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Research Article

Dependence of Error Level on the Number of Probes in Over-the-Air Multiprobe Test Systems

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Development of MIMO over-the-air (OTA) test methodology is ongoing. Several test methods have been proposed. Anechoic chamber-based multiple-probe technique is one promising candidate for MIMO-OTA testing. The required number of probes for synthesizing the desired fields inside the multiprobe system is an important issue as it has a large impact on the cost of the test system. In this paper, we review the existing investigations on this important topic and end up presenting rules for the required number of probes as a function of the test zone size in wavelengths for certain chosen uncertainty levels of the field synthesis.

1. Introduction

The multiple-input multiple-output (MIMO) is a key technology for evolving wireless technologies including LTE and LTE-Advanced (or IMT-Advanced) [1]. It involves multiple antennas to enhance the capacity and throughput in multipath propagation environments. The MIMO performance in a multiantenna communication system depends on the antenna placement and design at the terminal and on the channel environment. Furthermore, since the MIMO radio channel is a combination of the antenna characteristics and the radio propagation conditions, the antenna performance metrics, such as gain, radiation efficiency, and the difference of gain between the multiple antennas, do not directly point towards the MIMO performance.

At the moment, development on measurement methodologies and figures of merit for assessing the overall MIMO performance is being conducted by Radio Access Networks working group 4 (RAN4) of 3GPP [2] in Europe and by CTIA [3] in the North America. Over-the-air (OTA) testing, which has been used for single-input single-output (SISO) performance evaluation [4, 5], is an obvious choice also for MIMO performance evaluation; additionally radiopropagation channel must be taken into account. Several test methods have been proposed [6–14]. A strong candidate for the MIMO performance metrics is throughput [15].

The three main candidates MIMO-OTA test methods [6–14] are (1) anechoic chamber and fading emulator-based multiprobe methods [6–9], (2) reverberation chamber based methods [10–13], and (3) multistage method, often refers to the "two-stage" method [14]. In the latter one the first stage involves the pattern measurement of the device under test (DUT) over the air, and the second stage involves combining of the DUT patterns with the radio-propagation channel data and performing the MIMO performance test conductively.

It is now noted that geometric reference channel models with well-defined characteristics such as complex amplitudes, directions of arrival (DoA), directions of departure (DoD), the delays, and polarizations of the multipath components constitute a good means to describe the radio-propagation channel. These channel models are well accepted by 3GPP [2], and the use of such well-defined channel models in the MIMO OTA performance evaluation is very well justified for the sake of the repeatability of testing [15]. Several reference models have been proposed by [15], such as SCME TDL and WINNER II CDL models, as well as simplified single spatial cluster models.

The difficulty with reverberation chamber-based methods is that they are not well suited for synthesizing such channel conditions that would be in line with any geometric radio channel model. The two-stage method on the other hand has the problem with the cable connection to the antenna ports it requires, which means that the test is never performed in the realistic usage conditions of the DUT. From these technical points of view the anechoic chamber and fading emulator-based multiprobe methods appear to be the most promising method for MIMO performance evaluation.

One of the key issues addressed in anechoic chamber and fading emulator-based multiprobe systems is the number of required probes. Due to the fact that the cost for such a multiprobe system increases rapidly with the required number of probes, it becomes important to analyze in detail what the required number of probes is. The purpose of this paper is to establish accurate rules for the number of probes required for synthesizing the radio propagation channel inside the multiprobe system as a function of the size of the DUT in wavelengths and the uncertainty level of the field synthesis. These rules concern particularly 2D circular multiprobe systems, and hence they support well the development of test methods relying on 2D channel models like SCME and WINNER II. Here, the synthesis of the electromagnetic fields is conducted using the spherical wave theory which has been widely used in the spherical near-field as well as far-field antenna measurements to model the 3D radiation from antennas [16].

First, a review on existing studies on the required number of probes is presented in Section 2. The well-known general rules for the number of probes are first presented in Section 3, and the accurate rules are established in Section 4. Conclusions are given in Section 5.

2. Review of the Existing Investigations on the Number of Probes

2.1. General. Anechoic chamber- and fading emulator-based multiprobe methods involve several probes placed on a circle in 2D case or on a sphere in 3D case, and the DUT is in the center of the circle or sphere [6–9, 17]. An illustration of a 2D MIMO OTA test system based on multiprobe technology is in Figure 1.

