Automotive OTA Measurement Techniques and Challenges

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***Abstract* — Characterizing the performance of automobile-mounted antennas has been an ongoing and evolving challenge for the antenna measurement community. Today, the automotive test environment poses unique challenges with its diversity and complexity of wireless on-board systems and the large electrical size of the test article. The evolution of cellular technologies over the past decade means that the basic mobile handset has now become a smartphone with significantly increased capability; this exact same trend has been mirrored by the automotive industry where we have witnessed the basic car radio and cassette player evolve into a multi-function infotainment unit. Modern vehicles include a multitude of wireless technologies, including cellular (2G, 3G, LTE), Bluetooth, WiFi, Global Navigation Satellite System (GNSS), collision avoidance radar, and more. Testing the complete vehicle is currently the only method available that certifies the correct mode of operation for each technology (including co-existence and interference) and also assures the manufacturer that the various sub-systems are performing as expected in the presence of all other sub-systems and the vehicle itself.**

While modern vehicles now function like large mobile devices, the conventional Over-the-Air (OTA) measurement systems and techniques available for small form factor devices (e.g. mobile phones) are ill-suited to testing such large devices. In this paper, we will highlight some of the unique challenges encountered in the automotive test environment. We will start by looking into existing methods of measuring radiation patterns of automobile-mounted antennas and providing a qualitative assessment of the various techniques with a focus on near-field solutions. A brief description of OTA testing will follow, coupled with an in-depth look into how techniques that are proven for handset type OTA measurements are being translated to automotive measurements. This section will provide a breakdown of key OTA test metrics, the measurement hardware typically required and key assumptions about the device under test. Finally, some performance tradeoffs and challenges associated with designing a multi-purpose antenna/OTA measurement system will be described.

***Keywords* — OTA, automotive, near-field**

I. Introduction

The testing of automobile-mounted antennas presents a set of perpetually evolving challenges that must be addressed by the antenna measurement community. In its infancy, automotive antenna testing was performed primarily outdoors by either driving a vehicle in circles around a fixed source [1] or rotating the vehicle on a turntable [2]. In either case, a receiver was placed within the vehicle and a measurement of gain vs. angular position was performed for vehicle-mounted AM/FM antennas or handheld cellular antennas located within the vehicle. Some of these systems employed cellular or GPS receivers to measure power received from transmitting cellular base stations or GPS satellites [3], respectively.

In the late 1990's and early 2000's, a number of indoor automotive test facilities were being commissioned [1, 4, 5]. These systems eliminated the complexities associated with testing outdoors, although some still used outdoor far-field source towers to characterize the vehicle's FM antennas. Commercial spherical near-field (SNF) to far-field transformation packages were also becoming readily available during this time. These systems were still primarily used for antenna pattern characterization, although some additional power-related metrics were measured using CW signals.

Today, indoor automotive antenna measurement systems are commercially available. These systems collect SNF data over a hemisphere (or more) around the vehicle. The vehicle is rotated on a turntable while a revolving gantry, a fixed arch with moving probe or array of probes collect amplitude and phase data for transformation to the far-field. Many of these systems also include remotely located source towers to enable quasi-far-field measurements.

With the increase in the number of vehicle-mounted antennas and associated wireless protocols, the modern vehicle functions similarly to a conventional user mobile device. As such, there is an increasing demand to expand the role of the automotive antenna measurement systems to become fully fledged OTA test facilities. The large electrical size of these vehicles and lack of formal OTA standards for the automotive industry make the design of such a system challenging.

In Section II, some common features of modern automotive antenna measurement systems will be outlined, including a description of the system at Antenna Technology Center GmbH (ATC) in Itzehoe, Germany. In Section III, a description of OTA measurements as they relate to smaller user devices will be provided. Section IV provides some details and measured results of a drive test OTA measurement campaign conducted by ATC. A list of challenges associated with the adaptation of conventional, indoor antenna test ranges for OTA measurements will be presented in Section V. Finally, some concluding remarks are presented in Section VI.

II. Automotive Antenna Measurements

Today, the majority of automotive antenna measurement systems are used exclusively to characterize the radiation patterns of vehicle-mounted antennas. These measurements are carried out in the far-field, quasi-far-field or in the near-field over a partial sphere surrounding the vehicle.

