Challenges for the Automotive Industry on MIMO OTA Testing

Mihai Berbeci[1], Patrick Pelland[2], Thomas Leifert[3]

[1] NSI-MI UK Ltd.
Sheffield, S119SE, UK
[2] NSI-MI Technologies
Suwanee, GA 30024, USA
[3]Keysight Technologies
71034 Böblingen, Germany

Abstract — **The evolution of cellular communication technologies has been replicated by the automotive industry with modern vehicles being almost universally fitted, as a bare minimum, with a radio system, a cellular communication system and Bluetooth capability. Higher end vehicles have additional capabilities such as WiFi, GNSS, TPMS, smart keyless entry and smart start/stop feature. All these systems are highly integrated as part of the vehicle's infotainment unit and they must operate satisfactorily in a co-existing manner.**

Automotive wireless testing is currently facing several challenging aspects with one such aspect being MIMO OTA (Multiple-Input-Multiple-Output Over-the-Air) testing of the terrestrial cellular communication system of the vehicle. In this paper, we will examine the current approach for MIMO OTA testing in the 4G and 5G cellular environments and discuss various scenarios on how existing techniques can be adapted to support MIMO OTA testing in the automotive industry.

Index Terms MIMO, OTA, Automotive, MPAC, RTS, CTS

I. INTRODUCTION

The measurement of vehicle mounted systems has evolved in complexity in order to keep up with the technological advances of vehicle mounted infotainment and safety equipment. In its infancy, automotive antenna testing was performed primarily outdoors and was typically limited to antenna radiation pattern characterization. In the early 2000s, a number of indoor automotive test ranges were being delivered. These systems were still primarily used for antenna pattern characterization with some additional power-related metrics measured using CW signals. Today, indoor automotive antenna measurement systems are commercially available and the industry's preferred solution.

Meanwhile, in the cellular communications industry, over-the-air (OTA) testing for wireless systems was necessitated by the roll out of 4G cellular technology and the need to measure system level parameters such as data throughput. The objective of OTA testing is to quantify the performance of the device under test (e.g. cellular phone) in real world conditions and, in very simple terms, it can be thought of as a cellular handset that is powered on inside a test environment and its performance measured by the instrumentation.

As both 4G and 5G cellular technologies are data focused, both technologies rely on a concept called Multiple Input Multiple Output (MIMO) to increase the data capability or the resilience of a communication link. MIMO uses multiple transmitters and receivers to transmit and receive multiple data streams at the same time.

The introduction of MIMO in the cellular communication world for 4G and 5G technology is now starting to be mirrored by the automotive industry and vehicle manufacturers are adapting the technology to be used on modern vehicles. This is a natural step in the direction of improving vehicle connectivity and the user experience, but it presents one fundamental: How does one characterize the performance of vehicle- mounted MIMO systems?

The typical test setup for MIMO OTA testing consists of a shielded anechoic enclosure, a scenario emulator (base station emulator for cellular technology tests) , a channel emulator and a multiple-probe system[1][2]. The implementation details are well understood for small form factor devices such as cellular handsets, tablets or laptops. The challenge presented by testing a MIMO system on a vehicle is the physical size of the article under test, i.e. car, bus or van; even the smallest car is several orders of magnitude larger than a handheld cellular device. This means that existing MIMO OTA test methods which are applicable to small form factor devices may not necessarily be fully scalable to MIMO OTA testing in an automotive environment.

The typical technology that can be found in a modern vehicle includes systems such as infotainment (radio, DAB DVB) wireless communication capabilities (Cellular 4G/5G, Bluetooth and WiFi), satellite guidance system (GPS etc), vehicle condition monitoring (telemetry) to name but a few. Automotive test ranges are becoming increasingly more complex and capable such that they can accommodate the testing of existing vehicle mounted systems. MIMO is a technology subset of cellular communication and given its success in the handset implementation means that automotive manufacturers have started introducing MIMO on modern vehicles. The large electrical size of these vehicles and lack of formal OTA standards for the automotive industry make the testing of such a system challenging. Characterizing the MIMO OTA performance of such a vehicle is an area of great interest today and the focus of this paper. A survey of five possible MIMO test methodologies will be outlined in Section II. Advantages and disadvantages of each technique will be included. Some concluding remarks will be shared in Section III.

