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System-Level Assessment of Volumetric 3D Vehicular MIMO Antenna Based on Measurement

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***Abstract*—This paper presents the evaluation of a volumetric 3D multi-element antenna for vehicular connectivity based on a system-level approach. First, the antenna design to be used in Long Term Evolution (LTE) networks and its realization based on molded interconnect device (MID) technology are shown. During the antenna evaluation, system-level key performance indicators (KPI) like condition number and channel capacity are investigated and are compared to indicators like return loss, inter-element coupling and radiation characteristics. System-level KPI include effects due to vehicular antenna integration or channel conditions, which have an impact on the overall performance. A suitable 2D reference antenna arrangement is developed to evaluate the performance gain of the volumetric antenna design approach by performing test drives in a live LTE network.**

***Index Terms*—Antenna, MIMO, Vehicular Connectivity, Volumetric Design, 3D, System-level Evaluation, LTE-measurement.**

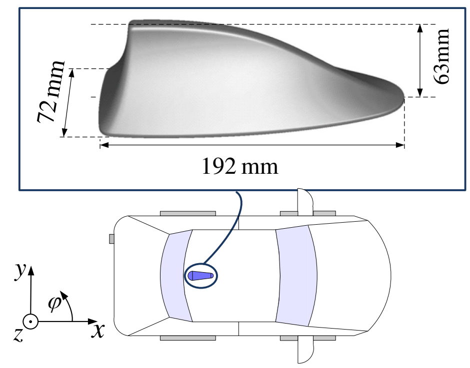


Fig. 1. Top view of the used sedan type vehicle: Positioning antenna compartment on the vehicle roof top.

I. Introduction

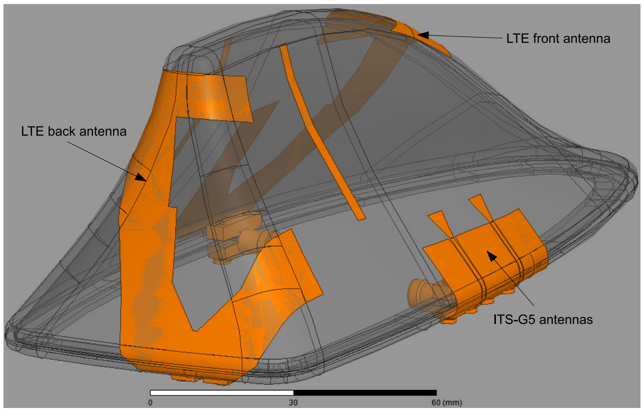
Future vehicles have to connect to a large variety of wireless services in order to provide advanced services for assistance, safety and infotainment purposes to the driver as well as passengers. Thus, extensive equipment has to be integrated on-board to meet these requirements for applications in both broadcasting and telematics. An important part of the vehicular connectivity architecture is the on-board antenna, which is used to connect the vehicle to cellular networks or to receive broadcasting services. Usually, automotive antennas are employed as on-glass antennas, rod antennas or conformal roof-top antennas to cover the variety of different wireless services. A well designed antenna system is necessary to provide best connectivity and quality of service at the vehicle. In addition aesthetic design contraints have to be met. The roof-top antenna has to be designed to fit into a given antenna housing as an example shown in 1 [1], [2]. Its overall size is usually fixed even though the number of antennas increases as more and more new wireless services have to be integrated into the vehicle. Especially cellular networks like Long Term Evolution (LTE) are of interest for the automotive industry and have recently been investigated for use in the vehicular domain with a main focus on driver assistance and informations services. It enables high data rates and low latencies [3]. In order to exploit the benefits of LTE, it is necessary to employ multiple-input-multiple-output (MIMO) antenna systems both at the base station as well as at the vehicle. Since multiple antenna technology is used, additional antennas have to be integrated into the present integration volume represented here by the dielectric antenna housing.

Single elements of MIMO antenna systems need sufficient spacing to lower the inter-element correlation and coupling in order to provide a good MIMO performance based on highly decorrelated subchannels [4]. Coupling between the radiating elements inside the antenna compartment, which is limited regarding the available space, may lead to a performace degradation of the whole connectivity system.

So far, antenna manufacturing techology has been based on two-dimensional printed circuit boards (PCB). The particular antenna elements like monopole-like structures or patch elements are mounted onto a base plate inside the antenna compartment. This technology can lead to a deterioration of antenna performance in terms of limited return loss or mutual coupling between the antenna elements due to an inefficient use of the available three-dimensional space [2], [5].

