Advances in Mode-Stirred Reverberation Chambers for Wireless Communication Performance Evaluation

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ABSTRACT

Reverberation chambers (RC) are a popular tool for laboratory wireless communication performance evaluation, and their standardization for Over-The-Air (OTA) measurements is underway. Yet, the inherent limitations of single-cavity RCs to emulate isotropic Rayleigh-fading scenarios with uniform phase distribution and high elevation angular spread put their representation of realistic scenarios into jeopardy. Recent advances in the last few years, however, have solved all these limitations by using more general mode-stirred reverberation chambers (MSC), wherein the number of cavities, their stirring and coupling mechanisms, and their software post-processing algorithms is far from simple, representing a new era for wireless communications research, development, and over-the-air testing. This article highlights recent advances in the development of second-generation mode-stirred chambers for wireless communications performance evaluation.

INTRODUCTION

A reverberation chamber (RC) is a highly conductive enclosed cavity typically equipped with metallic paddles and turntables. The independent movement of paddles and turntables dynamically changes the electromagnetic field boundary conditions. In this way the natural multimode electromagnetic environment inside the single cavity is stirred. With this continuous mode stirring in time, the chamber provides the same statistical distribution of fields independent of location, except for those observation points in close proximity to walls and nearby objects. This required field uniformity also implies polarization balance in the chamber. At any observation point within the chamber, the field will vary from a maximum to a minimum as the different elements (stirrers and turntables) change the boundary conditions [1]. The standard deviation of the mean field throughout the chamber is typically the figure of merit used to assess the performance of the RC. In a perfectly-stirred RC, the real and imaginary parts of the rectangular components of the electric and magnetic field throughout the chamber are Gaussian distributed, independent with identical variances. Thus, the electric or magnetic field inside a perfectly-stirred RC follows a single-cluster Rayleigh probability density function in amplitude and uniform distribution of phase, which resembles the multipath fading in urban scenarios of wireless communications systems. If we assume that the introduction of a matched antenna does not perturb the preexisting field distribution within the chamber, the power received by this matched antenna inside the RC is independent of the antenna gain, directivity, or equivalent area [2]. This, along with the repeatability and reliability of the stochastic reference fields emulated in the RC, makes them ideal candidates to evaluate antenna radiated power for wireless communications systems. Since for handheld wireless communications systems antenna radiated power-related parameters such as Total Radiated Power (TRP) and Total Isotropic Sensitivity (TIS) are the standardized figures of merit, RCs have become a popular tool for evaluating wireless communication performance. Yet, propagating scenarios experienced by users outdoors rarely follow the behavior of a uniform Rayleigh-fading scenario with single-cluster isotropic scattering. A single-cluster assumes that waves that are reflected or diffracted at the receiver and propagated toward the receiver are grouped into just one collection, corresponding to a group of buildings or objects in a room. In urban environments, for instance, one can find several buildings on both sides of the street and each of them can be modeled as a cluster of scatters. Hence, to describe properly this scattering environment, multiple clusters are needed. An isotropic scattering scenario, also known as uniform, assumes that all angles of arrival at the receiver have equal probability, that is, there is no preferred direction of upcoming waves. A distribution of scatters that leads to a uniform distribution of angles of arrival is also difficult to justify in practice [3]. In consequence, recent years have witnessed a relatively large number of papers describing novel concepts using more general mode-stirred reverberation chambers (MSCs) [4] with both hardware and software modifications to that of simple single-cavity RCs in order to overcome their innate limitations. In MSCs, the fields do not necessarily have to be constrained to a single cavity or even be provided in a reverberating mode to the researcher. In consequence, MSCs may contain more than one metal cavity that could be coupled through a variety of means, including waveguides, slots or metal plates, among others. Likewise, the shape of these cavities does not have to be restricted to the canonical ones, and additional software control and algorithms allow extraordinary advantages to the researcher over conventional single-cavity RCs.

This contribution is a short tutorial that highlights the recent advances in wireless propagation emulation using complex MSCs instead of simple RCs. While only a few of these enhancements have reached commercial stage, the novelty accumulated in the last few years could clearly identify mode-stirred reverberation chambers as a direct competitor of more expensive multiprobe multipath spatial fading emulators using anechoic chambers and an excellent tool for wireless communications R&D processes.

