This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LAWP.2016.2637560, IEEE Antennas and Wireless Propagation Letters

Concealed CFRP Vehicle Chassis Antenna Cavity

Gerald Artner, *Student Member, IEEE,* Robert Langwieser, *Member, IEEE,*
and Christoph F. Mecklenbräuker, *Senior Member, IEEE*

***Abstract*—A concealed vehicular carbon fiber reinforced polymer (CFRP) cavity in the roof which contains antennas is proposed, prototyped and measured. Compared to state of the art roof mounted shark-fin modules this offers significantly more room for antennas and radio frequency hardware, thus enabling a smooth transition of vehicular connectivity towards 5G. Three antennas were prototyped and embedded in the cavity: Two laser direct structured (LDS) antennas (inverted-F antenna for $2\,$GHz, monopole for $5.9\,$GHz), as well as a broadband conical monopole antenna milled from brass that characterizes the feasible frequency range from 2 to $6\,$GHz by measurement. It is shown that near-omnidirectional radiation from the concealed automotive antenna cavity is achievable.**

***Index Terms*—CFRP, antennas, concealed, hidden, automotive**

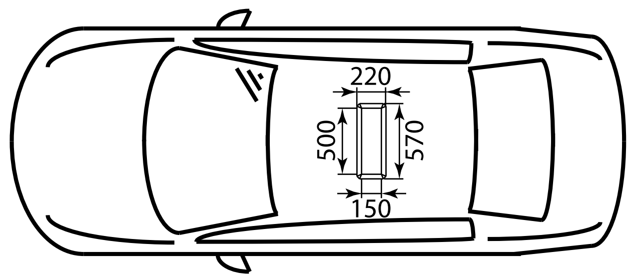


Fig. 1: Exemplary location of the chassis antenna cavity on a car roof. All dimensions in millimeter.

I. Introduction

WITHIN the next decade our perception of cars will change tremendously. The image of a moving combustion engine is already fading and a trend towards electric, computerized vehicles that move cooperatively is evident. The car of the future is aware of its environment and actively protects its passengers and surroundings from harm, all while connecting its users and itself to the information networks around it.

To enable the reliability, low latency and high data rates, the wireless communication systems of vehicles are expected to grow further. The amount and diversity of antennas mounted on vehicles will certainly increase. Roof mounted automotive modules now include antennas for satellite navigation, mobile telephony and internet access, terrestrial and satellite radio, remote keyless entry, wireless LAN, vehicle-to-vehicle and vehicle-to-infrastructure communication, with antenna diversity deployed to increase reliability and throughput where necessary [1]–[3].

In roof mounted automotive antenna modules antennas are confined within a limited space. Module size is limited by their negative influence on the vehicles' drag coefficient and aesthetics. Radio frequency hardware is often connected with coaxial cables routed from the car roof, as automotive antenna modules only contain the antennas and matching networks.

Several concealed antenna positions have been previously proposed, with extensive contributions from Langley et al. [4]. Previously proposed hidden module locations include: bumpers [4], an aperture in the rear end of the roof for FM radio [5], spoilers [6], side and rear-view mirrors [7], [8], a tiny cavity on the roof only for SDARS [9] and many others. However, finding a concealed antenna mounting position, that does not influence the cars drag coefficient, while offering enough space for most automotive antennas without impairing their radiation patterns is a challenging task.