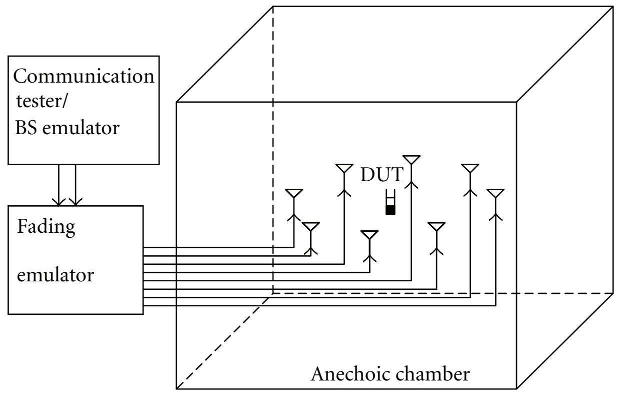

Figure 1: Illustration of a MIMO-OTA test system based on multiprobe technology.

The base station emulator creates the test signal which is fed to the fading emulator to create delay dispersion, Doppler spectra, and fast fading behavior. The emulator is connected to the probes inside the anechoic chamber with the prefaded signal. To achieve a high level of accuracy, more probes are needed to emulate the desired power azimuth spectra (PAS) around the test zone (the test zone is the geometrical volume inside which the DUT is located during the measurement) of the DUT.

In [17–22] studies have been done which directly provide rules for or discuss theoretically how to determine the required number of probes and the test zone size with a given accuracy. Two different ways for determining the required number of probes as well as the test zone size can be identified: (i) through spatial correlation function [18–20] and (ii) through plane wave synthesis [17, 21, 22]. The analysis is done (a) for the multiple cluster 2D channel model with uniform distributed PAS, where the probes are assumed to be placed equidistantly in 360° angular region in φ ($\theta = 90^\circ$) and (b) for the single cluster spatial 2D channel model with the Laplacian distributed PAS when the freedom of placing the probes in an optimum angular sector is considered. In this section we review those concepts reported in [17–22] and make a comparison between the obtained results.

2.2. Spatial Correlation Function. Spatial correlation characteristics, which influence the MIMO transmission performance, depend on the PAS of the radio channel. These characteristics are often expressed using the Bessel series of the Fourier spectrum of the PAS as coefficients. In [18–20] investigations have been performed on the required number of probes through spatial correlation function of the PAS for both the multiple-cluster model and the single-cluster model with the criterion that the correlation deviation, as defined in [18–20], should be less than 0.1.

2.3. Plane Wave Synthesis. The plane wave synthesis technique reported in [17, 21, 22] is based on the synthesis of the electromagnetic field environment using the spherical wave theory [16]. In [17, 21, 22] the influence of the number of probes on the geometrical size of the test zone and the quietness of the test-zone field in terms of an equivalent reflectivity level has been investigated for the 2D case. Here, the equivalent reflectivity level means the maximum relative error between the synthesized plane-wave field and a target plane-wave field on the circumference of the test zone. Hence, the given reflectivity level values are the worst case values. In [17, 21, 22], the required number of probes is calculated as a function of different accuracy level and test zone size. It is noted that the number of probes required to synthesize the incoming plane waves with a fixed accuracy is dictated by the radius of the test zone and not affected by the number of incoming plane waves of the channel model.

2.4. Comparison between the Obtained Results of Required Number of Probes and Test Zone Size. The comparisons of the results for the required number of probes as a function of test zone size obtained by different methods given in [17–21] are presented in Figures 2 and 3. The results in Figure 2 are for the multiple-cluster model with uniform distributed PAS where the probes are assumed to be placed equidistantly

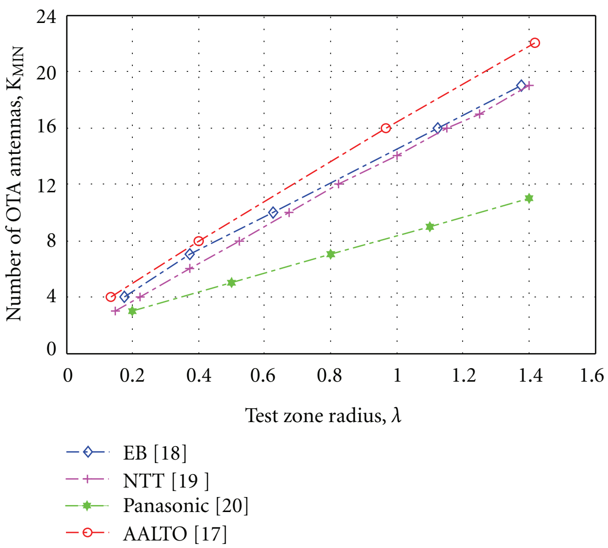

FIGURE 2: The number of probes as a function of the test zone radius for the multiple cluster model with uniform distributed PAS when the probes are placed equidistantly over the 360° angular region in φ.

