Automotive Pattern Reconfigurable Antennas Concealed in a Chassis Cavity

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***Abstract*—Pattern-reconfigurable antennas for the 2.45 GHz ISM band are concealed inside a chassis antenna cavity. Three antennas are designed to reconfigure between near-optimum radiation patterns for urban scenarios by toggling between front/back and left/right radiation. The three antennas follow distinct design principles and have different gain switching capabilities. Antenna performance is evaluated based on gain pattern measurements. It is shown, that the antennas retain their reconfiguration functionality when they are placed in the chassis cavity beneath the vehicle's roof.**

I. Introduction

It is not a trivial task to design pattern reconfigurable low-profile antennas for vehicles, due to the roof acting as a large ground plane. An excellent example is a $2.45\,\mathrm{GHz}$ low-profile antenna for vehicles that is reconfigurable between twelve patterns [1]. The authors show that any reconfigurability is lost, when the antenna is mounted on a ground plane larger than $1.2\,\lambda$ ($\approx 15\,\mathrm{cm}$). Also optimality criteria for the number and shapes of the patterns is typically not given in the literature.

Roof mounted automotive shark-fin antenna modules have been introduced in the 2000's. They now contain antennas for telephony (long term evolution, LTE), car-to-car communication (C2C), Wi-Fi, satellite navigation systems, satellite audio radio and remote keyless entry [2], [3] with multiple-input-multiple-output (MIMO) antennas to increase throughput and reliability [4], [5]. However, shark-fin modules can not excessively grow in size as they protrude from the vehicle.

Instead of designing low-profile antennas to put in shark-fins on the car roof, we propose to place the antennas in a cavity in the vehicle chassis [6]. This allows antennas with a taller profile that are nevertheless fully concealed below the roof. We recently proposed such an antenna cavity, which can be hidden in the vehicle chassis [7]. The chassis cavity can be seamlessly mass-produced as part of the car roof and it is significantly larger than previously proposed roof cavities [8], [9]. The concealable module keeps the car roof as preferred mounting position for vehicular antennas. Measurements in [10] show that the cavity is operable in a wide frequency range and includes all services currently used in shark-fin modules. The cavity prototype is placed on a $1\,\mathrm{m}^2$ ($\approx 8\,\lambda$) ground plane, to show that pattern-reconfigurability is retained on vehicles.

The antennas presented in this work can be reconfigured between near-optimum radiation patterns, which were derived in prior work. These near-optimum vehicular MIMO radiation patterns are synthesized in [11], [12] from ray-tracing simulations. It is shown that in urban scenarios mutual information can be increased by using MIMO systems with radiation patterns pointing towards front/back and left/right directions, instead of omnidirectional radiation patterns. An exemplary position of the chassis cavity on a vehicle with near-optimum radiation patterns is depicted in Fig. 1.

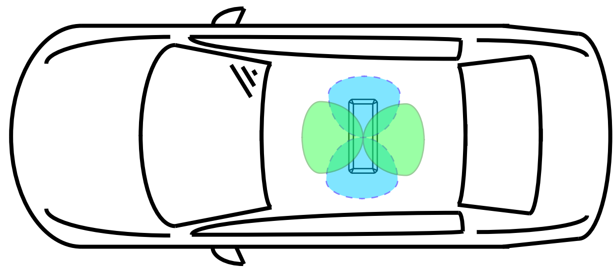


Fig. 1. A pattern reconfigurable antenna is concealed inside a chassis antenna module. Exemplary mounting location on a car roof.

Contribution — Three pattern reconfigurable antennas for the industrial, scientific and medical (ISM) band at $2.45\,\mathrm{GHz}$ are fully concealed for vehicular applications. All three antennas reconfigure between near-optimum radiation patterns, but they are designed with different gain between reconfigurable states in driving direction. The synthesis methodology for near-optimum patterns is summarized in Sec. II. The antenna designs and measurements on small ground planes are given in [13]–[15], but are recapitulated for the sake of completeness. The chassis cavity prototype made from carbon fiber reinforced polymer (CFRP) is discussed in Sec. III. In Sec. IV the antennas are evaluated based on measured S-parameters and measured gain patterns. Conclusions for vehicular antenna design are drawn in Sec. V.