II. MIMO OTA Test Methodologies

The main metric of interest when testing a MIMO system is the data throughput that can be achieved under various scenarios. MIMO system designers work to optimize MIMO antenna placement to yield a balance between data throughput and aesthetics/practicality. The performance of a MIMO system is influenced by a number of factors, including channel fading, antenna interference, coupling effects and more. As such test methodologies for MIMO have evolved to ensure that conditions inside a test environment replicate real-world operating conditions. To date there are three distinct MIMO OTA test methods available in the literature. These include the Conducted Two Stage (CTS) Method, Radiated Two Stage (RTS) Method and the Multi Probe Anechoic Chambers (MPAC).

These three methods are outlined in this section and their applicability to the automotive test environment is discussed. Two newly proposed methods, namely Analytic Two Stage (ATS) and Ad-hoc MIMO are subsequently discussed along with their potential benefits to the automotive testing industry.

A. *Multi-Probe Anechoic Chamber (MPAC)*

An MPAC is the most realistic test environment for MIMO OTA measurements due to the flexibility and number of scenarios that can be tested on a single system. As the name suggests an MPAC consists of a shielded anechoic environment fitted with a number of probes which are located around the test zone. These probes are weighted with appropriate coefficients and this generates quasi-plane waves inside the test zone. The addition of a base station emulator and a channel emulator makes it possible to generate complex spatio-temporal channels to replicate realistic wireless channel conditions.

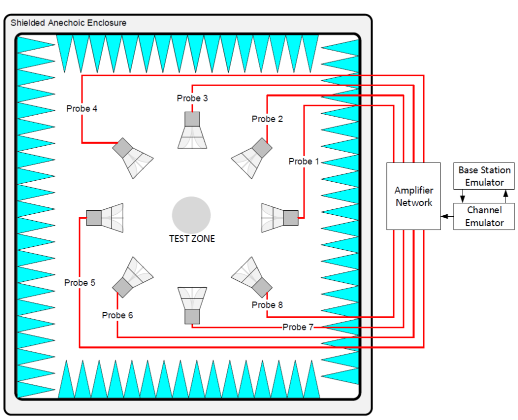

Figure 1. Typical MPAC Range for MIMO OTA Test

A typical layout for an MPAC is shown in Figure 1. and this type of test system is well established for small form factor devices such as a cellular handset. The size of the test zone for such devices is typically around 20 cm and a significantly larger test zone would be required if the MPAC approach was to be used for automotive testing. As the size of the DUT increases, the test zone increases which in turn means that the overall size of the chamber and number of probes will grow.

Table I. gives estimates of the number of probes required in a single angular dimension (e.g. ϕ) for a small (4.5m x 1.8m) and large (6.4m x 2.0m) vehicle at the lowest and highest frequencies of 5G FR1. Even at the lowest frequencies for 5G operation, the number of test probes is quite large. At the highest frequency for FR1, the number of probes becomes physically unrealizable, not to mention financially prohibitive. Scaling this to larger vehicles like commercial passenger busses or considering 5G FR2 (24 – 53 GHz) further exacerbates the issue. While this method is technically robust, the application of an MPAC to automotive testing appears to be untenable for both 4G and 5G tests.

TABLE I. Estimated number of probes for automotive MPAC

Frequency	Small car	Large truck
410 MHz	49	68
7.125 GHz	851	1178

B. *Conducted Two-Stage (CTS)*

The conducted two-stage (CTS) method enables testing with repeatable, controllable channel models [3] which yields accurate and repeatable results. The test is carried out in two distinct steps (or stages) where the first stage is a radiated measurement and the second stage is a conducted measurement. In the first stage, the antenna patterns of the DUT are measured in an anechoic chamber over a full sphere using a dual polarized probe as shown in Figure 2.

