other components can be tested conducted. Later, accommodating standardisation's requirements for a full end-to-end characterisation instead of a component test, and under fading conditions, a connected test was added to the test suite and the name of method changed to "decomposition method", see Section 11.6.

A clear advantage of the method is:

- The two-channel method principally does not use CEs. The decomposition method, though, requires two single-input CEs for two channels, three for three channels, etc.

Disadvantages of the method are:

- An anechoic chamber is needed with a two-way mechanical positioner. For future higher-order constellations, multiple-way positioners could be required.
- Influences of the spatial characteristics of incoming fields are only available in a non-linear fashion as with the RC method, i.e., through (in this case, optionally 3-D angularly weighted) averaging over measured TPs per combination of two incidence angles.
- The conducted test added afterwards does not embed antenna directivity in the channel (in contrast to the two-stage method), implicitly assuming some generic (presumably omnidirectional) pattern.

11.3 General Research Topics

At the start of TWG MIMO OTA mid 2011, standardisation and certification groups such as 3GPP and Cellular Telecommunication and Internet

Association (CTIA) were heavily engaged in MIMO OTA. The TWG MIMO OTA chose to support those efforts consolidating the expertise of its members on topics important for properly evaluating MIMO OTA devices.

The initial scope adopted by standardisation and certification groups was based on tests intended to determine what constitutes a good versus a bad performing MIMO-capable user equipment (UE). As the project progressed, it became clear that just determining what constitutes a good or a bad performing MIMO UE is quite challenging, and, therefore, MIMO OTA performance would require more than one test condition in order to properly assess MIMO-capable devices across their entire performance range.

The challenges associated with MIMO OTA performance evaluation differ substantially from those the wireless communications industry faced when defining a measurement methodology for SISO-radiated performance measurements [CTIA14]. Because a SISO receiver (Rx) does not require a special propagation environment, an LoS radio path within an anechoic chamber is employed. MIMO, on the other hand, requires a spatially-diverse radio channel in order to deliver maximum performance, resulting in more than one MIMO OTA candidate methodology being proposed.

Given the diverse nature of the methodologies available for assessing MIMO OTA performance, it became evident that the fundamental aspects of the OTA measurement should be scientifically validated. In addition, result comparison between labs would also be required. The comparison of measurement techniques is nothing new. Over the years, the industry has established round-robin test efforts designed to identify the strengths and weaknesses of proposed measurement methodologies, while at the same time attempting to quantify device performance in such a way that results can be directly compared between labs and measurement techniques. However, because MIMO performance is related to the spatial–temporal aspects of the operating environment, special techniques were required. In response to this need, COST IC1004 collaborated with those groups validating fundamental concepts and defining measurement techniques. These research topics, relevant to all MIMO OTA test methodologies were defined as follows:

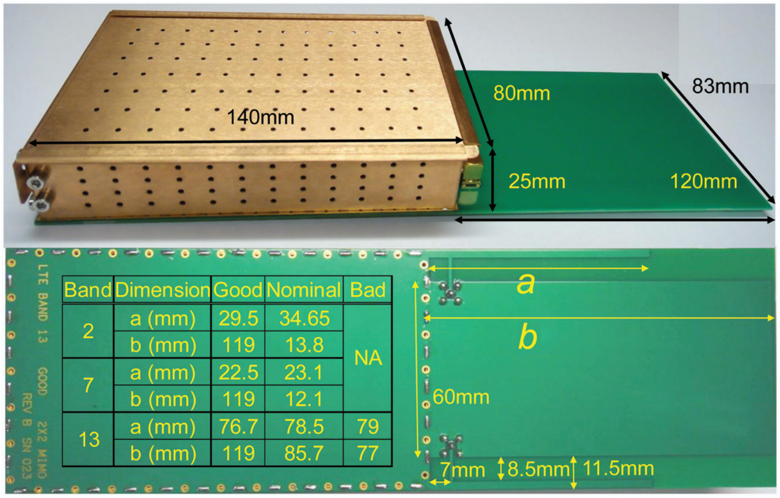
- Definition of MIMO reference antennas
- Fundamental limitations of test environments
- The expected data TP value for a real mobile device
- Definition of figure of merit (FoM) post-processing
- Definition and characterisation of measurement campaigns

11.3.1 Definition of MIMO Reference Antennas

Understanding that the industry was overlooking fundamental aspects of good academic and engineering practices the MIMO reference antennas as shown in Figure 11.1 were proposed. Initially solving the issue surrounding the unknown antenna radiated performance in all devices under test, the MIMO reference antennas shown in Szini et al. [SPDBF12, SPSF12, SYP14] was proposed as a solution to this problem, therefore, eliminating this variable from the list of unknowns that affect the MIMO OTA measurement campaign outcome. Those antennas were proposed in mid 2011 during the first face-to-face meeting of the recently formed MIMO OTA sub group (of CTIA) (MOSG) and initial designs in the COST IC1004 action, and were adopted during two additional measurement campaigns organised by CTIA and supported by 3GPP RAN4 MIMO OTA *ad hoc*.

11.3.2 Fundamental Limitations of Test Environments

A number of common channel models including 3GPP SCME and wireless world initiative new radio (WINNER) interpret the cross-polarisation coupled power (as described by the XPR) as power added to the co-polarised powers [SPSF12]. Thus, if the co-polarised V–V or H–H signals were normalised to unit power, the cross-polarised terms would represent scattered or reflected power originating from the other polarisation and modelled as power added to the co-polarised unit power driving the value above unity. Thus, receiving



Band	Dimension	Good	Nominal	Bad
2	a (mm)	29.5	34.65	NA
	b (mm)	119	13.8	
7	a (mm)	22.5	23.1	
	b (mm)	119	12.1	
13	a (mm)	76.7	78.5	79
	b (mm)	119	85.7	77

Figure 11.1 MIMO reference antennas and respective dimensions.

in one polarisation benefits from transmitting in both polarisations due to the scattering in the environment. In a system simulation, the cross-polarised powers vary due to the SCME and WINNER phases selected on each drop. However, for link level evaluation, such as in a MIMO OTA test environment, the random processes are replaced by a fixed set of parameters including the polarisation phases in order to generate reproducible channel conditions. The following simple power normalisation produces unit power in a Rx test volume:

$$\frac{P_{\mathrm{V}}}{P_{\mathrm{V}}+P_{\mathrm{H}}}+\frac{P_{\mathrm{H}}}{P_{\mathrm{V}}+P_{\mathrm{H}}}=1, \tag{11.1}$$

with $P_{\mathrm{V}}, P_{\mathrm{H}}$ the powers in the vertical and horizontal polarisation, respectively. When multiple taps are defined, the power in each polarisation is normalised per tap and the powers per tap are then weighted according to the power delay profile (PDP) to arrive at the total normalised power. With this normalisation, a constant unit power will be presented to the DuT, while having a variety of spatial, temporal, correlation, XPR, and polarisation properties as defined by the given channel model. When different channel models are selected, they will use these parameters only at a normalised power level.

Manufacturers of cellular handsets most commonly adopted radiation pattern diversity as MIMO antenna system design technique. The reference antennas described previously were, therefore, designed to emulate such designs. However, this does not mean that the OTA test methods should tune their tests optimally to these types of antenna design. Different perspectives do exist as shown in Szini et al. [SFR^{+}14], where a MIMO antenna system based on pure polarisation diversity was presented. The objective was to bring to attention that conclusions based on limited sample of reference antennas cannot be extrapolated to a wide variety of MIMO antenna systems. It was demonstrated that fundamentally different test methodologies, regarding channel models and cross-polarisation definitions, evaluated identical devices quite differently. Especially, RC-based methods cannot discriminate between MIMO antenna systems based on pure polarisation diversity, due to the lack of cross-polarisation control (Figure 11.2). While achieving pure polarisation diversity is a challenge in low frequency and small form factor units like handsets, it is common in larger mobile devices such as tablets, laptops, machine-to-machine (M2M) devices, etc.

Traditionally, the channel models used in standardisation are exclusively 2-dimensional, i.e., only azimuthal angles are taken into account, with development of 3-D models under way. Although reducing a 3-D to a 2-D propagation environment is a clear simplification of reality, it does not need to have a relevant impact on the results. Simulation results, based on channel

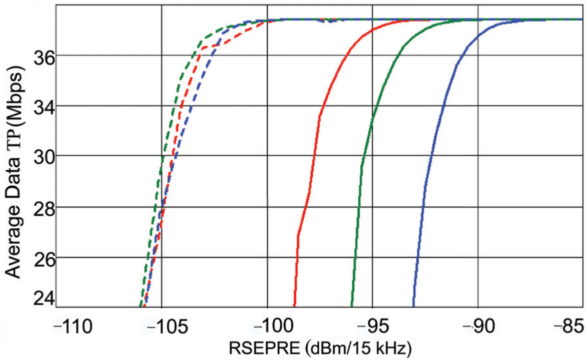


Figure 11.2 Polarisation discrimination between different antennas, measured in MPAC (solid lines) and RC (dotted). Red: Band 13 "Bad", green: Band 13 "Nominal", and blue: Band 13 "Good" antenna.

measurements in Ilmenau in which the MIMO Reference Antennas were embedded, [LGP+13], showed little loss of TP (less than 10% uplink), as long as the channel remains full-polarimetric and perfect power control is assumed (among others, the UE is located away from the cell edges). Further simplifying the channel environment, from 3-D dual-polarised to 2-D single-polarised, clear deviations in channel characteristics can be noticed (on average 10–15% additional loss, up to 50%). There are indications the rank of the channel may be impaired by the simplifications. This bears implications for the multi-probe anechoic chamber (MPAC) method with annular arrays or the use of 2-D cuts in the two stage methods, when dealing with real 3-D propagation data instead of with 2-D SCME models.

During work on device characterisation, it was discovered that operating the UE at high TP for extended periods of time created unreliable results [Jen11]. The issue was found to be related to a temperature rise within the UE, impacting the transceiver (TRx) IC. This is the reason why further study of MIMO OTA has been carried out using an uplink power of only –10 dBm. In real life use cases, cell edge reference sensitivity also coincides with the highest UE output power and so it should be understood that continued reliance on low UE output power is not fully representative of performance for devices whose performance degrades at high temperatures.

11.3.3 The Expected Data TP Value for a Real Mobile Device

With the MIMO antenna performance issue addressed, the next issue to be faced by the standardisation community was the validation of base station (BS) settings and channel model emulation in the test environment baseline realisation. These technical problems were the motivation for the follow-up work shown in Szini et al. [SPTI13]. The Absolute Data Throughput Framework was a method coined to establish a deterministic MIMO OTA figure of merit and stimulate the industry to proper defined the channel model pertinent to each proposed MIMO OTA test methodology as demonstrated in Figure 11.3. Adopting the MIMO reference antennas already accepted by the industry, the Absolute Data Throughput Framework compares the conducted data TP measurement (through the CE including the spatial and temporal characteristics of the defined channel model and the embedded complex radiation pattern of the MIMO reference antennas) with an over the air measurement using the same channel model, same DuT and same reference antennas (of which the complex radiation pattern was measured). In this way, the expectation of radiated channel model emulation is validated. This method was extensively used during the conclusion of the 3GPP RAN4 MIMO OTA work item, and was considered one of the fundamental criteria to validate MIMO OTA test methodologies.

11.3.4 Definition FoM Post-Processing

Although data TP had been agreed and defined as the fundamental MIMO OTA figure of merit, the way to post-process raw data continues to be a topic of discussion and constant investigation that must be addressed before the conclusion of MIMO OTA certification process.

