Virtual Drive Testing based on Automotive Antenna Measurements for Evaluation of Vehicle-to-X Communication Performances

F. Saccardi, A. Scannavini, L. Scialacqua, L. J. Foged
Microwave Vision Italy SRL
Via dei Castelli Romani 59, 00071, Pomezia, Italy
lars.foged@mvg-world.com

N. Gross, A. Gandois, S. Dooghe, P. O. Iversen
MVG Industries
13 rue du Zéphyr 91140 Villebon-sur-Yvette, France
nicolas.gross@mvg-world.com

***Abstract*—In vehicle communications, so as Vehicle-to-X (V2X), field trials are challenging due to high mobility scenarios and dynamic network conditions. It is complex to interpret measurements, to isolate performance from different components in an integrated system. Consequently, it is desirable to test under repeatable laboratory conditions in the early stages of the development cycle, where designers can quickly validate performance and make rapid modifications to prototype hardware and software cost-effectively.**

Virtual Drive Test (VDT) has attracted great interest from industry and academia. The objective of VDT is to recreate an approximation of the real-world communication conditions in a controlled laboratory environment. VDT is appealing, since testing can be performed in an automated, controllable and repeatable manner, which can considerably reduce testing time and costs, and meanwhile accelerate actual infrastructure deployment.

In this paper we present a new VDT technique which allows to evaluate the V2X communications performances taking into account the measured characteristics of transmit and receive antennas installed on vehicles. The proposed VDT technique is a multistage process where radiation characteristics of the vehicle mounted antennas are first measured in free-space conditions in a controlled and repeatable laboratory environment. The Spherical Wave Expansion (SWE) is then applied to the acquired data in order obtain the Spherical Wave Coefficients (SWC) of the measured devices. From the SWC, the transmission formula (or coupling equation) normally involved for probe correction purposes in spherical near field measurements, is then applied in order to evaluate the coupling between two vehicles. The transmission formula has been properly adapted in order to consider variable distances between the vehicles and arbitrary vehicle orientation so that a generic road path can be easily emulated. In the proposed formulation also variable ground conditions can be considered allowing for a more realistic emulation of the final environment. The proposed technique is presented taking into account measurements of a representative scaled automotive scenario.

I. Introduction

Modern vehicles have multiple wireless communication systems for mobile and vehicle-to-x (V2X) communications. Fast and accurate characterisation of these systems, require new and reliable techniques for electromagnetic measurements of system performance as performance testing move towards Over-The-Air (OTA) system testing.

Near-field (NF) methods to determine full 3D radiation of vehicle antennas is the industry standard and the fundamental technology for future testing of modern communication technologies [1-2]. In order to fully characterize the radiating properties of vehicle mounted antennas, a properly dimensioned system accommodating the full vehicle is required.

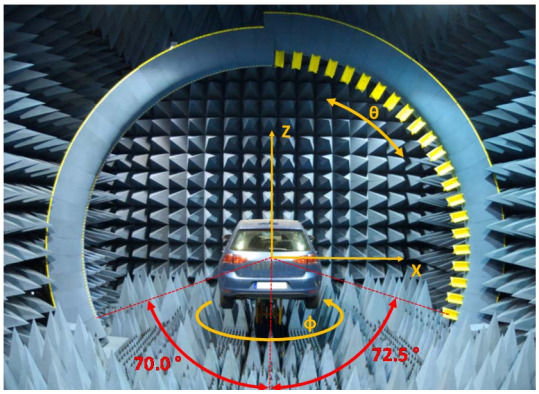

Figure 1. Automotive antenna measurement system at Ilmenau based on multi-probe technlogy from MVG covering the 70 MHz to 6 GHz range.

Figure 2. Automotive antenna measurement system at Laird based on multi-probe technology from MVG covering the 400 MHz to 6 GHz range .

Due to vehicle size, weight and/or economic factors, truncated spherical scanners are typically preferred. This is achieved by placing the vehicle in a condition similar to free-space using absorber materials on the floor. Examples of free-space condition system [3-6] are shown in Figure 1 and Figure 2. The absorber covered floor is a key enabling factor to perform accurate NF measurements at low frequency such as 70MHz [3]. In many cases, the emulated free-space condition is also a good approximation of realistic environments such as asphalts and soil. Furthermore, an infinite ground-plane with arbitrary conductive and dielectric properties can be emulated from the free space response of the measured vehicle by image theory. This function is implemented in the "ANY-Ground" software [7].