Due to the inherently long range lengths required for far-field measurements, this type of system is typically located outdoors. It usually consists of a single turntable used to measure azimuthal pattern cuts and therefore lacks the ability to fully characterize the radiation pattern over a hemisphere above the vehicle. This arrangement reduces facility costs, but increases complexities related to environmental control and security. Indoor far-field measurements are typically conducted in the quasi-far-field region, where the commonly accepted far-field condition of $2D^2/\lambda$ is not met. These systems are used to demonstrate pass/fail performance criteria where exact pattern information is less critical.

Most SNF test systems are located indoors and provide operators the ability to measure radiation patterns over a partial sphere surrounding the vehicle. These systems combine the motion of a turntable with either a pivoting gantry, fixed arch or array of probes to complete the spherical geometry. Each implementation has its own set of advantages and disadvantages.

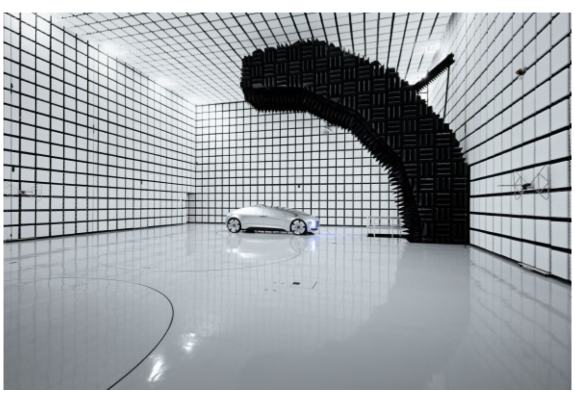

Figure 1. Automotive Test System with High-Accuracy Arch for SNF Measurements and Three Independent Turntables. Photo Courtesy of Frankonia Germany EMC Solutions GmbH

Figure 1 shows an arch-based SNF test system used for radiation pattern measurements from 0.2 to 10 GHz. The vehicle is shown mounted on the SNF turntable, whose design uses materials meant to simulate real world road conditions. This facility includes two additional turntables: one to allow quasi-far-field measurements from 0.07 to 3 GHz, and another to facilitate OTA measurements.

Figure 2 shows a rendering of an automotive test system that pairs a pivoting gantry with a turntable at floor level to conduct SNF measurements. This system includes a vertical translation stage behind the gantry pivot point to change the height of the rotation axis from the floor. This feature can be used to fine tune the minimum sphere surrounding the antenna and at its highest position, the gantry can measure data 10° below horizon. This gantry riser also allows the entire assembly to be stowed below floor level to create an ideal anechoic environment for other types of tests.

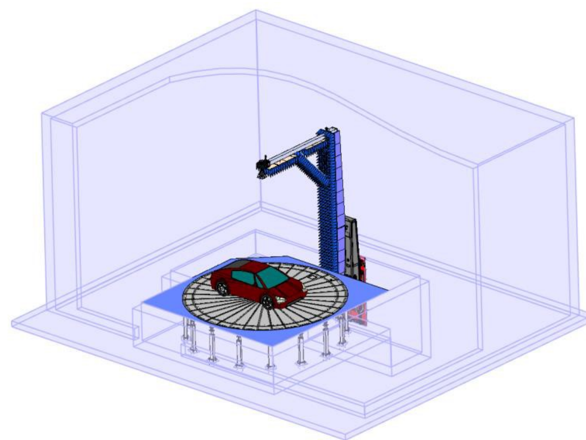

Figure 2. Rendering of Automotive SNF Test System with Stowable Gantry

Figure 3 shows an example of a combination indoor/outdoor SNF/far-field test system used for antenna radiation pattern measurements. This system is located at ATC in Itzehoe, Germany. The far-field system consists of a turntable inside of a radome and an outdoor far-field source tower located roughly 120 m away. This semi-anechoic test range operates in open air with a metallic, reflective ground plane.

Figure 3. ATC Antenna Test Range in Itzehoe, Germany with Views of the SNF System inside a Radome (left) and Outdoor Far-Field Range (right)

The far-field system is rated from 50 MHz to 2 GHz but is mainly used for broadcast services like FM, DAB and TV (70 to ~800 MHz). The output is azimuthal pattern cuts in the far-field. The SNF system combines the turntable with a dual-drive, dielectric gantry to enable hemispherical measurements around the vehicle from 70 MHz to 6 GHz. In practice, it is primarily used from ~400 MHz to 6 GHz to characterize antennas for communication, satellite navigation, Vehicle-to-Everything (V2X) and more.

As the number of antennas and complexity of wireless protocols grows, it is clear that the entire communication system must be evaluated, instead of just individual antennas. To address this, ATC performs drive tests in real world conditions. This technique, along with some measured data, is further described in Section IV.