In this letter a cavity for vehicular antennas is presented. The cavity is designed for seamless industrial mass production as part of a carbon fiber reinforced polymer (CFRP) chassis. It can be integrated into the car roof, as is depicted in Figure 1. With a volume content of about $3\,\mathrm{dm}^3$ the cavity offers significantly more space than contemporary roof mounted automotive antenna modules. Currently the largest commercially used automotive roof module [1] offers approximately $0.2\,\mathrm{dm}^3$. The antennas are concealed inside the cavity, the cavity does not influence the drag coefficient of the vehicle and due to its large dimensions antennas can be further separated. Its size allows to move radio frequency hardware close to the antennas, eliminating the requirement to route (expensive) coaxial cables from the car roof. Like roof modules, the cavity volume is dedicated antenna space, so that antennas can be developed independent from other automotive assembly groups. A prototype was manufactured from CFRP and is presented in Section II. The feasibility of omnidirectional radiation from the rectangular cavity and radiation in the horizontal plane from a position below the roof is discussed in Section III with an inverted-F antenna and a monopole antenna for current generation mobile communication and vehicle to anything (V2X) communication respectively. Measurements of the antennas inside the cavity are discussed in Section IV.

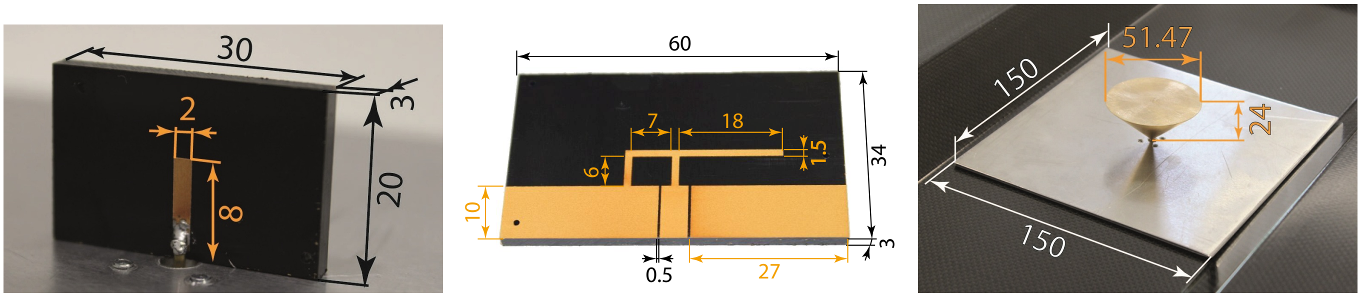
II. Integrated Vehicle Chassis Antenna Cavity

The proposed antenna cavity can be integrated into the chassis of a vehicle. For mass production the rectangular cavity, which contains an antenna module, is to be included into the chassis by the vehicle manufacturer. A manufactured cavity prototype has outer dimensions of about

G. Artner, R. Langwieser and C.F. Mecklenbräuker are with the Institute of Telecommunications, Technische Universität Wien, 1040 Vienna, Austria (e-mail: gerald.artner@nt.tuwien.ac.at, rlang@nt.tuwien.ac.at, cfm@nt.tuwien.ac.at).

G. Artner and C.F. Mecklenbräuker were with the Christian Doppler Laboratory for wireless communications for sustainable mobility.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LAWP.2016.2637560, IEEE Antennas and Wireless Propagation Letters



(a) Monopole antenna for 5.9 GHz. (b) Inverted-F antenna for 2 GHz. (c) Broadband conical monopole antenna.

Fig. 2: Dimensions of the antenna prototypes measured inside the chassis antenna cavity. All dimensions in millimeter.

570 mm×220 mm×40 mm with inclined cavity walls. To protect the antennas placed in the cavity, it would typically be covered with a non-conductive material such as a polymer or glass. The proposed cavity is shallow enough to fit into a car roof and short enough to fit alongside a panorama roof window. An exemplary mounting as part of a car roof is shown in Figure 1.

It is expected that usage of CFRP as chassis material in car production will further increase. The feasibility for lightweight construction of the cavity as part of a vehicle chassis made from a fiber-reinforced composite is investigated. A prototype was manufactured with the autoclave method from plain weave CFRP prepreg stacked as $[(0/90)_4]$. Mass production with a different method is certainly possible. The cavity is located in the center of a 1 m×1 m sheet. The edges around the cavity were reinforced with unidirectional fiber strands.