Other than the pattern characterization of the vehicle mounted antennas, the verification of higher-level performances, such as Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) coupling, are needed. Such performances can be evaluated with Virtual Drive Test (VDT) techniques [8] which allows to recreate an approximation of the real-world communication conditions in a controlled laboratory environment. VDT techniques are appealing, since testing can be performed in an automated, controllable and repeatable manner reducing the testing time and costs.

In this paper we present a technique to evaluate V2V communication using transmit and receive characteristic of antennas installed on different vehicles from separate measurements of each vehicle. From the Spherical Wave Expansion (SWE) [2], available for each measured antenna the V2V coupling can be evaluated. By applying the "ANY-Ground" software [7], the V2V coupling can be evaluated for arbitrary conductive and dielectric properties of the ground material in which the vehicles are moving.

The efficiency and ease of use of this technique will be demonstrated using measurements of a 1:12 scaled car model [9-11] in a full 3D multi-probe spherical NF system SL18GHz [4]. A discussion on further "ways forward" to manage future complex OTA scenarios will finally be presented.

II. Typical Automotive measurement Setup

The current industry standard for automotive testing is a multi-probe system placing the vehicle in a condition similar to free-space using absorber materials on the floor. Such solution enable to perform accurate NF measurements even below 70 MHz [3]. An alternative method is to use a perfectly Electric Conductor (PEC) as ground-plane [12-13]. Although the PEC condition simplifies the NF/FF transformation, it is often far from being representative of realistic automotive environments such as asphalt that is strongly dielectric. The PEC solution also suffers from strong interaction between ground-plane and the system, thus compromising the quality of the measurements. For this reason, NF measurements are rarely performed below 400 MHz in PEC based systems.

A standard automotive system, such as the system shown in Figure 1 has 111 probes with 1° angular spacing for frequency ranging from 400 MHz up to 6 GHz, and 22 probes with 5° angular spacing for frequencies down to 70 MHz. Due to safety regulations, the vehicle will make a full rotation in about 2 minutes. At lower frequencies, a full NF scan can be completed in a single rotation. At higher frequencies and depending on the number of frequency points, more turns may be needed. A full 3D characterization of a vehicle, considering 20 frequency points, can thus be completed in 2-12 minutes depending on the frequency.

Recent developments in multi-probe systems has extended the frequency range to 50 GHz by interleaving different probe arrays in the same support structure [5]. Future systems will benefit from increased the sampling density at higher frequencies due to a limited mechanical movement of the probe array [14].

III. Test Case Description

The car considered for the measurement is a 1:12 scaled model of a 1965 Morris Minor 1000 with original dimensions: LxWxH = 3.76x1.55x1.52m. A wideband low directivity patch antenna has been installed on the rear hood of the car.

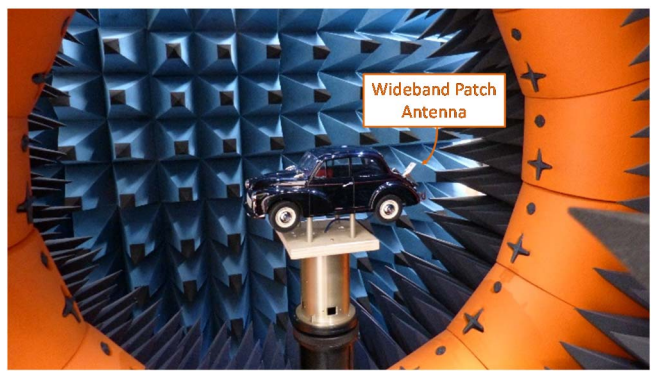

Figure 3. Wideband patch antenna mounted in the hood of a scaled car model during measurement in the MVG StarLab SNF multi-probe system.

The measurement are performed in a spherical NF multi-probe system, SL18GHz with measurement radius 45 cm as shown in Figure 3. The scaled car model has been measured in in the frequency range 1.1-18GHz, where the patch antenna is well matched. The scaled measurements correspond to testing the original sized Morris Minor in a larger automotive multi-probe system of radius 5.4m in the frequency range 91.7–1500MHz.

