The Evolution of RF Instrumentation and Antenna Measurements: Bridging the Gap in Active Device Testing

Lars J. Foged[1], FELLOW, AMTA, Francesco Saccardi[1], FELLOW, AMTA and Nicolas Gross[2], MEMBER, AMTA
(1) MVG, MICROWAVE VISION GROUP, POMEZIA, ITALY
(2) MVG, MICROWAVE VISION GROUP, PARIS, FRANCE

***Abstract*— Modern wireless standards such as LTE, HSPA, WiMAX, and 5G have introduced the need for more sophisticated testing of devices that use multi-antenna systems. Traditional Over-the-Air (OTA) test methods, initially developed for single-input single-output (SISO) devices, fall short when evaluating complex systems like Multiple-Input Multiple-Output (MIMO) devices. This paper discusses the convergence of traditional testing methodologies based on conducted RF testing and OTA antenna system test methodologies toward testing of the full antenna equipped device. This convergence embraces two important testing needs and scenarios: replay of preconfigured scenario, based on spatial fading emulation (SFE) / channel modelling and dynamic hardware-in-the-loop testing, where changes in the hardware state in reflected in the status of the testing scenario. By the integration of channel emulation and multiprobe anechoic configurations, scalable and flexible test strategies can be achieved accommodating testing needs in personal and automotive communication systems but also defense applications.**

This paper gives an overview of existing MIMO OTA test methodologies and indications on developments to come ahead.

Index Terms—antenna, automotive, calibration, communication, channel model, MIMO

I. INTRODUCTION

The rapid evolution of wireless protocols necessitates increasingly advanced testing solutions. MIMO technologies exploit spatial diversity to improve throughput and link reliability, especially in multipath-rich environments. However, MIMO performance depends on both antenna characteristics and channel conditions, which are inseparable in real-world usage. The traditional OTA figures of merit Total Radiated Power (TRP) and Total Isotropic Sensitivity (TIS) are insufficient to evaluate multi-antenna performance [1]. Instead, absolute data throughput under realistic channel emulation becomes the primary metric.

SISO OTA testing evaluates device radiation using Effective Isotropic Radiated Power (EIRP) and Sensitivity (EIS), aggregated as TRP and TIS. While sufficient for single-antenna systems, these metrics fail to account for spatial channel characteristics and antenna correlation in MIMO configurations. SISO-based setups cannot replicate the propagation complexity required to evaluate MIMO behavior, where the interaction between the antenna system and environment is key to performance [2].

II. WHY IS MEASURED SYSTEM SENSITIVITY INSUFFICIENT

The addition of multiple antennas in a complex wireless system can lead to an improvement in overall sensitivity, often quantified by Total Isotropic Sensitivity (TIS). As an aggregate figure of merit, TIS is useful for making simplified comparisons and system design trade-offs. However, it does not capture the full picture for MIMO systems. Performance in MIMO configurations depends not only on sensitivity but also on spatial parameters such as antenna correlation, diversity gain, and the richness of the propagation channel, none of which are reflected in a single integral metric like TIS.

To illustrate the limitations of relying solely on TIS as a performance qualifier of MIMO, consider a simple experimental setup as shown in Figure 2. A laptop is equipped with two external antennas mounted on its lid, with adjustable spacing between them. These antennas are connected to a MIMO enabled device that can operate with either one or both antennas simultaneously 900MHz. The configuration is tested using a spherical near-field OTA system (SL18GHz) capable of accurately determining TIS.

Measurements of the directional sensitivity of the system with one and two antennas as a function of spacing between the antennas were performed in an angular grid around the MIMO enabled laptop as test device. The measurement device and setup are shown in Figure 1.

Figure 1: TIS test scenario with multiple antennas. Laptop with external antennas (left), antenna placement on the laptop lid (right), and SL18GHz spherical near-field measurement system used for accurate TIS determination (below).