Based on measurement in both an anechoic chamber and a reverberant chamber set-up, differences where noticed between calculating average TP versus power, typical for a reverberant chamber result, and calculating TP

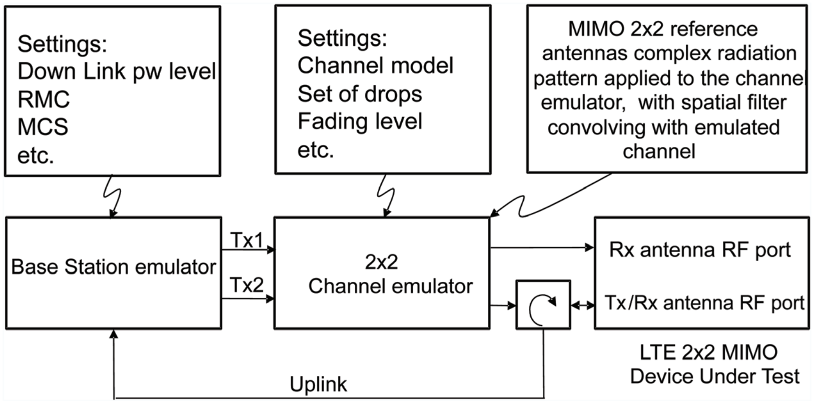


Figure 11.3 Absolute Data Throughput conducted measurement block diagram.

versus average power, with average power defined as the inverse of the average of the inverse used for sensitivity [Szi14b]. Since the shape of a single TP versus power curve is very different from that of the average of the TP across the total spread in power, the resultant curves differ considerably. The results indicate that a simple average over all data spread does not provide proper characterisation or discrimination of the device's radiated performance in user centric defined modes, such as hands free, navigation/data portrait, navigation/data/gaming landscape, or hotspot.

11.3.5 Definition and Characterisation of Measurement Campaigns

One of the relevant open issues in the MIMO OTA industry and standards nowadays is the definition of the test measurement uncertainty (MU), different test methodologies have different hardware and software requirements and unique system implementations. While some test methodologies require multiple CE ports, PAs, probe antennas, cables, connectors etc., other MIMO OTA methods are based on antenna system complex radiation patterns gathered in SISO anechoic chambers and conducted measurements, clearly a single MU value cannot capture both methods uncertainty properly.

A measurement campaign was started for investigating the root cause of MU in anechoic chamber multi-probe set-ups, in which three independent implementations of the same test methodology [FSF$^+$14] were compared. Two of these implementations, those of Aalborg University and Motorola Mobility were built from ground-up, where the third set-up of ETS-Lindgren was based on a commercially available installation. Details are given in Section 11.3.4.

Other measurement campaigns revealed consequences of strong correlation at the BS side for the SCME urban-macro (UMa) channel model, being approximately 0.95. A cross-polarised 45 slanted antenna at the BS is defined, assuming to represent the most common network deployment scenario. As the angles of departure are close to 90° (representing the end-fire direction of the array), the AoD spread is about 2°. Based on the foreshortening effect of the array elements, the horizontal component is also reduced in this model. Results from these measurements indicate that there is a significant improvement in DuT performance, approximately 6 dB, for the UMa model when the BS correlation is removed. It was later decided to preserve the BS antenna correlation effects so that the test conditions could distinguish device performance differences. The urban-micro (UMi) model is quite different, having the AoDs all near 0°, which results in a nearly balanced polarisation ratio and very low correlation between BS array elements. The DuT will perform better when using the UMi channel model due to these effects. It was also noted that the slope of the TP curve, averaged over the various device orientations, is affected by the variation in the individual TP curves. The larger the variations over the orientations, the shallower the slope of the average curve.

The emulation of a well-determined SNR during testing showed to be non-trivial. Four different methods of generating noise in the test environment were analysed [JKR13], from noise injection before channel faders to noise injection at OTA antenna feed points. As a result, a definition of SNR based on omnidirectional unfaded additive white Gaussian noise (AWGN) was proposed, to be used for the future evaluation of MIMO OTA test methods along with non-AWGN test cases. This definition of SNR minimises the correlation between the signal and noise without going as far as defining directional or time-variant noise which remain items for future study. The use of omnidirectional noise has since been adopted by CTIA and is under consideration by 3GPP. An analysis showed that in low-noise environments, antenna efficiency is dominant, but in high-noise environments, antenna correlation is far more important [JKR13].

Apart from noise, also interference needs to be considered, as the performance of long-term evolution long-term evolution (LTE) mobile terminals in cellular systems is limited by interference, e.g., the inter-cell interference. Open questions are which the characteristics of interference are in real environments, which characteristics are essential for radio link performance in an OTA measurement, and how to emulate interference realistically, especially in the MPAC set-ups. To answer these questions, background interference was measured, power levels were determined, and variations depending on the AoA at the mobile location [NFP13]. Background interference has been defined as signals and noise received within the band of a particular cellular system, excluding the signals originating from the system itself. A small series of initial exploratory measurements were performed with a spectrum analyser connected to a spherically scanning horn antenna. The measurements were done in different geographical locations, urban, sub-urban, and rural. Power distributions were successfully obtained within frequency bands where various systems are known to transmit. However, the median power levels were generally too close to the system noise floor around. To solve the problem of too high-noise floors in the analysis, future work will likely involve measurements selected frequency bands only.

Averaging TP results became a topic too as two different ways to derive average TP were proposed in industry. One way is to generate an average

TP curve across all 12 DuT rotations and then compute the reference signal energy per resource element (RS EPRE) value necessary to reach the 70 or 95% of the peak TP on this average curve. The other way is to compute the RS EPRE values (i.e., energy per resource element of the reference signal and is expressed in dBm/15 kHz) necessary to reach the 70 or 95% of the peak TP for each curve corresponding to the rotations and then calculate the average performance metric across all rotations. It was shown that the first method incorrectly estimates the FoM due to the non-linear relationship between the RS EPRE and TP, whereas the second method provides the correct average representation of the performance metric and also generates a useful visualisation of the data [IMU13, Iof14].

11.4 MPAC Method

The antenna design and the propagation channels are the two key parameters that together ultimately determine MIMO device performance [JW04]. As antennas are considered inherently in the OTA testing, it is important to also include realistic channel models for MIMO device performance evaluation. The MPAC set-up has attracted great research attention both from industry and academia due to its capability to emulate realistic multipath environments with controllable channel characteristics, making it a suitable method for testing terminals equipped with multiple antennas. This part is organised as follows. The MPAC set-up and the basic idea are introduced first. Then, channel emulation techniques, which are widely discussed and investigated in the literature, are described. And finally, a state-the-art of topics related to MPAC set-ups is presented.

11.4.1 Introduction

An illustration of the MPAC set-up is shown in Figure 11.4. The MPAC system often consists of a radio communication tester, a CE, a PA box, multiple probe antennas located around the DuT in an anechoic chamber. The radio communication tester is used to emulate the cellular network end of the link. The CE and the multiple probes are used to create desired spatial–temporal channels and intended interferences within the test area. The PA are used to adjust the signal to the desired power level. A network analyser is often used for channel validation investigations. As illustrated in Figure 11.4, the current set-up is focused on emulating realistic downlink channel models (i.e., communication from BS to mobile terminal), while the uplink is realised by a direct antenna and cable connection. As the testing is performed in the anechoic chamber, the generated multipath environment will be free from reflections inside the chamber and

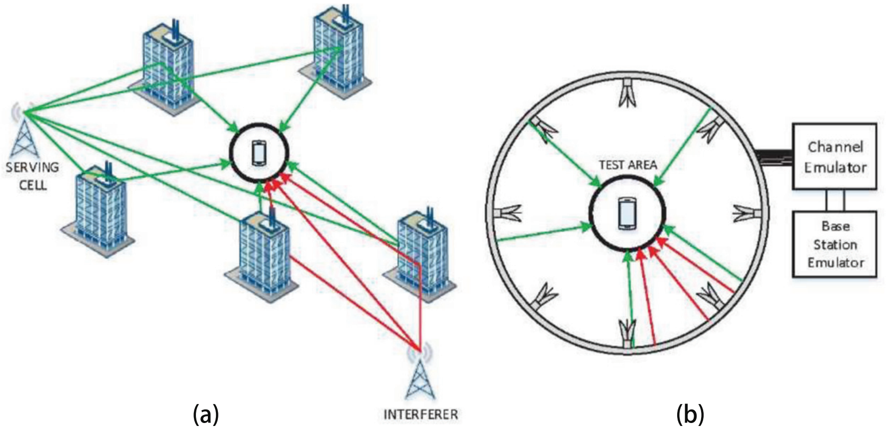


Figure 11.4 The multipath environment (a) and channel emulation in the MPAC set-ups (b).

external unwanted interferences. The testing is realistic as well, since the DuT is evaluated as it is used in the real network. The main disadvantage with the MPAC method is the cost of the set-up. The number of output ports of the CE is often limited, and, therefore, the number of probes utilised for synthesising the channel is limited, which would result in a test area with a limited size.

11.4.2 Radio Channel Emulation Techniques

One of the main technical challenges for OTA testing of MIMO capable devices is how to emulate the spatial channel models in the volume where the device is to be tested. The key idea of channel emulation is to ensure that the signals emitted from the probe antennas are properly controlled such that the emulated channels experienced by the DuT approximate the target channel models within the test area. In this section, different channel emulation techniques are revisited and summarised.

11.4.2.1 Prefaded signal synthesis

The PFS technique was proposed in Kyösti et al. [KJN12], and has been widely used in commercial CEs. With the PFS technique, fading signals, generated with the sum of sinusoid technique, are transmitted from each probe antenna. Each cluster is emulated by several probe antennas. Fading signals associated with the same cluster are independent and identically distributed. The emulated channel, which is a linear summation of contributions from the multiple probes, matches with the target channel in the temporal domain. For each cluster, the Rx side spatial characteristics are reconstructed by allocating appropriate power weights to the fading signals from the probes. The size of

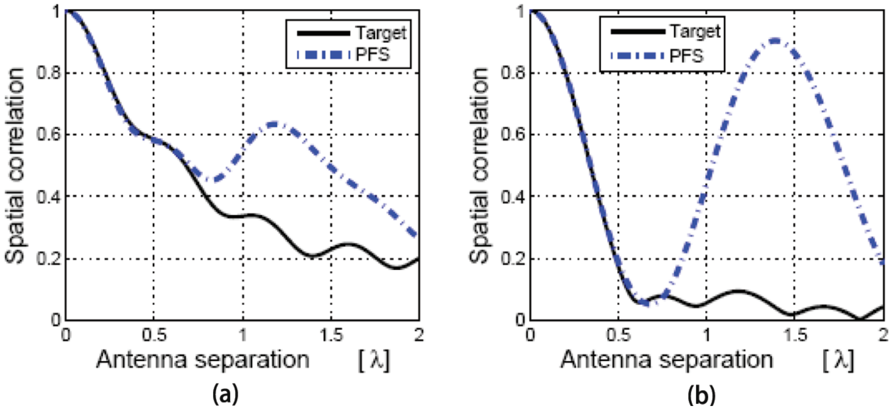


Figure 11.5 Target and emulated spatial correlation at the Rx side for the SCME urban macro channel model (a) and SCME urban micro channel model (b), with eight OTA probe antennas.

test area with acceptable accuracy is only determined by how well the Rx side spatial characteristics can be emulated, as temporal characteristics could be perfectly reproduced. An example of how well the emulated channel matches with the target channel in terms of spatial correlation at the Rx side is shown in Figure 11.5, where a test area of 0.7 wavelength diameter can be achieved with eight probe antennas. For channel models that consist of multiple clusters, each cluster is emulated independently. For dual-polarised channel models, vertical and horizontal polarisations are emulated independently. The effects of other channel characteristics, e.g., the transmitter (Tx) antenna array, channel spatial characteristics at the Tx side, are considered and modelled in the fading signals. Geometry-based stochastic channels (GBSCs) are often selected as the target channel models for the PFS technique. The PFS technique has gained its popularity due to its capability to emulate GBSC, with only probe power calibration required in the MPAC set-ups.