To increase the utilization of the accessible space, [6] has investigated the direct implementation of antenna functions on top of the surface of the vehicular antenna housing using molded interconnected devices (MID) technology. This provides the possibility to integrate circuits as well as antennas directly onto plastic surfaces.

In this contribution, we will evaluate the multi-element antenna developed in [6] for use in MIMO wireless systems based on the system-level performance evaluation metric presented in [7]. Typically used antenna performance indicators gained in laboratory evaluations on generic ground planes during the design process like return loss, decoupling, radiation characteristic and efficiency do not necessarily cover



(a)

(b)

Fig. 2. (a) 3D-model of the metallized antenna housing showing the antenna structures for simulation purposes. (b) Picture of the metallized antenna housing mounted ontop the sedan type vehicle used for measurement.

effects resulting from vehicular integration. We employ a set of system level key performance indicators (KPI) as an approach for evaluation and assessment of vehicular MIMO antenna systems. For comparison we present a reference antenna system based on a 2D design approach. This enables a comparison of a 2D antenna system versus the presented 3D antenna system regarding their performances and utilization of the available space.

The paper is organized as follows. In Section II we first introduce the 3D LTE antenna system which is then evaluated based on the assessment methodology presented in Section III. Section IV presents a 2D reference antenna arrangement to be compared to the 3D antenna system. Following in Section V we present our results and illustrate the changes in antenna performance with regards to a volumetric design approach for vehicular antenna systems. Finally, in Section VI the conclusions of this evaluation are drawn.

II. 3D-MID Antenna System

In this section a short description of the evaluated antenna system presented in detail in [6] is given. The antenna system consists of an LTE (800 MHz, 1800 MHz, 2600 MHz) two antenna system and a two antenna system to cover ITS-G5 (5.9 GHz). The integration space is the cover of an roof top antenna module as shown in Fig. 1. For a volume efficient integration the molded interconnect device technology (MID technology), i.e. metallizing the plastic cover, is used. The antennas are positioned on the outside of the plastic cover as shown in Fig. 2a.

For the LTE antennas, broadband monopols with an additional electrical length for the LTE 800 MHz band is used. The antennas are positioned on the plastic cover optimizing the decoupling between both LTE antennas. For ITS-G5, a monopole antenna with a coplanar feed is used. The coplanar feeding allows a positioning of the short antennas higher above the groundplane reducing pattern deterioration.

In the following the measured and simulated results of the examined antenna system are presented. All simulations are done with Ansys HFSS 14.0. The realized antenna system is positioned over a metallic ground plane ($1\,\mathrm{m} \times 1\,\mathrm{m}$) and structured on a laser direct structuring (LDS) capable MID substrate material as depiced in Fig. 2. The LDS material used is Vectra E840i LDS, a liquid crystal polymer, suitable for thin walled injection molding. The metallization in the LDS process is done with copper and a nickel/gold covering to reduce oxidation and metallization losses. For the measurements the feeding point of the antenna has to be routed inside the housing and needs to be geometrically matched to a connector. Therefore a stripline is routed from the feeding point used for simulations straight under the housing.

First, the scattering parameters of both LTE antennas are investigated. The results for the input matching and the isolation are depict in Fig. 3. The measured and the simulated results show a good agreement. They indicate an input matching better than -10 dB and a coupling lower than -10 dB in the desired LTE bands. The radiation properties of the antennas are measured in an anechoic chamber. The results for both LTE antennas at 800 MHz in the horizontal plane are depict in Fig. 4. The measured and simulated results show a good agreement.

III. Performance Metric

Antenna evaluations can be performed on different levels in the RF signal chain, cf. Fig 5. Typically indicators for performance assessments are situated on the impedance or radiation level. For example, return loss, inter-element coupling and radiation patterns are often investigated and commonly specified in order to describe antenna performance metrics. In this contribution, we follow a different approach to include integrations effects of vehicular antenna systems. Based on system level performance indicators, which include the aforementioned parameters, we assess the overall performance of the vehicular MIMO antenna system. This includes the