HARDWARE ADVANCES

MSCS WITH ENHANCED RAYLEIGH-FADING EMULATION

One of the very first enhancements was related to the ability to stir the modes more efficiently. There are many contributions regarding the shape and size of stirrers to ensure quasi-perfect mode stirring. Effective paddles should be large and asymmetrical [3], and some specific shapes have been analyzed [3]. But not only the shapes of the stirrers play a role in the effectiveness of the RC. Beyond the simple linear movements of paddles or circular movement of the turntable typically employed in RCs, recent findings have shown that complex paddle and device-under-test (DUT) movements also provide for some additional enhancements. Both non-linear and complex stirrer movements have been proposed for enhanced field uniformity [5].

MSCS WITH RICIAN-FADING EMULATION

One important enhancement is related to the ability to emulate Rician-fading environments. The Rayleigh-fading case ($K = 0$) typically emulated by an RC is a special case of a more general Rician-fading case ($K > 0$). The Rician K-factor is defined as the ratio between the power of the coherent component (corresponding to the direct path) over the power of the incoherent component (corresponding to the scattered component) of the received field. In fact, when the RC is not perfectly stirred, the unstirred field component being preserved defines a Rice field in coexistence with the Rayleigh field generated by the stirred components. Stochastic plane wave superposition and separation theories can be employed to obtain both stirred (equivalent to non-Line of Sight or Rayleigh-fading components) and unstirred contributions (equivalent to Rician-fading components). Yet, in most cases the separation of these two components is aided by employing an excitation source that is pointed toward the DUT, and then it is assumed that all wall reflections interact with the paddles [6]. With only one transmitting antenna, other ways of controlling the K-factor are now possible in an MSC. This includes that the transmitting antenna, with a well-defined radiation patter (azimuth change), can be rotated with respect to the DUT, altering the distance between the transmitting antenna and the DUT (distance change), changing the polarization orientation of the transmitting antenna (polarization change), or varying the cavity's Q-factor by chamber loading (Q-factor change) [6]. Some variable K-factor results in [6] are illustrated in Fig. 1.

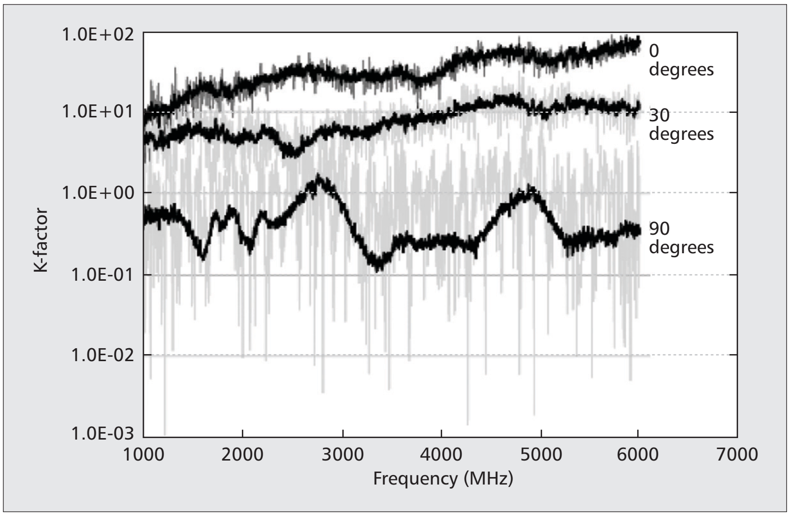

Figure 1. *Variable K-factor in a mode-stirred reverberation chamber when altering the azimuth orientation of the transmitting antenna [6].*

If two transmitting antennas are used, a wide range of K-factors can be obtained by pointing one of them toward the DUT and the other one toward the stirrers [6]. Interestingly, the K-factor obtained in a mode-stirred reverberation chamber has also been found to be dependent on the number and position of absorbers placed within the main cavity [7].