Measured TIS variation with one and two antennas enabled on a notebook device with varying spacing between the antennas are shown in Table I. It was found that the theoretical, upper limit TIS improvement of 3dB was achieved at a distance between the two antennas of 4.5in or 114mm. It should be noted that other than the measurements errors relative to measurement of TIS, the relative TIS improvement is effected by measurement uncertainties, particularly from slight performance differences between the two antennas, such as internal losses or design mismatches, which may influence the results.

Table I: Measured TIS variation with two and one antenna enabled on notebook device with different spacing's between the antennas.

Antenna Spacing	Correlation Coefficient	TIS One Antenna	TIS Two Antenna	Δ TIS
1.0 in	0.31	102.1 dBm	104.0 dBm	1.9 dB
1.5 in	0.15	102.6 dBm	104.7 dBm	2.1 dB
3.0 in	0.01	102.6 dBm	104.9 dBm	2.3 dB
4.5 in	0.03	102.9 dBm	106.0 dBm	3.1 dB

From these measurements, the dual-antenna configuration demonstrates a clear design improvement, achieving up to a 3 dB increase in sensitivity. This is consistent with the theoretical upper bound for using two antennas. However, a closer examination of the spatial sensitivity distribution reveals a more complex picture. Figure 3 presents the 3D sensitivity patterns for both single- and dual-antenna setups. Although the overall TIS improvement is evident, the gains from the second antenna are concentrated in angular regions already well-covered by the single-antenna configuration. Consequently, even with both antennas active, the device continues to exhibit regions of poor sensitivity, indicating that the improvement is not spatially uniform.

This highlights the critical importance of evaluating design improvements not solely on integrated performance metrics like TIS. Spatial performance indicators, such as angular coverage and sensitivity distribution, must also be considered to ensure that enhancements address the full range of operational scenarios.

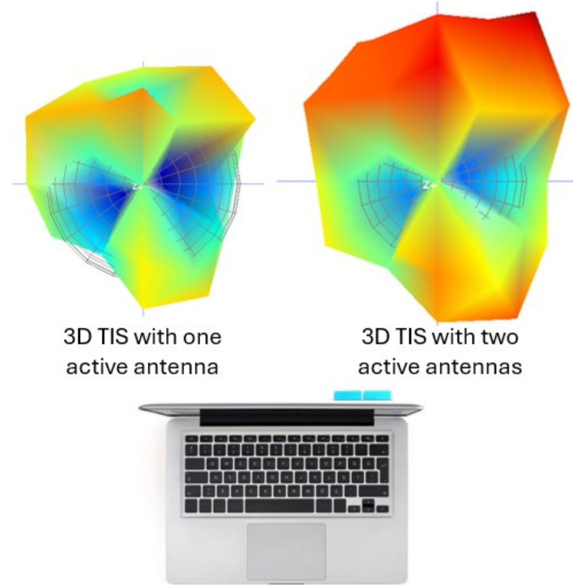

Figure 2: Measured 3D TIS pattern of device with one (left) and two (right) antennas enabled.

III. MIMO OTA TESTING OF DEVICES

MIMO OTA testing aims to determine system-level performance parameters such as data throughput relative to received power levels at the Device Under Test (DUT) in a realistic, emulated environment. This testing is guided by standardized channel models that capture both RF and spatial domain characteristics [3]. Channel models represent the radio environment experienced by the DUT and are composed of:

- RF Contributions: Modulation, polarization, temporal delay, Doppler effects
- Spatial Contributions: Angular spread and wavefront directions, approximated as plane waves

Figure 3 illustrates how a general channel model combines these components.

