Over-the-Air Testing of MIMO-Capable Terminals

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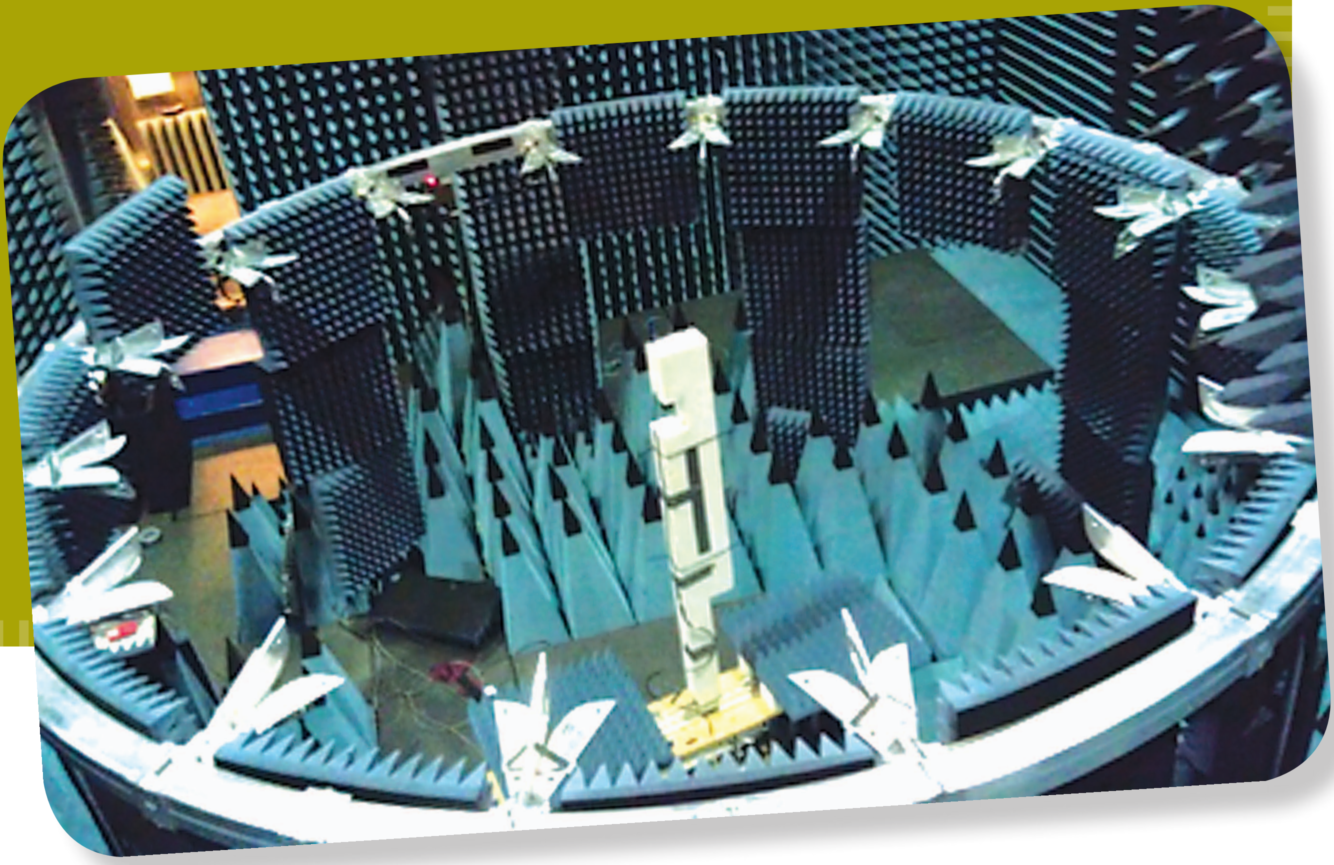

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A new over-the-air (OTA) testing method is required for evaluating multiple-antenna systems in realistic multipath propagation environments. Antenna design and propagation channels are the two key parameters that ultimately determine the multiple-input, multiple-output (MIMO) device performance. As antennas are inherently included in OTA testing, it is important to also consider realistic channel models for MIMO device-performance evaluation. This article shows that the multiprobe anechoic chamber (MPAC) setup is capable of emulating realistic and accurate multipath environments, making it a suitable method for testing terminals equipped with multiple antennas. In comparison to the mode-stirred reverberation chamber (RC) setup that represents an isotropic multipath environment, the MPAC method is capable of generating arbitrary spatial channel models with polarization characteristics.

This article addresses some of the key aspects associated with MPAC systems, such as methods to reproduce spatial channel

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models with desired temporal and spatial characteristics with a limited number of probe antennas, measures to determine the test-area size with a limited number of probes, and the existing challenges with MPAC methods. A state-of-the-art review on current research is given as well.

MIMO Terminal Testing

MIMO Terminal Performance Testing

MIMO technology uses multiple antennas at both the transmitter (Tx) and the receiver (Rx) side. Compared to single-antenna systems, multiple-antenna systems are more attractive and promising due to their capability to improve the system performance, e.g., data capacity and transmission reliability. New wireless technologies such as long-term evolution (LTE), LTE-advanced, 802.11n, and worldwide interoperability for microwave access have already adopted multiple antennas on mobile terminals. Cellular operators and mobile manufactures urgently require standard testing methods that are suitable to evaluate the radio performance of MIMO-capable terminals. For cellular operators, poor terminal performance might result in bad coverage or low-data-rate connections, which might force cellular network operators to install more expensive base stations. Furthermore, a priori knowledge of the radio performance of MIMO devices before massive rollout in the network is important for network operators. As for wireless device manufacturers, a performance evaluation is mandatory before product release.