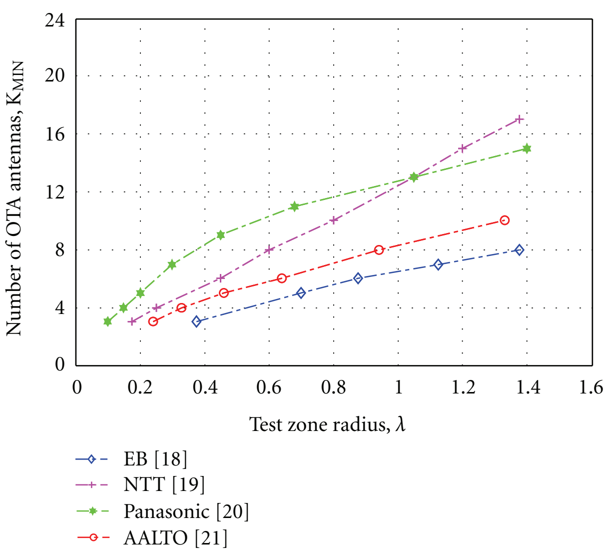

FIGURE 3: The number of probes as a function of the test zone radius for the single cluster model with the Laplacian distributed PAS with the angular spread of 35° when the probes are placed in an optimum azimuth region.

in 360° angular region in φ. The results in Figure 3 are for the single cluster model with the Laplacian distributed PAS with the power angular spread of 35° when the probes are placed in an optimum azimuth region. In [18–20] the number of probes is determined with the correlation deviation of 0.1. For the plane wave synthesis technique [17, 21], a −15 dB equivalent reflectivity level is considered here for the comparison which gives the correlation deviation between the target and synthesis fields of 0.1 approximately.

For the multiple-cluster model, the results obtained from [17–19] show the similar trend with just a small difference, but the results in [20] clearly provide different values compared to the others. For the single-cluster model with the Laplacian distributed PAS with the angular spread of 35°, the results obtained from [19, 20] show some difference from the other results obtained from [18, 21]

Based on the analysis, the same conclusion is drawn in [17–19, 21]; that is, for the synthesis of the multiple-cluster model, a higher number of probes is needed than for the single-cluster model with the Laplacian distributed PAS when the probes are placed in an optimum azimuth region. From the simulated results presented in [20], a remarkable difference on the number of probes for synthesizing the Laplacian-distributed PAS is observed. It is stated in [20] that the number required for the Laplacian distributed PAS is higher than that for the uniform distributed PAS. The likely reason is that the weights for the probes are obtained by directly synthesizing the PAS rather than the field.

Although there are some differences in the results between the two techniques, we have chosen to go deeper to the theory with the plane wave synthesis technique in the next section of this paper. The reason for this is that the plane wave synthesis technique provides a straightforward way for the theoretical justification of the number of probes through the plane wave to spherical wave expansion (SWE) and the well-known cut-off properties of the spherical wave functions. In the following section we will present the plane wave synthesis technique in more detail in a similar fashion as presented in [17, 21, 22].

3. General Rules for the Required Number of Probes

3.1. Introduction. The electromagnetic fields in the test zone, which are synthesized by the probes located either on a 2D circle around the DUT or on a 3D spherical surface, may be considered for composing plane wave fields arriving from different spatial directions at the centre of the test zone. Any radio channel conditions may as well be considered as a sum of plane waves by additionally taking into account, for example, the delay spread and Doppler effects, by using proper RF electronics.

The purpose of this section is to briefly review the spherical wave theory in the context of plane wave fields and to present the well-known general rules for the number of required probes for the plane wave synthesis. These general rules provide the basis for establishing the accurate rules for the number of required probes later in Section 4.