MSCS WITH HYPER-RAYLEIGH-FADING EMULATION

While Rayleigh and Rician fading are commonly used in wireless propagation emulation, small-scale fading encountered in several new scenarios such as vehicle-to-vehicle systems present frequency-dependent and spatially-dependent fading whose severity exceeds that predicted by the Rayleigh fading model. These scenarios are coined as Hyper-Rayleigh, and a very recent paper has been able to accurately emulate these scenarios using a modified reverberation chamber [8]. In [8], an electrically switched multi-element antenna array was added to an RC, and the enclosure size was made considerably smaller than conventional RC for the same tested fre-

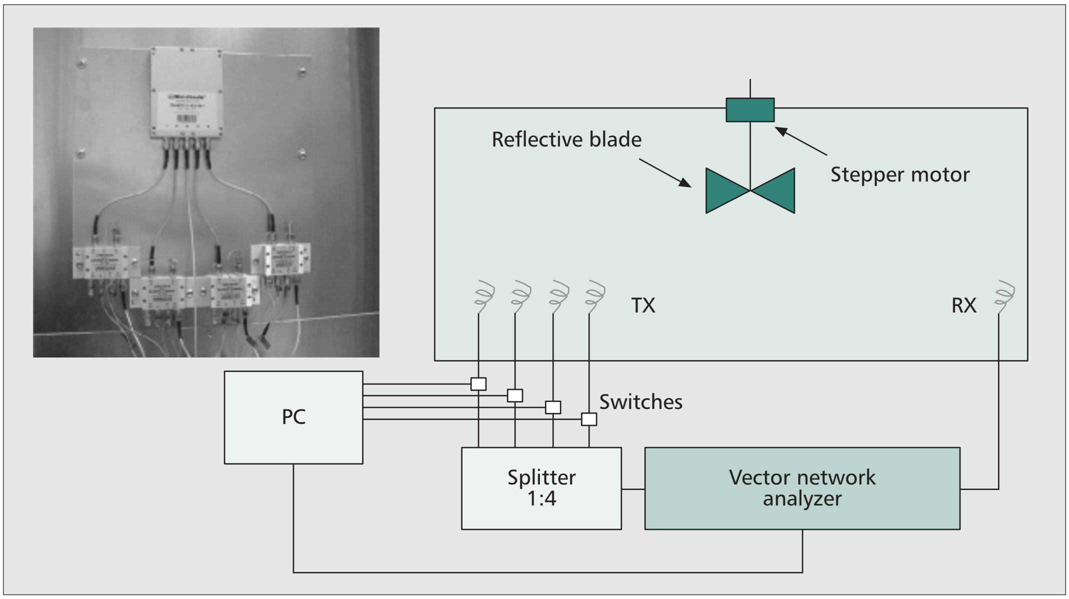

Figure 2. *Block diagram and picture of modified RC in [8] including electrically controlled fading mechanisms and small size.*

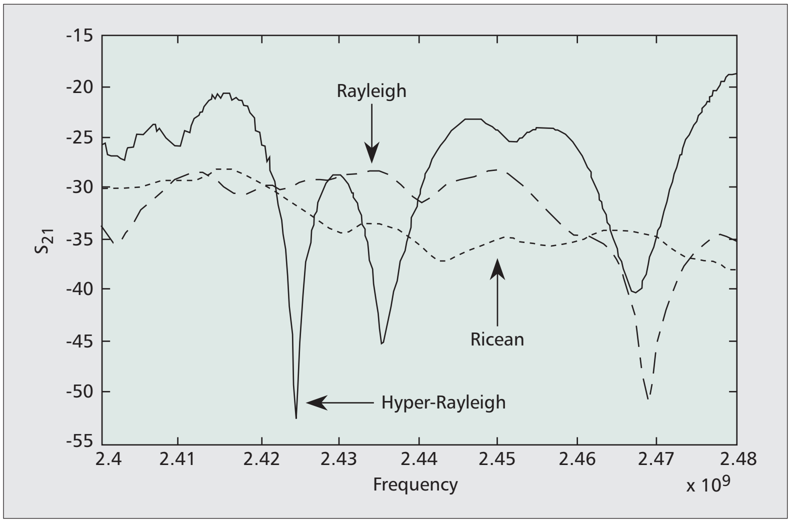

Figure 3. *Plots of signals that experience Rayleigh, Ricean, and Hyper-Rayleigh fading in [8].*

quency range. Figure 3 depicts the plots of signals experiencing Rayleigh, Ricean, and Hyper-Rayleigh fading scenarios in the MSC of [8].