OTA Testing for Single-Antenna Systems

Also called *radiated testing*, OTA testing is performed without cable connection to the device. Therefore, there is no need to break or otherwise modify the device. OTA testing for single-antenna systems has been standardized for more than ten years, where figures of merit (FoMs) such as total radiated power and total isotropic sensitivity are selected to characterize single-antenna performance [1]. For single-input, single-output (SISO) OTA testing, a nonfaded line-of-sight (LOS) path is generated from a probe antenna to a device under test (DUT) in an anechoic chamber. However, these FoMs are only antenna gain-related parameters and are not sufficient for characterizing the performance of MIMO-capable terminals [1].

As for antenna designers, propagation channels are often neglected for the design of single-antenna systems since their focus is primarily on antenna efficiency. However, for multiple-antenna systems, the performance is determined by the antenna design and the propagation channels. Furthermore, new capabilities with multiple-antenna systems, e.g., an adaptive radiation pattern to improve signal level or to reduce interference, require a knowledge of propagation channels [2].

A NEW OTA TESTING METHOD IS REQUIRED FOR EVALUATING MULTIPLE-ANTENNA SYSTEMS IN REALISTIC MULTIPATH PROPAGATION ENVIRONMENTS.

OTA Testing for Multiple-Antenna Systems

MIMO terminal performance can be evaluated in a conducted manner, where internal antennas are disconnected and replaced with coaxial cables. The testing results would be incomplete and unrealistic because the antennas are not considered, and important factors such as user interaction and self-interference are difficult to include. An alternative is to test MIMO devices operating in the real network, the so-called field drive testing. However, field drive testing is expensive, time consuming, and labor intensive. Furthermore, due to the open-air environments, the testing might be uncontrollable and unrepeatable.

Various OTA methodologies have been proposed and discussed in the standardizations, e.g., Cellular Telephone Industries Association (CTIA) and Third-Generation Partnership Project (3GPP) Radio Access Network 4 [2], where the objective is to assess the performance of MIMO devices in a reliable, repeatable, and feasible way in laboratory conditions. Other techniques have also been proposed, e.g., the RC-based method [2], the conducted/radiated two-stage method [3], the decomposition method [2], and the MPAC method [2]. The RC is useful in emulating rich multipath environments, and the system cost is relatively low. However, the emulated channel is limited to isotropic power-angular spectra, 0-dB channel cross-polarization ratio (XPR), and limited temporal characteristics (e.g., power Doppler spectrum). Although short delay spread can be emulated by adding absorbers inside the RC, an additional channel emulator is required to create multiple delays. The propagation channels experienced in the field are often directional, rarely with an isotropic incoming power-angular spectrum. Furthermore, the RC-based method will be unable to evaluate MIMO devices equipped with adaptive antennas, which adapt their radiation patterns to directional channels. The so-called two-stage method is capable of generating arbitrary spatial channels, and antenna radiation patterns are considered during testing. However, the two-stage method requires nonintrusive, complex radiation-pattern measurements in the first stage, which is very challenging [3].

Multiprobe Anechoic Chamber Technology

An illustration of the basic idea of MPAC setups is shown in Figure 1. An MPAC system consists of a radio communication tester, a channel emulator, a power amplifier box, multiple probe antennas located around