Like zinc coated steel roofs before, CFRP can be used as ground plane material for antennas. At frequencies in the gigahertz range the radiation efficiency of antennas on CFRP is expected to be a bit less than on a metal ground plane. In this frequency range the influence of the CFRP anisotropy on radiation patterns is negligible, both for small ground planes [10] and whole car roofs [11]. It is expected that the vehicles' geometry and materials will influence the antennas inside the chassis cavity similarly to the conventional roof-mounted antennas; however, this should be studied in the future work.

III. Omnidirectional Antennas Inside the Cavity

Insertion of directional antennas facing towards zenith into a cavity is straightforward. An antenna for satellite digital audio radio services (SDARS) and global positioning system (GPS) inside a 40 mm × 40 mm × 10 mm cavity was presented in [9]. To show the feasibility of omnidirectional radiation patterns with standard antennas, an inverted-F antenna (IFA) and a quarter wavelength monopole antenna are investigated inside the cavity. The cavity is designed to be usable in a wide frequency range, as is demonstrated by measurements of a broadband conical monopole antenna.

The IFA and the quarter wavelength monopole antenna are manufactured with laser direct structuring (LDS), a production process for molded interconnect devices (MID). The LDS monopole antenna and the possibility to improve radiation efficiency of antennas on CFRP with a superimposed LDS layer are discussed in [12]. The LDS process allows the manufacturing of volumetric and conformal antennas and it's suited for mass production. Recently LDS was applied to build MID automotive antennas in [13]–[15]. The substrate material Xantar LDS3720 (PC/ABS) contains an additive that is activated by laser in desired areas. Activated areas are plated in currentless metal baths. The plating of the presented prototypes are layers of copper, nickel and gold, with a layer thickness of about $6-8\,\mu$m, $5-7\,\mu$m and $0.1\,\mu$m respectively. Material properties of the substrate material for simulation were taken from [16].

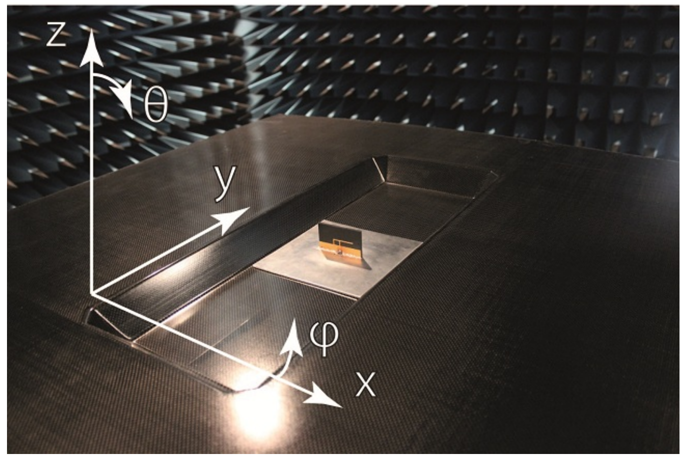


Fig. 3: Inverted-F antenna for 2 GHz inside the CFRP antenna cavity prototype.

The quarter wavelength monopole antenna radiates at 5.9 GHz, a frequency band which is reserved for intelligent transportation systems. The LDS monopole antenna and its dimensions are depicted in Figure 2a. The inverted-F antenna (IFA) radiates at 2 GHz. The LDS IFA and its dimensions are depicted in Figure 2b. The conical monopole antenna is a standard design dimensioned according to [17]. The cone is milled from brass, a photograph of the antenna inside the cavity with added dimensions is shown in Figure 2c.

As the contacting of CFRP is still an open issue and the sheet is too thin to be threaded, all antennas are measured on a 150 mm×150 mm aluminum ground plane which was placed on the cavity floor (see Figure 3). Coaxial cables for measurement are attached with SMA flanges. The inner conductors of

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LAWP.2016.2637560, IEEE Antennas and Wireless Propagation Letters

the SMA connectors are soldered to the antennas. For the IFA conductive epoxy was used as the heat deflection temperature of the substrate is around $100°C$ and the metalized layers start to separate from the substrate at soldering temperatures. The inverted-F antenna on the aluminium sheet inside the manufactured CFRP prototype is depicted in Figure 3.