3.2. Spherical Wave Expansion of the Plane Wave Field. The electric field $\overline{E}_0 e^{i\overline{k}_0\cdot\overline{r}}$ of a time-harmonic plane wave coming from a direction (θ_0, φ_0) in free space can be represented by an infinite sum of SWE modes as [16]

$$\overline{E}_0 e^{i\overline{k}_0\cdot\overline{r}} = \frac{k}{\sqrt{\eta}} \sum_{s=1}^{2} \sum_{n=1}^{\infty} \sum_{m=-n}^{n} Q_{smn}^{(1)} \overline{F}_{smn}^{(1)}(r, \theta, \varphi). \quad (1)$$

Here $\overline{E}_0$ describes the amplitude and complex polarization of the wave, $\overline{k}_0 = -k\sin\theta_0\cos\varphi_0\overline{u}_x - k\sin\theta_0\sin\overline{u}_y - k\cos\theta_0\overline{u}_z$ is the propagation vector, k is the wave number, η is the wave admittance of the medium, s, m, and n are the spherical mode indices, $Q^{(1)}_{smn}$ are the spherical vector wave coefficients for spherical standing waves, and $\overline{F}^{(1)}_{smn}(r,\theta,\varphi)$ represent the corresponding power normalized spherical vector wave functions in standard spherical coordinates (r,θ,φ) [16].

3.3. Cut-Off Property and General Rules for Minimum Number of Probes. It is known that the spherical vector wave functions $\overline{F}^{(1)}_{smn}(r,\theta,\varphi)$ are separated into radial, elevation, and azimuth functions, where the radial functions are the spherical Bessel functions and their derivative functions, the elevation functions are the associated Legendre functions, and the azimuth functions are the exponential functions [16]. Importantly, due to the cut-off property of the spherical-wave functions, in particular that of the spherical Bessel function and its derivative function, the expansion in (1) can be truncated appropriately at a finite $n = N$. Hence the expansion of the plane wave field with the truncated series of spherical wave functions becomes

$$\overline{E}_0 e^{i\overline{k}_0\cdot\overline{r}} = \frac{k}{\sqrt{\eta}}\sum_{s=1}^{2}\sum_{n=1}^{N}\sum_{m=-n}^{n} Q^{(1)}_{smn}\overline{F}^{(1)}_{smn}(r,\theta,\varphi), \tag{2}$$

where the truncation number N is

$$N = [kr_0 + n_1]. \tag{3}$$

In (3) r_0 is the radius of the spherical test zone, n_1 is a small integer number, and the square brackets indicate the nearest integer number greater than or equal to the number inside the brackets. Typically, n_1 varies from $n_1 = 0$ to 10 [16] depending on the desired accuracy of the field characterization (or synthesis). The triple summation over $n = 1\cdots N$, $m = -n\cdots n$ and $s = 1,2$ in (2) has in total $J = 2N(N+2)$ terms. Hence, with (3) the number of spherical wave modes J can be written as

$$J = 2N(N+2) = 2([kr_0 + n_1])^2 + 4([kr_0 + n_1]). \tag{4}$$

Now, in theory, for synthesizing all J modes, the minimum number of probes, K_{MIN}, is equal to the number of modes J. Hence, the general rules for required number of probes becomes

$$K_{\mathrm{MIN}} = 2([kr_0 + n_1])^2 + 4([kr_0 + n_1]). \tag{5}$$

The noticeable issue in (5) is that the number of the probes K_{MIN} is proportional to the square of the test zone radius r_0 for $r_0 \gg 1/k$ and the value of n_1.

It is noted that the general rules for the required number of probes presented in (5) are for the 3D case, where the probes are distributed over a sphere and both the elevation and azimuthal distribution of the incoming waves are considered. However, in the case of such 2D channels like SCM or SCME, where the test zone fields are coming from the direction of $\theta_0 = 90^0$, we need to consider only the azimuthal distribution of the incoming field. Hence, we need to consider only the azimuthal dependency of the spherical wave function in (2), and the expansion can be presented by

$$\begin{aligned}\overline{E}_\theta e^{i\overline{k}_0(\theta_0=90^\circ)\cdot\overline{r}} &= \sum_{m=-N}^{N}\overline{C}^{\theta}_m(r,\theta=90^\circ)e^{im\varphi},\\ \overline{E}_\varphi e^{i\overline{k}_0(\theta_0=90^\circ)\cdot\overline{r}} &= \sum_{m=-N}^{N}\overline{C}^{\varphi}_m(r,\theta=90^\circ)e^{im\varphi},\end{aligned} \tag{6}$$