III. Over-the-Air Testing

Over-the-Air (OTA) testing is a measurement concept used to characterize the radiated performance of a device under test in real-world operating conditions. OTA testing is a complement to existing test methods such as antenna pattern measurements or conducted measurement techniques. It provides an extra level of confidence and assurance that the device under test (DUT) will perform in accordance with its design specification when integrated into a larger wireless system and used in operational scenarios.

OTA testing was introduced with the roll out of the 4G cellular technology and one of the key reasons for its introduction was the need to measure system-level performance metrics. Whilst individual component-level tests such as antenna radiation patterns and transmit power level measurements provide very useful performance benchmarks, it was deemed necessary to also test the performance of the complete DUT. This includes the antenna, the transmitter and the receiver, fully integrated inside the device with it operating using its own power source.

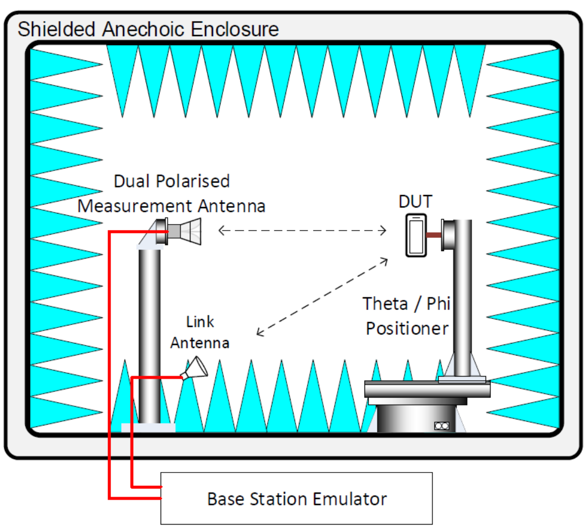

Figure 4. OTA Test Setup

Figure 4 shows a typical test setup for cellular OTA measurements. This system consists of a shielded anechoic enclosure, a base station emulator (for cellular technology measurements), a link antenna (used to establish a communication and control link between the DUT and the base station emulator) and a dual-polarized measurement antenna. The measurement antenna transmits/receives to measure the required OTA test metrics of the DUT.

Standards associated with OTA testing have evolved continuously over the years. Two of the organizations heavily involved in the development and maintenance of wireless test standards are The Wireless Association (CTIA) in the United States and the 3[rd] Generation Partnership Project (3GPP) on a more global scale. Some of the test metrics typically measured on such a system, and recommended by CTIA/3GPP, include the total radiated power, total isotropic sensitivity, error vector magnitude, carrier aggregation, adjacent channel leakage ratio and occupied bandwidth. A complete list of test metrics commonly measured using conventional OTA systems can be found in the appropriate CTIA and 3GPP wireless measurement procedures [6, 7, 8, 9].

IV. Drive Test OTA Measurements

Currently available OTA test systems and measurement techniques are ill-suited for large vehicles and the automotive industry's growing demand for system performance analyses. To address this, ATC has begun developing a process to evaluate automotive antennas in real-world environments using drive tests. This technique uses existing 4G mobile network infrastructure in real environments. Neither the size of vehicle nor a lack of investment capital hinders the ability to characterize 4G systems using this technique.

Various types of antennas under test (AUT), e.g. screen printed or shark fin antennas, are evaluated in several mounting positions and simultaneously compared to a reference system. This reference consists of either existing reference antennas or a standalone mobile phone. In these scenarios, an optimal mounting position is determined or the benefit can be estimated of vehicle-mounted antennas compared to a smartphone placed inside a car.

A test setup schematic used to optimize a 2x2 MIMO array in LTE Band 20 (~800 MHz) is shown in Figure 5. For this test, two monopole antennas mounted on the roof of the car act as reference. The AUT's (A1, A2) and reference antennas are connected to a measurement solution based on the Keysight "Nemo Outdoor" system [10] to determine quality of experience metrics.

