Conformal Automotive Roof-Top Antenna Cavity With Increased Coverage to Vulnerable Road Users

Gerald Artner, *Member, IEEE,* Wim Kotterman, Giovanni Del Galdo, *Member, IEEE,* and Matthias A. Hein, *Senior Member, IEEE,*

Abstract—**Cooperatively driving cars benefit from increased coverage towards driving direction for communication with vulnerable road users. Antenna cavities were designed, prototyped and measured for integration into car roofs above the windshield. Two different antenna cavities were investigated. First, an antenna cavity made from carbon fiber reinforced polymer was measured without a vehicle, to obtain general results without model specific influence. Second, a metal cavity was built into the roof of a sedan type passenger car to include the marked effects of the car body and provide a proof of performance. Gain patterns were measured in anechoic chambers. Results show that the antenna structure and mounting position are suitable for omnidirectional radiation with increased radiation towards low elevation angles in driving direction.**

Index Terms—**antenna, cavity, conformal, automotive, vehicular, windshield, CFRP**

I. Introduction

COOPERATIVE and connected driving will require communicative vehicles that actively share sensor information and warning messages between them [1]. Currently used shark-fin antenna modules [2], [3] can't grow in size to accommodate the antennas for this increase in communication. Conformal automotive antennas, not visible from the outside, are increasingly investigated as alternative to shark-fins. Alternative concepts include apertures [4], transparent antennas on the windows [5], [6], car body-mode antennas [7], [8], and antennas in the side mirrors [9], [10]. Chassis antenna cavities were recently introduced as means to build hidden conformal automotive antennas [11]. Antenna cavities offer ten times the volume of shark-fins. They present dedicated antenna spaces and the cavity floor isolates the antennas from the cabin. While circular cavities are used for single antennas [12], [13], rectangular cavities are preferred for automotive applications as they tend to be easier to integrate. Smart reconfigurable antennas have been shown to operate properly inside chassis antenna cavities [14].

An antenna cavity at the roof edge right above the windshield is proposed, prototyped and evaluated. This position is preferable for several reasons. It is available on most car types like sedans, hatchback, station wagons etc. and it can be combined with model variations such as sunroofs and panorama roofs. A front position is also closer to the control electronics (shorter cables). Intuitively antenna cavities could be tilted to follow the roof curvature, as considered in [15]. Instead, it is proposed to insert a horizontal cavity above the windshield, remove the front cavity wall and adjust the side walls to the roof curvature, as sketched in Fig. 1.

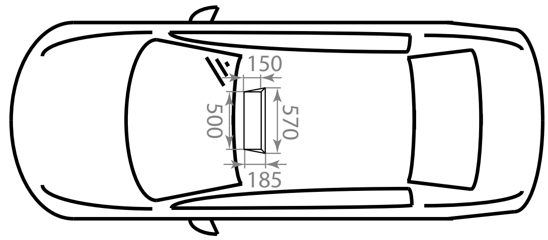

Fig. 1. Sketch of a chassis antenna cavity above the windshield on a sedan type vehicle. Dimensions are in millimeters.

The position of an antenna on a car has a strong influence on the directions that it can cover [16] and communication in driving direction is paramount for cooperative driving. This research was further motivated by preliminary investigations of a quarter-wavelength monopole antenna for 5.9 GHz intelligent transport systems in [17]. Results showed that open cavities can drastically increase coverage towards lower elevation angles in drive direction. Only similar concepts are theoretically described in patents, but have not been prototyped and evaluated. [18] describes an antenna shelf that extends from the roof under the windshield. [19] introduces a resin roof portion between window and car roof to place the antennas underneath it. [20] describes an antenna module in the roof frame cross member. A depressed roof portion is sketched in [21], which has the windshield extending above it.

Contribution — An antenna cavity suitable for a flexible and adaptive insertion into the roof of an automobile above the windshield is proposed. Sec. II describes a prototype of the cavity manufactured from Carbon Fiber Reinforced Polymer (CFRP). It was tested without a vehicle to obtain general results and show feasibility for light-weight constructed electric vehicles. A second prototype was then built into a sedan type vehicle, as described in Sec. III. Performance is discussed based on measured gain patterns in Sec. IV. As shown in this work, antenna modules in this position allow omnidirectional radiation, and increase coverage towards vulnerable road users compared to shark-fins and cavities in the roof center. This holds when the cavity is embedded in a sedan type vehicle.