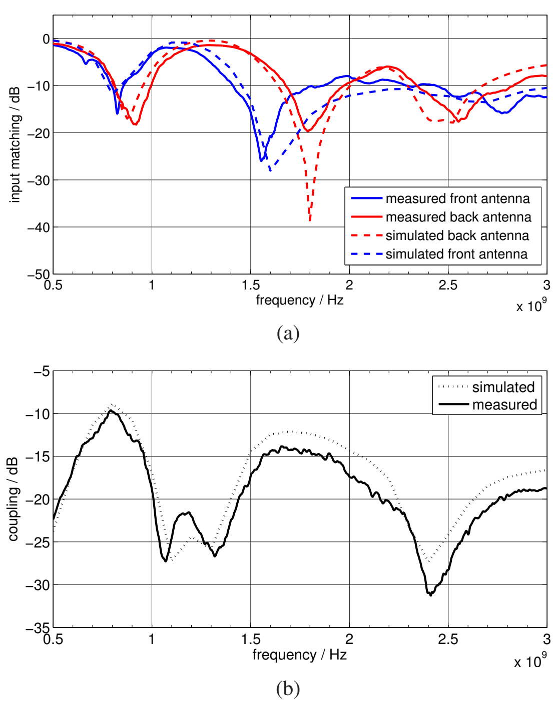


Fig. 3. (a) Simulated and measured input matching for both LTE antennas and (b) coupling between the antenna elements both for measurement and simulation on a $(1\,\mathrm{m} \times 1\,\mathrm{m})$ groundplane.

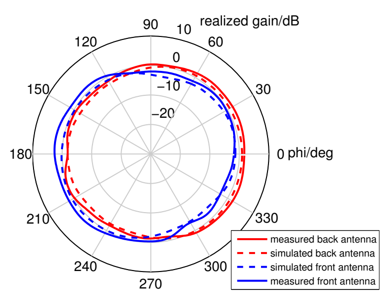


Fig. 4. Radiation pattern

influence of integration effects such as positioning on the rooftop or roof insets on performance like shown in [8]. Other consequences on the impedance and radiation level are mismatch or non-omnidirectional radiation characteristic for terrestrial services, cf. Fig. 5.

In this paper, we evaluate the measured channel matrix $\boldsymbol{H}$ of a 2×2 MIMO LTE system according to [7]. The channel matrix includes both the properties of the antenna under test (AUT) as well as effects due to vehicular integration. The measurements are carried out in a live LTE network with a radio network analyzer at a center frequency of $f_c = 796\,\mathrm{MHz}$ and a bandwidth of $B = 10\,\mathrm{MHz}$ fixed by the carrier. The radio network analyzer evaluates the signaling traffic (pilot signals) and performs a channel estimation to calculate the channel matrix $\boldsymbol{H}$ for each ressource block within B. During postprocessing spatial filtering is performed to reduce the impact of different traffic conditions (eg. traffic jams, red lights) [9]. The obtained values are then used to compute the condition number κ and capacity C according to (1) and (2), cf. [10].

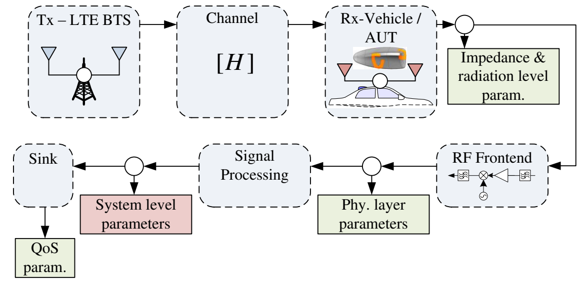


Fig. 5. RF signal chain for for evaluation of the AUT on different layers.

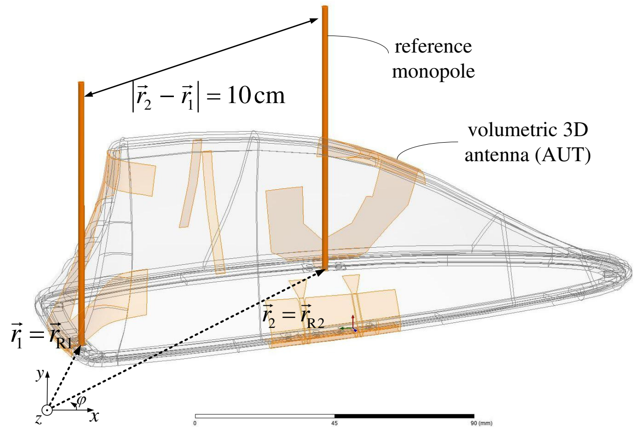
$$\kappa = \frac{\sigma_{max}}{\sigma_{min}} \quad (1) \qquad C = \sum_{i=1}^{K} \log_2 (1 + \lambda_i \cdot \mathrm{SINR}) \quad (2)$$

With (1), the condition number is defined as the quotient of the largest and the smallest singular value σ_i of the channel matrix. The lower the condition number, the lower is the correlation of the multiple antenna subchannels. κ has a range of $1 < \kappa < \infty$. The channel is well conditioned for small values of κ. In (2), K denotes the number of subchannels which equals the number of non-zero eigenvalues λ_i. $SINR$ denotes the signal to noise and interference ratio (SINR) of the respective resource block. As only physical layer parameters are measured, the results are independent of higher layer effects such as cell usage or other network-related impacts.