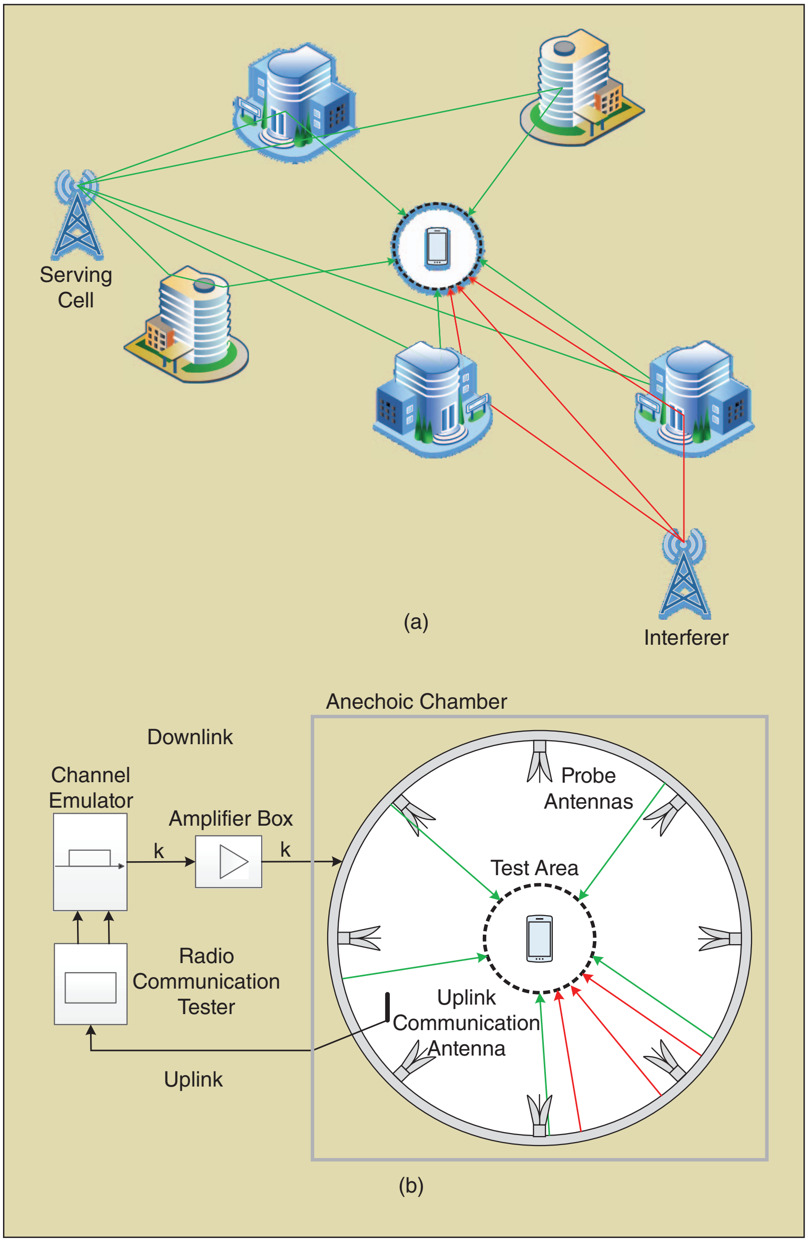

FIGURE 1 (a) The multipath environment and (b) channel emulation in MPAC setups.

the DUT, and an anechoic chamber. The radio communication tester, also called a *base station emulator*, is used to emulate the cellular network end of the link. The power amplifiers adjust the signal to the desired power level. The channel emulator and multiple probes are used to emulate desired spatial channels and intended interferences within the test area. The test area is a geometric area in the center of the MPAC setup where 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. In a practical MPAC setup, the probes connected to the output ports of the radio channel emulator are limited. The test-area size depends directly on the number of probes used to reproduce the desired channel. Consequently, the test-area size for an MPAC setup is often limited. As shown in Figure 1, the current setups are focused on emulating realistic downlink channel models (i.e., communication from the base station to the mobile terminal), while the uplink is realized by an antenna and cable connection. As the testing is performed in an anechoic chamber, generated multipath environments will be free from undesired reflections inside the chamber and unwanted external interferences. Therefore, the testing is repeatable and controllable. The DUT is tested in a realistic way since it is evaluated as it is used in a real network. The main disadvantage with the MPAC is the cost of the setup. A practical MPAC setup is shown in Figure 2, where the OTA ring is covered by absorbers to reduce reflections.

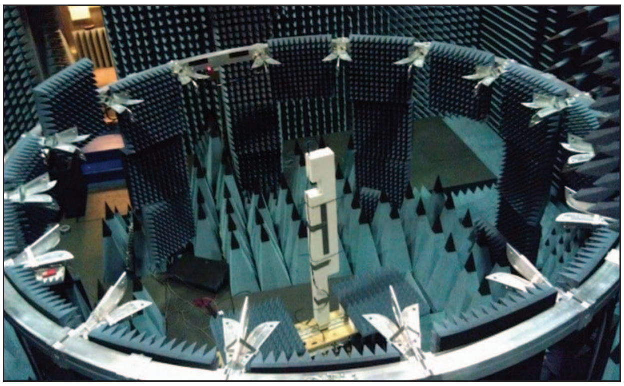

FIGURE 2 A practical MPAC setup with 16 probe antennas.

Radio Channel Emulation in MPAC Setups

Although channel coding and signal processing are important aspects to consider for a successful implementation of MIMO systems, the channel's spatial components and antenna design represent major parameters that primarily impact system performance. The main 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 [2], [4]–[10]. The focus of channel emulation is on the spatial domain of the channel at the Rx side, as it is new and critical as we move from SISO

OTA to MIMO OTA. In the following sections, different channel emulation techniques in MPAC setups are revisited and summarized.

Spatial Channel Emulator Method [6]

The basic idea of the spatial channel emulator method is to transmit a single sinusoid, which is characterized by its amplitude, Doppler frequency, and a random initial phase, from each probe. The amplitudes are obtained via direct sampling of the target incoming power-angular spectra at the probe antenna angular locations. The Doppler frequencies depend on the relative angle between the DUT travel direction and the probe angular locations. The main drawback with this technique is that both the temporal domain (e.g., temporal correlation, power Doppler spectra, and the field distribution) and spatial domain (spatial correlation and power-angular spectrum) depend on the number of probes because a limited number of sinusoids (probes) are used. Furthermore, other channel characteristics, such as the Tx antenna array, channel spatial characteristics at the Tx side, polarization, and delay, were not modeled in [6].

Prefaded Signal Synthesis Technique [4]

Geometry-based stochastic channels (GBSCs), e.g., spatial channel model extended (SCME) channels [5], are selected as target channel models for the prefaded signal synthesis (PFS) technique [2]. Unlike the method presented in [6], in this technique, fading signals, generated with the sum of sinusoid technique, are transmitted from each probe antenna. A GBSC model is composed of multiple clusters (i.e., groups of multipath components), each of which is modeled by its cluster power, delay, nominal angle of arrival (AoA), nominal angle of departure, angle spread of arrival, angle spread of departure, and cluster XPR [5]. Each cluster is emulated by several probe antennas. The fading signals associated with the same cluster are independent and identically distributed, and they are generated to match the target temporal characteristics. As a result, the emulated channel, which is a linear summation of contributions from multiple probes, matches the target channel in the temporal domain [4]. An illustration of the spatial fading channel that is generated in the MPAC setup is shown in Figure 3.