G. Artner was with the Institute of Telecommunications, Technische Universität Wien, 1040, Vienna, Austria. email: gerald.artner@nt.tuwien.ac.at, website: www.geraldartner.com

W. Kotterman, G. Del Galdo, and M. Hein were with the Thuringian Centre of Innovation in Mobility at Technische Universität Ilmenau, Germany.

W. Kotterman and G. Del Galdo were with the Fraunhofer Institute for Integrated Circuits IIS, Germany.

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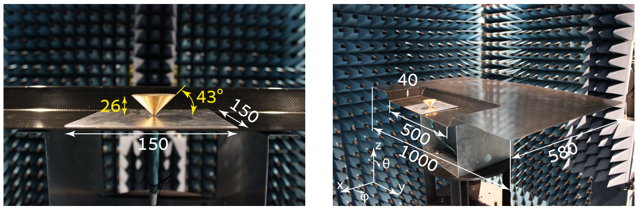


Fig. 2. Conical monopole antenna in the CFRP chassis antenna cavity that is open towards one side. Dimensions are in millimeters.

II. Stand-Alone Prototype

Car roofs act as large ground planes, which pushes gain patterns upwards and reduces gain in the horizontal plane and below. A cavity located at the roof edge benefits from the shorter ground plane in one direction and the front cavity wall can be omitted. In the first investigation, a prototype of the antenna cavity was measured without a vehicle such that results were obtained, which do not include vehicle model specific geometry. The prototype is a modified version of the cavity in [11] that was cut open along its long side. It includes neither windshield nor radome nor roof curvature adaptation. It was built from CFRP to demonstrate applicability of the proposed concept for light-weight-constructed vehicles [22]. The composite was built as a laminate with the autoclave method from plain-weave CFRP prepreg stacked as $[(0/90)_4]$. The dimensions of the cavity are $150\,\mathrm{mm}\times500\,\mathrm{mm}$ on the floor and $185\,\mathrm{mm}\times570\,\mathrm{mm}$ at the CFRP sheet, which has a size of $580\,\mathrm{mm}\times1000\,\mathrm{mm}$. The prototype is shown in Fig. 2.

The antenna was a standard design turned from brass [23]. The angle of the cone was designed to match the feeding impedance to the $50\,\Omega$ coaxial cable. The antenna was not directly mounted on the CFRP, but on a square aluminum ground with a side-length equal to the cavity floor width ($150\,\mathrm{mm}$) as in previous work [11]. This was done because of the difficulty to make proper contact with the conductive carbon fibers buried in epoxy. Also, commercial antenna modules are expected to include a metal base. Multiband monopole antennas are the standard for WLAN, LTE, Vehicle-to-Everything (V2X) and many other services available on cars. Therefore, the mounting position was characterized by measuring a wideband conical monopole antenna that covers the frequency bands of these services. Measurements were performed in the anechoic chamber at Technische Universität Wien, Austria. The chamber is a spherical near-field system and the θ-arm can move to a maximum polar angle of $160°$.

III. In-Situ Prototype

In the second investigation, a cavity was built into the roof of a sedan type car and measured in situ. This prototype was again open towards driving direction and had the same dimensions as the prototype of Secion II, but it was made from aluminum as it can be much more easily machined on-site than CFRP. The cavity's sides were trimmed to match the roof curvature (Figs. 3a and 3b). It was located behind the roof frame cross-member that connects the A-pillars, at a distance of $13\,\mathrm{cm}$ from the windshield. For prototyping it is easier to cut the roof open behind the roof frame cross-member, but in production the antenna module can be arranged above it. In order to install the cavity, the roof was cut open, then paint was removed around the opening and the cavity was inserted. Finally, gaps were closed with adhesive electrically conductive aluminum tape. The cavity was not covered, such that the results were not modified by an arbitrarily chosen radome. Wideband characterization from 0.8 to $6\,\mathrm{GHz}$ was done with a conical monopole antenna turned from aluminum. The cone was built larger than the one in Sec. II to lower the frequency range of the antenna and to characterize the lower LTE bands (Fig. 3c). Aluminum has a higher conductivity, makes the antenna lighter and mechanically more stable, but turning it on a lathe is a bit more difficult than it is with brass. Measurements were performed in the Virtual Road – Simulation and Test Area (VISTA) at the Thuringian Centre of Innovation in Mobility at TU Ilmenau, Germany [24]. VISTA contains a spherical near-field measurement system. The 110 probe antennas on the θ-arm cover elevations reaching from zenith to 20 degrees below horizon (see Fig. 3d).