MSCs WITH NON-CANONICAL CONFIGURATIONS

By carefully controlling the excitation source of an RC, the homogeneity and isotropic characteristic of the field at a specific position can be controlled. The key to obtain enhanced performance is the ability to shift and weight each mode within the chamber, and an array of exciting antennas was proposed to alleviate the mechanical requirements of RCs [9]. This is straightforwardly derived if one takes into account the fact that the field strength at any observation point within the chamber can be obtained by the integration in the source. Changing the sources therefore changes the resulting field strengths. This particularly useful advance has even made researchers coin new terms for MSCs, such as scatter-field chamber or source-stirred chamber, among others. In order to excite additional transversal electromagnetic modes, other non-canonical chamber configurations have been proposed. By exciting the chamber with transmission lines [10], for example, new TEM modes that are transversal to those wires can be excited, further increasing the frequency range of operation. In particular, for the same cavity size, the lowest usable frequency becomes smaller. Different wire and phase shift excitations are also possible. Other noncanonical configurations include those contributions that employ a variable geometry, a moving wall [11], or non-parallel walls [12]. In such non-canonical MSCs no eigenmodes exist and a diffuse, statistically uniform field is created without the use of a mechanical mode stirrer. As a result, test times can be drastically reduced.

One recent contribution for enhanced emulation using MSCs is the opening of the door [13]. The aperture of the door transforms one wall that was perfectly electric into a perfectly magnetic wall, but at the same time with a varying aperture degree. Some modes will try to propagate through the opening, and therefore the chamber can no longer be called a reverberation chamber as both reverberating and non-reverberating modes exist. In this way, non-isotropic fading emulation can also be performed using a mode-stirred reverberation chamber, providing for a different number of multipath components (MPC), angle of arrival (AoA), or angular spread values (AS) of the emulated scenarios. Furthermore, the opening of the door can be used for enhancing the accuracy of the chamber for performing antenna radiated power measurements by a more accurate characterization of losses in the chamber by this opening of an aper-

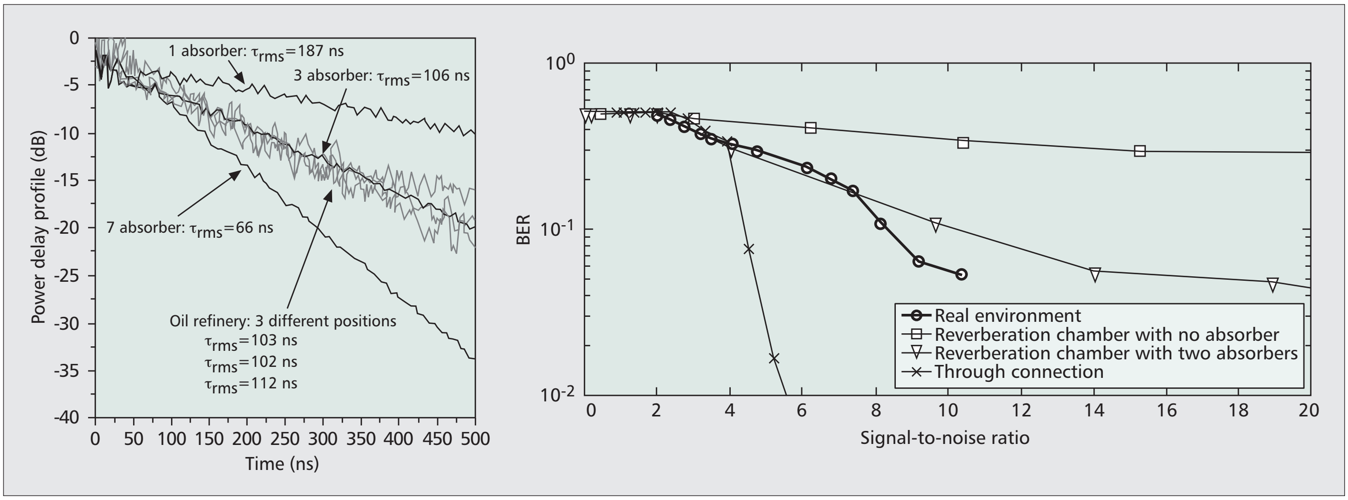

Figure 4. *Different PDPs (up) and BER (down) measured using an MSC [14].*

ture [2]. It seems that the door of the MSC has been really open, in the wide sense of the word.