11.4.2.2 Plane wave synthesis

The basic idea of the plane wave synthesis (PWS) technique is that a static plane wave with an arbitrary impinging angle can be generated within a test area by allocating appropriate complex weights to the probe antennas on the OTA ring. Target plane wave is with a uniform power distribution and ideal linear phase front along the impinging direction within the test area. Different techniques have been proposed to obtain the complex weights, see, e.g., least square technique in Kyösti et al. [KJN12] Fan et al. [FCnN$^+$12] Kotterman et al. [KSLDG14], and trigonometric interpolation in Fan et al. [FNF$^+$13].

An example of the emulated field with eight probe antennas for a test area of 0.7 wavelength diameter is shown in Figure 11.6, where the target plane wave is with impinging angle 22.5° (i.e., from between two adjacent probes). Two ideas were proposed to create spatial–temporal channel models based on static plane waves. Each snapshot of a time-variant channel can be considered as static, and can be modelled by multiple static plane waves, each with a complex amplitude, angle-of-arrival (AoA) and polarisation. The PWS technique can then be applied to approximate each snapshot. Another idea is to emulate GBSC models. A cluster with a stationary power angular spectrum (PAS) can be discretised by a collection of plane waves, each with a specific AoA. Each plane wave can be approximated by the PWS technique. A Doppler shift can then be introduced to each static plane wave to enable time variant channels [KJN12]. With the first idea, arbitrary multipath environments (e.g., channels with time-varying AoA) can be reproduced. For the second idea, the reproduced channel is stationary with a fixed AoA, as the incoming power angel spectrum has a specific shape. The main disadvantage is that both phase and power calibration are required for the multiple probes, as complex weights have to be obtained. Otherwise in hardware requirements both the PFS and PWS methods are alike.

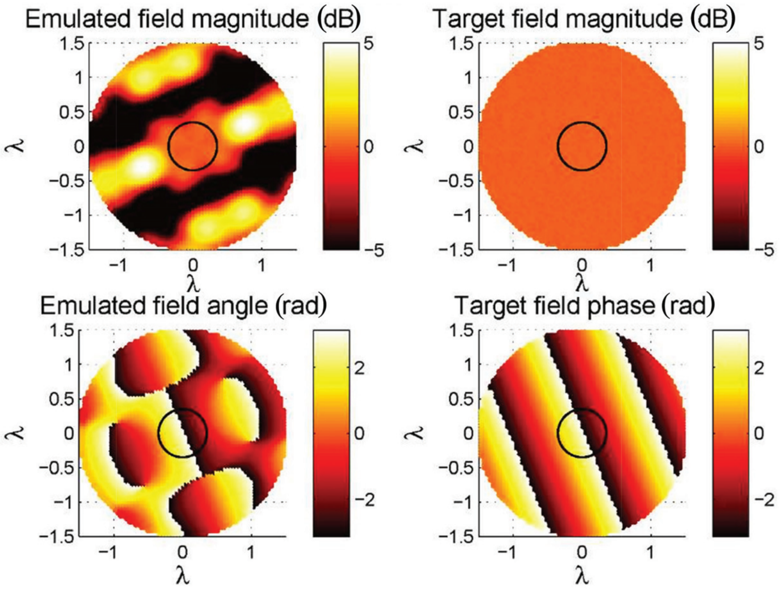


Figure 11.6 Emulated magnitude and phase distribution over the test area with eight probe antennas. *Black circle* denotes the test area.

11.4.3 The MPAC Set-up Design

The cost of the MPAC set-up depends directly on its design. Key aspects related to the MPAC design are physical dimensions of the OTA ring on which the probe antennas are located, number of required probe antennas, probe antenna design, probe configuration, MIMO OTA testing in small anechoic chambers, and the probe selection concept [FSNP13].

11.4.3.1 Chamber size

The physical dimension of a ring of antennas in an OTA set-up is limited by the size of the anechoic chamber. The physical dimensions are important in planning of the MPAC set-ups. It is important to understand up to which maximum size devices can be accurately measured for given dimensions of a ring of OTA antennas and a given range of frequencies. The physical dimension criteria of the MPAC set-ups based on field strength stability and phase stability across the test zone were often investigated [KH12]. Due to the limited distance between OTA probes and test area, the path loss is non-uniform and phase fronts are curved over the test area. Three classes of criteria for physical dimensions of the MPAC set-ups are considered. The criteria were

1. Non-uniform field strength caused by varying path loss, which may result in power imbalance between DuT antennas,
2. Phase variation caused by curved non-planar waves, which may result in correlation errors on DuT antennas, and
3. CTIA far field criteria. As error thresholds, 0.05 root mean square (RMS) correlation error and 0.5 dB average power imbalance were selected.

With the selected error thresholds, a maximum ratio of $r/R = 0.33$ was found from the power imbalance criterion and $r/R = 0.1$ from the correlation error criteria on the frequency range of 0.5–6 GHz, where r and R denote the test area radius and OTA ring radius, respectively.

OTA testing of MIMO capable terminals is often performed in large anechoic chambers, where planar waves impinging the test area are assumed. Furthermore, reflections from the chamber, and probe coupling are often considered negligible due to the large dimensions of the chamber. It is interesting to explore the possibility of performing MIMO OTA testing in a small anechoic chamber. It was concluded that 1.5 m distance between test antennas and DuT is generally sufficient [Mli11]. It was also investigated how to accommodate probe antennas used to synthesise clustered radio signal with 35° rms Laplacian distribution per the SCME standard. However, the proposed set-up is limited to a single spatial cluster with restricted AoA.

11.4.3.2 Probe configuration

Probe configuration is another topic related to the MPAC set-up design. Different 3-D (full sphere) and 2.5-D (three elevation rings) probe configurations are assessed with 3-D extended IMT-Advanced channel models in Kyösti and Khatun [KK13b]. The FoMs for assessing the probe configurations are the RMS error on spatial correlation function and the synthesis error. It is demonstrated that the emulation accuracy depends on both channel model and probe configuration. It is shown that a configuration with 16 dual-polarised probes could be sufficient for testing of terminals with diameter of 0.75 or even 1λ. In Kotterman et al. [KSLDG14], it is shown that the orientation of dual-polarised antenna elements has influence on the size of the test zone for 3-D electromagnetic wave field synthesis. The customary choice of polarisation directions along azimuth and elevation allows for the full angular range over which wave fields can be synthesised. But, this choice effectively reduces the number of available active radiators in case a single-polarised wave is to be synthesised with direction of incidence near maximum elevation. One option to maintain synthesis quality is driving both types of polarised elements, meaning also adding CEs that are an appreciable cost factor. However, not all applications need fully 3-D incident fields. For instance in outdoor cellular applications, a limited elevation range is not uncommon, avoiding the problematic angular region.

With respect to the number of probes, the flexibility of field emulation increases with the number of probes. However, probes become increasingly closely spaced, causing increased scattering from the neighbouring probes. In a 16-probe set-up, scattered fields were 25 dB below the main signal, in an eight-probes set-up 30 dB [BFKP14]. The consequences of scattering from neighbouring probes on field quality in the test zone need to be further investigated, in order to define a maximum acceptable level.

11.4.3.3 Probe design

One part of the MPAC set-up is OTA probe design. The antennas need to offer good polarisations properties and, at the same time, to be directive for creating variable radio channel conditions within the test zone. One option is to use narrow band transmitting antennas for every test frequency. This is not a very handy approach as huge banks of antennas are needed to cover different test frequencies. Another option is the use of wideband antennas to cover all necessary test bands. Several probe antennas are utilised in the MPAC set-ups, e.g., horn antenna, dipole, and Vivaldi antennas. In Sonkki et al. [SSEH$^+$15], a wideband dual-polarised cross-shaped Vivaldi antenna is presented. The antenna offers good polarisation properties over a wide frequency bandwidth with good impedance matching and very low mutual coupling between the antenna feeding ports.

11.4.3.4 Calibration

For the MPAC set-up, proper calibration of the system is required before the actual measurement. For the PFS technique, as the signals transmitted from the probes are power weighted, it is required to ensure identical path losses from the probes to the test area centre. For the PWS technique, complex weights are allocated to the probes, and hence it is required to ensure both identical path losses and phase lags from the probes to the test area. A calibration antenna, usually an electric or magnetic dipole, is placed instead of the DuT and connected to the vector network analyser (VNA). The main drawback is that for each calibration, the set-up has to be changed. In Fan et al. [FCnN$^+$13], it is shown the main cause of the signal drifting over time is the active elements of the set-up, hence a specific calibration method focusing on those elements should be considered [CnFN$^+$13]. By adding electronic switching units after the power amplifier (PA), a connection between the VNA, the CE, and the PA can be created. This way, the chamber and all the elements inside are bypassed and a calibration of the active elements can be done without physically changing the set-up [CnFN$^+$13].

11.4.3.5 Test area size investigation

One of the key questions to be addressed is how large the test area can be supported with a limited number of probes. The test area is an area where the desired channel models can be accurately reproduced. The antenna separation on the DuT should be smaller than the test area size to ensure that the DuT is evaluated under the desired channel conditions.

Different FoM are proposed and analysed in the literature to determine the test area size for different channel emulation techniques. For the PWS technique, often field synthesis error $|E - \hat{E}|$ is selected as the FoM, where E and $\hat{E}$ represents the target and emulated field, respectively. $|V - \hat{V}|$ is suggested as the FoM, with V being the received voltage for the target plane wave and $\hat{V}$ being the received voltage for the emulated plane wave [FNF$^+$13]. In this FoM, the DuT antenna pattern is included in the evaluation. Other FoMs could be adopted as well, e.g., spatial correlation, wave front direction accuracy, power flow/time-averaged Poynting vector, phase of the field vector elements, ellipticity, and group delay are under discussion. The question remains, though, which FoM describes the reaction of the DuT on the emulated field best, the answer likely being (radio) system dependent.

For the PFS technique, often the spatial correlation error at the Rx side $|\rho - \hat{\rho}|$ is selected, as it represents how well the emulated impinging PAS follows the target. In Fan et al. [FNF$^+$13], the antenna correlation error $|\rho_\mathrm{a} - \hat{\rho}_\mathrm{a}|$ is proposed to determine test area size, where ρ_a is the correlation of the received signals at antenna output ports for the target impinging power angle spectrum and $\hat{\rho}_\mathrm{a}$ is the similar correlation for the emulated impinging power angle spectrum. Fan et al. [FKNP16] investigated how well the capacity of the emulated channels matches with that of the target channel models. The test zone size depends on the probe configuration, carrier frequency, number of probes, channel emulation techniques, target channel models, acceptable error level, and DuT radiation patterns.

Intrinsic disadvantages of 2-D synthesis are amplitude drop-off within the test area and a small usable height. Coherent wave-field synthesis through the use of an annular antenna array suffers from remaining wave-front curvature normal to the plane of the 2-D array, and hence the usable test volume is limited to a thin disc [KLHT11]. Additionally, the amplitudes of the (approximately) cylindrical emulated waves drops with the inverse of the square root of distance and this decay over the test area is noticeable, especially when using a metric like EVM. As an alternative to real 3-D synthesis, the use of small sub-arrays is proposed, replacing the OTA antennas. Each of the sub-arrays locally generates wave-fronts with only curvature in the plane of the test area, which can be compensated by the field synthesis [Kot12]. Using three antennas per sub-array, with two wavelengths separation and passive power division and phasing, the test area size could be enlarged to approximately a sphere with less than 1° wavefront direction error and a total amplitude variation of 0.7 dB.