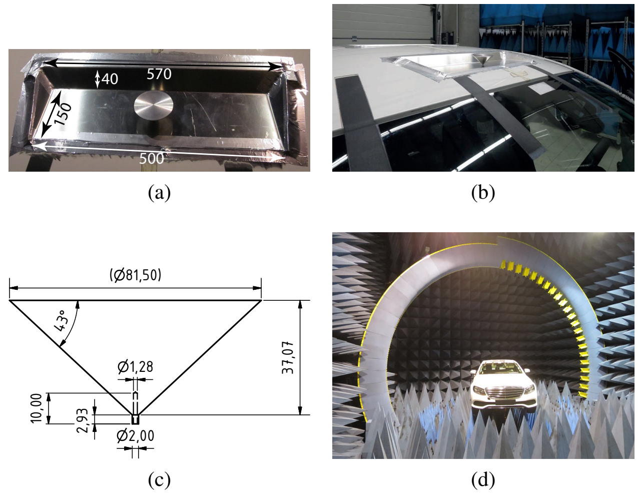


Fig. 3. a) Antenna cavity adapted to the roof curvature. b) Prototype of the antenna cavity located above the windshield. c) Dimensions of the larger cone for the car prototype. d) Measurement in VISTA. Dimensions are in millimeters.

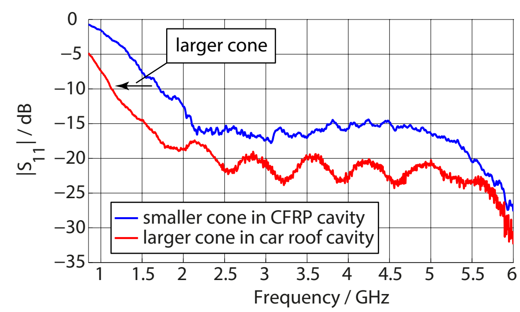
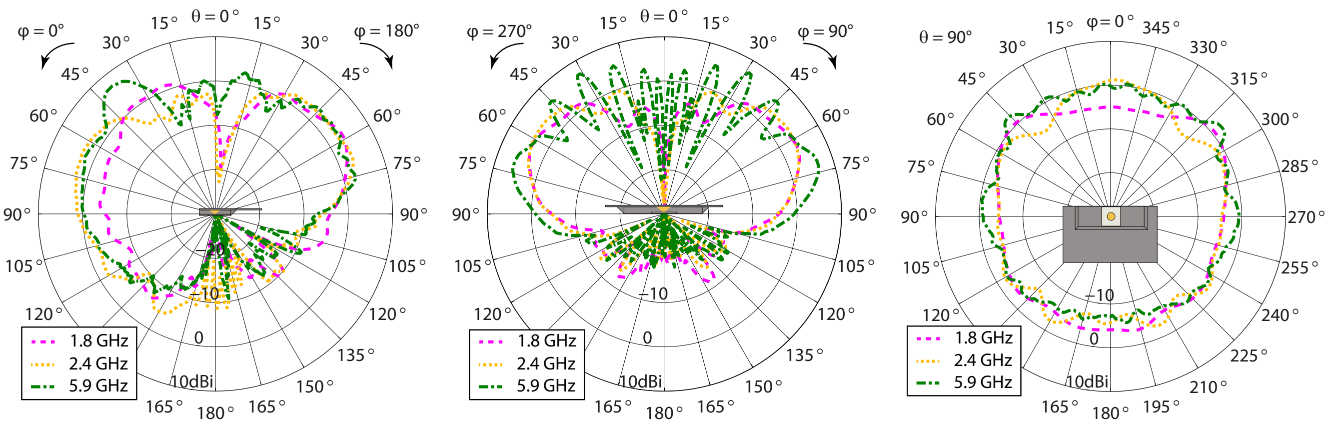
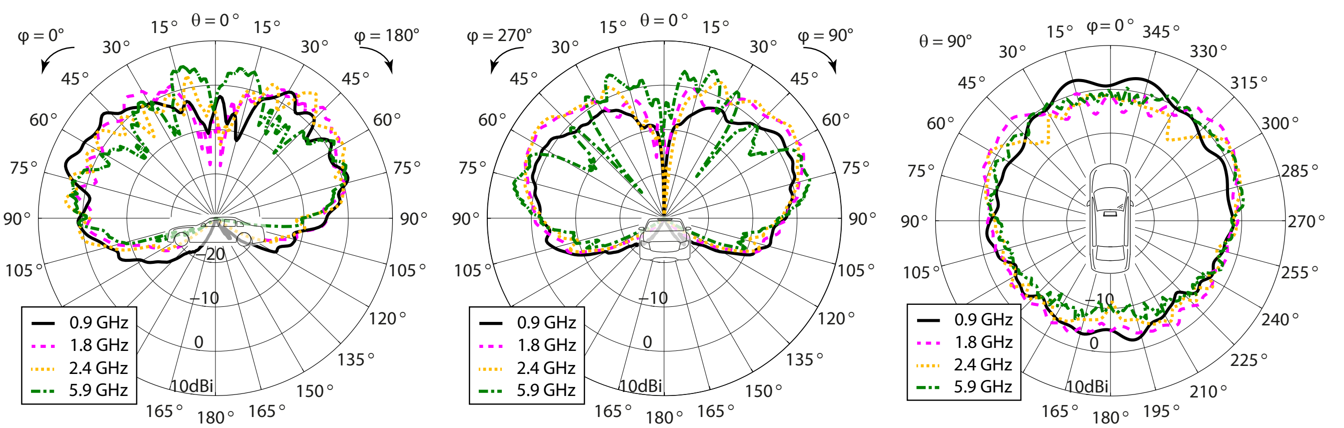