where $\overline{E}_\theta$ and $\overline{E}_\varphi$ are the vertical and horizontal polarizations of the test zone field. The $\overline{C}^{\theta}_m$ and $\overline{C}^{\varphi}_m$ are the azimuthal mode coefficients of the test zone field derivable from (2). In this way, instead of having a triple summation as in (2), we have, for the two polarizations, a single summation over all m azimuthal modes with $2N+1$ terms. Hence, by including the two polarizations, the number of required modes J_1 for the field characterization becomes

$$J_1 = 2(2N+1) = 4([kr_0 + n_1]) + 2, \tag{7}$$

which directly indicates the minimum number of probes, K_{MIN} for 2D case. Hence, the general rules for required number of probes in 2D case becomes

$$K^{\mathrm{2D}}_{\mathrm{MIN}} = 4([kr_0 + n_1]) + 2. \tag{8}$$

Here the superscript 2D refers to the 2D case. Now $K^{\mathrm{2D}}_{\mathrm{MIN}}$ is proportional to the test zone radius r_0 for $r_0 \gg 1/k$ and the value of n_1.

4. Accurate Rules for the Number of Required Probes in the 2D Case

In (5) and (8) of Section 3, we presented the well-known general rules for the minimum number of probes as a function of the radius of the test zone in wavelengths through the spherical wave theory. The equations contain the unknown number n_1 related to the accuracy of the field synthesis. Although for practical applications the range in which n_1 can vary is relatively small, from approximately 0 to 10 [16, 23], the choice of n_1 significantly affects the K_{MIN}. The purpose of this section is to find accurate values for n_1 for certain selected uncertainty levels of the field synthesis for, in particular 2D case. This we do by reviewing the work done in [17] and by making use of the findings in [24].

In [17] the influence of the number of probes on the test zone size and the quietness of the test zone field in terms of the equivalent reflectivity level have been analyzed for the 2D multiple cluster case. In that study the equivalent reflectivity level refers to the maximum relative error (ε) between the synthesized (E_{syn}) and the target (E_{tar}) plane wave fields as

$$\varepsilon = \max\left(\frac{\left|E_{\mathrm{syn}} - E_{\mathrm{tar}}\right|}{\max(|E_{\mathrm{tar}}|)}\right). \tag{9}$$

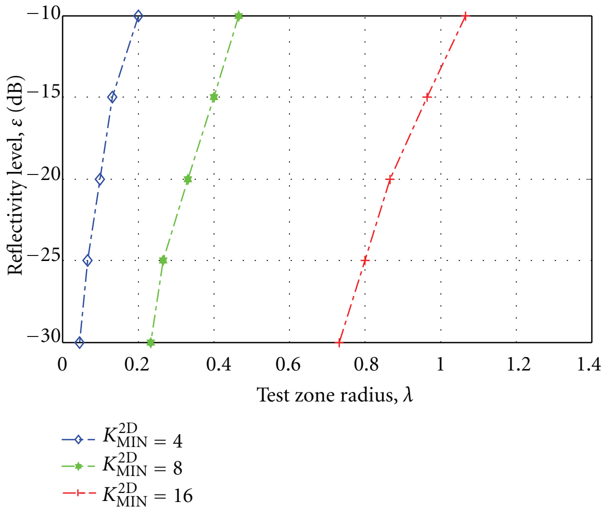

Figure 4: The equivalent reflectivity level as a function of the test zone radius for different number of probes for a single-polarized probes in 2D case.

The synthesis was performed by a simple 2-norm matching of the fields of the probes with the incoming plane wave fields arriving to the test zone. The z-polarized (vertically polarized) electrical Hertzian dipoles were considered as probes, and they were placed in the horizontal plane ($\theta = 90^\circ$) on the entire 360° angular region with constant φ intervals and the synthesis of the z-polarized plane wave field arriving from ($\theta = 90^\circ$) was investigated. For the considered single-polarized case, the required number of probes is $K_{\mathrm{MIN}}^{2\mathrm{D}} = 2[kr_0 + n_1] + 1$ instead of the form of (8) for the dual-polarized case. A summary of the results of this investigation is presented in Figure 4.