The influence of complex amplitude errors on the quality of synthesised wave fields was investigated in Kotterman [Kot13]. Simulation of the influence of errors in the excitation signals (i.e., the complex weights), with the aim to determine which accuracy is needed when including all errors from different sources like calibration, drift, mechanical vibration, phase noise, etc. It was noted that the influences of individual error distribution realisations were quite different, depending on whether the strongest excitation signals were impaired with larger or smaller random errors. Based on the simulation results, it is recommended to keep the maximum phase error span limited to $[-10^\circ, +10^\circ]$.

The test area size can also be expressed in terms of capacity emulation accuracy [FKNP16]. The investigation is based on the well accepted channel models in the standards for OTA testing of MIMO capable terminals, i.e., the SCME Umi and SCME Uma. The impact of spatial correlation at the Tx side, the channel model, and the spatial correlation at the Rx side on the capacity emulation accuracy was investigated. Simulation results show that the number of probes is irrelevant when the spatial correlation at the Tx side is in the high region (e.g., $\rho > 0.7$). Furthermore, when correlation at the Tx side is low, the spatial correlation accuracy is less critical with small correlation at the Rx side. The simulation results are supported by measurements in a practical set-up [FKNP16].

Attempts have been made to define the test area size in terms of TP, being the relevant FoM in standardisation [Szi14a, IY14], but further study is required.

11.4.4 Practical Channel Emulation

11.4.4.1 Measurement uncertainty

A mandatory step for evaluating MIMO devices in practical set-ups, is analysis of the sources of errors and uncertainties in the measurements. The uncertainty level can help to understand the level of confidence associated with testing results.

Some investigations on MU were reported in the literature, where some error sources were identified and analysed, as detailed below. However, the actual impact of the error levels on the testing results is still unclear. Quantifying the impact of errors on the important parameters, e.g., signal correlation accuracy, received voltage accuracy on the antenna, capacity and TP would be more interesting.

The probes are often assumed accurately placed on the OTA ring, however, probe placement error, e.g., probe orientation error and probe location mismatch error might exist in practical set-ups. Probe placement can introduce error in the system [FNCn$^+$12, FNCn$^+$13]. Probe orientation error might effectively modify the complex weights allocated to the probes and hence have an impact on the field synthesis accuracy. It was concluded that radial location errors are most critical, since the synthesised field for a radial error of a quarter of a wave length is no longer the plane wave-field with the target AoA. The impact of probe placement error on spatial correlation emulation was investigated in Fan et al. [FNCn$^+$13], the emulated correlation depending on the power weight allocated to each of the probe and on the probe angular location. The simulation results show that the probe angular location error is critical for spatial correlation emulation. Note that both probe orientation errors and radial location errors can be compensated during the calibration of the set-up.

Measurement uncertainty levels for different labs, i.e., at Aalborg University (AAU), Motorola Mobility (MM), and in ETS-Lindgren (ETS) were investigated to show key aspects related to MPAC set-up design [FSF$^+$14]. The MPAC set-up in AAU was equipped with an aluminium ring of 2 m and 16 dual-polarised horn antennas. Polystyrene placed on top of the turntable was used to support the DuT. Cables are connected to the DuT directly. The MM set-up was equipped with eight uniformly placed horn antennas on a OTA ring with 1.2 m radius. Choke and cartridge at various frequency bands were used to connect to the DuT. The set-up in the ETS was equipped with 16 dual-polarised Vivaldi antennas on a ring of radius 2 m. Ferrite-loaded cables are used to connect to the DuT. An illustration of the MPAC set-ups are shown in Figure 11.7. The main testing items of the MU investigations include, e.g., dipole radiation pattern measurements, turntable stability, CE stability, system frequency response, power coupling between probes, reflection level inside the chamber, and field synthesis. It was concluded that cable effect will distort the radiation pattern of the DuT and hence affect the results of the measurements. By the use of a choke/cartridge or ferrite-loaded cable, the cable effect can be minimised. Field synthesis measurements demonstrated the improved results with chokes/cartridges and ferrite-loaded cables. The polystyrene, used to support the DuT in the AAU set-up, introduces mechanical instability after movement. Non-flat frequency response of the OTA system can be introduced by the CE, termination of the cables (probe antenna) and mismatch between the components. Good agreement between the measured plane wave and the target plane wave both for the vertical and horizontal polarisations is obtained in the MM and ETS set-up. Sources of errors and uncertainties and probe coupling levels between neighbouring probes were addressed in Fan et al. [FCnN$^+$13] Barrio et al. [BFKP14] as well.

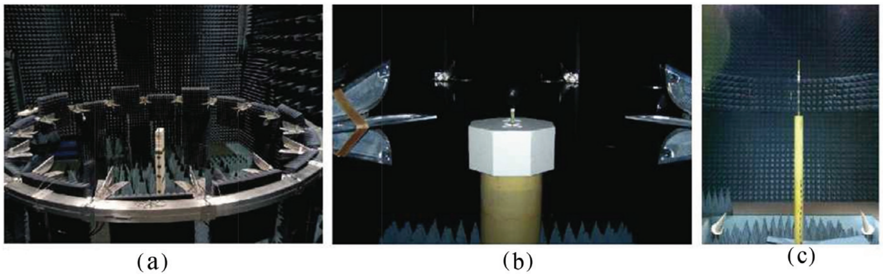

(a) (b) (c)

Figure 11.7 Three different MPAC set-ups, that of AAU (a), of Motorola Mobility (b), and of ETS-Lindgren (c).

A fundamental way of measurement system analysis is setting up assessment procedures under the Gage Repeatability and Reproducibility framework, of which an example for a specific MIMO OTA test set-up was given in Wu et al. [WCY$^+$12]. The advice, however, is that laboratories yet do not rely on GRR alone for assessment of set-ups.

The probes are often in the near field, and, importantly, there may also be scattering from the neighbouring probes. It is anticipated that these near-field and scattering effects will increase the uncertainties in the multi-probe testing. Therefore, it would be desirable to have a way to compensate those effects to generate fields identical to a plane wave in the test zone. The work in Parveg et al. [PLK$^+$12] proposed a calibration technique for partially compensating the near-field effects and scattering contributions from the neighbouring probes in 2-D MPAC system. The results show that both the near field effects and scattering contributions in the test zone can be partially compensated effects by using the proposed technique.

11.4.4.2 Validation of the emulated channel

The goal of the channel validation is to ensure that the created channels within the test area follow target channels in the practical set-ups, and hence, comparable testing results could be obtained among different laboratories. Validation of four domains of GBSC is required in 3GPP and CTIA, i.e., delay (PDP), temporal (temporal correlation or Doppler power spectrum), polarisation (cross-polarisation ratio), and spatial (spatial correlation or PAS) domains. The focus of PWS validation measurement was to check whether the measured complex field in the test area matches the target field.

For static PWS, good agreement between the measured and emulated field in the test area has been achieved for all the scenarios in Fan et al. [FCnN$^+$12, FCnN$^+$13, FSF$^+$14]. Similar correspondence was observed for the simulated and measured plane wave field for all scenarios outside the test area. Analysis of the results made it possible to identify sources of inaccuracies like DuT placement errors and cable effects resulting from bending. Several aspects of the PFS were subject of investigation [FCnN$^+$13, FCnA$^+$13, WCY$^+$13, SAG14]. An investigation of channel model validation in the MPAC set-up with a radius of 3.2 m and eight dualpolarisation probes was performed in Sun et al. [SAG14], where the characteristics of the channel environment emulated using different CE were measured and compared. Channel validation results for the single spatial cluster channel models are presented in Wu et al. [WCY$^+$13].

When estimating the PAS of the emulated channel with the PFS technique, one should realise that the emulated PAS at the Rx side is discrete, characterised by the angular locations and power weights of the active probes [FNP14]. In practical set-ups, knowledge on how the channel is emulated in commercial CE is very limited. Therefore, estimation of the discrete PAS can be used to verify how well the target channel is implemented in the test area. Beam-forming techniques on measurements on virtual arrays are proposed. However, direction of arrival (DoA) and power estimates are prone to inaccuracy due to low spatial resolution and side lobes. In Fan et al. [FNP14], the MUSIC algorithm was chosen for its high resolution. The power estimates based on DoA estimates match well with the target in the measurements. To improve accuracy and robustness in elevation DoA estimation, the use of an (virtual) array with large aperture in elevation too is recommended.

11.4.4.3 Actual OTA measurements

Data TP has been selected as the FoM in MIMO OTA standards to rank MIMO capable terminals, as it reflects the end-user experience. The Inter-Lab OTA performance comparison testing campaign of CTIA started in 2012, where the focus was on comparing results of the same methods in different labs. Extensive measurement campaigns have been performed in different laboratories and numerous results have been reported [KHNK11, IMU13, Iof14, CnFN^{+}13]. However, deviations in terms of TP in measurement results still exist among laboratories and explanations for the causes are not determined yet. There is a strong need to develop a TP simulation tool with reasonable accuracy, as it would give more insight into the test results and would help with eliminating systematic errors in measurements.

The TP performance of a commercial LTE mobile terminal, subjected to different channel models in practical 2-D and 3-D MPAC set-ups, was investigated in Kyösti et al. [KHNK11]. More specifically, GBSC models, e.g., IMT-Advanced, WINNER, SCME, and different single spatial cluster channel models were selected to evaluate the TP performance of the device. The DuT was evaluated with three different tilt angles. The measurement results indicate that the channel model has impact on TP performance. The 3-D channel model gives higher TP than the 2-D. Different multi-cluster models with the 2-D configuration have performance variation from 0.5 to 2.5 dB, while the single cluster model with different angular spread parameters with the 2-D configuration has more than 14 dB performance variation. It is also pointed out that DuT TP results over different tilt angles under the same channel model are different. Note that the DuT TP results over different tilt angles in RC are expected to be the same due to the isotropy of the channel.

11.4.4.4 Arbitrary spatial channel emulation

The MPAC method is known for its capability to physically synthesise arbitrary radio propagation environments under laboratory condition. 2-D GBSC, where the incoming power angular spectra of the channels are defined only on the azimuth plane, are targeted in PFS current set-ups. GBSC are generated based on sum-of sinusoids techniques, with each sinusoid characterised by its amplitude, Doppler frequency, and random initial phase. Although different in their synthesis approach, both synthesis methods are capable of equal performance, as shown by simulations [RBRH14, Kyö12], and have almost equal variation of ergodic capacity and equal time variance over random initialisations. Also, simulation and emulation are comparable for both methods times. Note that conclusions in Kyösti et al. [Kyö12] are valid in the single-polarised case only. When introducing a dual-polarised configuration, the matrix product of 2 × 2 random initial phase matrix and dual-polarised Tx (/Rx) antenna gain patterns will result in variant gains of rays, which will lead to a non-ergodic simulator [Obr13, RBRH14].

In general, three aspects of the radio field are to be considered in emulation, i.e., directivity or spatial correlation, polarisation properties, and 3-D field incidence (Section 11.2.7). With respect to the latter aspect, only 2-D standard channel models have been used in MPAC set-ups so far, as the channel models in standardisation are still 2-D. However, since long, from measurements is known that elevation spread cannot be ignored in many propagation environments [KLV$^+$03]. In order to evaluate MIMO terminals in realistic environments in the lab, it would be desirable that 3-D radio channels can be accurately reproduced in MPAC set-ups. However, costs, in terms of the much greater number of CE needed, become a major issue when an appropriate 3-D probe configuration is required [KK13b, KSLDG14].