Fig. 4. Measured matching of the monocone antennas in the CFRP cavity and in the car roof. A larger cone was used for in situ measurements to obtain results for the lower LTE bands.



(a) (b) (c)

Fig. 5. Cuts of the measured gain patterns in the CFRP cavity; realized gain; linear polarization in θ direction; a) vertical cuts front/back b) vertical cuts left/right and c) horizontal cuts for polar angle $\theta = 90°$.



(a) (b) (c)

Fig. 6. Cuts of the measured gain patterns in situ on a sedan; realized gain; linear polarization in θ direction; a) vertical cuts front/back b) vertical cuts left/right and c) horizontal cuts for polar angle $\theta = 90°$.

IV. Measurement Results

The input reflection of the monocone measured in this arrangement is given in Fig. 4. With the small cone the return loss is better than 10 dB for frequencies > 1.71 GHz. The larger cone moves the 10 dB intersections 500 MHz towards lower frequencies and allows to measure the gain patterns at 900 MHz LTE frequencies with a return loss of 6 dB. We have no other explanation for the better return loss performance of the larger cone than a higher machining precision.

The measured gain patterns are shown in Fig. 5 for the stand-alone CFRP cavity and in Fig. 6 for the sedan in-situ prototype. The evaluated frequencies are spaced throughout the measured band and include frequencies for mobile and V2X communications and industrial, scientific and medical (ISM) applications. Wideband measurements in Fig. 5a confirm the good uniform coverage towards low elevation angles. This is also the case on the sedan in Fig. 6a, where coverage angles of course stop with the bonnet at $\theta \approx 105°$. The improved coverage in driving direction for $\theta > 90°$ is a direct consequence of the short ground plane between antenna and window, because radiation patterns of monopole antennas get sharpened upwards on large ground planes. This wide coverage area towards the driving direction is invaluable for communication with vulnerable road users and could not be achieved with antennas located in the rear end of the roof.