IV. Emulation of Different Ground Properties

The free-space condition of the floor is one of the key features enabling accurate NF measurements even below 70 MHz. The free-space environment from the absorber covered floor can be considered in many cases a good approximation of realistic automotive environments such as asphalt that is strongly dielectric.

Using the "ANY-Ground" techniques and the measured free-space pattern of the antenna, infinite ground-planes with different material characteristics can be evaluated with very low computational effort and with good accuracy, as described in [7].

By moving the reference coordinate system of the measured vehicle antenna, the relative position of the ground plane can be regulated. An example of such emulation applied to the measured of the scaled car model fed by the patch on the hood of the car is reported below for different materials such as PEC, asphalt and soil. The considered electrical propertied of the materials have been taken from [15-16] and are reported in Table I. The considered measured working frequency is 18 GHz, which scales to 1.5 GHz.

TABLE I. ELECTRICAL PROPERTIES OF THE GROUND PLANES

	Relative Permittivity (ε_r)	Conductivity (σ)
Asphalt	4.61	$3.69 \cdot 10^{-4}$
Soil	2.25	0.16

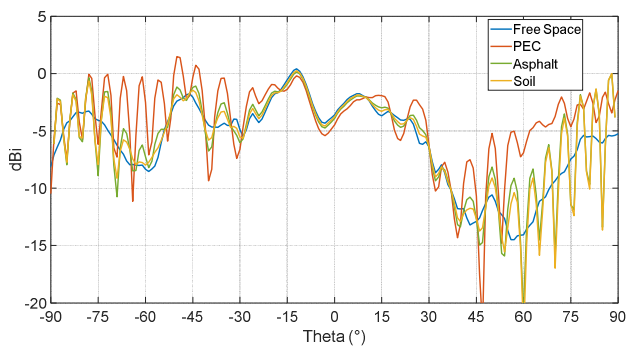

Figure 4. Measured elevation gain pattern at 18 GHz (1.5 GHz). Measued in free-space vs. emulation of different grounds from free-space measurements.

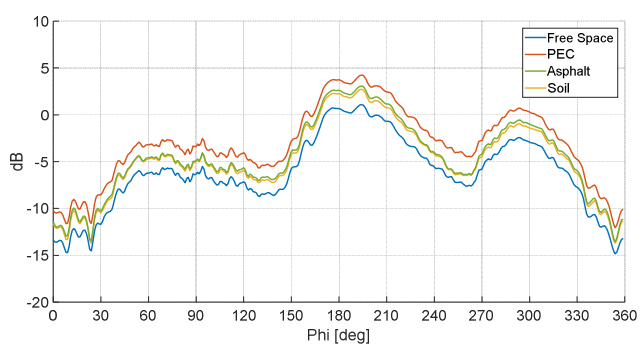

Figure 5. Measured averageg azimuth gain pattern at 18 GHz (1.5 GHz). Measued in free-space vs. emulation of different grounds from free-space measurements.

The comparison on an elevation cut is shown in Figure 4 while the averaged azimuth cut in the 60-90° elevation angles is shown in Figure 5. It is easy to appreciate that the free-space condition is already a good approximation of the considered dielectric ground materials for elevation angles of more than +/-45°. As can be seen in Figure 5, at higher elevation angles, the response over dielectric ground is approximately the average between the free-space and the PEC condition.

The emulation is an approximation as the interaction between the antenna and the artificial ground-plane is ignored. It should be noted that when the "ANY-Ground" technique is applied to truncated ranges as the one discussed above, the validity region of the emulated ground-plane scenario is limited to 70-90° elevation angles [7]-[11].

V. VDT EVALUATION OF V2V COUPLING USING MEASURED SPHERICAL WAVE EXPANSION

The V2V coupling can be evaluated from SNF measurements by first computing the Spherical Wave Expansion (SWE) [2] of the measured vehicles and then using the transmission formula report below in equation 1.

$$w(r,\chi,\theta,\varphi) = \\ = 0.5 \sum_{\substack{smn \\ \sigma\mu\nu}} Q_{smn}^{(\mathrm{car\#1})} e^{jm\varphi} d_{\mu m}^{n}(\theta) e^{j\mu\chi} C_{\sigma\mu\nu}^{sn(3)}(kr)\, R_{\sigma\mu\nu}^{(car\#2)} \qquad (1)$$