IV. Measurement Results

Near field measurements were performed in the institute's anechoic chamber, gain patterns were obtained with a near-to-far-field transformation. During measurements, a single antenna under test (AUT) is placed in the center of the cavity. All measurements are carried out without covering the cavity. Measured return losses of the antennas inside the cavity are depicted in Figure 4. Measurement of the conical monopole antenna show, that the cavity is usable in a wide frequency range. As comparison the cone is measured on a circular aluminium ground plane with a diameter of $300\,\mathrm{mm}$. The return losses of the two cone measurements are in good agreement, the influence of the chassis cavity on the return loss is small.

Vertical cuts of the measured gain patterns are depicted in Figures 5 and 6. Figure 5 shows the cut along the short dimension of the cavity. If the antenna cavity is mounted on a vehicle according to Figure 1, then $\varphi = 0°$ will coincide with the driving direction. The lengthwise cut is depicted in Figure 6, this might coincide with the left and right side of a vehicle. Both antennas have near-omnidirectional patterns. A zero at zenith is expected in the radiation pattern of monopole antennas, the cavity creates additional zeros near zenith. Note that for directional antennas embedded into roof cavities facing zenith (such as satellite navigation or satellite radio) this is not an issue [9]. Although the antennas are placed in a recess below the $1\,\mathrm{m}\times1\,\mathrm{m}$ CFRP sheet, near-omnidirectional radiation patterns are achieved in the horizontal plane (Figure 7). The gain in the horizontal plane varies between $-7.5\,\mathrm{dBi}$ and $-1.5\,\mathrm{dBi}$. At $5.9\,\mathrm{GHz}$ the gain pattern has ripples of about $3\,\mathrm{dB}$ in direction of the cavity corners. The IFA has omnidirectional radiation for polar angles between $15°$ and $90°$ – omnidirectional radiation for mobile communications (3G, 4G) is achievable. Both monopole antennas shows good radiation at $5.9\,\mathrm{GHz}$ for polar angles between $45°$ and $90°$, an angular range that is necessary for V2X communication with other road users and roadside units. No zeros are caused in this region by the cavity, which is important for reliable V2X communication at $5.9\,\mathrm{GHz}$ [18].

V. Conclusion

Key characteristics of a concealed antenna cavity for integration into the vehicle chassis are discussed. Feasibility for future vehicles with CFRP chassis is demonstrated by building a prototype. The cavity offers much more space than contemporary vehicular antenna modules and can house all the antennas for future automotive communication systems. It retains advantages of roof mounted antennas (uniform reception, a large ground plane, isolation to passengers and electronics) in contrast to other concealed mounting positions on vehicles such as windows, roof spoilers, bumpers or pillars.

Radiation in the horizontal plane is feasible, even when antennas are embedded below the roof surface - a prerequisite for cooperative intelligent transport services based on vehicle-to-vehicle communication. Measurements of an inverted-F antenna and a monopole antenna show near-omnidirectional radiation characteristics (variation by $4\,\mathrm{dB}$). The purpose of these measurements is to show performance of standard antennas in such a cavity. Overall, the new mounting option offers both the space and the design freedom required to develop future vehicular antennas.