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 the test area in which the channel is emulated with acceptable accuracy is only determined by how well the Rx-side spatial characteristics are reproduced, as temporal characteristics could be perfectly reproduced. An example of how well the emulated channel matches the target channel in terms of spatial correlation at the Rx side is shown in Figure 4, where a test area with a 0.7 wavelength diameter can be achieved with eight probe antennas. For channel models that consist of multiple clusters, each cluster is emulated independently. Similarly, for dual-polarized channel models, vertical and horizontal polarizations are emulated independently. The effects of other channel characteristics, e.g., the Tx antenna array and channel spatial characteristics at the Tx side, are considered and modeled in the fading signals.

BOTH CELLULAR OPERATORS AND MOBILE MANUFACTURES URGENTLY REQUIRE STANDARD TESTING METHODS SUITABLE TO EVALUATE THE RADIO PERFORMANCE.

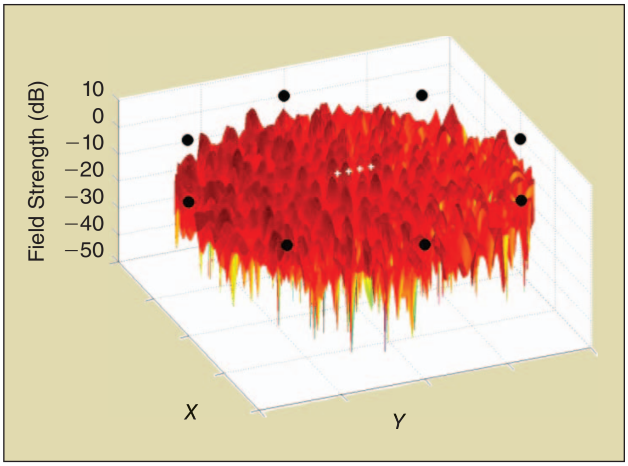

FIGURE 3 An illustration of the spatial fading channel generated with the MPAC setup, where the black dots represent the multiple probes.

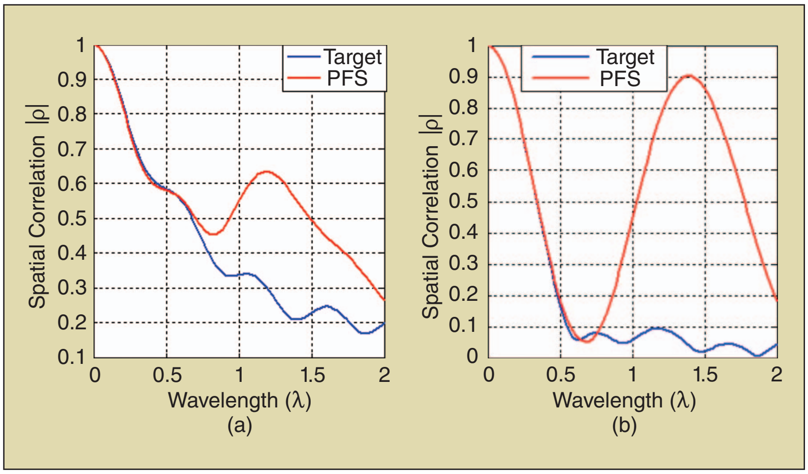

FIGURE 4 The target and emulated spatial correlation for (a) the SCME Uma tapped delay line (TDL) channel model [2] and (b) the SCME Umi TDL channel model [2] with eight OTA probe antennas.

THE BASIC IDEA OF THE SPATIAL CHANNEL EMULATOR METHOD IS TO TRANSMIT A SINGLE SINUSOID, WHICH IS CHARACTERIZED BY ITS AMPLITUDE, DOPPLER FREQUENCY, AND A RANDOM INITIAL PHASE, FROM EACH PROBE.

Plane-Wave Synthesis Technique [8], [9]

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 the test area by allocating appropriate complex weights to the probe antennas on the OTA ring. Different techniques have been proposed to obtain the complex weights, e.g., the least-square technique in [4], spherical wave expansion in [7] and [13], and trigonometric interpolation in [9]. An example of the emulated field with eight probe antennas for a test area of 0.7 wavelength in diameter is shown in Figure 5, where the target plane wave is with impinging angle 22.5° (i.e., from between two adjacent probes). Within the test area, the emulated field matches well with the target field and has uniform power distribution and a linear phase front. Two ideas were proposed to reproduce spatial channel models based on static plane waves [4], [7]. In the first idea, each snapshot of a time-variant channel can be considered as static and can be modeled by multiple static plane waves, each with complex amplitude, AoA, and polarization [7]. The PWS technique can then be applied to approximate each snapshot [7]. The second idea is that a cluster with a stationary power-angular spectrum can be discretized by a collection of plane waves, each with a specific AoA. A Doppler shift can then be introduced to each static plane wave to enable time-variant channels [4]. Arbitrary spatial channel models can be selected as target channels with the PWS technique. The main disadvantage is that both phase and power calibrations are required for the multiple probes, as complex weights have to be obtained. Otherwise, in terms of hardware requirements, the PFS and PWS methods are similar.