Such formula is described in detail in [2] and is widely used for probe correction purposes in spherical NF measurements. However, the formulation can also be employed to emulate the coupling between two generic transmitting/receiving devices such as cars as shown in Figure 6. The spherical wave coefficients (SWC) of the first car are denoted with $Q_{smn}^{(\mathrm{car\#1})}$ while those of the second car with $R_{\sigma\mu\nu}^{(car\#2)}$. The other operators shown in the formula are needed to properly place and orient the second car with respect to the first one (see [2] for more details). The first car (Car #1) is placed in the origin of the (x,y,z) coordinate system, where normally the AUT is considered in the conventional use of the transmission formula. The second car (Car #2) is instead placed in the primed (x',y',z') coordinate system, where normally the probe is described, and different positions along a trajectory are considered. As can be seen the z'-axis always points toward the origin of (x,y,z) hence, to maintain the correct direction of the second car, different rotations must be considered. Such rotations can be implemented efficiently directly in the spherical wave domain by using the Euler's angles as described in [2].

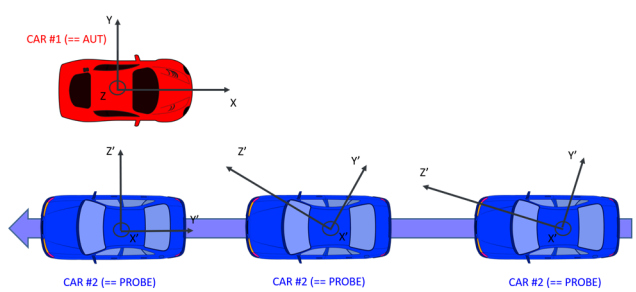

Figure 6. Illustration of the coordinate systems (xy-plane) for the application of the transmission formula to evaluate the V2V coupling between two cars.

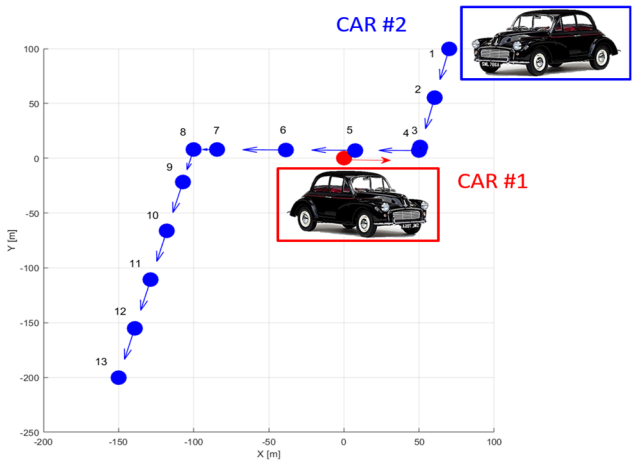

Figure 7. Emulated scenario for the evaluation of the V2V coupling between two cars: scaled car model fed by a patch antenna in the hood at 18 GHz (1.5 GHz)

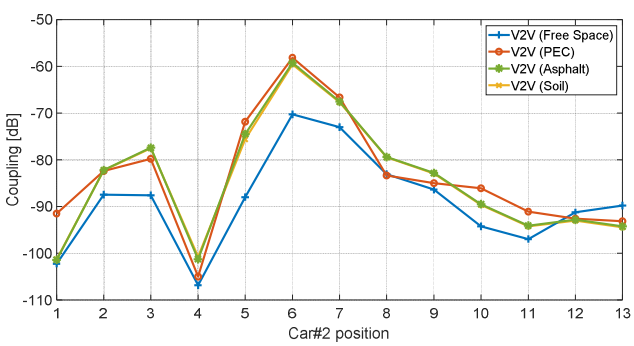

Figure 8. Evaluated V2V coupling in free-space and for thee different ground materials: PEC, asphalt and soil.

The V2V coupling has been evaluated for the scaled measurement of the Morris Minor fed by the patch antenna installed on the hood. The considered measured working frequency is 18 GHz which scales to 1.5 GHz. The emulated V2V communication scenario is illustrated in Figure 7. The same car/antenna configuration has been considered for the first and second car. The path traveled by the second car is illustrated by the blue points and arrows. As can be seen, the coupling at 13 different points along the path between the two cars has been evaluated (for simplicity the first car is kept fixed in the origin of the (x, y, z) coordinate system).