The discussions on channel models in MIMO OTA standards concentrate on SCME channel models, i.e., on Rayleigh fading channel models.

On one hand, attempts are made to simplify the structure of the SCME models, in order to save on emulation hardware. The basic idea is to simplify the SCME sub-paths and then to evaluate the uncertainty resulting from this simplification [Szi11a, Szi11b]. For this, data TPs for the same complex antenna radiation pattern are compared between SCME and sub-sets of modified SCME channel models. On the other hand, a strong need is felt to include Rician channel models as well for lab-testing in more realistic environments. A novel technique is proposed to model the Rician fading channel models in the MPAC [FKH$^+$14], in which a LoS path with arbitrary incidence is possible and a NLoS component with arbitrary PAS shape can be modelled.

More specifically, the specular path is modelled using the PWS technique, with the scattering NLoS component modelled by the PFS technique. Simulation results showed that the reproduced Rician channels match very well with the target models, in terms of field envelope distribution, estimated K-factor, spatial correlation, and Doppler power spectrum. The emulated spatial correlation follows the target curve well up to $0.71\ \lambda$ distance and deviates after that. Replaying ray tracing simulated channels in the MPAC set-ups was brought up in Llorent et al. [LFP15]. MIMO OTA performance testing requires devices to be tested under realistic channel conditions. Standard channel models such as SCME or WINNER aim at modelling environments that are generic, representing defined general channel conditions, e.g., urban, suburban, rural, or indoor environments. As an alternative, replaying field measurements or using ray tracing models would result into more realistic models since they are site-specific. Ray tracing simulations of an urban environment with LoS and NLoS conditions are used in Llorent et al. [LFP15] to obtain the complex amplitudes of rays that subsequently are to be emulated in a MPAC set-up using PWS. An evaluation of simulated fields promised high accuracy both for an arbitrary ray and for the total received field.

11.4.5 Other Applications

The main driver for MIMO OTA research up to now has been the radiated performance of small cellular mobile UE, like handsets and laptops. But, there are many more radio systems that depend on interaction with the EM environment in which they operate, not all necessarily radio communication systems. Often they share with cellular systems that they operate in Multi-User environments with the resulting (directional) interference. In those cases, OTA testing can be well applied, as its essence is emulating the (system-) relevant properties of the system's radio environments. In this context, the expression virtual electromagnetic environment (VEE) has been coined [SKL^{+}13]. Radio systems not primarily intended for communication are, e.g., radio location and positioning systems that observe their environment mainly from the directional/angular spectrum point of view. Then, installed performance can only be tested OTA. The same is true for cognitive radio (CR) systems whose operational environment is characterised by the (time-variant) interference that normally also shows directionality [SKL^{+}13]. Note that truly emulating interference is likely to be the next step in MIMO OTA for cellular mobile UE too. Intelligent transportation systems (ITS) like ITS-G5 with their road/user-safety relevance are thought to be interference-prone when massive deployment is reached. With ITS G5 installed on cars, OTA installations necessarily become big and TU Ilmenau had to build a separate, large MPAC facility for vehicular OTA applications [HBK$^+$15], in connection with C2X-research, which will have real-time connections with other testbeds on the campus. The goal is creating a large VEE for communication with an operational vehicle, virtually driven by a human driver through a defined, virtual, traffic environment while subjected to generic traffic scenarios. Coherent synthesis in the MPAC is unachievable, though, as the test objects, cars, have largest dimensions of the order of 100 wavelengths at 6 GHz, for example. Therefore, simpler approaches are taken elsewhere too, as in Nilsson et al. [NAH$^+$13].

11.5 RC Method

The RC can be used for OTA measurements [WB10, Che14b]. A typical measurement set-up is depicted in Figure 11.8. Detailed descriptions on the theory and operation of RCs can be found in Hill [Hil09].

Any lossy objects present in the chamber, including the building material of the chamber itself, antennas, and microwave absorbers, will load the RC cavity. Thus, when the RC is excited by an antenna in the chamber, it decays exponentially [DDDLD08]. This decay is usually described using the RMS delay spread (DS). The RMS DS can be decreased by adding lossy material inside the chamber. The size of RCs used for OTA testing typically have an inherent RMS DS of 200 ns without any added microwave absorbers.

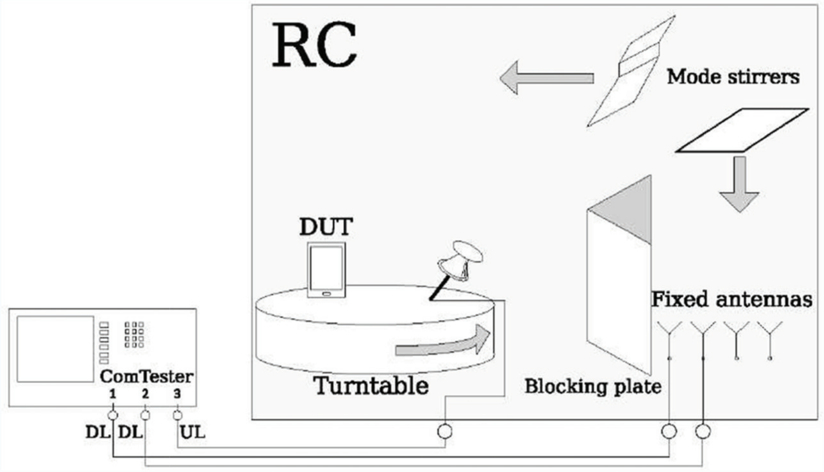


Figure 11.8 Typical set-up of an OTA measurement using an RC.

A decrease in RMS DS corresponds to an increase in coherence bandwidth. The spatial receiving characteristics are cumulative isotropic, meaning that isotropy is achieved only after completing the full measurement sequence. The field in each mode stirring position is not isotropic. Channel properties of RC are discussedin Skårbratt et al. [SLR15] and Kildal et al. [KCO^{+}12].

11.5.1 RC as An OTA Measurement Environment Extended Using a CE

For advanced multi-antenna Rxs the RC can be complemented by a CE to provide testing in more complex channels. This set-up is depicted in Figure 11.9. The receiving spatial properties of the RC are not affected by the addition of a CE. The temporal properties of the measurement set-up can be further controlled by the addition of a CE. DS profile, fading statistics, and Doppler spread can be modified. Also the BS antenna correlation, as seen by the DuT Rx, can be changed by modifying the BS correlation using the CE. The channel properties of the RC test set-ups are further elaborated in Skårbratt et al. [SLR15].

The total downlink MIMO channel experienced by the communication system when using both an RC and a CE can be described by

$$\mathbf{r} = \mathbf{H}_{\mathrm{RC}}\mathbf{H}_{\mathrm{CE}}\mathbf{s} + \mathbf{n}, \tag{11.2}$$

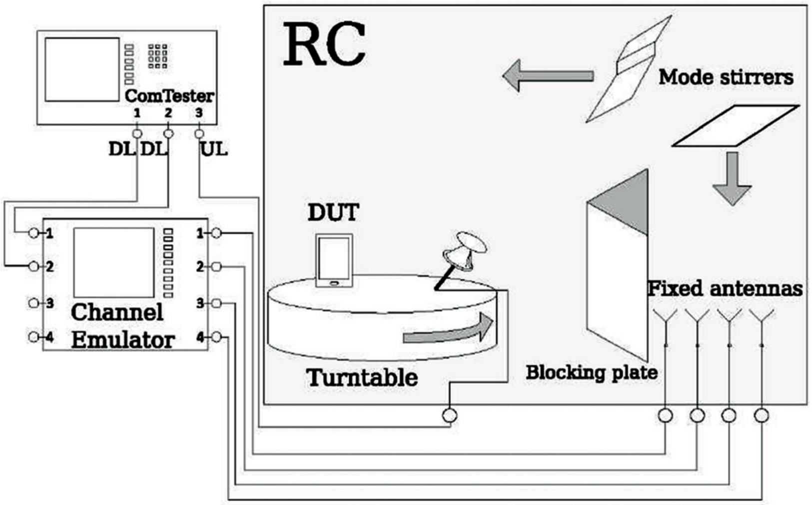


Figure 11.9 Typical set-up of an OTA measurement system using an RC complemented with a CE.

where $\mathbf{H}_{\mathrm{RC}}$ represent the channel matrix of the RC and the DuT and $\mathbf{H}_{\mathrm{CE}}$ the channel matrix of the CE and the communication tester; **s** and **n** are the signal and additive noise vector, respectively. The RC creates a Rayleigh faded environment due to the stirrers moving in the chamber. Often Rayleigh fading is also enabled in the CE. Due to the cascading of these two according to Equation (11.2), the DuT Rx experiences a double-Rayleigh faded signal. This can be mitigated by using multiple antennas, independently faded between the CE and the RC. This increases the richness of the MIMO channel and makes it behave closer to regular Rayleigh fading (see Skårbratt et al. [SLR15]).

11.5.2 Common RC Channel Realisations

The most commonly used channel models for the RC+CE set-up are the short delay low correlation (SDLC) an long delay high correlation (LDHC) channel models, see 3GPP [3GPP14b], even though other channel models can be realised as well (see for example Skårbratt et al. [SRL15]). These are based on the SCME UMi and UMa channel models [BHdG^{+}05], but modified to be realisable in an RC environment with the average isotropicAoA.

As a complement to these, the National Institute of Standards and Technology (NIST) model exists, described in 3GPP [3GPP14b]. The NIST model does not require a CE to be realisable in an RC, which can be favourable for some applications due to the lower complexity of this test set-up. As an example, this test set-up does not require phase calibration for stable measurements, which has been shown to be a significant source of uncertainty for methodologies including a CE. More detailed discussions about the NIST model canbe found in Matolak et al. and Remley and Kaslon [MRH09, RK13].

11.5.3 LTE Measurements in the RC Test Set-ups

The testing of LTE UE revealed a number of separate issues, related to the LTE system and the test methodology.

When testing LTE devices with a CE augmenting the RC, it is important that the output phase from the communication tester is calibrated to the CE. The problem is illustrated in Figure 11.10, where different phase offsets cause the TP to vary significantly [SLR15]. However, as it relates to the definition of the channel models (Section 11.2.10), this is not only an issue for the RC method.

The UE total isotropic sensitivity (TIS) depends on the fading conditions. It might be appropriate to define a new TIS measurement to handle the wideband signal and different MIMO technologies incorporated in the LTE standard. No conclusions were drawn on how this procedure should be defined.

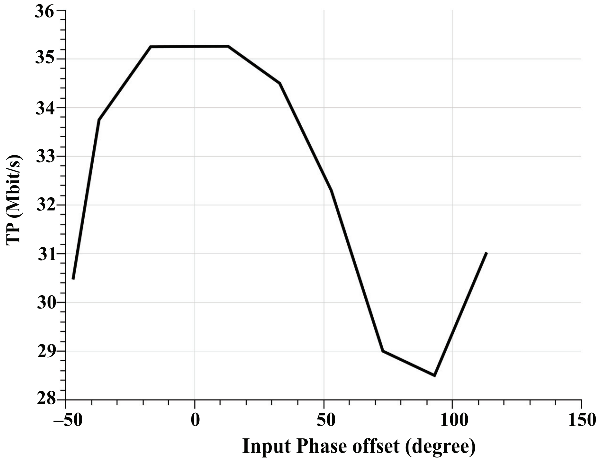


Figure 11.10 TP variation as a function of input phase offset for a DuT with LDHC as channel model.

For example, CTIA is considering to replace the existing TIS test with transmission mode 2 (TM2) TP testing, since this is considered a more realistic test due to the included fading properties of the channel models used for the testing. This is further discussed in Arsalane [Ars13].