II. Pattern Synthesis and Near-Optimal Pattern Reconfigurable Antennas

Channel simulations from a ray tracer are used to synthesize patterns for vehicular antennas. The procedure for vehicular antenna pattern synthesis for multiple antenna systems is presented in [11]. In [12] the synthesis procedure is enhanced and real-world dynamic channel measurements are used for the pattern synthesis. First, for each channel realization radiation patterns are synthesized, which are optimum in that they maximize channel capacity for that given channel. In a second step radiation patterns are averaged over time, as vehicular antennas can not adapt to the channel instantaneously. Finally, the patterns are averaged over different driving scenarios,

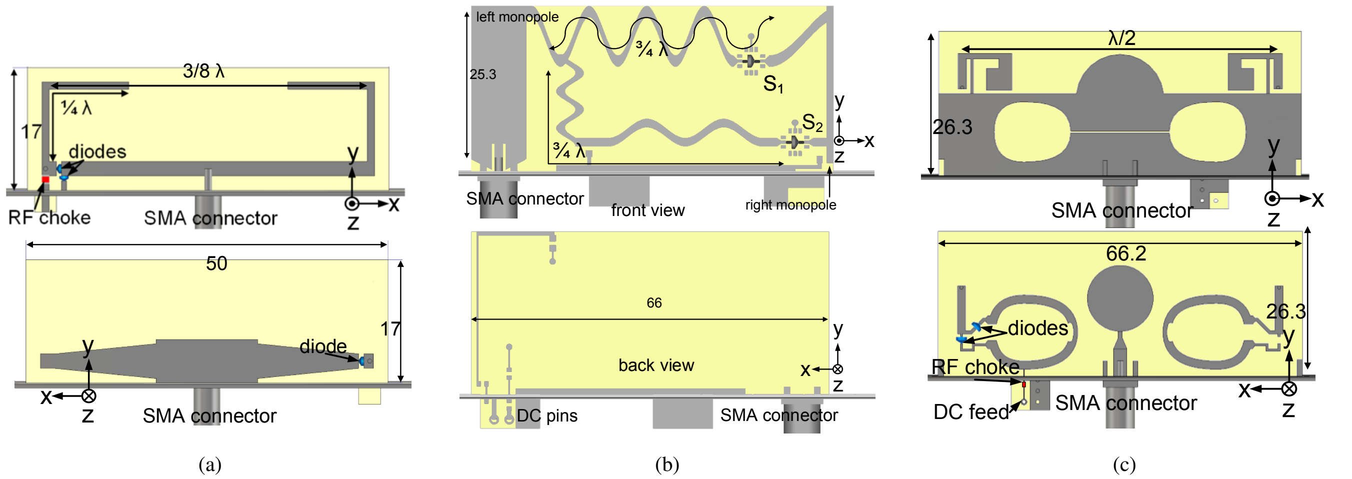


Fig. 2. Dimensions of the antenna prototypes. The antennas are denoted as a) antenna 1 (Reprinted with permission from [13]; ©2016 IEEE.), b) antenna 2 (Reprinted with permission from [14]; ©2016 IEEE.) and c) antenna 3 (Reprinted with permission from [15]; ©2017 IEEE.) Dimensions are in millimeter.

which are either simulated in the ray tracer or measured in drive campaigns. This way radiation patterns are synthesized that are optimum in an average sense (depending on the used metric), but are near-optimum for any given channel realization. In all cases the best synthesized radiation patterns have high gain towards front and back of the car, which is due to the waveguide effect in street canyons. The radiation pattern synthesized for second best sub-channel covers the directions to the sides of the car (left/right) [16].

