Simulation Model for Chassis Antenna Cavities Made from Carbon Fiber Reinforced Polymer

Gerald Artner[1], Philipp K. Gentner[2], Robert Langwieser[1], Christoph F. Mecklenbräuker[1]
[1]Institute of Telecommunications, Technische Universität Wien, Vienna, Austria,
gerald.artner@nt.tuwien.ac.at, robert.langwieser@nt.tuwien.ac.at, cfm@nt.tuwien.ac.at
[2]KATHREIN-Werke KG, Rosenheim, Germany, philipp.gentner@kathrein.de

***Abstract*—Cavities built into the vehicle chassis have recently emerged as receptacle for hidden antennas. In the automotive sector they potentially replace the roof mounted shark-fin antenna modules. Simulation models for chassis antenna cavities are critical, because they must both accurately predict antenna performance, while staying computationally reasonable. Moreover, if the chassis of electric cars, airplanes and boats are built with carbon fiber reinforced polymer, then a model for the composite laminate is required. In this paper a simple simulation model for chassis antenna cavities is developed. The carbon fiber composite material is modeled as a linear, homogeneous and isotropic conductor, and several cavity geometry details are omitted. Simulation results are in good agreement with measurements in the frequency band at 5.9 GHz for intelligent transport systems.**

***Index Terms*—antenna, automotive, carbon, cavity, chassis, composite, concealed, hidden, laminate, simulation, vehicular.**

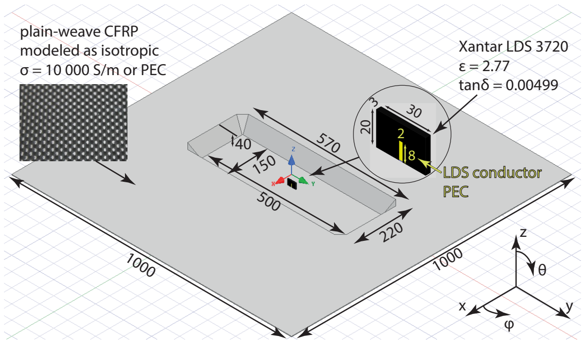


Fig. 1: Simulation model of a chassis cavity with a laser direct structured (LDS) monopole antenna for 5.9 GHz. All dimensions are in millimeter.

I. Introduction

Shark-fins have been exceedingly successful as antenna modules in the automotive sector. They already contain antennas for telephony (2G - 4G), positioning systems (GPS, GLONASS), Satellite Digital Audio Radio Service (SDARS), Digital Audio Broadcast (DAB), Remote Keyless Entry (RKE), Vehicle-to-any communication (V2X), etc; but they can't grow in size and won't be able to contain the antennas required for future vehicles. Chassis antenna cavities are investigated in the automotive sector as an alternative to shark-fins, and they are considered as concealed antenna modules for airplanes, trains and unmanned aerial vehicles (UAV). A cavity-backed ultra-wideband spiral antenna is built into the car trunk in [1]. An antenna for SDARS and GPS inside a $40 \times 40 \times 10\,\mathrm{mm}^3$ cavity is built in [2], and a LTE antenna inside a $200 \times 200 \times 30\,\mathrm{mm}^3$ cavity is designed and simulated in [3]. For aircraft applications a wideband monopole antenna inside a cavity is used in [4].

It has recently been proposed to increase the size of chassis antenna cavities, such that they can contain whole antenna modules instead of single antennas [5]. This chassis antenna cavity has a size of about $150 \times 500 \times 40\,\mathrm{mm}^3$ (see Fig. 1) and fits into the car roof alongside a panorama window. An antenna for vehicle-to-any (V2X) communication and a wideband conical monopole antenna in such a large automotive chassis antenna cavity are presented in [6]. A pattern reconfigurable antenna inside a cavity is measured in [7] and a multiple-antenna configuration in [8]. A chassis antenna cavity at the car's roof edge directly above the windshield is presented in [9], and it is shown that this position substantially increases radiation towards lower elevation angles.