Regarding ranking LTE UE based on TP, it was found that SDLC, LDHC, and NIST more or less agree on UE ranking when using the 50% TP level [PF11b]. Repeatability and reproducibility are reported to be within 0.5 dB of the measurements when using an RC.

During the testing of laptop LTE modems, influences of the host laptop on the dongle-under test were noticed [PF11a]. In order to prevent such influences from affecting the testing, a laptop phantom is required to yield repeatable and accurate results. Such a laptop phantom was later developed and standardised in 3GPP [3GPP12].

The use of adaptive modulation for OTA testing LTE UEs was investigated. It was found that in an RC, adaptive modulation gives the same device ranking as using the fixed modulation and coding scheme (MCS) [SRL15]. However, while good devices rank similarly when using adaptive modulation, the bad device performed even worse using adaptive modulation compared to the fixed MCS.

11.6 Two-Stage Test Method

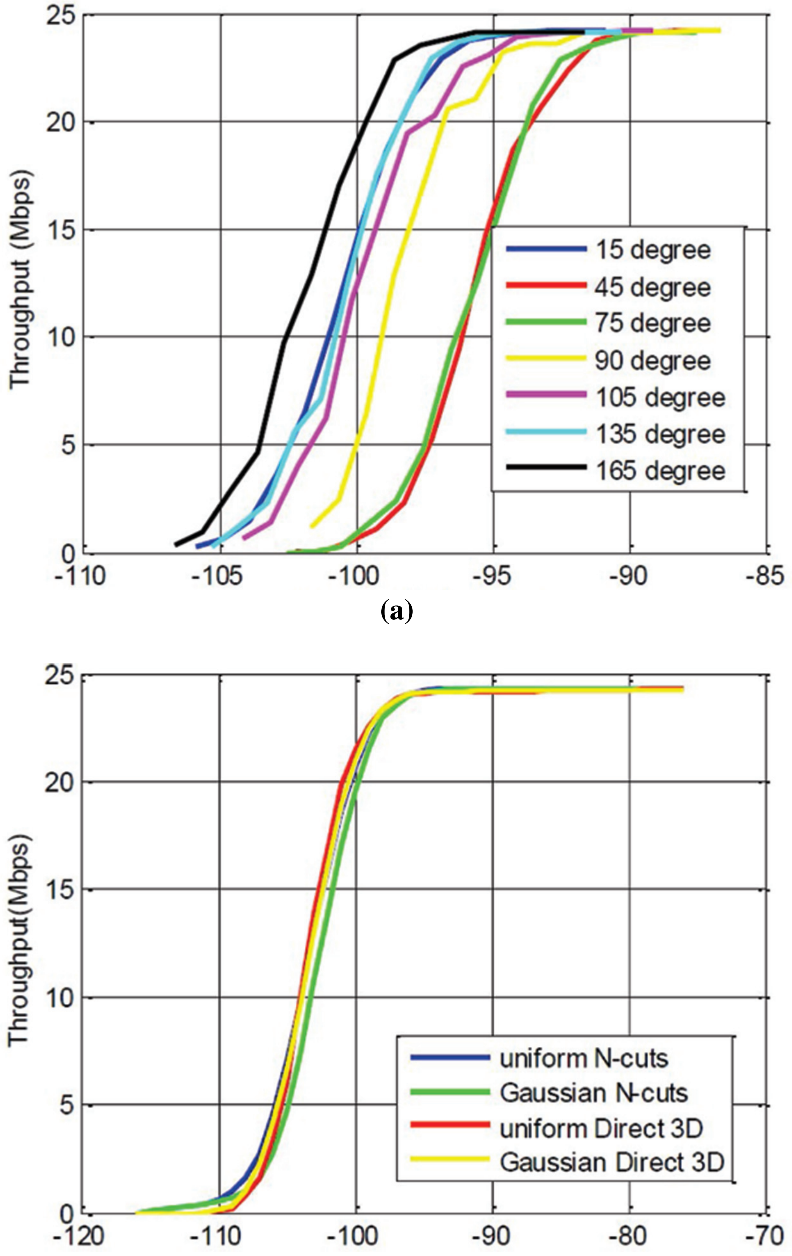
For an overview of the two-stage MIMO OTA test method, refer to Sections 11.2.3 or 6.3.1 of 3GPP [3GPP14b].

11.6.1 UE Antenna Pattern Measurements Proof of Concept

In order to avoid cumbersome and possibly biased measurements of UE antenna patterns at the UE antenna ports by the use of external equipment, the definition of a standardised UE-internal measurement routine was proposed, the UE antenna test function (ATF). As proof of concept of the ATF, patterns of reference dipoles measured using the ATF and by the traditional passive approach were compared [KJZ11a]. The relative accuracy and linearity of UE-measured antenna amplitude and phase was seen to be <0.1 dB from –30 to –60 dBm and 1° at –50 dBm. The channel capacity resulting from the antenna patterns measured by passive and active ATF methods were similar with $<2\%$ difference in channel capacity at 25 dB SNR, thus proving the principle of the two-stage test method. A similar procedure was performed on real (hence unknown) antennas of two commercial universal serial bus (USB) LTE dongles [KJZ11b]. One of the dongles was modified to enable traditional passive antenna pattern measurement and for the other, unmodified, device of the same type the active ATF approach was used. TP was measured (using the conducted second stage approach) to show consistency. A channel capacity simulation based on manufacturer-provided theoretical antenna patterns was also performed to cross check with the TP test results. It was shown that the two-stage MIMO OTA test method can rank the antenna performance correctly. The measured test results aligned with the antenna channel capacity simulation results once the differences in conducted performance between the dongles were taken into account.

11.6.2 Study of 2-D versus 3-D Device Evaluation

To investigate the differences in MIMO OTA performance using 2-D and 3D evaluation fields, the variation in performance of a UE in a 2-D field at different elevation angles was determined [JZK12]. As the elevation angles were independent of azimuth, the 2-D incident fields were defined on conical surfaces. The analysis found an 8 dB variation in performance. Furthermore, a model was proposed to use the capability of the two-stage test method to emulate 3-D fields and it was shown that the performance from a single 3-D field equalled the average performance from 10 (conical) 2-D cuts as shown in Figure 11.11. The conclusion was that UE orientation relative to the field is important and that a single 2-D cut is not sufficient to determine total performance [JZK12]. Further analysis of reference antenna performance over different 2-D elevations was carried out with band 13 reference antennas [Jin12a]. This showed a smaller variation of 5 dB than the device with real antennas used in the study of Jing et al. [JZK12].



(a)

(b)

Figure 11.11 Variation in UE performance for different 2-D cuts and comparison of averaging ten 2-D cuts with a single 3-D measurement using the two-stage method. Along the abscissae, received power in 15 kHz bandwidth [dBm].

11.6.3 Limitations of the Conducted Second Stage with UE Desensitisation

A limitation of the two-stage method using the conducted second stage is that UE self-desensitisation is not measured since the UE antennas are disconnected at the temporary antenna connector. One method to overcome this limitation the use of UE-based noise estimation (Iot, [3GPP15]) was studied [Jin12b]. This analysis showed that it was possible to very accurately measure UE self-interference with reference signal received quality (RSRQ) measurements. This measurement of Iot can then be added back into the conducted second stage signal TP measurements to get the same overall results as would be seen using a fully radiated approach. However, a better solution to the limitation of the conducted second stage was later developed by using a radiated second stage, as described in Rumney et al. [RKJZ15], see Section 11.5.4.

11.6.4 Introduction of the Radiated Second Stage

An alternative approach to that taken in Jing [Jin12b] to correctly measure device desensitisation was developed, known as the radiated two-stage method and described in [RKJZ15]. This development means that the radiated desense is now fully covered by the two-stage method, overcoming the limitations of the conducted second stage approach. A further advantage of the radiated second stage is that the calibration method used for the radiated second stage means that the absolute accuracy of the UE measurements from the first stage pattern measurements does not contribute to the overall accuracy of the two-stage method. The only requirement on the UE is that the ATF measurements used to build the antenna pattern are monotonic over a give power and phase range. When monotonicity is fulfiled, the test system can fully validate, and if necessary linearise the measurements against test signals of known accuracy.

11.6.5 Formal Definition of the Two-Stage ATF

The formal definition of the ATF measurements was specified in 3GPP TR 36.978 [3GPP14a] and described in Rumney et al. [RKJZ15]. The TR defines two ATF measurements, reference signal antenna power (RSAP) and reference signal antenna relative phase (RSARP). In addition, a layer-3 signalling protocol is defined enabling the test system to query the UE antenna attributes without relying on proprietary UE interfaces as has been the case to date. The ATF message definition includes two important aspects for future flexibility, firstly, the number of UE receive antennas is a reported parameter enabling up to 8 RSAP and RSARP results to be reported, and second, the carrier number is specified in the request message making the ATF extendible to the use of arbitrary numbers of channels for carrier aggregation.

11.7 Two-Channel/Decomposition Method

11.7.1 Introduction

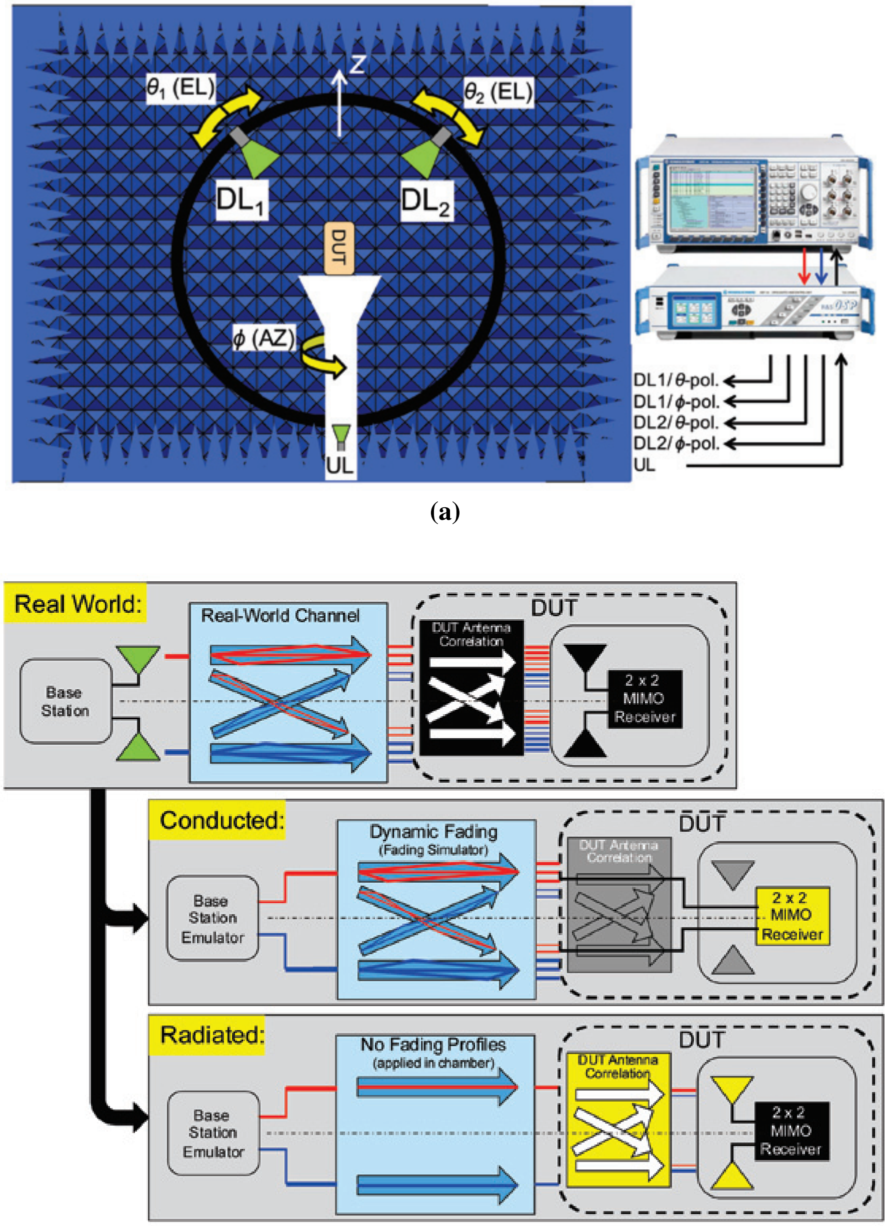
In this Section, 2 × 2 down-link (DL) MIMO OTA testing is addressed from the point of view of commercial testing of UE. Consequently, it strives for MIMO OTA metrics that can unambiguously be related to physical attributes of a DuT and for measurement procedures that are simple and of high reproducibility. The name "Decomposition Method" relates to the fact that the proposed radiated measurements focus on performance and spatial properties of UE antennas. Other properties of the UE can also be measured in conducted testing. "Two-Channel Method" is motivated by the fact that the relevant physical attributes of a DuT are characterised in measurement set-ups where two data streams from the evolved Node-B (eNB) are mapped to two measurement antennas (probes). In a later stage, this measurement method was enhanced to a test plan named "Decomposition Method", comprising a part that focuses on performance and spatial properties of UE antennas and a part that focuses on Rx performance under conditions of a fading channel, as described in the second paragraph of this subsection.