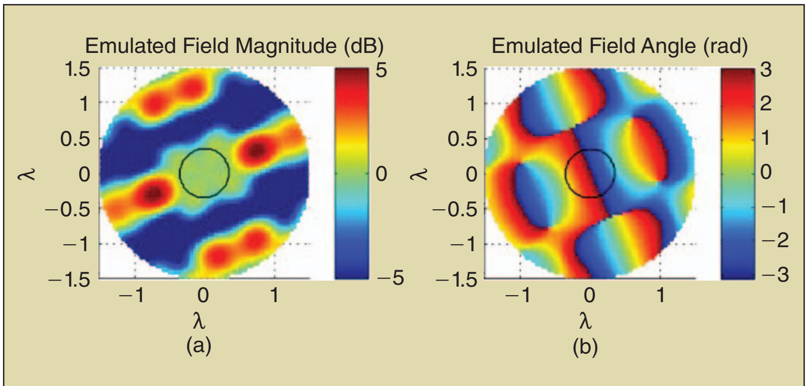

FIGURE 5 The emulated (a) power and (b) phase distribution over the test area with eight probe antennas. The black circle denotes the test area.

Other Methods in MPAC Setups [2], [3], [14]

The radiated two-stage method was proposed in [3], where the second stage was performed in the MPAC setup. Compared to the previously discussed methods, a nonintrusive, complex radiation-pattern measurement of antennas on the DUT in the first stage is required. The measured radiation patterns are incorporated with target channel models in the channel emulator, and the second stage is performed in a radiated approach. The main advantage of this method is that the required number of probes is equal to the number of Rx antennas on the DUT, and the test-area size is unlimited and irrelevant to the number of probes under ideal conditions. In addition, a small chamber can be utilized for the second stage. However, a nonintrusive complex pattern measurement of the antennas on the DUT in the first stage is challenging. More work on the concept verification is required for practical setups.

The decomposition method decomposes MIMO device testing into radiated and conducted tests where only the device front ends, including antennas, are tested in a radiated manner without fading channels [2], [14]. Like the two-stage method, the test-area size is unlimited and the required number of probes is equal to the number of Rx antennas on the DUT with the decomposition method.

State of the Art

The MPAC setup has attracted much attention from both industry and academia in recent years due to its capability to physically reproduce realistic multipath environments in the laboratory [2]. Various contributions on different aspects of the MPAC method have been published in the literature and are summarized here.

Test-Area Size Investigation

As mentioned earlier, the test-area size will be limited since the number of probe antennas used to reproduce the channel is limited by the number of output ports of the radio channel emulator. Different FoMs are proposed and analyzed in the literature to determine the test-area size for different channel emulation techniques. For the PWS technique, a field synthesis error $|E-\hat{E}|$ is often selected as the FoM, where E and $\hat{E}$ represent the target and emulated field, respectively, [7], [8], [13]. In [9], $|V-\hat{V}|$ is suggested as the FoM, with V being the received voltage at the DUT antenna port for the target plane wave, and $\hat{V}$ is the received voltage for the emulated plane wave. In this FoM, the DUT antenna pattern is included in the evaluation. For the PFS technique, often the spatial correlation error at the Rx side $|\rho - \hat{\rho}|$ is used as the FoM [5], as it represents how the emulated impinging power-angular spectrum follows the target. In [9], the antenna correlation error $|\rho_a - \hat{\rho}_a|$ is proposed to determine the test-area size, where ρ_a is the correlation of the received signals at antenna output ports for the target impinging power-angular spectrum, and $\hat{\rho}_a$ is the similar correlation for the emulated impinging power-angular spectrum.

Arbitrary Spatial Channel Emulation

The MPAC method is known for its capability to physically synthesize arbitrary radio propagation environments in laboratory conditions. Two-dimensional (2-D) GBSCs, where incoming power-angular spectra of the channels are defined only on the azimuth plane, are often targeted in the current setup [2], [4]. This article is extended to emulate three-dimensional (3-D) channel models, seen in [8], where an appropriate 3-D probe configuration is required, as shown in Figure 6. In addition, unlike most work limited to reproduce Rayleigh fading channel models with accurate spatial characteristics, the results in [10] have demonstrated that a Rician fading channel with an arbitrary impinging LOS component can be accurately reproduced within the test area.

Validation of the Emulated Channels [2], [11]

The goal of channel validation is to ensure that the reproduced channels follow target channels within the test area so that comparable testing results can be obtained among different laboratories. The validation of four domains of GBSCs is required by the 3GPP and CTIA: 1) delay (power delay profile), 2) temporal (temporal correlation or Doppler power spectrum), 3) polarization (cross polarization ratio), and 4) spatial (spatial correlation or power-angular spectrum) domains [11].

Reference Antenna Concept [12]

To better interpret the testing results, it is important to understand the reproduced channels in MPAC setups and the impact of the antenna characteristics of the DUT. The basic idea of a reference antenna is to replace the internal unknown antennas of the MIMO device by well-defined external reference antennas during testing. Reference antennas can help reduce measurement uncertainties, isolate the impact of unknown antennas of the DUT by placing known antennas, and, hence, are used to validate test methods [2], [12]. Several reference antennas for different LTE frequency bands were proposed in [12], although the analysis was carried out for isotropic incoming power-angular spectra only. The impact of antenna design is shown in Figure 7, where the internal antennas of the DUT were replaced by different reference antennas and exposed to the same spatial channel model.