The three antennas in this paper are reconfigurable between these near-optimum front/back and left/right radiation patterns [13]–[15]. All antennas consist of two radiating elements and a switchable feeding network embedded into the antennas. Different patterns are obtained by switching the signal phase between the radiators. If an antenna is oriented along the x-axis (see Fig. 2) a phase difference of $180°$ is required between inputs of the radiating elements, such that the two radiating elements placed in distance of about $\lambda/2$ interfere constructively along the x-axis to generate patterns covering front/back direction. If there is no phase difference between the inputs of the radiating elements the radiated fields interfere constructively along the z-axis to generate patterns covering left/right directions. This idea is implemented in different ways in the three antenna designs.

Antenna 1 is presented in [13] and uses two bent monopoles. The feeding line is connected in the middle to a coaxial connector and thus a T-junction is established. The lines routed to the radiating elements are modified so that a tapered line balun is formed (see Fig. 2a). This way a signal with either $0°$ or $180°$ phase is generated at the feeding point of one of the radiating elements. The phase change is obtained by connecting one of the radiators to the front feeding point line ($0°$) or the back line ($180°$). The switching is done by applying DC to pin-diodes. When the upper front diode is on and the other two are off, the radiators are fed with a signal which is in phase. For the opposite phase the upper front diode has to be off and the other two on.

Antenna 2 uses two monopoles that are fed in series (see Fig. 2b, [14]). The left one is fed with a coaxial connector and loaded with a line on top, which is connected to a monopole on the right. The phase switching is realized by choosing between two lines feeding the second monopole either on top ($180°$) or bottom ($0°$). This concept functions such that the length of the left monopole is $\lambda/4$, and the line feeding the second monopole is chosen to be $3\lambda/4$ long. In order to place a $3\lambda/4$ line at $\lambda/2$ distance, the feed lines to the second monopole are meandered. The chosen line lengths result in good matching in both states, since the $3\lambda/4$ line transforms the open at the switch to an open at the T-junction. Thus the wave does not enter the inactive branch and most of the power is directed to the active branch.

The radiating elements (inverted-F antennas) of antenna 3 [15] are fed in parallel and a more flexible feeding network is designed. A back-to-back balun (see Fig. 2c) is used to generate the phase difference between the radiating elements. It can generate almost any phase difference and therefore different radiation patterns could be realized too, unlike for the tapered line balun used in antenna 1. Back-to-back baluns are mostly used for microstrip-to-slotline transition (or vice-versa). If a circular slot is used for slotline-to-microstrip transition (like in Fig. 2c), a symmetrical signal ($0°$ and $180°$ phase) at the output lines is obtained. This feeding structure also decouples the input port from the DC. A T-junction is established as power splitter by feeding the horizontal slotline with a vertical microstrip connected to the coaxial SMA connector.

All antenna prototypes are printed on Rogers 5880 substrate, but FR4 is applicable for mass production. Pin-diodes are chosen as switches over microelectromechanical systems (MEMS) for automotive application. Just like spatial-diversity antennas, pattern-diversity antennas can be switched with different strategies [17].

III. Chassis Antenna Cavity

Hidden automotive antennas have been proposed in side mirrors [18], bumpers [19] and modules in the windshield [20]. Positions on the roof are preferred, because they offer omnidirectional coverage and the front-end can be placed close-by [21]. A number of authors have suggested to place antennas in small cavities in the vehicle roof. Cavities are preferred over apertures [22], as they offer increased isolation to the vehicles' passengers and electronics. An antenna for satellite digital audio radio services (SDARS) and the global positioning system (GPS) embedded in a $40 \times 40 \times 10\,\mathrm{mm}^3$ cavity in the car roof is measured in [8]. An LTE antenna inside a $200 \times 200 \times 30\,\mathrm{mm}^3$ hole is discussed in [9]. The cavity prototype in [9] is located on the roof and not underneath it and deviations over $10\,\mathrm{dB}$ are caused in the gain pattern by inserting the antenna into the hole. A cavity-backed spiral antenna hidden in the trunk is presented in [23]. A wideband antenna concealed in a $43\,\mathrm{mm}$ deep circular cavity with a diameter of $280\,\mathrm{mm}$ in an aircraft fuselage is presented in [24].

