Abstract— While MIMO studies have been with us for quite some time now, practical mass implementation of MIMO is encountering more problems than initially foreseen. In an unusual multidisciplinary approach, signal-processing and RF-antenna engineering techniques are being jointly applied to solve implementation problems. Ergodic capacities initially predicted are disguised by blind-prototypes, and to further complicate the dispute, recently-presented diagonally-correlated MIMO channels have shown higher ergodic capacity than that provided by independent and identically distributed (i.i.d.) fading channels. In this presentation the academic rigor of the pure signal-processing approach will be abandoned and challenged by a less-conventional electromagnetic approach. Several well-known and assumed formulas will be put in jeopardy with the aim of identifying lines of collaboration between diverse disciplines. This is the way forward for future MIMO challenges, such as the important handset MIMO already specified for 4G terminals. In addition, novel multimode-stirred cavities as testing techniques which pose themselves as good alternatives to OTA MIMO testing will be described, and their capabilities demonstrated.

Index Terms— Diversity methods, MIMO systems, spatial correlation, polarization, reverberation chamber.

I. INTRODUCTION

Since the publication of Claude Shannon’s communications theory in 1948 researchers worldwide have been trying to break his channel capacity limits. Channel coding has traditionally received their attention to achieve this goal when it regards to wireless link, which has been successfully in other areas, such as fiber optics. If we have a look at the spectral efficiency evolution for fiber optics, there has been a 20-fold increase over a decade (from 0.05 b/s/Hz in 1996 to 1 b/s/Hz today). The break at the wireless scenario was finally promised by Telatar and Foschini, who challenged Shannon with the MIMO concept. For a given bandwidth, MIMO promised to improve the bit-error rate and data throughput. The aim was to build a multiple antenna system in which as many as possible of the transmit- and receive-antenna pairs would be able to distinguish the information channels sharing the band. A wireless system with four transmitting and four receiving antennas operating in ideal propagating conditions, i.e., with lots of multipath, and with a signal-to-noise ratio of 12 dB at 10% channel outage could provide a spectral efficiency of 11 b/s/Hz. In comparison, a single antenna system would require 2048 constellation points and an SNR of more than 33 dB to achieve the same spectral efficiency. Instead of scaling linearly with the bandwidth (Shannon), the capacity scales linearly with the number of antennas. No wonder why in recent years we have witnessed an increasing interest in MIMO systems. With these high expectations, MIMO is widely considered to be an integral technology to 4G. For example, a LTE 20 MHz channel consumes 800 times the spectral resources of a 200 kHz single-slot GSM channel. This represents a much higher delivery costs for high-speed services, and MIMO is already a reality for LTE. Yet, the high simulated capacities of MIMO systems for both correlated and uncorrelated scenarios [1-3] have not been obtained with realistic channels [4]. In future LTE systems, MIMO will also be present at the handset, and it is precisely this handset MIMO what has prompted new scenarios and results for MIMO in practice. In this contribution, several well-known formulas for MIMO will be challenged by the new handset MIMO situation. Novel definitions and concepts will be presented, and the important role of antenna engineering will be highlighted for using MIMO in practice. In this challenging scenario, novel test instruments are being developed, such as second-generation multimode-stirred chambers. The enormous capabilities of these tools and their inherent ability to properly emulate MIMO scenarios for 4G testing will also be described at the presentation.

II. DO I REALLY KNOW MIMO?

A. Polarization diversity

The improvement granted by polarization diversity in wireless systems is typically obtained by an additional de-correlated channel provided by a polarization state made orthogonal to the existing one. When trying to achieve efficient handset MIMO, one has to find ways of de-correlating MIMO branches due to the inherent volume limitation. It then comes to the mind why should we use only one orthogonal additional channel for polarization diversity in the first place since, a) multiple scattering may not be sufficient for a given polarization to decouple half its power into the orthogonal polarization [1] and b) both reflection and diffraction processes are polarization sensitive. Channel behavior is therefore different for different polarization states [5]. This enhances the potential of using multiple polarization states to avoid the possible lack of richness in multipath.

Recently, a tri-axial combination of polarization and pattern diversity has also been proposed [5-6]. For some reasons only publishers and editors could know this idea has appeared in the scientific literature also in in a recurrent way. The tri-axial idea, however, is still thinking of conventional signal propagation using orthogonal polarization states. A recent letter of ours [7] has proposed a novel true polarization diversity (TPD) technique. The idea is simple. In a large MIMO array, a true progressive polarization scheme could be achieved by an
arbitrary progressive angular separation between antennas in a similar way that a progressive spatial separation is employed for spatial diversity. In this way the third element in the array is rotated 2*D0 degrees respect to the first one, with D0 being the angular separation between contiguous antennas in the array. This is equivalent to spatial linear diversity scheme where the third antenna is separated a distance of 2*D from the first one, with D being the spatial separation between contiguous antennas in the array. Despite its simplicity, it was not been proposed before [7]. This is mainly due to the inherent complexity of the coupling mechanisms between different polarizations states [8]. In fact, an accurate prediction of the correlation coefficient between two dipoles separated by both a spatial distance and an arbitrary angular position (something required for proper emulation of TPD) has not been available until very recently [9]. TPD published results have demonstrated that it can be effectively combined with spatial diversity to nearly double the diversity gain and MIMO capacity for the same available volume. TPD outperforms conventional orthogonal polarization diversity (OPD) for reduced volumes. Some interesting figures will be presented at the workshop. TPD is patent protected by EMITE Ing.