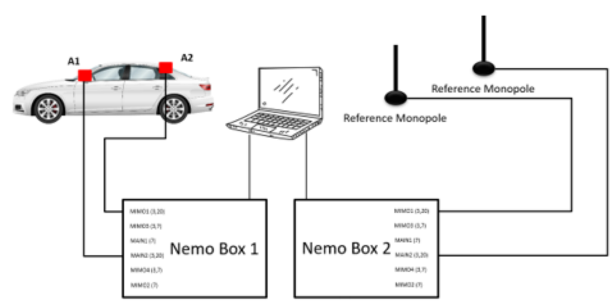

Figure 5. LTE Band 20 2x2 MIMO Drive Test Setup

For statistical evaluation, the drive test procedure is repeated several times on several well-known test routes. Each test route allows the ATC team to analyze different settings, such as frequency of the LTE band, network coverage, and carrier aggregation. These different test routes also allow ATC to investigate the AUT's behavior in worst-case and best-case scenarios. For example, AUT's tested in a good network coverage environment with the highest data throughput could suffer from link interruptions or low throughput in a bad network environment and vice versa. Under these circumstances, the complexity of analysis increases based on the huge amount of end-user key performance indicators (KPI) present in 4G networks which need to be considered. Received Signal Reference Power (RSRP) [11] relates to the gain of the AUT at the antenna-level and must be analyzed, although its effects are included in some system metrics. For system performance, Signal to Interference and Noise Ratio (SINR) and Physical Downlink Shared Channel (PDSCH) throughput stand out as the most valuable test metrics to be analyzed.

Table I shows measured data resulting from a series of drive tests performed by ATC in Germany in 2020. For simplicity, only five different antenna configurations are shown with their corresponding RSRP, SINR and PDSCH throughput results compared to the reference system. These metrics are accumulated over all drive test samples and the arithmetic mean is calculated for each. The PDSCH throughput is normalized to the reference system's PDSCH throughput and displayed as the Normalized Throughput (NTP). Throughput values greater than one indicates that the AUT received more data than the reference system. A positive ΔSINR indicates that the SINR of the AUT is greater than the SINR of the reference system and a negative value indicates a lower SINR.

TABLE I. DRIVE TEST METRICS

Config.	RSRP AUTs [dBm]	RSRP Reference [dBm]	ΔRSRP [dB]	ΔSINR [dB]	NTP	NAPI
1	-85.6	-80.6	-5.0	-0.27	1.01	1.05
2	-84.0	-79.8	-4.2	-0.03	1.03	1.06
3	-82.5	-79.7	-2.8	0.80	1.05	1.06
4	-83.6	-80.0	-3.6	0.57	1.04	1.05
5	-80.6	-79.2	-1.4	0.69	1.04	1.19

These drive test results show an inverse relationship between RSRP and PDSCH throughput (or NTP) which led ATC to perform a more thorough investigation of common KPI's. In general, ΔSINR is proportional to NTP and therefore it is a more valuable KPI than RSRP for the unfiltered throughput. ATC, in cooperation with Keysight and others, developed the Normalized Antenna Performance Indicator (NAPI) to provide automotive customers with a more useful drive test metric. This quality metric has been specially tailored for presenting performance results of a drive test but will not be described in detail in this paper due to its complexity.

The drive test results vary for the different configurations with some offering optimum performance for one metric but not all. When considering all performance metrics combined into a NAPI score, configuration 5 shows the best overall performance and is the highly recommended implementation to ensure a good user experience with maximum data throughput.

Figure 6 shows PDSCH throughput as a function of vehicle position on an urban test route in Hamburg, Germany. As expected, the results highlight that PDSCH throughput constantly varies during drive tests as a result of the multipath and multi-user environment. However, the wide range of measured throughput is quite remarkable. For example, some areas highlighted in red/orange along the test route (<10 Mbit/s) have network coverage with up to 150 Mbit/s maximum data throughput. In contrast, the spot marked with a red ellipse has up to three Carriers in LTE band 3 (~1800 MHz) & 7 (~2600 MHz) available and thereby has a maximum data throughput of 475 Mbit/s [12]. In this urban region ATC measured some samples with up to 130 Mbit/s data throughput, which is very high because data throughput is shared to all attached users. This type of measured data is an invaluable output of real-world drive tests that cannot be easily replicated on a conventional measurement system.