With the available manipulation of diverse spatial fading multipath characteristics using MSCs, another important step was the ability to control the time-dependent fading performance by being able to emulate variable root-mean square (RMS) delay spreads. Effects such as Doppler spread and fading, which are a consequence of a dynamically moving environment, can also be emulated inside an MSC by moving the paddles with different speeds or using them in stepped or non-linear modes. With the use of absorbers in [14], different RMS delay spread profiles can also be achieved. The ensemble average of the magnitude squared of the impulse response of the MSC is referred to as the power delay profile (PDP) and it is the way to include effects due to time-varying multipath. The shape of the PDP can have adverse effects on the performance of digital communication systems. The RMS delay spread of the PDP is often used to characterize a wireless communication environment because it is directly related to the Bit-Error-Rate (BER) performance of a channel. The BER is an end-to-end performance measurement that quantifies the reliability of the entire radio system from bits in to bits out. Standardized channel models are typically characterized by RMS delay-spreads. As the RMS delay spread in an MSC has been found to be proportional to the chamber Q-factor for a given frequency, this is yet another sign that very accurate standardized channel fading emulation is possible with MSCs. This includes emulating the behavior of the BER for different stirrer velocities [15, 16] and chamber loadings [14, 16], as illustrated in Fig. 4 [14].

While specific power delay profiles can be replicated by adding certain amounts of absorbers and averaging over many different paddle positions, in [17] the transmitter's excitation signal was injected into a fading emulator prior to introducing it into the chamber. In this way, a channel response having multiple discrete clustered distributions, typically found in both urban and suburban settings where reflecting structures may be located far from the receiver, was created. Very accurate emulation of these realistic environments can be performed using the method described in [17]. A clear advantage of this method compared to the one employed in the next section is the use of only one chamber. The disadvantage is clearly the requirement of a fading emulator.

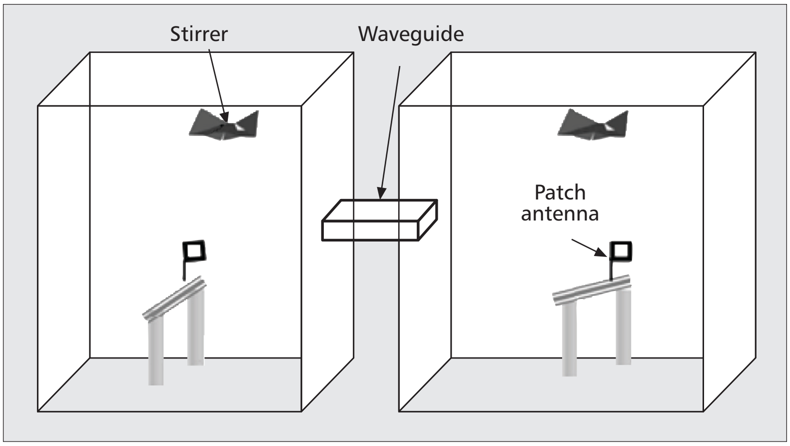

Figure 5. *An MSC with two coupled cavities [18].*

MSCs with Multiple Cavities

Another important advance is the use of multiple cavities in order to provide for some control of a complex multipath environment consisting on diverse clusters with different fading characteristics. A possibility is to use a metal plate with different-size irises separating two cavities. This can give some control over which modes are coupled to the main cavity and also enlarge the delay spread at the main cavity in comparison to single-cavity RCs [13]. Another possibility is to connect two cavities with waveguides or wires [18], as illustrated in Fig. 5. With this modification, the rank channel can be altered, and complex MIMO fading characteristics such keyholes can also be emulated. This enriches the emulating possibilities of MSC, which now include the ability to emulate degenerated H matrices as it happens in tunnels, for example. With multiple cavities, not only the propagation characteristics