Carbon Fiber Reinforced Polymer (CFRP) are already used in the production of commercially available mass-produced cars, where they replace metals for large and heavy parts, which are instead built as lightweight composite laminates, honeycomb and sandwich structures. From an antenna viewpoint metal ground planes are replaced by anisotropic materials. The radio-frequency properties of CFRP generally depend on a variety of parameters such as fiber type, fiber volume fraction, ply weave and laminate buildup sequence. Although CFRP laminates are anisotropic in general [10], recent publications demonstrate that the production of CFRP laminates with quasi-isotropic electric conductivity is feasible [11], [12]. The use of these CFRP with quasi-isotropic conductivity then only results in small changes in antenna performance, which can be neglected in automotive applications. This implies that these CFRP can be modeled as an isotropic material. A chassis antenna cavity made from CFRP is built and measured in [5].

Contribution — In this paper a simple model for chassis antenna cavities is presented, simulated and validated by measurement. The influence of a limited geometric complexity is discussed, because it is a widely used practice to speed up simulation time by reducing geometric details of large structures. CFRP are modeled as linear, homogeneous and isotropic conductors. It is shown that even this heavily simplified model yields results that are in good agreement with measurements.

II. Simulation Model

Simulation software for finite elements, method of moments, etc. is available for a wide variety of antenna and propagation problems. The task of antenna engineers is to select suitable geometric models for the shape of the antenna and its surroundings, as well as models for the materials.

Model complexity often has to be reduced with contemporary software and hardware, in order to reduce the simulation time and effort. For vehicular antenna simulations the three main problems are that vehicle size becomes electrically large with decreasing wavelength, that vehicles have detailed shapes and that they consist of a plurality of different materials. Simulation complexity is typically decreased by simulating only a portion of the vehicle (or choosing a hybrid approach), discarding details and choosing adequate material models. The simulation model is depicted in Fig. 1.

A. Geometric Model

Electromagnetic simulation of whole, fully-detailed vehicles is still not reasonable [13]. Automotive antenna simulation has significantly advanced in the recent years. Car models with coarse wire grids [14], [15] are now replaced by finely meshed simulations of chassis [16]–[18]. Structural details like seats, windows or passengers are only added when required [19], [20]. For roof mounted antennas proper modeling of panorama roof windows is critical [21], [22]. For research purposes the vehicle is typically omitted in the simulation, such that the results don't depend on an arbitrary vehicle type [23].

The proposed simulation model for the geometry of chassis antenna cavities considers the size of the cavity and the inclination of its walls, as well as the triangles in the cavities corners. Some details are omitted in the proposed model. All edges of the produced part have a radius of $5\,\mathrm{mm}$, but they are simulated as sharp angular transitions. This is a typical simplification, because cylindrical details require a dense mesh. As example such a simple simulation model for a cavity with sharp corners is used in [3]. The vehicle roof is modeled as a $1 \times 1\,\mathrm{m}^2$ sheet both for the prototype and the simulation, but while the produced part slightly bends downwards due to its own weight, this is not represented in the simulation model.

The antenna is a quarter-wavelength monopole antenna for $5.9\,\mathrm{GHz}$ V2X communication, which is manufactured with Laser Direct Structuring (LDS), see [6]. The substrate material is XANTAR LDS 3720, which is a polymer with a special additive that can be activated by laser. The stub of the monopole antenna is a rectangle metalized in currentless metal baths.

B. Material Model

Simplifications are also required for material models. For example paints that are applied with an electrostatic primer are known to have a significant influence on the gain pattern [24], but are often not modeled to reduce simulation effort. In this paper we focus on CFRP, as they are now used in the lightweight production of vehicles and replace antenna ground planes formerly built with metals.