IV. Reference Antenna for Comparison

To enable an evaluation of the 3D antenna presented in Section II regarding its performance with relation to its utilization of the available space, a reference system is needed for comparison. As the focus lies not only on the performance indicators presented in Section II and III but also on the exploitation of the integration volume with a volumetric design approach, see Figure 1, the reference antenna architecture has to be put into the same integration environment as the 3D antenna. This includes integration effects such as positioning on the rooftop or roof insets on performance like shown in [8].

We propose an arrangement of two ($\lambda/4$)-monopoles with their resonance at the frequency of evaluation ($f_c = 796\,\mathrm{MHz}$) which are positioned at the feeding points of the 3D antennas. The single elements have a separation of $d = 100\,\mathrm{mm}$. Figure 6a shows a model of the reference setup. In order to determine the validity of the proposed reference antenna system, we employ a model according to [11], in which the multimode antenna is based on the mathematical system of spherical harmonics $Y_{nm}^{e}(\vartheta, \varphi)$ and $Y_{nm}^{o}(\vartheta, \varphi)$. Its radiation patterns $\vec{C}(\vartheta, \varphi)$ define a subset of orthonormal functions [12]. According to [11], degree n and order m are related to the volume occupied by the antenna structure and the operating frequency of the system. The maximum degree N_{SME} is restricted to $N_{SME} = kr_{max}$, where k is the wave number and r_{max} is the radius of a sphere including all radiating sources.



(a)

(b)

Fig. 6. (a) CAD model of the 2D reference monopole setup (3D antenna shown only as reference). (b) Picture of the reference 2D antenna mounted ontop the sedan type vehicle used for measurement.

To ensure the validity of the reference antenna setup for the purpose of our analysis, there are two major requirements, which have to be fulfilled.

- Req. 1: All directive and shadowing effects due to the integration environment shall be identical for both arrays.
- Req. 2: The farfield transformations of both systems (3D antenna and reference system) shall be identical with an acceptable accuracy.

Req. 1 is fulfilled with adequate accuracy, as both antenna systems have identical feeding points and the position vectors of the 3D antenna $\vec{r}_i$ and reference antenna $\vec{r}_{Ri}$ are equal: $\vec{r}_1 = \vec{r}_{R1}$, $\vec{r}_2 = \vec{r}_{R2}$. Req. 2 is fulfilled, when the modal degree N_{SME} of both the AUT and reference system are similar to each other $N_{SME_{AUT}} \approx N_{SME_{ref}}$. This is the case, as the wave number $k = 2\pi/\lambda$ is constant for both systems, as the same frequency is used and the radius r_{max} of the source enclosing sphere is almost equal for both the volumetric 3D antenna as well as for the reference antenna system. For further information regarding the employed model, refer to [11], [12].

For performance comparison the 2D reference antenna has been mounted on the same sedan type vehicle at the same position as the 3D volumetric antenna according to Fig. 6b. According to [7], [9] inter-element coupling can have a significant impact on the performance of MIMO antenna system. Thus, for further reference and in ordner to allow a proper interpretation of the measurement results in the following section, Table I shows return loss and inter-element coupling of both the volumetric and reference antenna. Measurements have been taken with a calibrated network analyzer.

TABLE I
CHARACTERIZING IMPEDANCE-BASED VALUES OF THE VOLUMETRIC (AUT) AND REFERENCE (REF.) ANTENNA SETUP AT 796 MHz.

	$\lvert S_{11}\rvert$ front, back	$\lvert S_{21}\rvert$
AUT	13,23 dB, 10,47 dB	11,78 dB
Reference	19.17 dB, 22.92 dB	10.47 dB

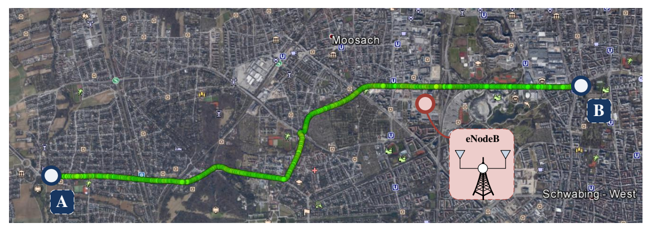


Fig. 7. Measurement track served by a LTE base station at 796 MHz.