Fig. 1. The TPD concept.

B. Efficiency-related effects on MIMO performance.

Likewise, it has been assumed for some time now that there is no need to use more receiving antennas (R) than transmitting antennas (T) [10-11], that is, β=T/R<1. This is due to a predicted minuscule capacity improvement, but yet under noise-limiting conditions and very large power angular spread (~360°), which may not be assumed in the presence of the user. Similarly, significant gain reduction occurs when an antenna is used close to the human body, with resulting radiation efficiencies below 50% [12]. When the antenna is integrated in a small volume, an additional efficiency reduction is also expected [13], aggravating potential MIMO performance. The user presence at the receiver end also affects MIMO performance by increasing the correlation coefficients when the head blocks the signals, diminishing dissimilarities in the radiation patterns away from the head [14-15].

In order to identify only efficiency-related effects, we have defined the ideal diversity gain (IDG), where the reference is the theoretical upperbound Rayleigh curve and measurements are taken for isolated antennas so as to avoid mutual coupling. With the introduction of IDG another term can immediately be coined for the employed combining scheme of the N receiving antennas; the diversity gain loss (DGL). Similarly, MIMO capacity loss due to efficiency (CL.MIMO∞) can be defined. Results will be shown at the presentation regarding the demonstrated important effect of efficiency on final MIMO performance. Efficiency plays an important role when determining MIMO capacity, particularly at low SNR. With a SNR of 15 dB, 25 % capacity loss can be expected when low efficient antennas are employed instead of highly efficient antennas, or simply when the user is present in close proximity to the MIMO receiving antennas. Consequently, the combining possibilities and antenna topology for MIMO systems in the presence of the user acquires great importance.

Figure 2 illustrates the simulated and measured effect of adding high efficiency transmitting or receiving antennas to a 3x3 MIMO system, initially comprising low efficiency receiving antennas. A good matching between simulated and measured results is again observed. As expected, the increment in MIMO capacity is clear when both transmitting and receiving antennas are simultaneously added to the system, even when these added antennas have a low efficiency. Yet, it is interesting to observe from this figure that, unlike what is widely accepted, there is a non-negligible capacity increase beyond R=T when high efficiency antennas are added to a low efficient MIMO system. Likewise, this increment beyond R=T is more important as SNR increases. Figure 2 also shows that just adding a high efficiency receiving antenna to the 3x3 MIMO system is better in terms of capacity increase than adding both a receiving and a transmitting low efficient antenna, but only for a specific SNR value that depends on the radiation efficiencies of the added antennas.

Results in figure 2 and others that will be presented at the workshop demonstrated that while it has been assumed for some time now that there is little incentive on using more R receiving antennas than T transmitting antennas, in the presence of the user this is no longer true and it depends very much on the radiation efficiencies of the antennas themselves. With β=T/R showing a much more complex optimum behavior than unity, results are particularly important for the novel recently proposed MIMO designs on handheld terminals. It has to be mentioned, however, that the capacity increase beyond β=1, or the equivalent reduction in capacity loss due to efficiency, is only important at low and moderate SNRs. [16].
III. MULTI-MODE STIRRED CHAMBERS

The novel concepts discovered in handset MIMO has prompted the need for novel test instruments. Laboratory research can be performed over an artificially-generated multipath environment. This can be done with multimode-stirred chambers. A multimode-stirred chamber is a metal cavity or coupled-cavities sufficiently large to support many natural resonant modes (multimode). The excited modes are perturbed with stirrers and other apparatus in order to create the desired multipath. It has been thought for some time now that these chambers were limited to Rayleigh-fading scenarios. Second-generation multimode-stirred chambers, however, have already demonstrated their ability to reproduce non-isotropic environments [17], Ricean-fading environments [18], indoor environments with different rms delay spreads [19], wideband in-vehicle environments [20], keyhole effects [21] or metallic windows, trees, walls and other artefacts in buildings [22]. In consequence, the emulation performed in multimode-stirred chambers has abandoned the classic Clarke’s model and it is now a reality for MIMO testing.