Typical diameters of carbon fibers are in micrometer region, and plies are woven from rovings that consist of several thousand individual fibers. From a simulation perspective the modeling of individual fibers in large parts is far from feasible. Various models for carbon composite materials obtain macroscopic material properties based on microscopic material structures. Holloway et al. propose equivalent layer models for CFRP laminates with unidirectional plies rotated against each other [25]. Senghor et al. derive the conductivity tensor from models on four levels scaling from individual fibers to yarns and layers [26].

It is well known that the conductivity of unidirectional CFRP is heavily anisotropic [10], which has a large influence on antenna performance. On the contrary, we have previously carried out extensive measurements to quantify the influence of quasi-isotropic CFRP onto antennas [12], [27]–[29]. CFRP with woven and shredded fibers have a quasi-isotropic conductivity in the single digit gigahertz region, which only varies within one decade (10^4-$10^5\,\mathrm{S/m}$) [12]. Measurements with narrowband monopole antennas [27], wideband monopole antennas [28] and whole automotive shark-fin antenna modules [29] show, that woven and shredded CFRP act as quasi-isotropic antenna ground planes with only negligible influence on radiation patterns. Laminates with unidirectional plies, which are rotated against each other when stacked, also exhibit quasi-isotropic behavior, as is shown by Gelehdar et al. [11]. The conductivity is then still anisotropic, with higher conductivity when the electric field vector is parallel to the fiber orientation of the top ply, but the difference to the perpendicular direction is within an order of magnitude. A patch antenna and a slot antenna are built with these CFRP laminates with rotated unidirectional plies and a gain difference of about $3.5\,\mathrm{dB}$ is found [11].

In addition to modeling quasi-isotropic CFRP's conductivity as isotropic some other simplifications are implicitly made. Quasi-isotropic CFRP reduce the radiation efficiency of monopole antennas, when they are used as ground plane material, but as the efficiency is reduced by less than $1\,\mathrm{dB}$ this can be neglected for automotive applications [28]. CFRP are modeled as homogeneous conductors. For manufactured parts this might only approximately be the case. Conductivity measurements of material samples taken from different positions (but with the same orientation) vary within one decade in [12] . CFRP are modeled as linear materials. Passive intermodulation products (PIMP) from CFRP antennas can be a problem in some applications [30].

From a design viewpoint a CFRP with favorable radio-frequency properties can be chosen (woven or shredded fibers; or laminates with unidirectional plies rotated against each other). The CFRP conductivity is then quasi-isotropic. The antenna is still significantly influenced by the quasi-isotropic ground plane; the changes are measurable, but they are small enough to be neglected in automotive applications. The material can therefore be modeled as isotropic. Furthermore, it

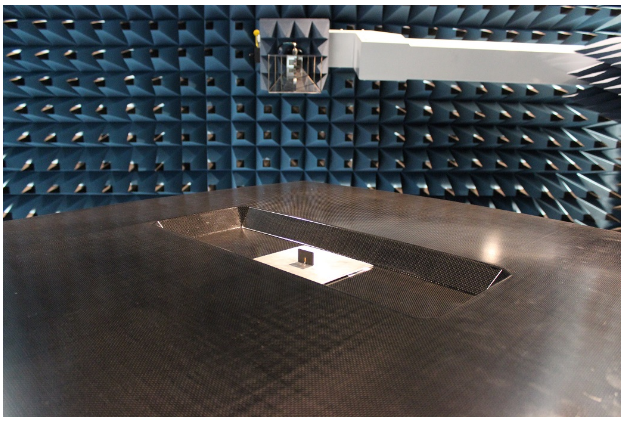


Fig. 2: Measurement of the monopole antenna for $5.9\,\mathrm{GHz}$ inside a CFRP chassis antenna cavity.