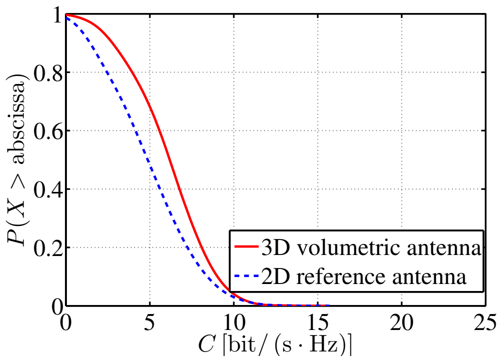
V. EVALUATION

In the following, we will present the results of the 3D antenna described in Section II as well as the results of the 2D reference antenna setup according to SectionIV. A comparison to the reference system and a conclusion will be drawn.

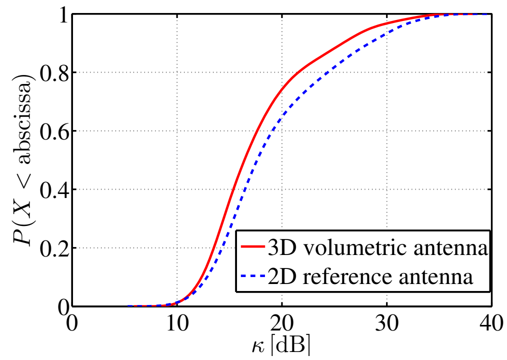
To include the influence of mobility and the effect of different channel conditions, the measurements have been carried out in an dynamic environment on a test track of 9 km length in the city of Munich, Germany according to the procedure proposed in [7]. The measurement track is depicted in Figure 7.

For the following evaluation, we measure the channel matrix for each measurement point on the track of the drive test according to Section III. Subsequently, we calculat the condition number κ and channel capacity C for each measurement point and show their distribution functions for both the 2D reference antenna and the 3D volumetric antenna system in Figure 8. We plot the complementary cumulative distributions function (ccdf) of the channel capacity C in Figure 8a, as large values are desired for the channel capacity whereas the condition number shall be minimized. Thus, we show the cumulative distributions function (cdf) for the condition number κ in Figure 8b.

In general, the results in Figure 8 show better performance for the antenna system based on a 3D volumetric design approach based on evaluation of the channel capacity and condition number. The 3D antenna's mean condition number



(a)



(b)

Fig. 8. (a) Complementary cumulative distribution function (ccdf) of the channel capacity C and (b) cumulative distributions function (cdf) of the condition number κ for measured channels.

is decreased by $1.42\,\text{dB}$ to $15.95\,\text{dB}$, which proves for a good performance regarding its overall MIMO efficiency [7]. As a well conditioned multi-element antenna system is a prerequisite but not a direct implication for increased data rates [7], the channel capacity is also evaluated to cover its dependancy on the sub-channel gains λ_i as well as SINR. Regarding the channel capacity, the volumetric antenna yields an improvement of mean channel capacity by $1.55\,\text{bit}/(\text{s Hz})$ to $6.52\,\text{bit}/(\text{s Hz})$.

This quantitative performance assessment shows cleary an increased overall performance of the 3D volumtric antenna systems when compared to a valid reference setup. Keeping in mind, that the AUT has been designed to serve three LTE bands [6] and fits into the available space at a better performance, it becomes clear, that the volumetric design approach yields various powerful possibilies and options for designing and developing vehicular antenna systems. Utilization of the avaible third dimension enables improved performance, as shown within this contribution, as well as efficient exploitation of the availble and usually very restricted space for antenna positioning.

VI. Conclusion

In this contribution, we presented the evaluation of a vehicular MIMO antenna for LTE based on a volumetric 3D design approach by means of a system-level evaluation methodology. In order to assess the performance gain of a 3D antenna design towards a 2D antenna design, we developed a reference antenna system. Based on this reference, we were able to analyse the improved system performance due to better utilization of the available space by employing a 3D volumetric design approach. By using system level parameters like the condition number and the channel capacity, we were able to capture the overall system performance under the impact of the evaluated antenna system and show an improved performance of the volumetric conformal multiband antenna when compared to a single band reference antenna. Measurements in a live LTE network were done and analyzed. The interpretation of the results shows clearly, that a volumetric MIMO antenna design approach enables both the efficient exploitation of the available integration space as well as improved performance properties based on system-level evaluation.

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