The results presented in Figure 4 clearly show that the number of probes, $K_{\mathrm{MIN}}^{2\mathrm{D}}$, increases as a function of the test zone radius for any selected equivalent reflectivity level. Now, our goal is to find the values for n_1 in (8) so that this equation would be in line with the results shown in Figure 4, of course by taking into account the fact that (8) is for the dual-polarized case and the results in Figure 4 for the single-polarized case. We make use of the same assumptions for calculating the values for n_1 as presented in [24], where it has been proposed that n_1 would depend on kr_0 as

$$n_1 = o\left(\sqrt[3]{kr_0}\right). \tag{10}$$

As a result of this, appropriate values for n_1 are found, and they are tabulated in Table 1 for the different uncertainty levels of the field synthesis.

The values of n_1 in Table 1 constitute the important contribution of this paper. Applying these values of n_1 in (8) directly provides the minimum number of required probes (dual-polarized) as a function of the radius of the test zone in wavelengths ($k = 2\pi/\lambda$) for the chosen uncertainty level of the field synthesis for the 2D case.

It is important to note that the values of n_1 in Table 1 have been established with the values of kr_0 in the range from approximately 0.2 to 6.1 from the basis of the results reported in [17]. It has been intentionally chosen that the square bracket round the number inside the bracket to the nearest integer larger than the number, because in that case, for small values of kr_0, (8) together with the values of n_1 indicates that the required number of probes would be 6 for the dual-polarized case and 3 for the single-polarized case. This is as it should be, because even if the DUT is electrically very small, it may still radiate the 3 azimuthal dipole modes [16] in single polarization. Having said this, it can be claimed that the values of n_1 may be considered to be well applicable also for values of kr_0 less than 0.2. It is further noted that, by comparison of the result of this paper with those presented in [25], we may conclude the values of n_1 are practically applicable for large values of kr_0, too. Although the application in [25] is the modeling of the radiation of DUTs and the application of this paper is the field synthesis, both rely on the spherical wave theory and the cut-off property of the spherical vector wave functions, and hence, these two things may be considered comparable.

Table 1: The values of n_1 for different uncertainty levels for the 2D case.

Equivalent reflectivity level, ε	n_1
−10 dB	$0.37 \times \sqrt[3]{kr_0}$
−15 dB	$0.74 \times \sqrt[3]{kr_0}$
−20 dB	$1.08 \times \sqrt[3]{kr_0}$
−25 dB	$1.45 \times \sqrt[3]{kr_0}$
−30 dB	$1.85 \times \sqrt[3]{kr_0}$

Here we have derived the accurate rules for the required number of probes for the 2D case only. Similar accurate rules could as well be derived for the 3D case, and instead of using (8), (5) would provide the required number of probes for that case. The values that we have provided for n_1 in Table 1 are for the 2D case. However, it is evident from [25] that the values of n_1 for the 2D case serve as a good approximation of those for the 3D case.

5. Conclusions

Anechoic chamber- and fading emulator-based multiprobe method is a very promising method for MIMO performance testing. A crucial aspect largely dictating the cost of the test system, the required number of probes for synthesizing the desired fields inside the multiprobe system, has been examined in this paper. First, through the review of the well-known spherical wave theory, the general rules for the number of probes required for synthesizing the radio propagation channel inside the multiprobe system as a function of the size of the DUT in wavelengths have been presented for both 2D and 3D cases. Based on the results presented in existing literature, accurate rules for the minimum number of required probes for the 2D case have been established that take into account also the uncertainty level of the field synthesis.

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References

[1] S. Sesia, I. Toufik, and M. Baker, *LTE-The UMTS Long Term Evolution*, John Wiley & Sons, Chichester, UK, 2nd edition, 2011.

[2] http://www.3gpp.org/.

[3] http://www.ctia.org/.

[4] 3GPP TS 34.114, "User equipment (UE) / mobile station (MS) over the air (OTA) antenna performance; conformance testing (release 7)," September 2009.

[5] CTIA Certification, *Test Plan for Mobile Station Over the Air Performance, Method of Measurement for Radiated RF Power and Receiver Performance, Revision Number 2.2.2*, December 2008.

[6] Elektrobit, "Updated concept—MIMO OTA testing," 3GPP TSG-RAN4 R4-092435.

[7] Vodafone, Panasonic, and Tokyo Institute of Technology, "MIMO OTA testing using RF controlled spatial fading emulator," in *R4-091390, 3GPP TSG RAN4 Meeting*, Seoul, South Korea, March 2009.

[8] Y. Okano, K. Kitao, and T. Imai, "Impact of number of probe antennas for MIMO OTA spatial channel emulator," in *Proceedings of the 4th European Conference on Antennas and Propagation (EuCAP '10)*, April 2010.