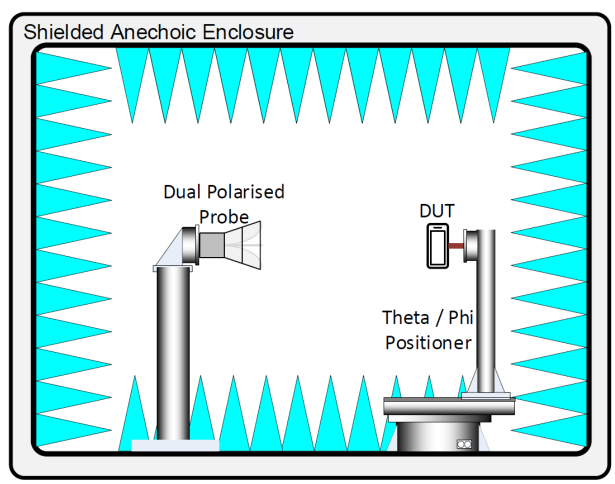

Figure 2. CTS First Stage - Measurement of DUT Antenna Patterns

The second stage connects the test instrumentation directly to the DUT receivers using RF cables thus bypassing the antennas of the DUT. In this particular case, the test instrumentation consists of a base station emulator and a channel emulator. The measured radiation patterns from the first stage are combined with the desired wireless test signal (generated by the base station emulator) and the channel emulator applies the spatio-temporal channel characteristics to the output. This output is then fed into the DUT receivers via a cabled connection. Figure 3. shows a simplified block diagram of a Conducted two-stage test setup.

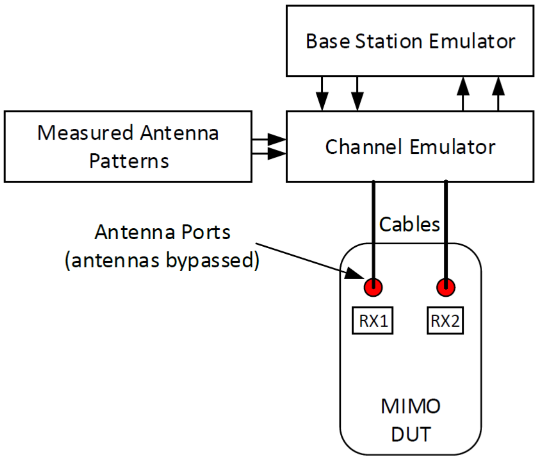

Figure 3. Conducted Two-Stage Block Diagram

The CTS method is a simple, inexpensive way to generate arbitrary channels and a real-world wireless environment by means of using a cabled connection. The CTS method does have two limitations, one of them being fundamental in nature. The major limitation is the need to access individual antenna ports on the DUT to cable the device for the second stage; if access to the antenna ports is not possible then the second stage of the measurement cannot be carried out. For 4G devices, access to antenna ports should be available and perhaps the same may hold true for some 5G devices operating at FR1. For 5G FR2 devices (mmWave frequencies), and even for some 5G FR1 devices, the high level of integration between the receive stage and antenna front end may mean that access to the antenna ports is not available thus making the CTS method nonviable.

The next limitation of CTS is that devices in general do generate their own internal noise which can sometimes couple into the antennas and therefore give rise to self-interference [6] and this phenomenon can impact the performance of the MIMO receiver. Bypassing the DUT antenna during the second stage of the measurement means that the impact of self-interference is not being accounted for during the throughput measurement; if the self-interference is high enough to impact the MIMO performance, then using the CTS method will produce and overly optimistic throughput measurement.

The CTS method is deemed a suitable option for testing MIMO systems fitted to vehicles equipped with 4G technology; the assumption that for such vehicles access to the antenna ports is possible is a reasonable one. Vehicles that are fitted with 5G cellular technology may still be tested using the CTS method, provided that access to the antenna ports is possible.

C. Radiated Two-Stage (RTS)

The radiated two-stage (RTS) method is the same as the CTS method, but instead of using a conducted measurement for the second stage, we measure the device in a radiated configuration [4][5]. This eliminates the need to access individual antenna ports for the second stage of the measurement. The number of probes required for the second stage has to match the number of MIMO data streams; Figure 4. shows a schematic layout for testing a 2x2 MIMO scenario.