The antennas retain their typical monopole gain patterns when placed in a cavity below the roof. For 0.9, 1.8 and 2.4 GHz the patterns are smooth and show typical variations originating from the car body [16], [25]. The patterns are less distorted towards the sides of the car (see Fig. 6b), where the ground plane (roof) is smaller and no bonnet or trunk lid are present. As the cavity becomes electrically large at 5.9 GHz, nulls appear in the pattern towards the sides. This was already shown in [11] and is visible in Figs. 5b and 6b. The unwieldy radiation pattern towards zenith does not impede typical V2V communications. Sources directly above the car (f.i. for V2X) are likely nearby. A realized gain close to 0 dBi is achieved in the horizontal plane in a wide angular range towards the front.

Shadowing from the roof causes reduced gain towards the back from -5 to -10 dBi. However, no deep zeros are introduced by the antenna cavity or the car and omnidirectional

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TABLE I
MINIMUM, MAXIMUM AND AVERAGE GAINS IN DBI OF THE IN-SITU PROTOTYPE TOWARDS PEDESTRIAN ($\theta = 90°$, $\varphi = \pm 20°$).

frequency	min	max	mean
0.9 GHz	0.72	3.02	2.17
1.8 GHz	-5.51	-0.01	-2.65
2.4 GHz	-2.98	-0.96	-2.10
5.9 GHz	-3.51	0.43	-1.53

TABLE II
MINIMUM, MAXIMUM AND AVERAGE GAINS IN DBI OF THE IN-SITU PROTOTYPE TOWARDS CYCLISTS ($\theta = 90°$, $\varphi = \pm 80°$).

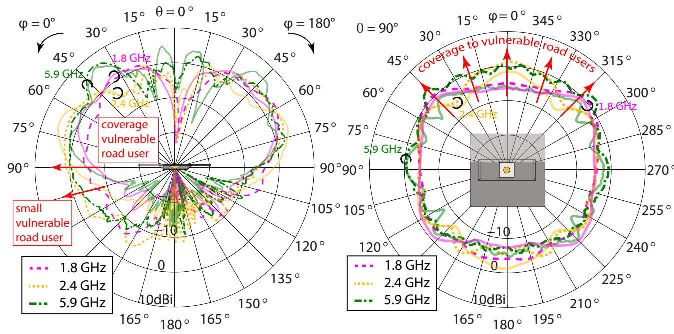
frequency	min	max	mean
0.9 GHz	-4.05	3.02	-0.71
1.8 GHz	-5.51	3.11	-0.36
2.4 GHz	-7.42	1.97	-1.87
5.9 GHz	-3.51	1.72	-0.66

coverage is still achieved, as the azimuth cuts in Figs. 5c and 6c show. As suspected from simulation results in [15], the curvature of the car roof is beneficial to antenna cavities and investigations with flat roof mock-ups underestimate performance. The gain towards the back is comparable to contemporary roof mounted shark-fin antenna modules [2], [26].

[27] investigated car accidents and quantified the positions of vulnerable road users three seconds before impact. It was found that 90 % of pedestrians were located within $\pm 20°$ and 90 % of cyclists within $\pm 80°$ of driving direction. Tabs. I and II summarize the minimum, maximum and average gain values of the in-situ prototype for pedestrians and cyclists, respectively. Shark-fin antennas are shadowed towards the front by the car roof, which results in typical gains of -5 to -15 dBi [26]. Coverage towards vulnerable road users is greatly increased by the proposed antenna position with average gains close to 0 dBi.

Opening the cavity on one side reduced the ground plane length in this direction, which increases the gain of monopole antennas in the horizontal plane and below. In Fig. 7 the measured gain patterns of the proposed cavity are compared to the cavity for the roof center in [11]. The comparison shows increased gain in horizontal plane and below across all frequencies. In the horizontal plane (Fig. 7b) the gain is increased in a wide angular range to cover pedestrians and cyclists.

The coverage towards vulnerable road users is quantitatively compared to previous work in Tab. III. Values are compared to a chassis antenna cavity in the center of a 1 m^2 CFRP ground plane [11] and a 5.9 GHz antenna in shark-fin module that is measured on a car in [26]. Due to the safety critical application, the minimum gain values are of interest. At all investigated frequencies, a cavity at the front of the car roof improves coverage towards vulnerable road users over a cavity in the roof center. At 5.9 GHz, the current frequency for V2X communication in intelligent transport systems, the minimum gain improves 3 dB over cavities in the center and drastically improves over currently used shark-fin antennas: +6.5 dB for pedestrians and +12.5 dB for cyclists.