THE RC IS USEFUL TO EMULATE RICH MULTIPATH ENVIRONMENTS, AND THE SYSTEM COST IS RELATIVELY LOW.

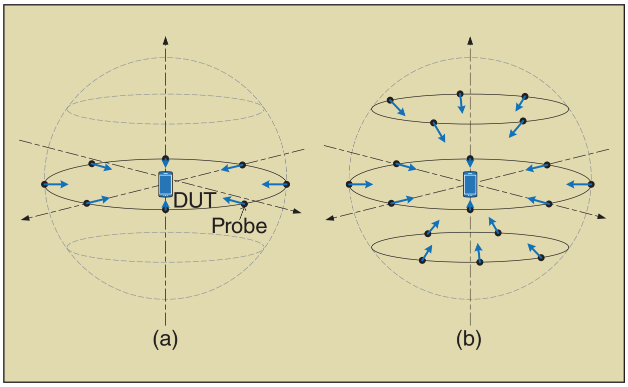

FIGURE 6 An illustration of (a) a 2-D and (b) 3-D probe setup. The black dots represent the probe antennas that are pointing toward the DUT, as indicated by the blue arrows.

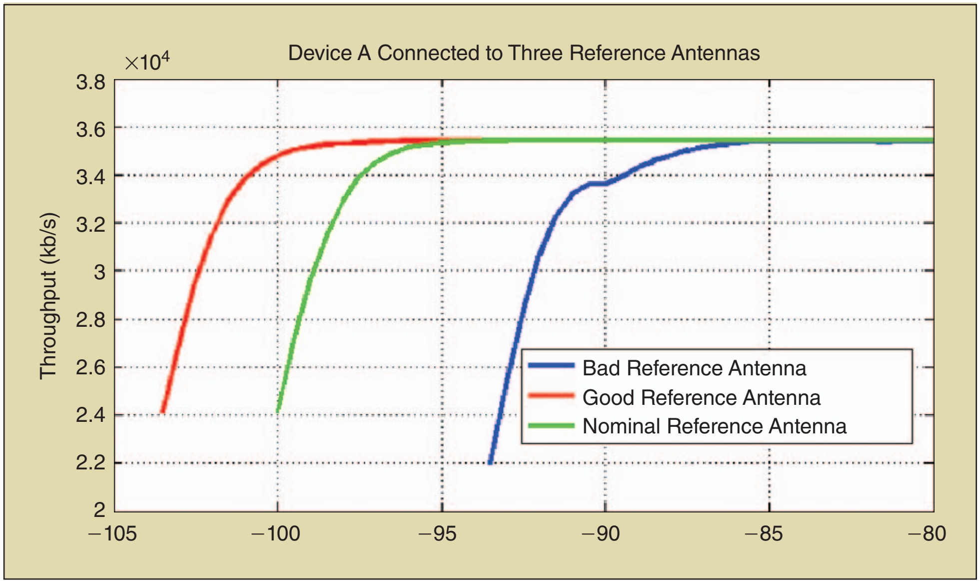

FIGURE 7 The measured throughput results of a mobile phone with three different reference antennas for the same spatial channel model.

THE CHANNEL EMULATOR AND MULTIPLE PROBES ARE USED TO EMULATE DESIRED SPATIAL CHANNELS AND INTENDED INTERFERENCES WITHIN THE TEST AREA.

MPAC Setup Design

The cost of the MPAC setup depends directly on its design. Some contributions have addressed key aspects related to the MPAC design, e.g., the physical dimension requirement of the OTA ring on which the probe antennas are located, the required number of probe antennas [6] [9], probe antenna design, and the probe selection concept.

Other Applications

The MPAC setup has been mainly investigated to evaluate the radiated performance of small MIMO terminals such as mobile handsets and laptops. The concept of testing a cognitive radio-capable device in the MPAC setup was briefly addressed in [15], where OTA testing was identified as mandatory in two scenarios: 1) directional sensing techniques can be realistically evaluated in MPAC setups, and 2) realistic interferences can be physically emulated in MPAC setups. Furthermore, OTA testing is being considered to evaluate car-to-car (C2C) and car-to-infrastructure (C2I) communications [15]. An illustration of testing cars in MPAC setups is shown in Figure 8, where a test area larger than the antenna separation is required.

Future Work

Throughput Prediction Model

Data throughput has been selected as the FoM in MIMO OTA standards to rank MIMO-capable terminals, as it reflects the end-user experience. The throughput measurement results of different LTE phones under the same spatial channel models with a spatial multiplexing transmission mode is shown in Figure 9. The measurement setups and procedures are detailed in [2]. Three different modulation and coding schemes (MCSs) were used in the measurement. It can be observed that a performance difference of up to 10 dB is due to different antenna designs in the commercial LTE phones. An interlab/intertechnique OTA performance comparison testing campaign was started in 2012 to compare results obtained with the same methods in different labs. Extensive measurement campaigns have been performed in different laboratories. However, deviations in terms of throughput in measurement results still exist among laboratories and the exact causes are still missing. There is a strong need to develop a throughput simulation tool with reasonable accuracy. A sound simulation tool is desired, as it can help eliminate potential systematic errors in measurements and would enable more insight into test results.