The V2V coupling results are reported in Figure 8 for the free-space case (blue trace) and for three different grounds: PEC (orange trace), asphalt (green trace) and soil (yellow trace). The peak of the coupling is observed at the 6th position. At such position in fact the two cars "look each other" at an azimuth angle close to $\varphi = 180°$ where, as observable in Figure 5, there is a peak of the azimuthal radiation pattern. Conversely, the weakest coupling is observed at the 4th position where the two cars face approximately at $\varphi = 0°$, where the azimuthal radiation pattern has the lowest level.

VI. "WAY-FORWARD" TOWARDS COMPLEX SCENARIOS

While the industry is currently taking advantage of the fast antenna testing by multi-probe systems, the discussion on how future OTA testing of realistic scenarios will be performed is still wide open [17]. Likely methodologies for OTA testing in the near future are based on direct emulation of the complex scenario [6] or a multi-stage simulation method as presented in this paper.

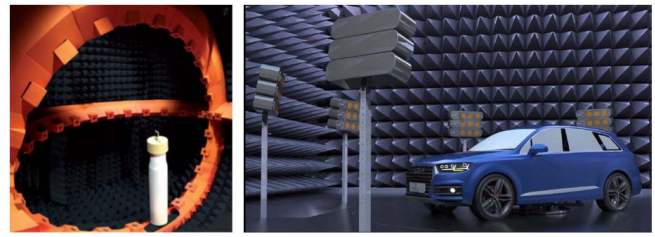

Figure 9. Direct emulation of the complex scenario Left: MIMO OTA testing Right: Same OTA testing concept in an automotive scenario.

The direct emulation of the complex scenario is a standard test of LTE enabled devices in personal communication [6]. A circular array of probes around the Device Under Test (DUT), simulates a complex multi-path environment at the DUT location in a repeatable way by using a radio communication tester and a channel emulator (see example in Figure 9-left). The common setup for such a system including its automotive equivalent is show in Figure 9-right.

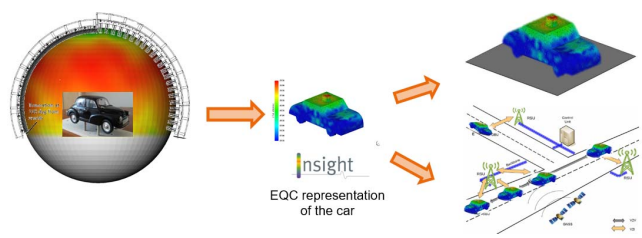

Figure 10. Ilustration of multi-stage simulation method. The measured vehicle antenna is represented by spherical waves or equivalent currents and imported in numerical tools for complex enviroment simulation.

The multi-stage simulation method takes advantage of the fact that NF measurements produce an accurate mathematical expression of the measured vehicle/antenna using spherical waves or equivalent currents [18-19]. This expression can be used to represent the antenna in a numerical simulation of the complex scenario including V2V, V2I and V2X scenarios [18-19]. The results presented in this paper are thus a first step in the direction of a more elaborate multi-stage simulation method based on numerical simulation of the environment as shown in Figure. 10.

VII. CONCLUSIONS

Virtual Drive Test (VDT) are intended to recreate an approximation of the real-world communication conditions in a controlled laboratory environment. VDT is appealing, since testing can be performed in an automated, controllable and repeatable manner, which can considerably reduce testing time and costs, and meanwhile accelerate actual infrastructure deployment. Combination of free-space near-field measurements of the whole car and recent progress in antenna measurement post-processing enables new ways to implement VDT scenarios.

The results presented in this paper are a first step in the direction of a more elaborate multi-stage simulation method. In the current implementation the V2V coupling can be evaluated at different car positions from free-space measurements of the cars and exploiting an adapted version of the transmission formula. Different ground parameters can be also taken into account with "ANY-ground" software tool. A logic extension of this method is to include further parameters such as Doppler, emulating the relative velocity of the two moving vehicles and a more elaborate representation of the complex physical environment using numerical simulation.