(a) (b)

Fig. 7. Comparison of the measured gain patterns between the proposed cavity above the windshield and the cavity for the roof center (solid transparent lines, [11]); realized gain; linear polarization in θ direction; a) vertical cuts front/back and b) horizontal cuts for polar angle $\theta = 90°$.

TABLE III
COMPARISON OF COVERAGE TOWARDS VULNERABLE ROAD USERS WITH PREVIOUS WORK. MINIMUM GAIN FOR $\theta = 90°$, $\varphi = \pm 20°$ FOR PEDESTRIANS AND $\varphi = \pm 80°$ FOR CYCLISTS.

	this work		cavity center [11]		shark-fin [26]	
φ	$\pm 20°$	$\pm 80°$	$\pm 20°$	$\pm 80°$	$\pm 20°$	$\pm 80°$
1.8 GHz	-5.51	-5.51	-6.65	-6.65		
2.4 GHz	-2.98	-7.42	-4.72	-7.72		
5.9 GHz	-3.51	-3.51	-6.76	-6.76	-10	-16

V. CONCLUSIONS

It is feasible to build antenna cavities or platforms into car roofs above the windshield. An automotive antenna cavity located above the windshield was proposed, prototyped and measured. Conformal antenna cavities above the windshield offer omnidirectional coverage around the car. A cavity, that is open towards the driving direction, increases antenna gain in the horizontal plane and below, which increases coverage for communication with vulnerable road users. As the presented benefits result from the cavity's geometry and location, with an omnidirectional monopole, they can be further enhanced by specialized antenna design.

While antennas in shark-fin modules are shadowed towards the front due to roof curvature [26], radiation from the cavity above the windshield is increased towards the front. The positions complement each other.

Although a cavity above the windshield was investigated in this work, the good performance motivates research into cavities located above the rear window, as an alternative to antennas in shark-fins and roof spoilers.

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REFERENCES

[1] J. Choi, V. Va, N. González-Prelcic, R. Daniels, C.R. Bhat, and R.W. Heath Jr., "Millimeter-Wave Vehicular Communication to Support Massive Automotive Sensing," *IEEE Communications Magazine*, vol. 54, no. 12, 2016, pp. 160-167.

[2] O.-Y. Kwon, R. Song, and B.-S. Kim, "A Fully Integrated Shark-Fin Antenna for MIMO-LTE, GPS, WLAN, and WAVE Applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 17, 2018, pp. 600-603.

[3] D.V. Navarro-Méndez, L.F. Carrera-Suárez, D. Sánchez-Escuderos, M. Cabedo-Fabrés, M. Baquero-Escudero, M. Gallo, and D. Zamberlan, "Wideband Double Monopole for Mobile, WLAN, and C2C Services in Vehicular Applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, 2017, pp. 16-19.

[4] L. Low, R. Langley, R. Breden, and P. Callaghan, "Hidden Automotive Antenna Performance and Simulation," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 12, 2006, pp. 3707-3712.

[5] M. Kashanianfard and K. Sarabandi, "Vehicular Optically Transparent UHF Antenna for Terrestrial Communication," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 8, pp. 3942-3949, 2017.

[6] J.H. Schaffner, H.J. Song, A. Bekaryan, H.-P. Hsu, M. Wisnewski, and J. Graham, "The Impact of Vehicle Structural Components on Radiation Patterns of a Window Glass Embedded FM Antenna," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 10, 2011, pp. 3536-3543.

[7] E. Safin, R. Valkonen, and D. Manteuffel, "Reconfigurable LTE MIMO Automotive Antenna System Based on the Characteristic Mode Analysis," *European Conference on Antennas and Propagation (EuCAP)*, 2015, pp. 1-3.

[8] A. Asgharzadeh, J. Singh, P. Hofmann, G. Reichert, and M.A. Hein, "Design Approach Towards Automotive FM Broadcast Antennas Based on Characteristic Modes," *IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, 2017, pp. 57-60.