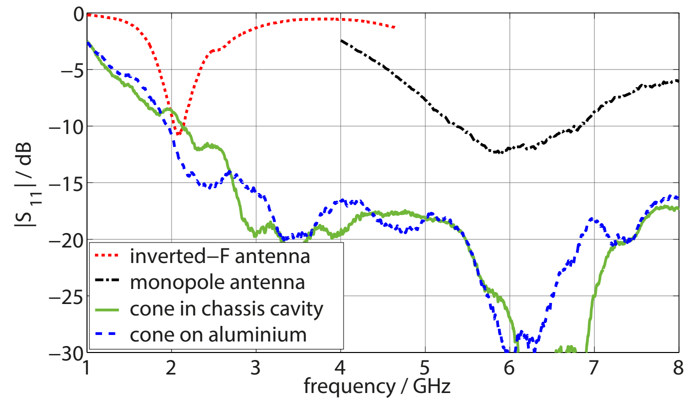


Fig. 4: $|S_{11}|$ of the inverted-F antenna and the monopole antenna inside the cavity.

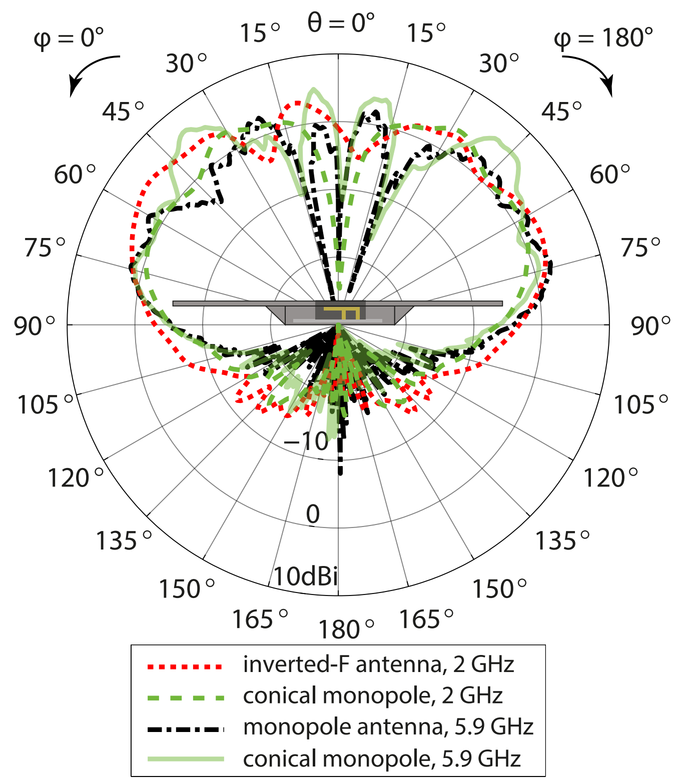


Fig. 5: Measured gain patterns of the IFA at $2\,\mathrm{GHz}$ and the monopole antenna at $5.9\,\mathrm{GHz}$ inside the cavity, vertical cut for $\varphi = 0°$.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LAWP.2016.2637560, IEEE Antennas and Wireless Propagation Letters