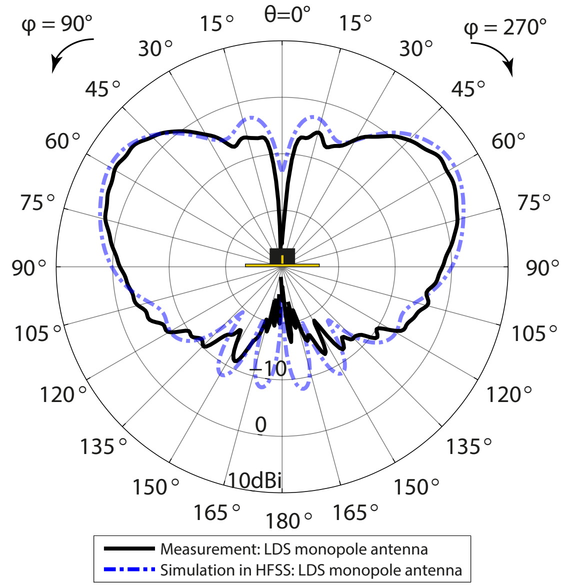


Fig. 3: Gain pattern of the LDS monopole antenna for $5.9\,\mathrm{GHz}$ without the cavity on a small $150 \times 150\,\mathrm{mm}^2$ ground plane.

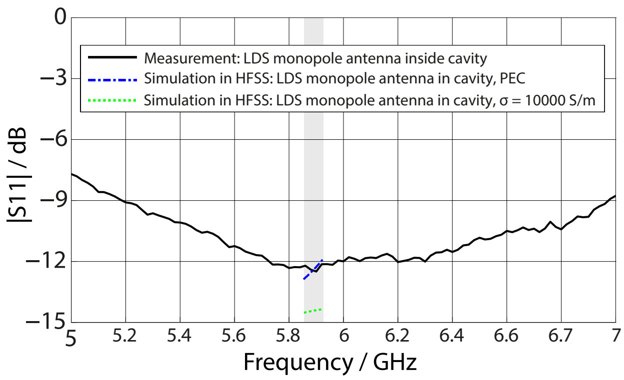


Fig. 4: Measured $|S_{11}|$ compared to simulation results.

should be considered that it is sufficient to only design the top layer(s) of stratified media according to RF requirements, should mechanical designs require CFRP with different structures. Layers below the electrically isotropic surface are not relevant as electric currents are confined to the skin-depth due to the skin effect.

The CFRP sheet is modeled as an isotropic conductor with conductivity $\sigma = 10000\,\mathrm{S/m}$. In a further step we also model the CFRP as Perfect Electric Conductor (PEC). This has no physical basis and is purely motivated by a desire to further reduce the simulation time. Comparisons in Sec. IV show that deviations are reasonable. The LDS monopole antenna is modeled according to [31]. The metalized monopole stub is a stack of copper (6-8 μm), nickel (5-7 μm) and gold ($0.1\,\mu$m) and it is modeled as a PEC. The LDS substrate material XANTAR LDS 3720 is modeled as a lossy dielectric with permittivity of $\epsilon = 2.77$ and a dissipation factor tan$\delta = 0.00499$ according to [32].

III. Prototype and Measurement

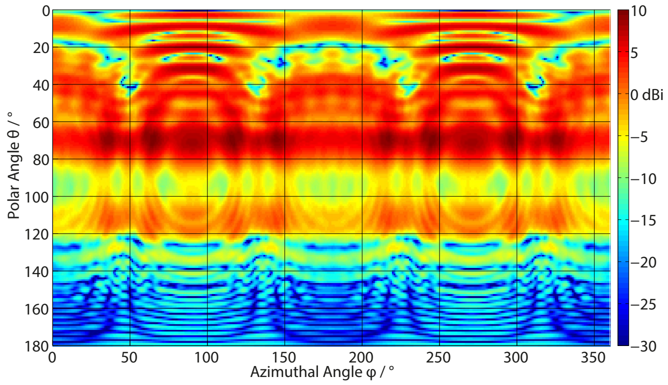
The simulation results are compared to measurements of a cavity prototype that is made from CFRP. It is the same chassis cavity, which is used in [5]–[8]. The cavity has a size of about $150 \times 500\,\mathrm{mm}^2$. It is embedded in a $1000 \times 1000\,\mathrm{mm}^2$ CFRP sheet which acts as a large ground plane such as a car roof or airplane wall panel. The CFRP is built as laminate with a thickness of about $2\,\mathrm{mm}$. It is made from plain-weave prepreg, vacuum bagged and cured in an autoclave (see [5]). The antenna inside the chassis cavity is measured in the institute's anechoic chamber as depicted in Fig. 2. The chamber is a spherical near-field measurement system. Far field results are obtained with a near-to-far-field-transformation.