[9] J. de Mingo, C. Roncal, and P.L. Carro, "3-D Conformal Spiral Antenna on Elliptical Cylinder Surfaces for Automotive Applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 11, 2012, pp. 148-151.

[10] L. Marantis, D. Rongas, A. Paraskevopoulos, C. Oikonomopoulos-Zachos, and A. Kanatas, "Pattern reconfigurable ESPAR antenna for vehicle-to-vehicle communications," *IET Microwaves, Antennas & Propagation*, vol. 12, no. 3, 2018, pp. 280-286.

[11] G. Artner, R. Langwieser, and C.F. Mecklenbräuker, "Concealed CFRP Vehicle Chassis Antenna Cavity," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, 2017, pp. 1415-1418.

[12] S. Lee, G. Jeoung, and J. Choi, "Three-dimensional-printed tapered cavity-backed flush-mountable wideband antenna for UAV," *Microwave and Optical Technology Letters*, vol. 59, 2017, pp. 2975-2981.

[13] N. Nguyen-Trong, S.P. Pinapati, D. Hall, and C. Fumeaux, "Ultralow-Profile and Flush-Mounted Monopolar Antennas Integrated Into a Metallic Cavity," *IEEE Antennas and Wireless Propagation Letters*, vol. 17, 2018, pp. 86-89.

[14] G. Artner, J. Kowalewski, C.F. Mecklenbräuker, and T. Zwick, "Automotive Pattern Reconfigurable Antennas Concealed in a Chassis Cavity," *International Symposium on Wireless Personal Multimedia Communications (WPMC)*, 2017, pp. 265-270.

[15] I.M. Yousaf, and B.K. Lau, "On Performance of Hidden Car Roof Antennas," *European Conference on Antennas and Propagation (EuCAP)*, 2018, pp. 1-5.

[16] M.E. Asghar, F. Wollenschläger, A. Asgharzadeh, J. Singh and M.A. Hein, "Influence of Antenna Mounting Location on the Radiation Pattern of an Automotive Antenna," *European Conference on Antennas and Propagation (EuCAP)*, 2018, pp. 1-5.

[17] G. Artner, R. Langwieser, and C.F. Mecklenbräuker, "Vehicular Roof Antenna Cavity for Coverage at Low Elevation Angles," *IEEE Int. Symp. on Antennas and Propagation (APS)*, 2017, pp. 853-854.

[18] L.L. Nagy, "Automobile roof antenna shelf," US Patent, US6118410, 2000.

[19] N. Yoshie, "Wave transmitting/receiving structure for vehicle antennas," European Patent Application, EP1921708A1, 2007.

[20] S. Kirtzakis, "Antennenanordnung für ein Fahrzeug," German Patent Application, DE102011106829A1, 2012.

[21] R. Weicker, and M. Albo, "Vehicle window assembly and method for mounting a vehicle window assembly," US Patent, US9126469B2, 2015.

[22] G. Artner and R. Langwieser, "Performance of an Automotive Antenna Module on a Carbon-Fiber Composite Car Roof," European Conference on Antennas and Propagation (EuCAP), 2016, pp. 1-4.

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

[24] M. Hein et al., "Emulation of virtual radio environments for realistic end-to-end testing for intelligent traffic systems," IEEE MTT-S International Conference on Microwaves for Intelligent Mobility (ICMIM), 2015, pp. 1-4.

[25] M.B. Diez, P. Plitt, W. Pascher, and S. Lindenmeier, "Antenna Placement and Wave Propagation for Car-to-Car Communication," *European Microwave Conference (EuMC)*, 2015, pp. 207-210.

[26] M. Gallo, S. Bruni, M. Pannozzo, and D. Zamberlan, "Performance Evaluation of C2C antennas on Car Body," *European Conference on Antennas and Propagation (EuCAP)*, 2013, pp. 3136-3139.

[27] J. Lenard, R. Welsh, and R. Danton, "Time-to-collision analysis of pedestrian and pedal-cycle accidents for the development of autonomous emergency braking systems," *Accident Analysis and Prevention*, vol. 115, 2018, pp. 128-136.