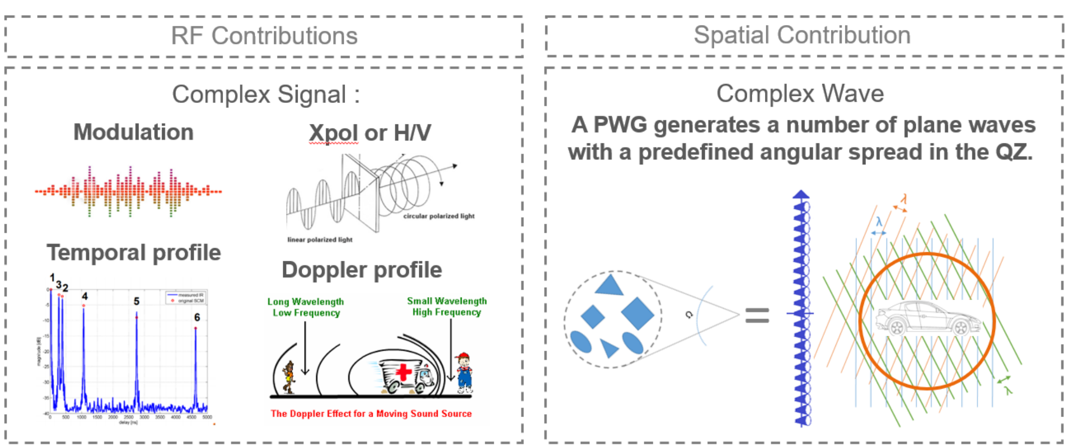

Figure 3: Components of a general OTA measurement system used to emulate a channel model in a controlled environment, such as an anechoic chamber. The emulation separates RF and spatial components, achieved through a combination of channel emulation and spatial probe array configuration..

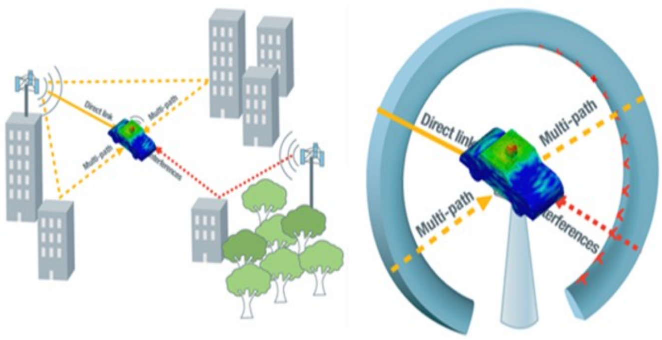

Figure 3: Illustration of a complex propagation scenario and how it is replicated within a controlled anechoic environment using a MPAC setup. As the device moves through the complex environment the RF and spatial representation of the environment changes accordingly.

The test setup emulates a time-varying scenario as the DUT virtually traverses through the modeled environment. The test output is data throughput as a function of the isotropic available power at the DUT position. The relationship between the known available power at probe level and the isotropic power available at the DUT is found through a system calibration step using a substitution technique with a known calibration antenna, often a dipole and/or loop. It is generally recommended to calibrate the system with reference antennas that radiate similarly to the unknown DUT antennas. The goal is to simulate a consistent, repeatable RF environment around the DUT without requiring feedback from the device. Throughput is measured at various power levels at the DUT position. The results for different azimuth angles are averaged to produce a single throughput-vs-power curve that characterizes the DUT in a given scenario [4]. An illustration of a complex propagation scenario and how it is replicated within a controlled anechoic environment is shown in Figure 4.

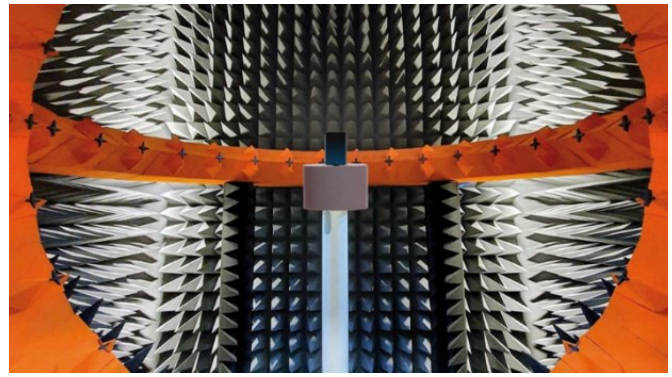

Figure 4: MPAC, MIMO OTA test setup with horizontal ring of probes to represent different azimuth directions of the desired channel models.