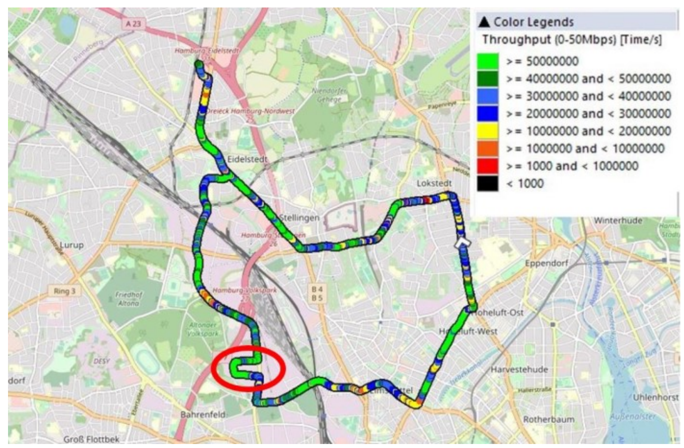

Figure 6. PDSCH Throughput Map Plot

More challenging to evaluate is the impact that the network operators' infrastructure has on KPI's. This impact can be a result of unknown and variable configuration including base station adjustments of the Physical Cell Identity (PCI), source power and more. Likewise, the number of other users, which are attached to the same PCI as the test system, limits the maximum data throughput. As the base stations and drive test routes are fixed in location there will be a dependency of the vehicle's orientation relative to the base stations. For example, antennas mounted in the rear screen will offer maximum performance since the vehicle will be moving away from the connected base station due to how optimum base stations are selected by mobile networks.

During drive tests, identical conditions for AUT's and reference systems are desirable but there will always be test samples in which the two are attached to different base stations. The lack of control over PCI handover is a fundamental limitation of the drive test methodology as this is automatically optimized by the mobile network operator. On the one hand, these samples are not meaningful to draw a comparison between AUT's and the reference system and hence they should be excluded for analysis. On the other hand, a delay between cell handover could affect the AUT's PDSCH throughput and clearly is related to a real operating scenario.

The drive test procedure described here offers a simple and cost-effective approach to characterize various OTA metrics using real-world conditions that would be difficult to achieve in an indoor test facility. The results presented here show that measured throughput can vary drastically from published coverage maps and there is no substitute for this type of empirical measured data. On the other hand, this approach places a great deal of reliance on the network operator to provide stable and consistent performance since this measurement technique relies on deployed base stations. The drive test techniques require that an active, robust network is in place and this is not necessarily true everywhere, especially not for the future generation of 5G enabled vehicles. The variability in environmental factors, network loading and multi-user interference can all be advantages and disadvantages of this technique.

V. Challenges of Adapting Automotive Systems for OTA Measurements

As vehicular wireless systems continue to evolve, so does the complexity of test and measurement challenges associated with characterizing their performance. While real-world drive tests like the one outlined in Section IV are invaluable, there is significant interest in the industry to develop multi-purpose, indoor test facilities for both antenna and wireless testing. The development of this next generation of indoor OTA facilities will make use of existing technologies from the conventional automotive antenna measurement systems outlined in Section II and the OTA test systems for smaller user devices outlined in Section III. These facilities will require positioning systems suitable for large automobiles with OTA test equipment to help communicate with the relevant wireless systems.

To illustrate the challenges associated with simply adapting/scaling existing wireless test systems for the automotive industry, the authors of [13] provide an example. While the Multi-Probe Anechoic Chamber (MPAC) [14] is a preferred solution for testing small, handheld user devices and is especially useful for characterizing 5G MIMO arrays (see Figure 7), a setup with 851 antennas is required to perform 5G MIMO testing at the highest frequency of 5G FR1 (7.125 GHz) on a sedan-size car. The number of required antennas will further increase as the size of the vehicle under test grows or one considers FR2 frequencies (24 – 53 GHz). Such an arrangement is impractical and physically unrealizable, not to mention financially prohibitive. While this method is technically robust, the application of an MPAC to automotive testing appears to be an untenable solution.

Rather than simply scaling a known OTA solution, an example of a combination antenna measurement and OTA test system is referenced in Figure 1. That system includes three separate turntables to maximize the utility and flexibility of the range. OTA range antennas on either side of the center turntable are used to transmit/receive wireless signals to/from a vehicle rotating on the turntable. Depending on the test equipment available, these antennas assist in characterizing a variety of different wireless systems within the vehicle, including cellular technologies (2G, 3G, 4G LTE, 5G NR), V2X, WiFi, etc. In addition to the fixed antennas visible in Figure 1, more antennas can be placed strategically around the vehicle using simple tripods to change the angle of incidence or to analyze MIMO system performance [13]. This strategy offers a flexible, low-cost solution for the placement of test antennas but requires significant user intervention and setup.