![Figure 3. The multipath environment emulated by a multimode-stirred chamber.](image)

A good example is that of the MIMO Analyzer by EMITE Ing, depicted in figure 4. The second-generation multimode-stirred chambers developed by EMITE Ing are a unique combination of multimode applicator stirring, broadband antennas, signal-processing and iris coupling know-how and patents. The MIMO Analyzers by EMITE Ing avoid polarization imbalance, emulating a wide variety of Rayleigh, Rician and both isotropic and non-isotropic environments, and can therefore accurately emulate realistic propagating environments. The MIMO analyzer provides both non-physical (effective, ideal, apparent and actual implemented diversity gain [EDG, IDG, ADG, DG], efficiency [η], diversity gain loss due to efficiency [DGL], MIMO capacity [CMIMO]), capacity loss due to efficiency [CMIMO]), and physical parameters (angle of arrival [AoA], number of multipath components [MPC], number of scatters [NS], mean and effective mean effective gain [MEG, EMEG]) to the MIMO engineer. Since it is highly unlikely that all receiving antennas have the same radiation efficiency and their position relative to the user is different, these two parameters help identifying the MIMO design optimum $\beta = T/R$ for a specific fading environment and angular spread, as depicted in figure 5, or even for a variety of conditions through multiple tests in the MIMO Analyzer. Future emulation techniques include the effects of metallic windows and other artefacts, trees and walls in buildings or more complicated fading scenario emulation such as Vehicle-to-Vehicle. A detailed description of the MIMO Analyzer capabilities will be shown at the presentation.

![Figure 4. The MIMO Analyzer by EMITE Ing.](image)

![Figure 5. Measured capacity increase when adding antennas to a 3x3 MIMO.](image)

IV. CONCLUSIONS

Results presented in this contribution have highlighted the emulating performance of multimode-stirred chambers beyond the conventional Rayleigh-fading environment with uniform angle and elevation distributions. The second-generation chambers like the MIMO Analyzer provide for accurate, fast and repeatable MIMO measurements, and can drastically reduce research and production costs and time to market schedules. These capabilities also provide a basis for comparing test results as system hardware/software is changed, or alternate devices are...
tested. Automated testing improves time to market, test coverage, repeatability as well as the collection and archiving of the results. Broadband speeds are bringing up new categories of devices such as smartphones, Mobile Internet Devices (MIDs), Ultra Mobile PCs (UMPCs) and netbooks, where MIMO has to be fully integrated. Consequently, the MIMO Analyzer is therefore of interest to both 3.5/4G cellular handsets and non-handsets wireless devices manufacturers, including chipsets, cellular phones, smartphones, wireless LAN access points, HSPA+ routers, compact handheld mobile computers, PCMCIA cards, PDAs, netbooks and others. The new tools like the MIMO Analyzer should find a way through standardisation for MIMO testing at international committees like 3GPP or CTIA.

V. REFERENCES


Juan F. Valenzuela-Valdés was born in Marbella, Spain. He received the Degree in Telecommunications Engineering from the Universidad de Malaga, Spain, in 2003 and his PhD from Universidad Politécnica de Cartagena, in May 2008. In 2004 he worked at CETECOM (Malaga). In 2004, he joined the Department of Information Technologies and Communications, Universidad Politécnica de Cartagena. In 2007 he joined EMITE Ing as Head of Research. His current MIMO communications, multimode-stirred chambers and SAR research areas cover over 80 patents. His current research interests encompass all aspects of the design and application of printed multi-band antennas for mobile communications, electromagnetic dosimetry issues and MIMO techniques for wireless communications.

David A. Sánchez-Hernández (M’00)(SM’06) obtained his Dipl.-Ing. in Telecommunications Engineering from Universidad Politécnica de Valencia, Spain, in 1992 and his PhD from King’s College, University of London, in early 1996. From 1992 to 1994 he was employed as a Research Associate for The British Council-CAM at King’s College London where he worked on active and dual-band microstrip patch antennas. In 1994 he was appointed EU Research Fellow at King’s College London, working on several joint projects at 18, 38 and 60 GHz related to printed and integrated antennas on GaAs, microstrip antenna arrays, sectorization and diversity. In 1997 he returned to Universidad Politécnica de Valencia, Spain, where he was co-leader of the Antennas, Microwaves and Radar Research Group and the Microwave Heating Group. In early 1999 he received the Readership from Universidad Politécnica de Cartagena, and was appointed ViceDean of the School for Telecommunications Engineering and leader of the Microwave, Radiocommunications and Electromagnetism Engineering Research Group. In late 1999 he was appointed Vice Chancellor for Innovation & Technology Transfer at Universidad Politécnica de Cartagena and member of several Foundations and Societies for promotion of R&D in the Autonomous Region of Murcia, in Spain. In May 2001 Dr. Sánchez-Hernández was appointed official advisor in technology transfer and member of The Industrial Advisory Council of the Autonomous Government of the Region of Murcia, in Spain, and in May 2003 he was appointed Head of Department. He is also a Chartered Engineer (CEng), IET Fellow, IEEE Senior Member, Ampere Board member, CENELEC TC106X member, and is the recipient of the R&D & J. Langham Thompson Premium, awarded by the Institution of Electrical Engineers (now formally the Institution of Engineering and Technology), as well as other national and international awards. He has published over 40 scientific papers and over 80 conference contributions, and is a reviewer of several international journals. He holds six patents. His current research interests encompass all aspects of the design and application of printed multi-band antennas for mobile communications, electromagnetic dosimetry issues and MIMO techniques for wireless communications.