IV. Example of MIMO OTA Testing

The antenna impact on MIMO system performance, in terms of throughput, can be illustrated by the MIMO 2×2 reference antenna concept reported in [5]. As shown in Figure 6 (left), three antenna pairs, representing the full range of "good", "nominal" and "bad" MIMO 2×2 antenna performance were conceived with low gain imbalance (ΔG≅0dB) each covering three LTE bands (2, 7 and 13):

- Good, Low correlation (σ~0.1), high efficiency (>90%).
- Nominal, Moderate correlation (σ~0.5), moderate efficiency (>50%).
- Bad, poor correlation (σ~0.9), poor efficiency (<50%).

To isolate antenna and transceiver performance, the antennas were designed attaching the MIMO 2×2 external antennas to a RF shielded enclosure, where the DUT and its RF connections are located as shown in Figure 6 (left).

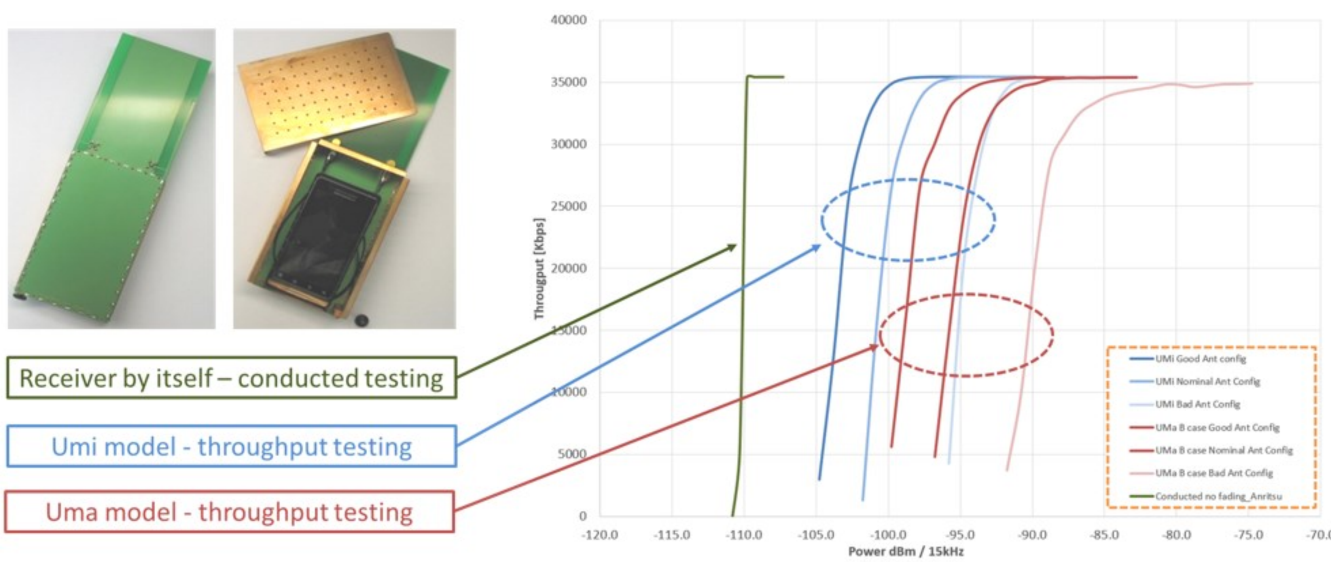

Figure 6: Comparison of measured MIMO throughput in a calibrated OTA setup for different propagation environments (Umi and Uma) using the "Good", "Nominal" and "Bad" reference antennas.

The conducted testing show that, as characteristic for devices, the modem is cable of full data throughput when the isotropic power level at the input is ~ -110dBm. As can be expected, the required isotropic power level at the device position in a realistic MIMO OTA testing scenario is higher than this value to achieve full data throughput as shown in Figure 6 (right). It can be observed that the difference between a "good" and "bad" antenna design is 8dB in this specific testing scenario. It can further be observed that the Uma SCME model is generally a more difficult environment than the Umi model, in this specific testing the difference is about 5dB.

V. CONCLUSIONS

This paper has provided an overview of existing MIMO OTA test methodologies. Two design example of a MIMO enabled device has been used to illustrate the design challenges and the need to include spatial dependencies in MIMO OTA testing of devices.

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