REFERENCES

[1] IEEE Std 1720-2012 "Recommended Practice for Near-Field Antenna Measurements"

[2] J. E. Hansen (ed.), Spherical Near-Field Antenna Measurements, Peter Peregrinus Ltd., on behalf of IEE, London, United Kingdom, 1988.

[3] P. Noren, Ph. Garreau, L. J. Foged, "State of the art spherical near-field antenna test systems for full vehicle testing", EuCAP, March 2012, Prague, Czech Republic.

[4] L. J. Foged, A. Scannavini, "Efficient testing of wireless devices from 800MHz to 18GHz, Radio Engineering Magazine, Vol 18, No 4, December 2009.

[5] A. Scannavini, L. J. Foged, A. Giacomini, L. Duchesne , N. Gross , F. Herbiniere, "Efficient Testing of Antennas for 5G mm-Wave Applications", EUCAP 2018, London, England.

[6] A. Scannavini, L. J. Foged, N. Gross, P. Noren, P., "OTA measurement of wireless devices with single and multiple antennas in anechoic chamber," EuCAP 2014, The Hague, The Netherlands.

[7] F. Saccardi, F. Mioc, A. Giacomini, L. J. Foged, "Estimation of the Realistic Ground Effect in Free-Space Automotive Measurements" 40th AMTA symposium, Nov 2018, Williamsburg, Virginia, USA

[8] W. Fan, L. Hentilä, F. Zhang, P. Kyösti and G. F. Pedersen, "Virtual Drive Testing of Adaptive Antenna Systems in Dynamic Propagation Scenarios for Vehicle Communications," in *IEEE Access*, vol. 6, pp. 7829-7838, 2018

[9] F. Saccardi, F. Rossi, F. Mioc, L. J. Foged, P.O. Iversen, "Application of the Translated-SWE Algorithm for the Characterization of Antennas Installed on Cars Using a Minimum Number of Samples", AMTA 2017, 15-20 October, Atlanta, GA, USA

[10] F. Saccardi, F. Mioc, P. O. Iversen, L. J. Foged, "Theory and Validation of Reduced Complexity Translated-SWE Algorithm with Applications to Automotive Measurements with Minimum Sampling" EuCAP 2018, 9-13 April, London, England

[11] F. Saccardi, F. Rossi, L. Scialacqua, L. J. Foged, "Truncation Error Mitigation in Free-Space Automotive Partial Spherical Near Field Measurements", AMTA, October 2017, Atlanta, GA, USA

[12] R. Cornelius, D. Heberling and D. Pototzki, "Spherical Near-Field Far-Field Transformation with Infinite Ground Plane At Arbitrary Height z", EuCAP 2017, 19-24 March, Paris, France

[13] R. A. M. Mauermayer and T. F. Eibert "Spherical Field Transformation for Hemispherical Antenna Measurements above Perfectly Conducting Ground Planes", AMTA, October 2016, Austin, TX, USA

[14] M. Le Goff, N. Adnet, N. Gross, L. Duchesne, A. Gandois, L. Durand, "A Novel and Innovative Near Field System for Testing Radomes of Commercial Aircrafts", AMTA, October 2017, Atlanta, GA, USA

[15] Gaoyuan-Ci, XieKuo-Jun, BaoJin-Fu, "Waveguide method for measuring dielectric constant of asphalt concrete at 2.45GHz", Proocedingof the 7thWSEAS International Conference, Athens, Greece, 2007

[16] "TAI IncConsuletterInternational" Vol 6, No 5, Earth Constants by Peter N Saveskie

[17] F. Wollenschläger, P. Berlt, C. Bornkessel, M. A. Hein, "Antenna Configurations for Over-the-air Testing of Wireless Automotive Communication Systems", EUCAP 2016, Davos, Switzeland

[18] L.J. Foged, L. Scialacqua, F. Saccardi, F. Mioc, Morten Sørensen, G. Vecchi. J. L. Araque Quijano,"Measured Antenna Representation of Flush Mounted Antennas for Computational Electromagnetic Solvers", EuCAP 2016, Davos, Switzerland

[19] J. A. Quijano, G. Vecchi, L. Li, M. Sabbadini, L. Scialacqua, B. Bencivenga, F. Mioc, and L. Foged, "3D spatial filtering applications in spherical near field antenna measurements," AMTA Symposium, October 2010, Atlanta, Georgia, USA.