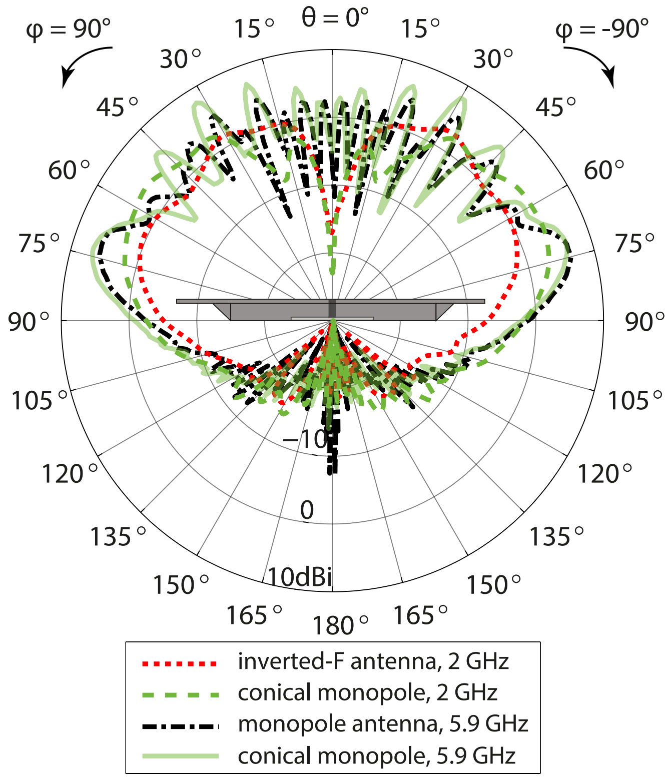


Fig. 6: Measured gain patterns of the IFA at 2 GHz and the monopole antenna at 5.9 GHz inside the cavity, vertical cut for $\varphi = 90°$.

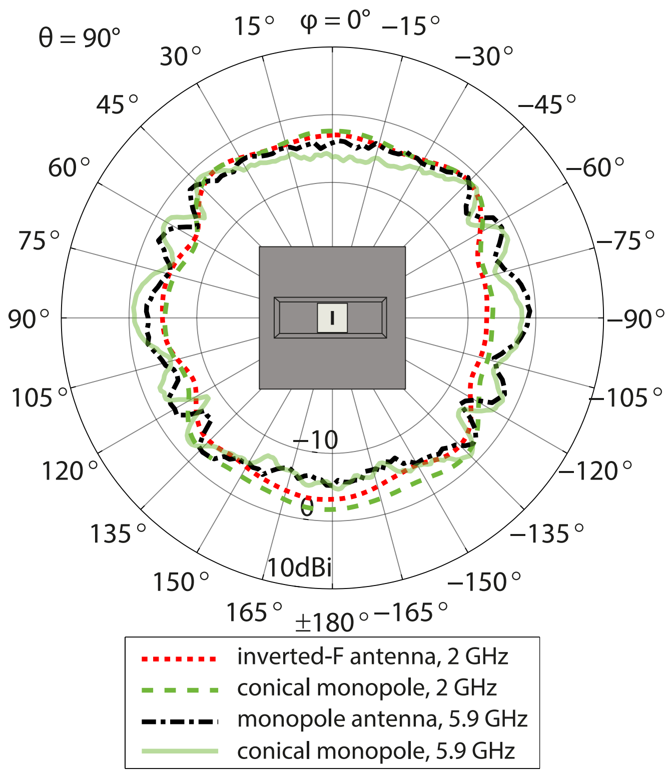


Fig. 7: Measured gain patterns of the IFA at 2 GHz and the monopole antenna at 5.9 GHz inside the cavity, horizontal cut for $\theta = 90°$.

Acknowledgment

This work has been funded by the Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility.

The financial support by the Austrian Federal Ministry of Science, Research and Economy and the National Foundation for Research, Technology and Development is gratefully acknowledged.

References

[1] A. Thiel, L. Ekiz, O. Klemp and M. Schultz, "Automotive Grade MIMO Antenna Setup and Performance Evaluation for LTE-Communications," in *Int. Workshop on Antenna Technology (iWAT)*, Karlsruhe, Germany, 2013.

[2] E. Ghafari, A. Fuchs, D. Eblenkamp and D.N. Aloi, "A Vehicular Rooftop, Shark-Fin, Multiband Antenna for the GPS/LTE/Cellular/DSRC Systems," in *IEEE-APS Topical Conf. on Antennas and Propagation in Wireless Commun. (APWC)*, Palm Beach, Aruba, 2014.

[3] N. Guan, H. Chiba, Y. Yamaguchi, Y. Niihara and H. Tayama, "A Flat Roof Automobile Antenna Module for LTE, GPS and SDARS Applications," in *IEEE-APS Topical Conf. on Antennas and Propagation in Wireless Commun. (APWC)*, Palm Beach, Aruba, 2014.

[4] R.J. Langley and J.C. Batchelor, "Hidden antennas for vehicles," in *Electron. & Commun. Eng. J.*, vol. 14, no. 6, pp. 253-262, Dec. 2002.