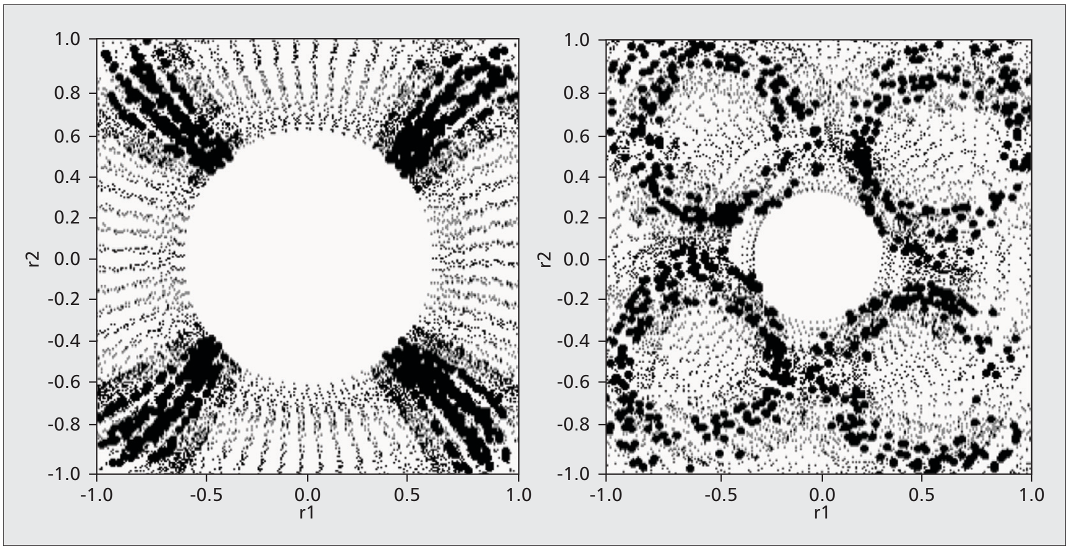

Figure 6. *Different coherence times at GSM1800 emulated in an MSC [15].*

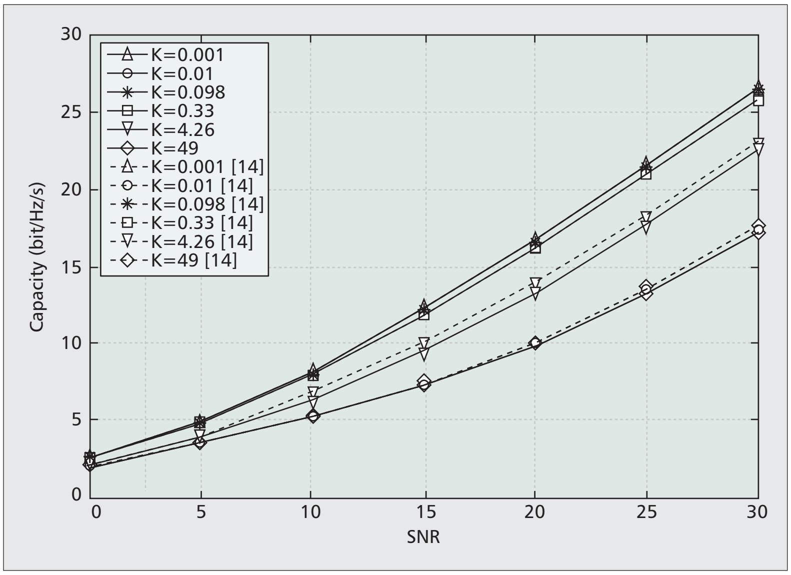

Figure 7. *Outdoor-measured and MSC-measured MIMO capacity vs. SNR for three different 3 × 3 MIMO systems using the offset technique [24].*

of the transmitter and receiver can be modified independently, but MSCs can also reduce the typically high elevation angular spread of RCs. Variable RMS delay spreads have also been obtained with coupled cavities, which have demonstrated their ability to emulate indoor environments, wideband in-vehicle environments [19], or metallic windows, tree canopies, walls and other artifacts in buildings [20]. Interestingly enough, it has been found that for a typical metal-framed window structure, the MIMO capacity is greater than that without metal frames. For an 8 × 8 antenna system, the MIMO capacity is increased by about 2.5 times when metal frames are introduced, and the presence of leaves increases that capacity even more when the transmitted power is kept constant [20]. These enhancements have paved the way for new MSC testbeds for MIMO systems able to emulate standardized fading channels.