The most comprehensive summary of ideas behind the two-channel method, its theoretical foundation, and its development up to the year 2012 can be found in Feng et al. [FSvG$^+$12, Fen13, BvGT$^+$11, FJS11].

The basic set-up can be seen in Figure 11.12(a). Two dual-polarised test antennas can be set to arbitrary elevation angles in a plane around the DuT. A turntable allows changing the azimuth of the DuT. The test antennas are fed from an eNB emulator via a switching unit that allows selecting freely the polarisations of the test antennas. Each selected azimuth and elevation setting together with the chosen polarisations is named a "constellation". While varying the DL power level, the observed TP is recorded. For the up-link (UL), an independent communication antenna is used.

11.7.2 Two-Channel Method

This approach focuses on characterisation of the performance of UE antenna systems that can only be tested OTA. It nevertheless qualifies the DuT as a whole. Selecting a channel model out from an infinite choice hardly is reproducing reality. Following established engineering practice, the goal is, therefore, to isolate the very properties of the DuT. Second, state-of-the-art



(a)

(b)

Figure 11.12 (a) Test set-up for two-channel method; (b) Decomposition elements.

mobile communication standards such as LTE are highly adaptive. The MIMO TM in particular is adaptively switched between, e.g., DL transmit diversity (TD), open-loop spatial multiplexing (OL-SM) and closed-loop spatial multiplexing (CL-SM) based on current channel state information. Likewise, the MCS is permanently adapted to the current channel conditions. It is, therefore, not meaningful to subject UE to arbitrary channel conditions unless an eNB emulator is also employed that fully supports the adaptive features of the standard. Still then, the adaptation rules used by the eNB emulator, that are not standardised, would enter into the UE test result. These and further fundamental aspects of MIMO OTA testing were discussed in Schroeder and Feng [SF11, STFvG13].

The two-channel method, therefore, builds on two complementary test cases and associated metrics that are in agreement with requirements for the DL TD and the OL-SM MIMO TMs, respectively, and with the use of fixed reference channels (FRCs). A detailed overview of the overall test plan was given in Böhler et al. [BvGT$^+$11].

The first test case evaluates isotropic sensitivity in DL TD mode for a noise-limited scenario. The test set-up is similar to a conventional TIS measurement with the difference that the two orthogonal copies of the DL transmit signal are mapped to the two polarisations of a dual-polarised horn antenna. Results are reported in terms of a cumulative distribution function (CDF) of sensitivity over all AoAs realised by the probe. As shown in Feng et al. [FSvG$^+$12, Fen13], the test evaluates the impact of the UE antenna system on first order channel statistics and includes Rx sensitivity as well as self-interference. It is noteworthy that this test fully qualifies diversity performance independently from the number of UE antennas and that the significance of the result could not be improved by adding additional test antennas carrying further de-correlated or faded copies of the DL signals. Detailed analyses were presented in Feng et al. [FSA$^+$11, FSK12].

The second test case evaluates SM performance in the high SNR regime. It is applied in OL-SM TM (for which FRCs are defined). The test set-up is extended by a second dual-polarised horn antenna whose angular position relative to the first can be varied independently. Outage power levels relative to a given block-error-rate (BLER) for a high-order MCS are recorded over a set of constellations. As shown in [FSvG$^+$12, Fen13], the test fully qualifies the SM performance of a UE with two antennas mainly influenced by the antenna correlation. The complementary cumulative distribution function (CCDF) curves for a given DL power level show clear differences for the various combinations of incoming polarisations.

A RAN4 round robin campaign with LTE USB modems allowed to do more tests with different constellations [BvGT$^+$11]. For example, in order to compare more easily with the results of other methodologies, a subset of geometrical constellations representing a 2-D plane was analysed.

The two-channel method is characterised by its simple set-up. In a comparison exercise, asmart phone was tested in similar ways in a large reference chamber, in a compact test chamber (R-Line), and in a desktop anechoic chamber (DST200). With some limitations in the constellations that can be used, each of the three environments correlated well with the others.

11.7.3 Decomposition Method

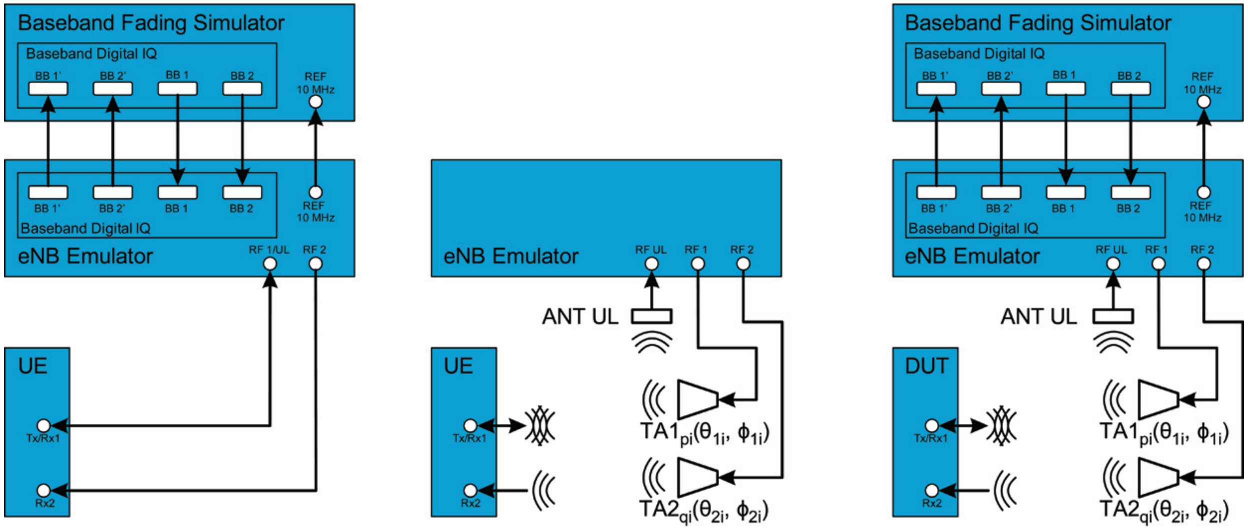
The set of tests in the decomposition method consists of a conducted measurement without channel impairment, a conducted measurement with channel impairment, and a radiated measurement using the 144 constellations mentioned earlier. The channel models used for the channel impairment are based on the SCME models UMa and UMi, with the exception that the spatial aspects are not included. The channel impairment is applied in a conducted test where no spatial information is used. The constellations used in the radiated test comprise sets of different elevation, azimuth, and polarisation settings for each of the two test antennas. Figure 11.12(b) shows the elements of the decomposition method, Figure 11.13 indicates the hardware set-ups.

The conducted test with channel impairment assesses primarily the MIMO Rx. Tests with UMi or with UMa channel models give quite different results. The radiated test without channel impairment, on the other hand, evaluates primarily the MIMO performance of the antenna system.

CTIA organised another Round Robin test in which two smart phones operating in bands 7 and 13 were tested. In addition, the downlink signals carried an additional noise contribution for some of the tests, resulting incurves of TP versus SNR.

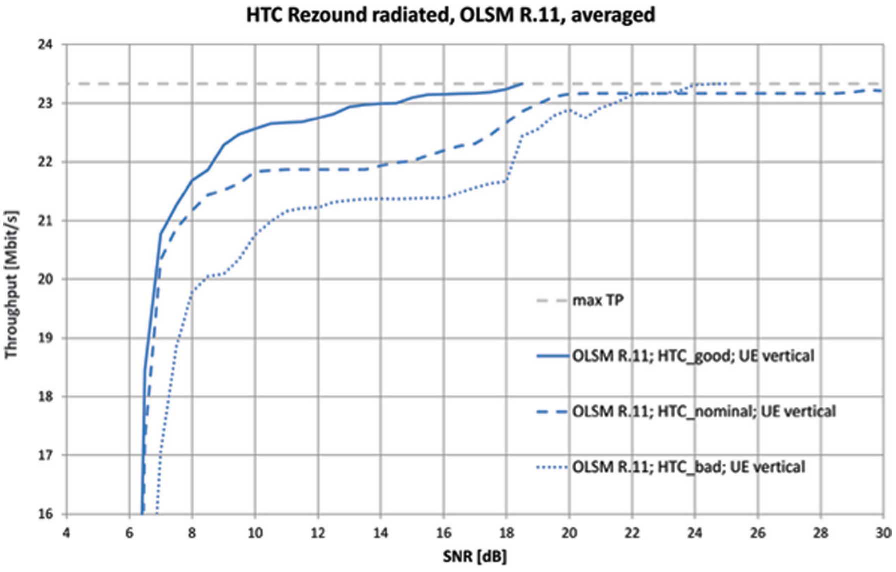
The results of the decomposition method for band 13 show a variety of interesting aspects. In a first test campaign, the elevation and azimuth angles were taken from a grid with 30° spacing, as in earlier testing. As can be seen in Figure 11.14(a), the three different reference antenna systems can clearly be distinguished. More background information and additional results can be found in Rohde and Schwarz [Sch12a, Sch12b].

Another selection of 128 constellations, based on phyllotaxy (“growth pattern constellations”) with an optimised distribution, was used in a subsequent measurement. No additional noise was injected. Figure 11.14(b) shows the final result obtained with the decomposition method for UMi channel models.