[9] A. Yamamoto, T. Sakata, H. Iwai et al., "BER measurements on a handset adaptive antenna array in the presence of Co-channel interference generated using a spatial fading emulator," in *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, pp. 26–29, Washington, DC, USA, July 2005.

[10] P. S. Kildal and K. Rosengren, "Correlation and capacity of MIMO systems and mutual coupling, radiation efficiency, and diversity gain of their antennas: simulations and measurements in a reverberation chamber," *IEEE Communications Magazine*, vol. 42, no. 12, pp. 104–112, 2004.

[11] D. Kurita, Y. Okano, S. Nakamatsu, and T. Okada, "Over-The-Air performance testing system for MIMO antennas employing reverberation chamber," IEICE Technical Report A·P2009-34, 2009.

[12] C. Wright and S. Basuki, "Utilizing a channel emulator with a reverberation chamber to create the optimal MIMO OTA test methodology," in *Proceedings of the Global Mobile Congress (GMC '10)*, October 2010.

[13] J. F. Valenzuela-Valdês, A. M. Martínez-González, and D. A. Sánchez-Hernández, "Emulation of MIMO nonisotropic fading environments with reverberation chambers," *IEEE Antennas and Wireless Propagation Letters*, vol. 7, pp. 325–328, 2008.

[14] Y. Jing, Z. Wen, H. Kong, S. Duffy, and M. Rumney, "Two-stage over the air (OTA) test method for MIMO device performance evaluation," in *Proceedings of the IEEE International Symposium on Antennas and Propagation (APSURSI '11)*, pp. 71–74, July 2011.

[15] Measurement of radiated performance for MIMO and multi antenna reception for HSPA and LTE terminals (Release 10) 3GPP TR 37.976 V1.1.0 (2010-05), R4-102357.

[16] J. E. Hansen, *Spherical Near-Field Antenna Measurements*, Peter Peregrinus, London, UK, 1988.

[17] T. Laitinen, J. Toivanen, P. Kyösti, J. Nuutinen, and P. Vainikainen, "On a MIMO-OTA testing based on multi-probe technology," in *Proceedings of the 20th URSI International Symposium on Electromagnetic Theory (EMTS '10)*, pp. 227–230, August 2010.

[18] P. Kyösti, J. Nuutinen, and T. Jämsä, "Simulated correlation accuracy of MIMO OTA spatial fading emulator," in *COST-2100, 11th MCM, TD(10)11061*, Alborg, Denmark, June 2010, http://www.cost2100.org/.

[19] T. Imai, Y. Okano, K. Koshiro, K. Saito, and S. Miura, "Theoretical analysis of adequate number of probe antennas in spatial channel emulator for mimo performance evaluation of mobile terminals," in *Proceedings of the 4th European Conference on Antennas and Propagation (EuCAP '10)*, April 2010.

[20] Panasonic and Tokyo Institute of Technology, "Procedure of the determining the dimension of a spatial fading emulator," in *R4-094317, 3GPP TSG RAN4 Meeting*, Jeju, South Korea, November 2009.

[21] T. Laitinen, P. Kyösti, T. Jämsä, and P. Vainikainen, "Generation of a field with a laplacian-distributed power azimuth spectrum scattered by a single cluster in a MIMO-OTA test system based on multiple probe antennas," in *Proceedings of the Asia-Pacific Microwave Conference (APMC '10)*, pp. 2127–2130, December 2010.

[22] T. Laitinen, P. Kyösti, J. P. Nuutinen, and P. Vainikainen, "On the number of OTA antenna elements for planewave synthesis in a MIMO-OTA test system involving a circular antenna array," in *Proceedings of the 4th European Conference on Antennas and Propagation (EuCAP '10)*, April 2010.

[23] T. Laitinen, *Advanced Spherical Antenna Measurements*, Thesis for the degree of the Doctor of Science in Technology, Helsinki University of Technology, Espoo, Finland, December 2005.

[24] V. I. Turchin and N. M. Tseytlin, "Antenna testing based on near-field measurements," *Radio Engineering & Electronic Physics*, vol. 24, no. 12, pp. 1–26, 1979.

[25] F. Jensen and A. Frandsen, "On the number of modes in spherical wave expansions," in *Proceedings of the 26th Annual Meeting & Symposium of the Antenna Measurement Techniques Association (AMTA '04)*, Atlanta, GA, USA, October 2004.