Some modifications are required to conduct measurements, which will influence the results. The antenna is placed on a square aluminum sheet with side length $150\,\mathrm{mm}$, because the CFRP sheet is too thin to thread and attach a sub-miniature version-A (SMA) connector flange to it. The coaxial cable that connects the antenna with the measurement equipment is routed through a hole in the cavity floor. The cavity can't float in free space as it does in the simulation. It is mounted in the chamber with an aluminum fixture on a glass-fiber reinforced polymer (GFRP) column. This limits the maximum angle of the elevation-arm with the probe antenna to polar angles $\theta < 160°$. Data from these angles is missing when performing the near-to-far-field-transformation.

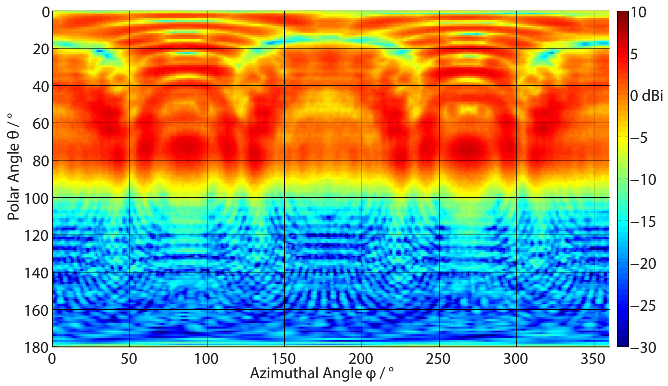
IV. Measurement Results Compared to Simulation

The simulation with the geometric model from Sec. II-A and the material model from Sec. II-B is compared to measurements. Simulations are performed with Ansoft HFSS, which is a finite element solver that is now part of the ANSYS Electronics Desktop 2017.1.0. Simulation and measurement results are compared for the LDS monopole antenna without the cavity in Fig. 3. They are in good agreement.

The antenna is placed inside the cavity for the other figures. Simulated and measured values for $|S_{11}|$ are compared in Fig. 4. The matching of the antenna is a bit better in the



(a)



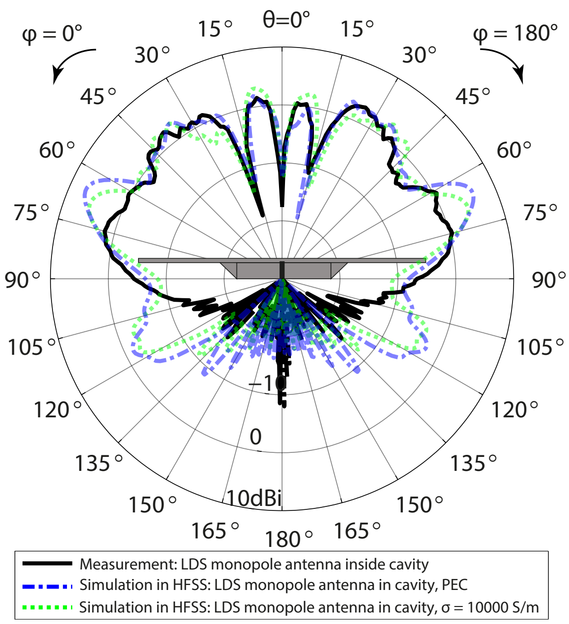
(b)