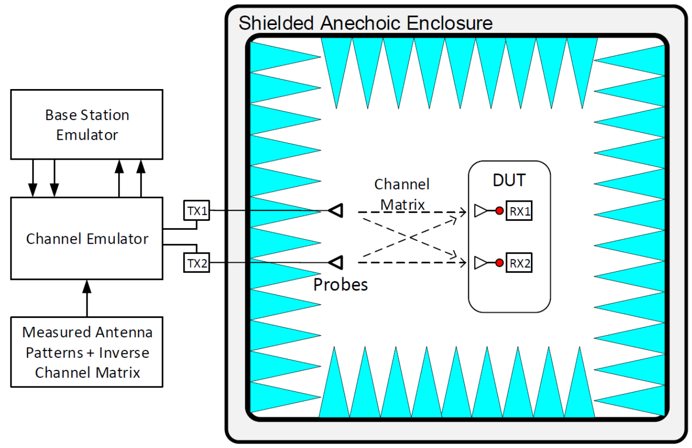

Figure 4. Radiated Two Stage Block Diagram

The test environment shown in Figure 4. contains a channel which is characterized by the channel matrix. In order for the RTS method to work, the channel matrix is inverted and combined with the measured DUT antenna patterns inside the channel emulator. This is one of the key limitations of RTS – it does require and invertible channel matrix. A typical test scenario in an automotive environment may not necessarily lead to an invertible channel matrix and thus may ultimately mean that RTS is only partially suitable for MIMO OTA testing in an automotive test environment.

Another limitation of this approach is the reliance on fixed antenna patterns. 4G devices do not employ beam steering techniques or adaptive antennas and the measured antenna patterns at stage 1 do not change for the remainder of the test. The new 5G/NR technology employs beamforming as a fundamental capability and the DUT antenna patterns will change whenever the beam state changes, invalidating the stage-1 data. There is a possibility that some 5G devices may have a beam lock test feature whereby the beam state is "frozen" for the duration of the test and that makes it possible to use the RTS method for such devices.

D. Analytic Two-Stage (ATS)

This method makes use of the DUT antenna pattern measurement during stage 1 of CTS/RTS and combines the measured patterns with analysis to compute the data throughput for a given propagation scenario. It is worth emphasizing that this computed data throughput is not an actual measured value but a calculated figure which describes the maximum theoretical data capacity that can be achieved for a MIMO system given the channels it sees.

The channel capacity is calculated using (1)

$$C = \log_2\{\det(I_{Nr} + SNR\ HH^H/Nt)\} \quad (1)$$

where C is the capacity expressed in bps/Hz, det is the determinant of a matrix, I_{Nr} is an identity matrix, Nr and Nt are the number of receive and transmit elements, SNR is the signal-to-noise ratio, H is the channel matrix and H^H is the Hermitian transpose of the channel matrix..

This method requires the definition of scenarios for which the analysis is to be done and a computational engine to combine the measured antenna patterns with the channel matrix for the given scenario. One advantage of this method is that it does not require access to the antenna ports of the DUT nor the invertibility of the channel matrix which were limitations of the CTS and RTS methods, respectively. The key limitation of the ATS method is that it does not account for the effects of the signal processing sub-system of the DUT.

The main advantage of this test method is that it can be used to assess the impact of the MIMO antenna array design and placement of the MIMO elements on the vehicle. Antenna design and placement is an important design parameter for maximizing the capacity of a MIMO link and ATS has the potential to offer a simple, robust method for testing MIMO devices during development and final design stages with repeatable and configurable wireless channels.

E. Ad-hoc MIMO

One of the main objectives of automotive testing is to optimize design, performance and placement of the antenna elements on a vehicle. The ATS method described in section D helps towards achieving this goal but there are limitations.

We therefore propose the following simplified MIMO-OTA test method as a complement to the ATS method for assessing relative MIMO performance. The test system consists of a shielded anechoic enclosure which is fitted with 2 or more movable probes (i.e. probes mounted on tripod) as shown in Figure 5.