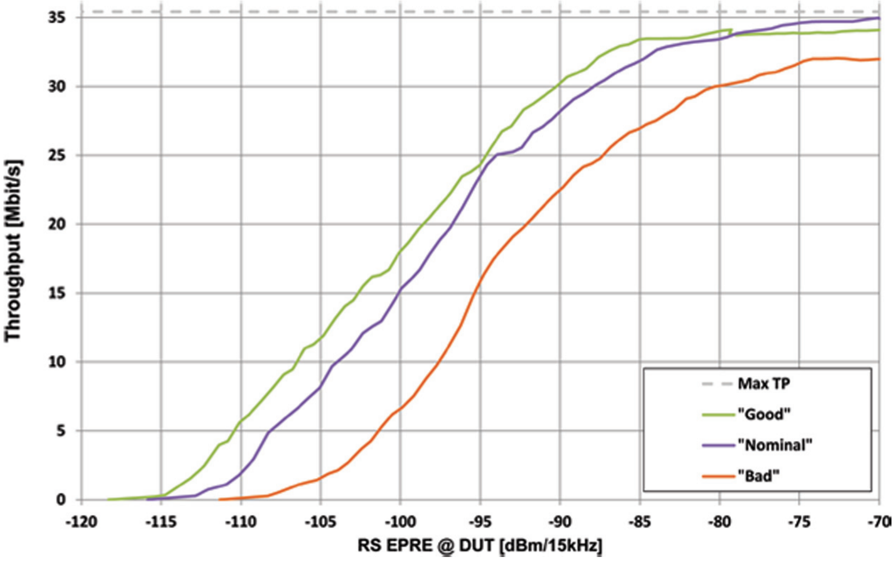


(a) **(b)** **(c)**

Figure 11.13 Set-up for decomposition method; (a) conducted part; (b) radiated part; and (c) radiated part with fading.



(a)



(b)

Figure 11.14 (a) Radiated TP, OL-SM R.11, averaged over 144 constellations; (b) Decomposed TP curves for UMi channel model.

The TP curves for UMa channel models are identical in shape, but with a shift of 2dB towards lower sensitivity.

A further extension of the decomposition method comprised, instead of applying the faded environment in a conducted test, moving this step to a radiated test as well [TvG14]. Figure 11.13(b) depicts the extension into faded radiated measurements. This way, the faded measurement can also be applied to a UE that does not carry any external connector. The agreement of results using either method was very good.

In order to underline the validity of the decomposition method, system level simulations using the simulation software SystemVue were performed for one of the CTIA Round Robin reference antennas as UE antenna. The results with different geometrical constellations show good agreement with measurements, especially when the condition number of the channel matrix is small [ATG$^+$13].

11.8 OTA Field Testing

11.8.1 Evaluating Low-Cost Scanners as Channel Measurement Devices in LTE Networks

Radio channel measurements using specialised multi-dimensional channel sounders offer good resolution and high accuracy which is beneficial for exploratory research, however the down-side is their cost and complexity. A cheaper and quicker alternative is using commercial channel scanners typically used in drive-test campaigns by operators. Some of these scanners can optionally be enabled for low-layer channel sampling, and they typically support two antenna ports. By using the network BSs as Tx sources, the need for a dedicated Tx and test licences to utilise the frequencies are eliminated. This also means that tests done using scanners reflect real operating environments. The resolution, however, is limited to the system parameters of the standards.

An evaluation of scanners for channel measurements has been conducted with a laboratory set-up as well as a field test [KK13a, KKJ14]. The study was performed using an LTE signal on band 3 (1800MHz). In the lab, the bandwidth was 10 MHz at 1842.5 MHz, while in the field, the bandwidth was 20 MHz at 1815 MHz. In the lab, a communication tester and fading emulator with different reference channel models were used, as shown in Figure 11.15.

The field measurements were done on a live LTE network with a number of BSs covering a closed route in the Oulu Technopolis area in Finland. Tests were done using both two omni directional orthogonally polarised antennas separated by one wavelength and directive Vivaldi antennas [AZW08, SS11].

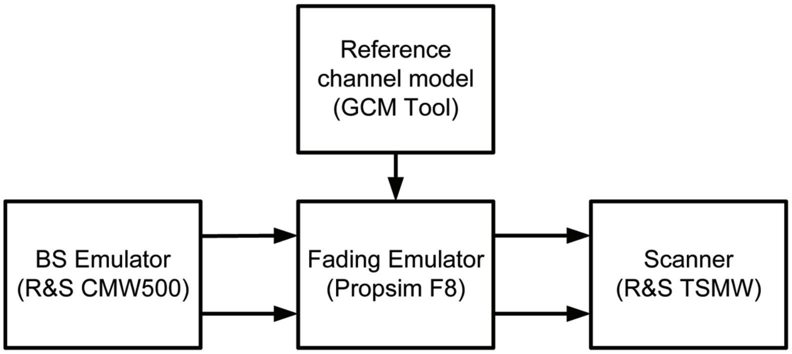


Figure 11.15 Set up of the laboratory measurements.

The data was analysed with respect to the frequency response, path loss, PDP, Ricean K-factor, Rx polarisation factor, and antenna correlation.

Path loss can be almost exactly estimated in the laboratory; however, in the field, this requires knowledge of the BS power. Still, the relative dynamic variation of path loss and shadowing can be measured. Similarly, only excess delays can be estimated in the PDP measurements, since the absolute delay is unknown. In measuring the PDP, estimations of fixed paths are quite accurate, less than 1 dB, however, dynamic delays are difficult to capture, most likely due to averaging over time and distance. The Ricean K-factor measurements show a good match as long as the reference K-factor is above 3 dB with a maximum deviation of roughly 4 dB. For lower K-factors the deviation increase, and in general dB-negative K-factors are difficult to estimate. Rx polarisation power ratio estimates follow the trend in the reference model, ranging from –16 to 11 dB. The scanner capability limits the estimation accuracy of the antenna correlation, mostly due to phase offsets between the elements of the frequency response matrix.

A comparison of the laboratory and field Rx power measurement was done using a field scanner measurement from a single BS link and an OTA radio channel emulation based on the same field measurement [KK13a]. Directional measurements include multiple cells, showing that the distribution of power in azimuth is not uniform. The variation is between 9 and 22 dB for nine different locations. The variation of the V/H XPR ratio is in the range of –8 and 13 dB and was measured directly using the two elements (±45° slant) of the directive Vivaldi antenna. The maximum excess delays of the PDP varied between 0.45 and 3.67 μs, which fits the 3GPP urban and macro channel models of 3GPP [3GPP14b]. As in the lab, the initial delay in the field cannot be estimated.

Scanner measurement and the corresponding analysis set-up can be utilised to create measurement based and site specific MIMO OTA channel emulations. By sampling a measurement route with a number of static locations, the extracted parameters can be utilised to generate fast fading inside an anechoic chamber with proper characteristics. The propagation parameters may be interpolated between locations or preserved constant. Overall Rx power level and PDP are obtained from the measurement with omni directional antennas. Angular power distributions and Rx XPR are captured with the directional antenna. Doppler spectra can be modelled with a synthetic model or Doppler shifts can be approximated based on the PAS and the selected velocity vector. All the necessary parameters for a measurement based MIMO OTA testing are available from the proposed set-up.

11.8.2 Measuring User-Induced Randomness for Smart Phones

An effect, that is not automatically included in OTA testing, is the randomness due to the user. Pure LoS and rich multipath (RIMP) environments are rarely present in real-life. Real-life environments will most likely show a mixture of LoS and NLoS conditions rather than one or the other. Further, introducing the user randomness means that the LoS component becomes 'random-LoS' due to the user [Kil13]. It means that the LoS experienced by a mobile terminal becomes completely random due to its random position and orientation with respect to the BS, as shown in Figure 11.16.

In real life, this randomness of the phone orientation is not known. One approach to estimate this is to use modern smart phones that all contain sensors providing information about the phones orientation in 3-D as well as sensing proximity to, e.g., head. Together with location information and different signal level and quality measurements, user-statistics could be produced. A smart phone application (app) can be be used to collect such sensor and radio

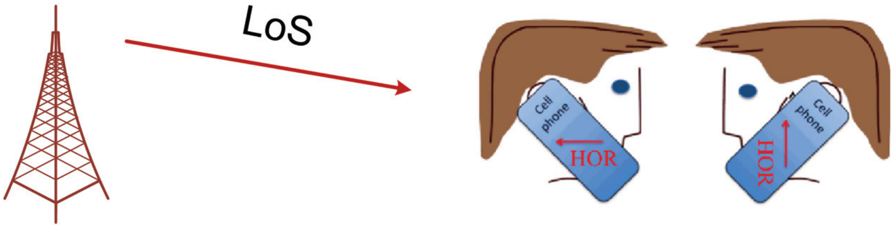


Figure 11.16 Illustration of random orientations of a wireless user device.

information data from a number of devices in daily use. Some of the available and relevant sensor data which can be easily retrieved on most smart phones are rotation, acceleration (linear and rotational), proximity, and location. Additionally, it is possible to retrieve some of the radio measurements, like received power and SNR.

Actually, more specific measurements would have been advantageous, especially more in-depth data on the RF link as defined by 3GPP. One example are measurement reports on channel state information related to MIMO for LTE, like the rank indicator (RI) and the precoding matrix indicator (PMI). However, this would require more in-depth access to the phone software than is possible using commercially available phones. By combining information from local sensors, network information, and signal quality, it is possible to find out whether user behaviour influences link quality and if so, how the correspondence is.

Data from a limited number of phones, collecting measurements over a period of more than 2 months, were analysed with respect to the phone orientation angles, pitch, roll, and azimuth [LMG$^+$15]. The pitch and roll are tilt angles, while azimuth is the rotation relative to magnetic north.

One immediate observation is a high peak around 0 degree for the pitch and roll, which means the phone is lying screen up on a horizontal surface. This is to be expected since phone applications do a lot of background data traffic without user interaction, and in those cases, the phone is often lying on a table or another horizontal surface. More interesting is the behaviour in voice mode where the early test measurements in normal usage show trends of typical rotations of the phone in voice mode [LMG$^+$15], however, much more data from a larger population are needed to draw any conclusions.

11.9 Discussion and Future Work

Even after the successful standardisation of OTA testing of SISO mobile terminals, the development of methods for multi-antenna devices proved to be a difficult one. Even though not all four proposed methods will make it into the standard, that does not mean the research effort into these methods is wasted, especially not while the respective research teams have contributed to the general understanding of the problems involved. Over the last 4 years, the process underwent a steep learning curve, in which first the influence of the antennas of the test objects had to be eliminated by the use of the CTIA reference antennas, then seasoned experts found themselves confronted with, among others, how to define the SNR of test signals or how to average measurement results. At the moment of writing, not all issues with the definition of the general measurement set-up are solved. Although looking forward to a successful completion of this standardisation process, most will agree it is just the first step. For instance, LTE, the most adaptive radio communication system in history, will be tested in stationary environments without any temporal evolution of large-scale effects and with its adaptation mechanisms switched off. Besides, the time-variant transmission channels are abstract models in two dimensions and the test set-up is that of a typical single-user link with infrastructure (interference represented by AWGN), at present only in DL.

Ahead lie enhancing the degree of realism of the test environments, with 3-D channels whose large-scale effects naturally evolve over time. Then, the operating point of test objects will be much closer to that in reality and technological advances like adaptive antenna systems or smart Rx algorithms/structures can prove their added value. Carrier aggregation will be a challenge for channel emulation, as will be multi-user environments and bi-directionality. Related to multi-user aspects are coexistence/interference issues between systems, of which operation of LTE-wireless local area networks (WLANs) in unlicensed bands at 0.7 and 2.6 GHz is one example. Another is coexistence between dedicated short-range communications (DSRC), ITS-G5, and WLAN at 5.8 and 5.9 GHz. Bi-directional multi-user environments are also important for other devices than those communicating with infrastructure, for instance, for adhoc network nodes in peer-to-peer communication (D2D, V2X) in which "uplink" and "down link" are meaningless terms. Furthermore, reactions to incoming messages are not necessarily directed towards the original sender(s). Just as challenging as these distributed communication partners is testing of devices with distributed antennas. It is expected that these subjects will become pertinent in 5G systems, that obviously will pose some other challenges. Certainly, there will be new physical layer and network concepts of which we should expect extremely wideband transmissions (apart from carrier aggregation) and migration into SHF and EHF bands, with many interworking issues. With the tight time schedule for 5G, it is foreseeable that testing of 5G BS will become pertinent in the next 4–5 years.