[5] L. Low, R. Langley, R. Breden and P. Callaghan, "Hidden Automotive Antenna Performance and Simulation," in *IEEE Trans. Antennas Propag.*, vol. 54, no. 12, pp. 3707-3712, Dec. 2006.

[6] E. Condo Neira, J. Carlsson, K. Karlsson and E.G. Ström, "Combined LTE and IEEE 802.11p Antenna for Vehicular Applications," in *European Conf. on Antennas and Propagation (EuCAP)*, Lisbon, Portugal, 2015.

[7] S. Senega, J. Kammerer and S. Lindenmeier, "Scan-Phase Antenna Diversity for Digital Satellite Radio (SDARS) in a Single Automotive Side Mirror," in *European Conf. on Antennas and Propagation (EuCAP)*, The Hague, The Netherlands, 2014.

[8] E. Safin, R. Valkonen and D. Manteuffel, "Reconfigurable LTE MIMO Automotive Antenna System Based on the Characteristic Mode Analysis," in *European Conf. on Antennas and Propagation (EuCAP)*, Lisbon, Portugal, 2015.

[9] J. Kammerer and S. Lindenmeier, "Invisible Antenna Combination Embedded in the Roof of a Car with High Efficiency for Reception of SDARS - and GPS - Signals," in *IEEE Antennas and Propagation Soc. Int. Symp. (APSURSI)*, Orlando, Florida, 2013.

[10] G. Artner, R. Langwieser, G. Lasser and C.F. Mecklenbräuker, "Effect of Carbon-Fiber Composites as Ground Plane Material on Antenna Performance," in *IEEE-APS Topical Conf. on Antennas and Propagation in Wireless Commun. (APWC)*, Palm Beach, Aruba, 2014.

[11] G. Artner and R. Langwieser, "Performance of an Automotive Antenna Module on a Carbon-Fiber Composite Car Roof," in *European Conf. on Antennas and Propagation (EuCAP)*, Davos, Switzerland, 2016.

[12] G. Artner, R. Langwieser and C.F. Mecklenbräuker, "Material Induced Changes of Antenna Performance in Vehicular Applications," in *IEEE Int. Conf. on Microwaves, Commun., Antennas and Electronic Systems (COMCAS)*, Tel Aviv, Israel, 2015.

[13] A. Friedrich, B. Geck, O. Klemp and H. Kellermann, "On the Design of a 3D LTE Antenna for Automotive Applications Based on MID Technology," in *European Microwave Conf. (EuMC)*, Nuremburg, Germany, 2013.

[14] A. Posselt, A. Friedrich, L. Ekiz, O. Klemp and B. Geck, "System-Level Assessment of Volumetric 3D Vehicular MIMO Antenna Based on Measurement," in *Int. Conf. on Connected Vehicles and Expo (ICCVE)*, Vienna, Austria, 2014.

[15] A. Friedrich, L. Berkelmann, T. Martinelli, B. Geck, O. Klemp and I. Kriebitzsch, "An Active Three-Dimensional GPS Patch Antenna Using MID-Technology," in *European Microwave Conf. (EuMC)*, Paris, 2015.

[16] Q.H. Dao, A. Friedrich, and B. Geck, "Characterization of Electromagnetic Properties of MID Materials for High Frequency Applications up to 67 GHz," in *Advanced Materials Research* 1038, pp. 63-68, 2014.

[17] A. Heilmann, *Antennen, Band 1*, Mannheim: Bibliographisches Institut, pp.108-111, 1970.

[18] S. Kaul, K. Ramachandran, P. Shankar, S. Oh, M. Gruteser, I. Seskar and T. Nadeem, "Effect of Antenna Placement and Diversity on Vehicular Network Communications," in *IEEE Commun. Soc. Conf. on Sensor, Mesh and Ad Hoc Commun. and Networks*, San Diego, California, 2007.