SOFTWARE ADVANCES

ACCURATE CONTROL OVER MSC ELEMENTS

If hardware advances are impressive, progress in software post-processing techniques using MSCs does not fall behind. In [15, 16], for instance, an accurate control of the coherence time of an MSC is achieved by means of a properly tailored modulation of the stirrer velocity, as depicted in Fig. 6. The coherence time is the time over which the channel can be assumed constant. This opens the door for very realistic emulation of the time variability of real propagation channels for wireless device performance and signal propagation testing. The coherence time is the most useful parameter for describing this frequency dispersiveness in the time-domain. Another good and useful advance in the field is to emulate multipath fading using a random time-variable phase for every direction of arrival [21], opening the door for complex standardized channel emulation with time- and phase-dependent parameters. A good example of this is the recent ability to measure the radiation patterns of antennas using a modified reverberation chamber [22]. In [22], the free-space field radiated by the antenna is retrieved from measurements in an MSC and time-reversal techniques. Accuracies typically better than 1 dB over the main lobes were achieved. Since more complex testing tools based on near-field and anechoic chamber methods use the radiation patterns of antennas to estimate the correlation properties and from these properties estimate the MIMO parameters, it seems clear that MSC can soon achieve the same level of performance as more complicated two-stage or multiple test probe methods.

STOCHASTIC HANDLING OF MEASURED DATA SAMPLES

A generalized stochastic field model capable of ensuring a continuous transition among very different scattering scenarios by a K-generalized PDF in an MSC has been readily available since 2004 [23]. The application of stochastic sample handling for mode-stirred reverberation chambers has not been suggested until recently [24-26]. Stochastic handling of the measured data set of samples is perhaps the most promising technique for further enhancements. For example, the use of an offset technique within the set of measured samples has been reported to emulate Rician-fading very accurately without any hardware change [24]. For a target K-factor, the required offset has to be defined in terms of the radius of cluster data, the distance of centroid of cluster from the origin, and its phase-coherence to the selected radius. A comparison between Rician-fading emulation using this technique and outdoor Rician measurements can be observed from Fig. 7. Good agreement is observed.

One very recent method that is able to emulate arbitrary fading scenarios is the sample selection technique [25]. The sample selection technique consists of selecting the sample subset that conforms to a specific target fading statistical ensemble from the whole sample set measured in the MSC using genetic algorithms. It has to be mentioned that the selection is possible because the originally-measured Rayleigh-fading set is composed of many different clusters due to the multiple-cavity slots-coupled system employed. Only with stochastic theory, this method can really target the emulation of standardized channel models (GSCM, SCM, SCME, Winner-II or IMT-Advanced), which is no longer unheard of for MSCs, as illustrated in Fig. 8. In this figure, the stand-alone normalized 1 × 2 MIMO throughput (spectral efficiency) for a IEEE 802.11n device measured in the E200 MIMO Analyzer by EMITE Ing (illustrated in Fig. 9) following the procedure in [27] is compared to the 1 × 2 802.11n MIMO capacity (Shannon) measured in the E200 by EMITE Ing with the sample selection method. The equivalent spectral efficiency calculated with the public Matlab™ code for the standardized IEEE 802.11n is also depicted for comparison purposes. The 802.11n target data sample for the sample selection algorithm was a 2 × 2 MIMO system at a frequency of 2.4 GHz with nine propagation paths in an office environment (indoor). The E200 MIMO Analyzer is a two-cavity MSC with dimensions of 0.82 m × 1.275 m × 1.95 m, eight exciting antennas allowing accurate source-stirring, polarization stirring due to aperture-coupling and to the different orientation of the antenna exciting elements, three mechanical and mode-coupling stirrers, one holder-stirrer and variable iris-coupling between the two cavities. Distribution fitness errors below $2*10^{-4}$ were achieved in less than 40 seconds using a hybrid linear-genetic algorithm. Despite the initial method constraints (the target distribution has to have the same mean power as the initial distribution), it is clear that unheard-of emulation possibilities are provided by the sample selection technique using MSCs. The possibilities for arbitrary emulation and testing in all spatial-, time- and code-domains are very interesting, and MSCs could really equal the performance of more complex spatial-fading emulators based on anechoic chambers at a fraction of the cost in the very near future.