Fig. 5: Rectangular projections of the gain patterns. a) simulation with $\sigma = 10000$S/m and b) measurement

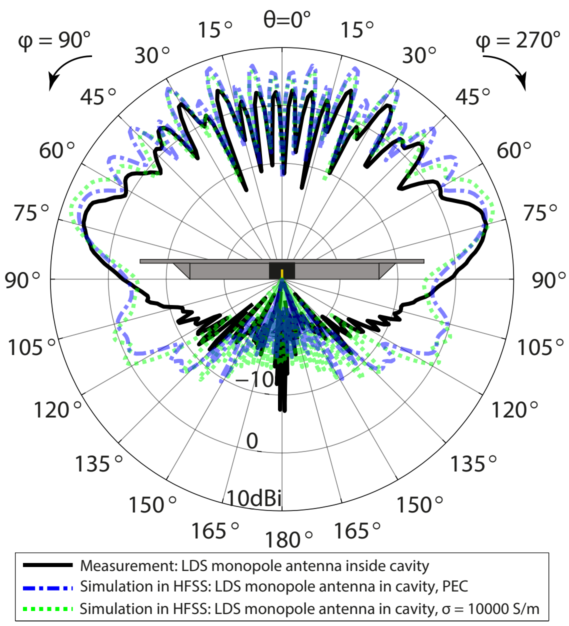
simulation, but the measured return loss is still slightly above 12 dB. Rectangular projections of the calibrated gain patterns are shown in Fig. 5 in order to give an overview. For an easier quantitative comparison Fig. 6a and Fig. 6b show vertical cuts of the gain patterns, along the short and long cavity sides, respectively. Sketches of the antenna and the cavity are depicted to help with orientation.

The gain patterns obtained from simulation and measurement are in good agreement. Simulation overestimates the backlobes around $\theta \approx 120°$, which are not present in the measurement and would not be expected on such a large ground plane (1000 mm or $20\,\lambda$). The simulation also overestimates the gain between $60° < \theta < 75°$ in Fig. 6a. The measured gain is much smoother and close to 0 dBi from $20° < \theta < 75°$.

The cavity is electrically larger along its longer side (Fig. 6b). Reflections from the cavity walls lead to additional zeros around zenith. While this effect is undesired from a performance viewpoint, the positions of the zeros are a good way to test simulation accuracy. The number and positions of these zeros match exceptionally well between simulation and measurement. But the gain of the lobes between these notches is overestimated in the simulation.



(a)



(b)

Fig. 6: Monopole antenna for 5.9 GHz inside a chassis antenna cavity. Simulation compared to measurement. Vertical cuts of the gain patterns along the a) short cavity side and b) long cavity side.

V. Conclusion

A simple simulation model for chassis antenna cavities is presented and it is evaluated by comparing simulation results to data obtained from measurements of a prototype inside an anechoic chamber. The main simplification is to model CFRP as a linear, homogenous, isotropic conductor. Details of the cavity's geometry are removed in order to reduce simulation time and processing power.

The inclusion of a CFRP material model makes the simulation model applicable for electric cars, airplanes, rockets and handheld devices that use a CFRP chassis, hull, or casing. A CFRP with quasi-isotropic electric conductivity is chosen (which is reasonable in antenna design) and the CFRP is then modeled as an isotropic material.

Comparison to measurement results show that even a heavily simplified model with sharp corners and isotropic conductivity yield simulation results that are in good agreement with measurements. The simplifications allow antenna cavities to be included in the simulation of large structures such as car chassis and airplane hulls.

The presented simulation model is expected to also yield good results for similar vehicular antenna positions such as recesses at the roof spoiler [33]

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