Measurement Uncertainty Investigation

As a mandatory step for evaluating MIMO devices in practical setups, analyzing the sources of errors and uncertainties in the measurements is required. The uncertainty level can help in understanding the level of confidence associated with testing results. Some investigations on measurement uncertainty were reported in the literature where some error sources were identified and analyzed. However, the actual impact of the error levels on the testing results is still unclear. Quantifying the impact of errors on important parameters, e.g., signal correlation accuracy, received voltage accuracy on the antenna, capacity, and throughput, would be more interesting.

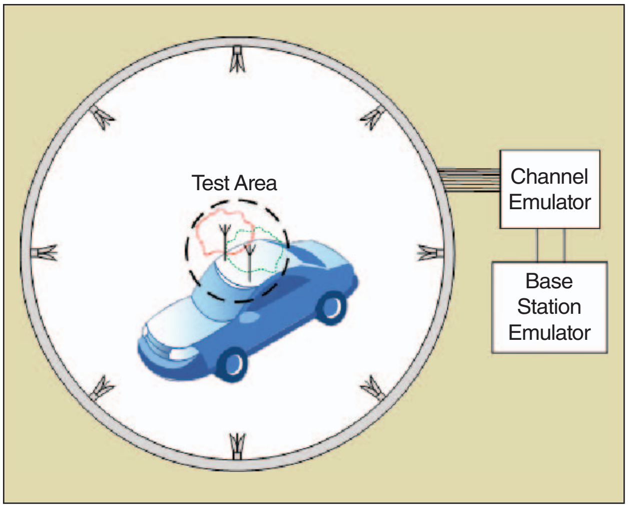

FIGURE 8 An illustration of testing wireless systems on a car in an MPAC setup.

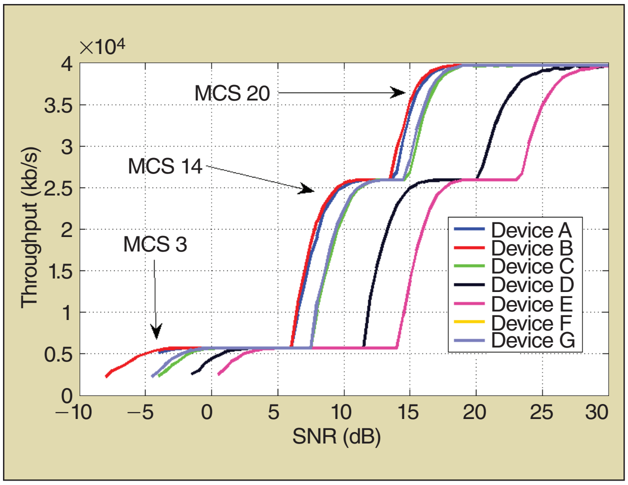

FIGURE 9 The measured throughput results of different mobile phones with three different MCSs for the same spatial channel model.

***A PRIORI* KNOWLEDGE OF THE RADIO PERFORMANCE OF MIMO DEVICES BEFORE MASSIVE ROLLOUT IN THE NETWORK IS IMPORTANT FOR NETWORK OPERATORS.**

Full Duplex Channel Modeling

Research work has been focused on emulating realistic downlink channel models where the uplink channel is generally realized through a single communication antenna and a cable. Emulation of realistic full duplex channel models (i.e., both downlink and uplink) is becoming increasingly important for LTE systems. The uplink channel-state information can be critical for downlink performance in some closed-loop communication systems with adaptive modulation, coding, and MIMO transmission modes. Furthermore, to reduce the difference in peak data rate on the uplink and downlink, uplink with up to four transmission antennas (i.e., four antennas on mobile terminals used for transmission) is introduced in LTE-Advanced (Release 10 and beyond). Realistic channel models have to be emulated for the uplink as well to evaluate the uplink MIMO performance. The open questions here are

- How do we model realistic uplink channel models?
- How do we emulate realistic uplink channel models in MPAC setups?

Testing of Larger Devices

More wireless systems are being included in modern vehicles. In addition to cellular service, C2C and C2I communications have attracted great attention as well. Therefore, there is a need to test the performance of these wireless systems in real environments. Compared to mobile handset testing, testing wireless systems in cars is more challenging due to the requirement of a much larger test-area size. In addition, measuring OTA performance for larger wireless products, such as base stations, is also desired.

Virtual Drive Testing

The research work in the literature has been focused on reproducing synthesized stationary radio channels (e.g., SCME channel models) in the laboratory [2]. Site-specific channel models are also interesting since they are more realistic and location dependent. Furthermore, emulating site-specific channels enables performing drive testing in the laboratory, where the base stations and mobile terminals are installed in a lab and realistic radio environments are reproduced with MPAC setups. As the reproduced propagation environments are fully controlled and repeatable, virtual drive testing can significantly reduce test time and work load compared to actual field drive testing. Site-specific channel models can be obtained via ray-tracing simulations or channel sounding. An illustration of the virtual drive-testing concept is shown in Figure 10. As the key idea of virtual drive testing is to replay field measurement data or ray-tracing-based nonstationary channel data, it is beneficial to have a channel emulator that is capable of file-based emulation.