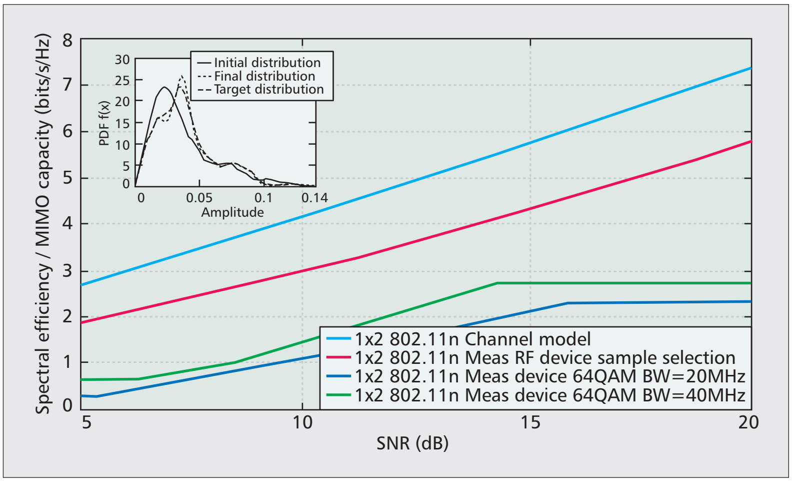

Figure 8. *Stand-alone normalized 1 × 2 MIMO throughput for a IEEE 802.11n device measured in the MIMO Analyzer [26].*

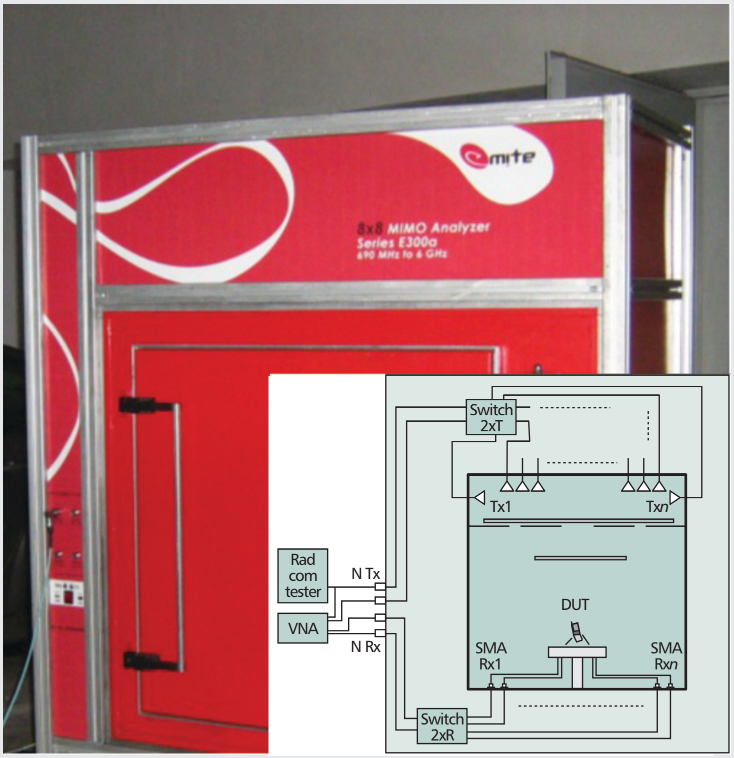

Figure 9. *The two-cavity MIMO Analyzer MSC [courtesy of EMITE Ing].*

CONCLUSIONS

In the last few years, different advances have enabled mode-stirred reverberation chambers (MSCs) to solve the inherent limitations of conventional single-cavity reverberation chambers (RC) for wireless communication performance evaluation. It is now clear that MSCs have considerably improved the Clarke's model followed by conventional single-cavity RCs, and that with arbitrary fading emulation using second-generation MSCs, a new era has started for MIMO research, development, and OTA testing.

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BIOGRAPHIES

MIGUEL Á. GARCIA-FERNANDEZ was born in Cartagena, Spain. He received the Dipl.-Ing. degree in telecommunications engineering from the Universidad Politécnica de Cartagena, Murcia, Spain, in 2005 and the Ph.D. degree from the Universidad Politécnica de Cartagena, Murcia, Spain, in January 2010. From 2005 onwards, he joined the Department of Information Technologies and Communications, Universidad Politécnica de Cartagena, Murcia, Spain. From October 2009 to September 2010 he also joined the Department of Applied Mathematics and Statistics, Universidad Politécnica de Cartagena, Murcia, Spain. His current research areas cover multiple-input-multiple-output communications, SAR measurements and thermoregulatory processes due to electromagnetic field exposure.

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