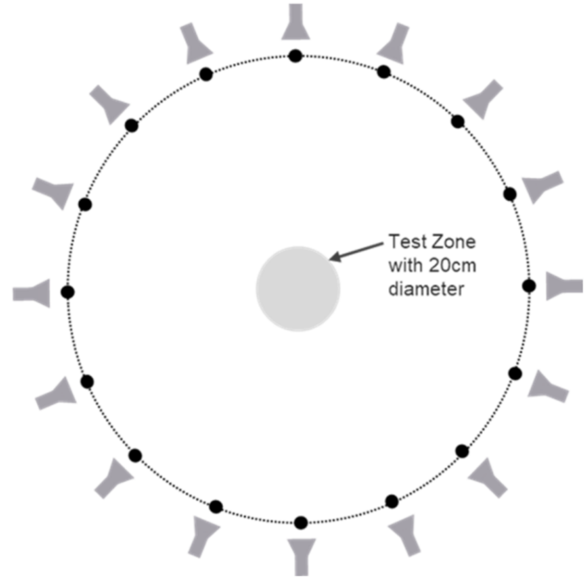

Figure 7. Multi-Probe Anechoic Chamber (MPAC) Diagram from 3GPP Standards showing Array Configuration for 20 cm Quiet Zone

Optimizing the number and placement of test antennas within the range is an important design consideration for an automotive OTA test range. These antennas are required for several applications, three of which are described below. The hardware used to position the antennas can range from something as simple as a stationary stand that is manually moved into place and aligned to something more complex like a multi-axis robotic positioning system. A robotic positioner offers more flexibility and positioning accuracy but adds cost and complexity. The right solution will depend on which OTA metrics must be measured and should offer a suitable balance between ease of use, flexibility and budget.

A particularly challenging task associated with wireless testing is the analysis of MIMO system performance. Depending on the MIMO test methodology used, two or more antennas must be strategically placed around the vehicle. The placement of these antennas should allow maximum flexibility or the system's ability to properly optimize MIMO arrays will be limited. For throughput measurements, a single antenna is used to determine performance at one angle of incidence. This antenna, in conjunction with the turntable allows one to measure throughput around the vehicle at a fixed elevation angle. If the antenna is connected to a gantry, arch or a semi-circular array, throughput can be measured over a partial sphere surrounding the vehicle. Another use for range antennas with a flexible placement strategy is to inject an interfering signal while another range antenna measures throughput (or other OTA metrics) in another direction. An example of such a test might be to measure throughput of a DUT in a direction of known poor performance while a strong, unwanted signal is transmitted in a direction of known good performance. If a throughput/reliability target is met, then the design holds up in a challenging environment.

It should be noted that such a test requires a priori knowledge of the antenna's radiation characteristics in all directions to select the right locations for strong/weak performance analysis. If a 3D positioning system is available using an SNF test system, one can either measure throughput over a partial sphere or a two-stage measurement can be conducted. The first stage is to measure the antenna radiation pattern (including gain) around the antenna. Using this pattern data, the second stage would be to simply measure OTA metrics at key locations determined from stage 1 (nulls, peaks, etc.). This type of two-stage approach will significantly reduce range occupancy time by limiting wireless testing to previously identified critical angles around the vehicle.

One of the biggest hurdles to overcome in the design and selection of a new, state-of-the-art automotive OTA test facility is the lack of formal industry standards. Standards developed by CTIA, 3GPP and others have continuously evolved since 4G deployment, but they are ill-suited to be used in the automotive environment without some modifications. Industry standards for the automotive wireless sector are in their infancy, but there is a significant demand for state-of-the-art systems now, prior to the release of such standards. This means that automotive manufacturers and third-party test labs are attempting to predict future standards to design flexible and technically compliant systems now.

Another obvious challenge associated with performing OTA testing on an indoor range is the lack of real-world emulation that it affords. This was highlighted in Section IV, but it warrants further comment. The main goal of an OTA test facility is to determine and optimize system performance in real operating conditions. There are several factors present in the real-world that simply cannot be simulated with sufficient flexibility within a test lab. These include user interference, multipath, base station handovers, channel loading, and more. A safe approach might be to follow-up range testing with a series of drive tests to compare range results to test route performance.

VI. Concluding Remarks

The next generation of automotive antenna measurement systems will be used for both antenna pattern measurements and OTA testing. These facilities will require positioning systems suitable for large automobiles with OTA test equipment to help communicate with the relevant wireless systems. In order to support a wide array of wireless protocols, it should be possible to place antennas around the vehicle in a flexible manner. While measurements performed in a controlled environment are necessary and useful, drive tests offer additional real-world performance metrics that cannot be realized in a test lab.

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