Previously proposed cavities are only large enough to contain a single antenna, but it is not desirable for car manufacturers to build a separate cavity for every antenna. The cavity used in this work is presented in [7] and it is significantly larger such that it can also contain other antennas. The cavity has a size of about $500 \times 150 \times 40\,\mathrm{mm}^3$ and inclined walls. Antennas inside the cavity can be concealed by a protective cover such that it visually blends into the vehicle roof, but measurements in Sec. IV are performed without cover such that the results don't depend on an arbitrarily chosen material. The chassis cavity is dedicated space for antennas, contrary to side mirrors or bumpers where antennas share the available space with other functional units that interfere with antenna performance.

The prototype of the chassis integrated antenna cavity is manufactured from plain weave carbon-fiber reinforced polymer (CFRP) (Fig. 3), to show the applicability for electric cars. Mechanical engineers increasingly use sandwich- and honeycomb-structures and CFRP in the construction of mass produced cars; lightweight construction methods that are already used for airplanes and sports cars.

The car roof is modeled by a CFRP sheet with a size of $1000 \times 1000 \times 2\,\mathrm{mm}^3$. Vehicle specific features like roof curvature or protective cover are not considered in the prototype. Influences such as roof windows [25], [26], gaps between car body elements [27], paint [28], etc. on the antennas inside the chassis cavity are expected to be similar to other locations on the car roof. These influences on the radiation characteristics of vehicular antennas are typically investigated separately and then considered by the car manufacturer during development [29]. The replacement of metals with woven CFRP as ground plane material has only negligible influence on vehicular antennas [30].

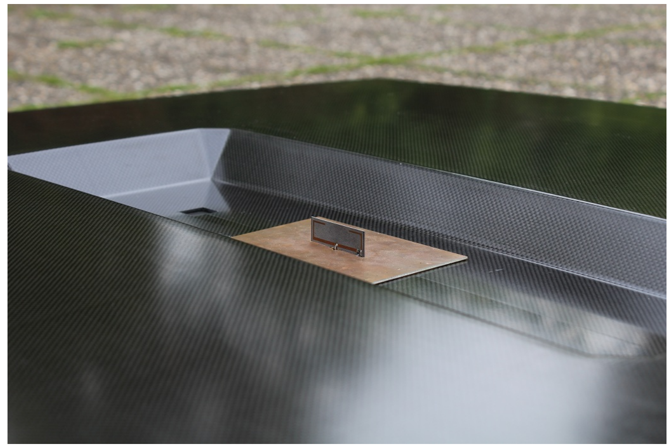


Fig. 3. Pattern reconfigurable antenna 1 inside the CFRP chassis antenna cavity.

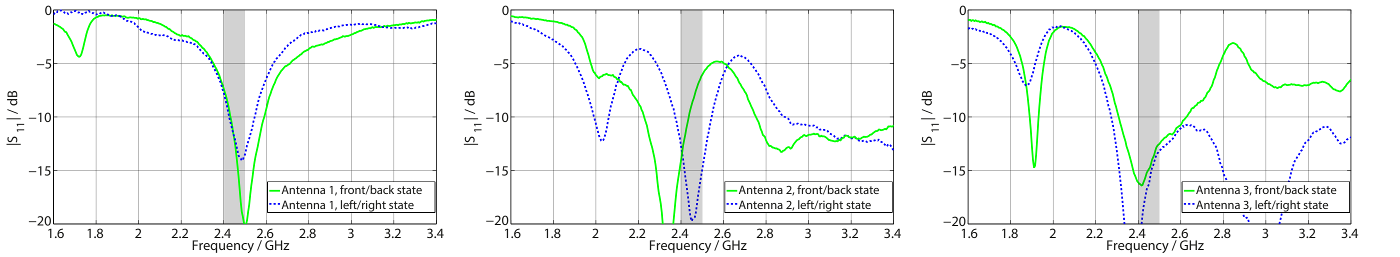
IV. Measurement Results

The antennas are placed centered on the chassis cavity's floor. For measurement purposes cables are routed through the floor of the cavity. In production it will be more suitable to connect the cables through the wall of the module as the vehicle roof thickness is limited. The states of the pattern reconfigurable antennas are switched by connecting the pin-diodes to a DC-power supply.