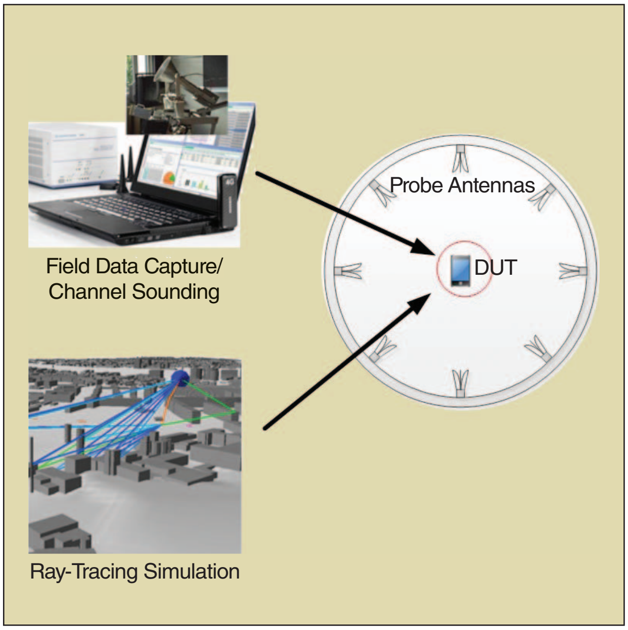

FIGURE 10 An illustration of the virtual drive-testing concept.

Interference Modeling

This article has focused on modeling the properties of the radio channel of the desired signal. However, the channel characteristics of interfering signals also need to be considered. The performance of LTE mobile terminals is limited by interference, e.g., the intercell interference. The open questions are

- What are the channel characteristics of interference in the real world?
- What channel characteristics of the interference are essential to radio link performance in an OTA measurement?
- How can realistic interference channels in MAPC setups be emulated?

Conclusion

This article presented an overview of the OTA testing methods of MIMO-capable terminals. More specifically, the main capabilities and challenges with the MPAC method are addressed. The main focus of this article is channel emulation techniques, limitations, state of the art, and existing challenges of the MPAC setup. The MPAC method is capable of generating arbitrary channels with controllable channel characteristics in spatial, temporal, polarization, and delay domains, making it a suitable method for testing terminals equipped with multiple antennas.

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Author Information

Wei Fan received his bachelor of engineering degree from Harbin Institute of Technology, China, in 2009; his master's double degree (highest honors) from Politecnico di Torino, Italy, and the Grenoble Institute of Technology, France, in 2011; and his Ph.D. degree from Aalborg University, Denmark, in 2014. From February to August 2011, he was with Intel Mobile Communications, Denmark, as a research intern. He conducted a three-month internship at Anite Telecoms Oy, Finland, in 2014. His main areas of research are over-the-air (OTA) testing of multiple-input, multiple-output (MIMO) terminals, radio channel modeling, and virtual drive testing.

Xavier Carreño received his master's degree from the Polytechnic University of Catalonia, Spain, in 2011. He has been deeply involved in baseband signal processing algorithms and multiple-input, multiple-output (MIMO) over-the-air (OTA) research topics within Intel Mobile Communications, where he currently has a leading role in the MIMO OTA development team as a system engineer. He is involved in the standardization of MIMO OTA methods and has authored several Third-Generation Partnership Project (3GPP), Cellular Telephone Industries Association (CTIA), and IC1004 Action on Cooperative Radio Communications for Green Smart Environments contributions and several conference and journal papers on the subject. His primary interests are within the area of MIMO OTA testing techniques, MIMO channel modeling, and long-term evolution (LTE) platform testing.

Pekka Kyösti earned his M.Sc. degree in mathematics from Oulu University, Finland. From 1998 to 2002, he was with Nokia Networks working on the field of transceiver baseband algorithms and signal processing. From 2002 to 2013, he was with Elektrobit, Oulu. Since 2002, he has been working on radio propagation, channel measurements, and modeling. He has participated in the channel modeling work, e.g., in European Mobile and Wireless Communications Enablers for the Twenty–Twenty Information Society project and Wireless World Initiative New Radio projects since 2004. He contributes actively to scientific conferences and European Cooperation in Science and Technology (COST) actions. He moved to Anite in January 2013 due to a company acquisition. Currently, his responsibilities are channel modeling for fifth-generation and multiple-input, multiple-output (MIMO) over-the-air (OTA) research in Anite.

Jesper Ødum Nielsen received his master's degree in electronics engineering in 1994 and his Ph.D. degree in 1997, both from Aalborg University, Denmark. He is currently employed at the Department of Electronic Systems at Aalborg University, where his main areas of interest are the experimental investigation of the mobile radio channel and the influence mobile device users have on the channel. He has been involved in multiple-input, multiple-output (MIMO) channel sounding and modeling as well as measurements using live global system for mobile communication (GSM) and long-term evolution (LTE) networks. In addition, he has been working with radio performance evaluation, including over-the-air (OTA) testing of active wireless devices.

Gert Frølund Pedersen received his B.Sc. degree (with honors) from the College of Technology in Dublin, Ireland, in 1991 and his M.Sc., E.E., and Ph.D. degrees from Aalborg University, Denmark, in 1993 and 2003. He is a full professor heading the Antennas, Propagation, and Radio Networking (APNet) Section. His research has focused on radio communication for mobile terminals, especially small antennas, diversity systems, propagation, and biological effects. He has been one of the pioneers in establishing over-the-air (OTA) measurement systems. The measurement technique is now well established for mobile terminals with single antennas, and he chaired various Cooperation in Science and Technology (COST) groups (swg2.2 of COST 259, 273, 2100, and now ICT1004) with liaison to the Third-Generation Partnership Project (3GPP) for OTA testing of multiple-input, multiple-output (MIMO) terminals.

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