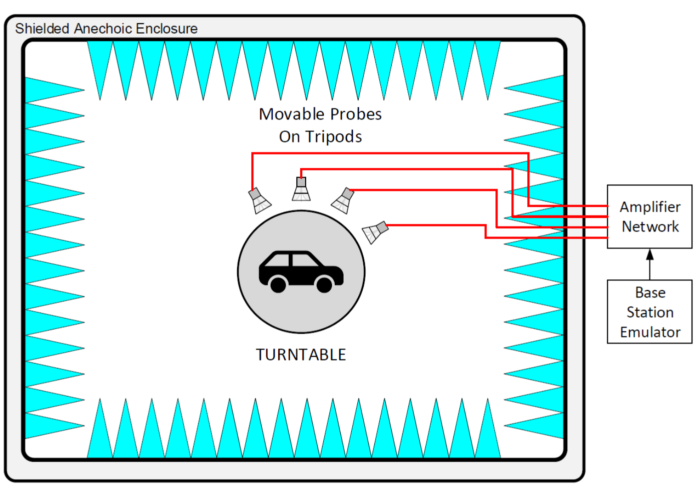

Figure 5. Test setup for Ad-hoc MIMO OTA

Using this setup, no attempt is made to invert or control the channel model and the MIMO tests are done using the channel conditions available inside the test environment. It is acknowledged that every test environment is likely to have a different channel model and those channels may not represent real-world channels which can be used for conformance testing. However this method does allow the measurement of vehicle mounted MIMO systems and it enables the comparison of relative performance of different antenna array configurations on a test vehicle. In addition to the ATS method, data throughput measurements using the Ad-hoc MIMO method also include the effect of the signal processing chain thus the measurements cover the complete system including antenna array, receiver and digital signal processing subsystem of the DUT. This yields useful measured data for multiple configurations of the vehicle mounted MIMO system and therefore enabling the design team to select the optimum configuration for a given set of criteria.

It is also possible to vary the channel inside the test environment by moving the test probes to different positions relative to the test article. The underlying idea is that the MIMO gain at the base station or base station emulator is not the important criteria for placing the antennas on the test article. This enables a “frozen” MIMO design on the DUT to be tested using different channel models created inside the test environment by changing the position of the probes.

The key advantage of this method is its simplicity to implement and it is not affected by any of the limitations of the previous methods. A drawback of the Ad-hoc MIMO method is the physical channel in the test environment may not allow for full multiplexing in all positions nor is it guaranteed to deliver the highest possible throughput. Nevertheless Ad-hoc MIMO does allow for testing of MIMO performance, including the use of beam switching in the DUT, in a repeatable and comparable fashion.

We recommend testing this method further and determine whether different configurations and positions of test probe arrays offer more realism than others.

III. CONCLUSIONS

The relative strengths and weaknesses of all five methods discussed in this paper are highlighted in Table II. below.

TABLE II. STRENGTHS AND WEAKNESSES OF PROPOSED MIMO TEST METHODOLOGIES

Method	Strengths	Weaknesses
MPAC	Realistic response, Repeatable	Not feasible for large DUT’s
CTS	Simple, inexpensive	Requires access to individual antenna ports
RTS	Avoids limitations of CTS	Calibration matrix may not be invertible, fixed beam states only
ATS	Avoids limitations of CTS/RTS	Does not test RF/DSP chains, array design/placement only
Ad-Hoc MIMO	Avoids limitations of all the other methods, allows beam switching of DUT	No direct control of channel

Of the five methods discussed, CTS may be the best method for 4G testing as long as the DUT allows direct connection to individual antenna ports. If not, then RTS, ATS, and/or ad-hoc MIMO may be reasonable choices. For 5G testing, RTS, ATS, and ad-hoc MIMO are likely the only viable options, but each has different limitations.

The ATS method requires development of scenarios and a computational engine. The Ad-hoc MIMO method requires additional testing to understand the impact of different probe configurations on the realism of the realized channels.

ACKNOWLEDGEMENT

The authors are indebted to Dr. Brett Walkenhorst for his contribution to this paper.

REFERENCES

[1] A. Scannavini, L.J. Foged, N. Gross, P. Noren, "OTA Measurement of Wireless Devices with Single and Multiple Antennas in Anechoic Chamber", *European Conference on Antennas and Propagation (EuCAP) 2014*

[2] Xavier Carreño, Wei Fan, Jesper Ø. Nielsen, Jagjit Singh Ashta, Gert F. Pedersen, Mikael B. Knudsen. "Test Setup for Anechoic Room based MIMO OTA Testing of LTE Terminals", *European Conference on Antennas and Propagation (EuCAP) 2013.*

[3] 3GPP, "Measurements of radiated performance for MIMO and multiantenna reception for HSPA and LTE terminals," Tech. Rep. 37.976, v11.0.0, 2012

[4] W. Yu, Y. Qi, K. Liu, Y. Xu, J. Fan, "Radiated two-stage method for LTE MIMO user equipment performance evaluation," *IEEE Trans. on Electromagnetic Compatibility*, vol. 56, no. 6, Dec 2014.

[5] M. Rumney, H. Kong, Y. Jing, Z. Zhang, P. Shen, "Recent advances in the radiated two-stage MIMO OTA test method and its value for antenna design optimization," *European Conference on Antennas and Propagation (EuCAP)*, Apr 2016.

[6] Nokia, "Analysis of DUT pool 4 test results," presented at the 3GPP TSG RAN WG4 Meeting #61, Rep. R4-115655, San Francisco, USA, Nov.2011.