The absolute values of the measured S-parameters are depicted in Fig. 4. The resonance frequency of the left/right state of antenna 1 is slightly shifted towards higher frequencies (Fig. 4a) compared to [13] while no change is observed for the front/back state. A return loss better than $10\,\mathrm{dB}$ is still achieved in the band of interest. Antenna 2 has a return loss better than $10\,\mathrm{dB}$ in left/right state in the whole ISM band, the resonance frequency of the front/back state is shifted towards lower frequencies (compared to [14]) and therefore antenna 2 only has a return loss better than $6\,\mathrm{dB}$ in the ISM band (Fig. 4b). The resonances of antenna 3 are slightly shifted towards lower frequencies for both states compared to [15], however $|S_{11}|$ is still lower than $-10\,\mathrm{dB}$ in the whole ISM band. For all studied antennas a shift towards lower frequencies is observed after embedding the antennas into the cavity. These shifts in resonance frequency can easily be accounted for in future designs iterations.

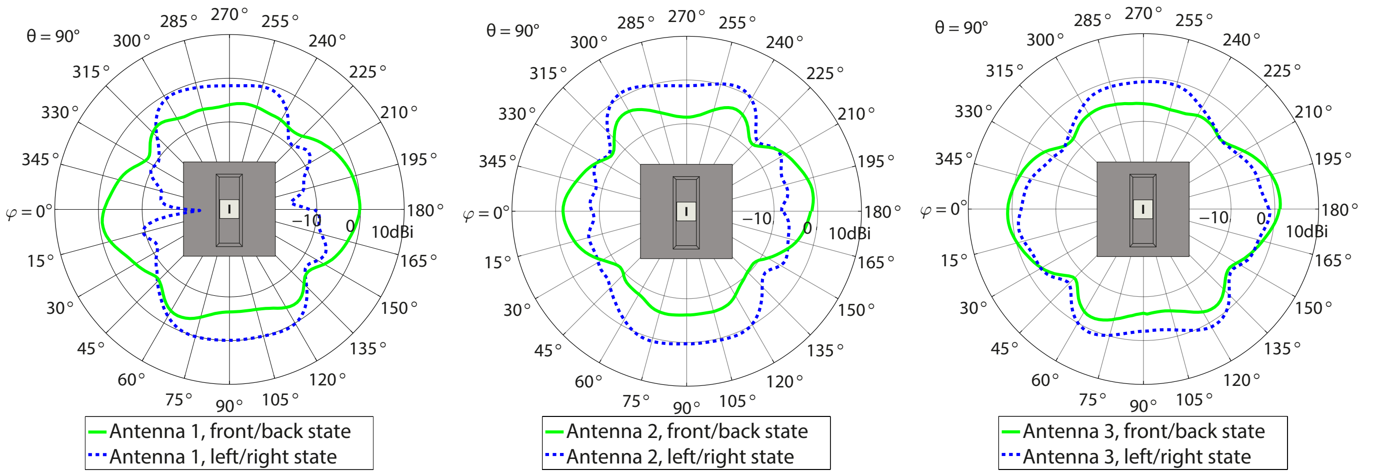
Calibrated gain pattern measurements are performed inside an anechoic chamber. All gain patterns are measurements of realized gain. Gain pattern cuts are depicted for $2.45\,\mathrm{GHz}$, which is the center frequency of the ISM band. The chassis cavity with the antenna inside is mounted on an azimuth rotary column. All antennas work as expected with increased radiation in the desired directions. The antennas retain their ability to reconfigure between a front/back and left/right pattern when placed inside the chassis cavity below the roofline.

The horizontal gain pattern cuts are depicted in Fig. 5. All three antennas have a gain close to $0\,\mathrm{dBi}$ in the directions of their desired pattern states. $0\,\mathrm{dBi}$ gain in the horizontal



(a) (b) (c)

Fig. 4. Measured absolute values of the S-parameters with the antennas placed inside the chassis module a) antenna 1, b) antenna 2 and c) antenna 3.



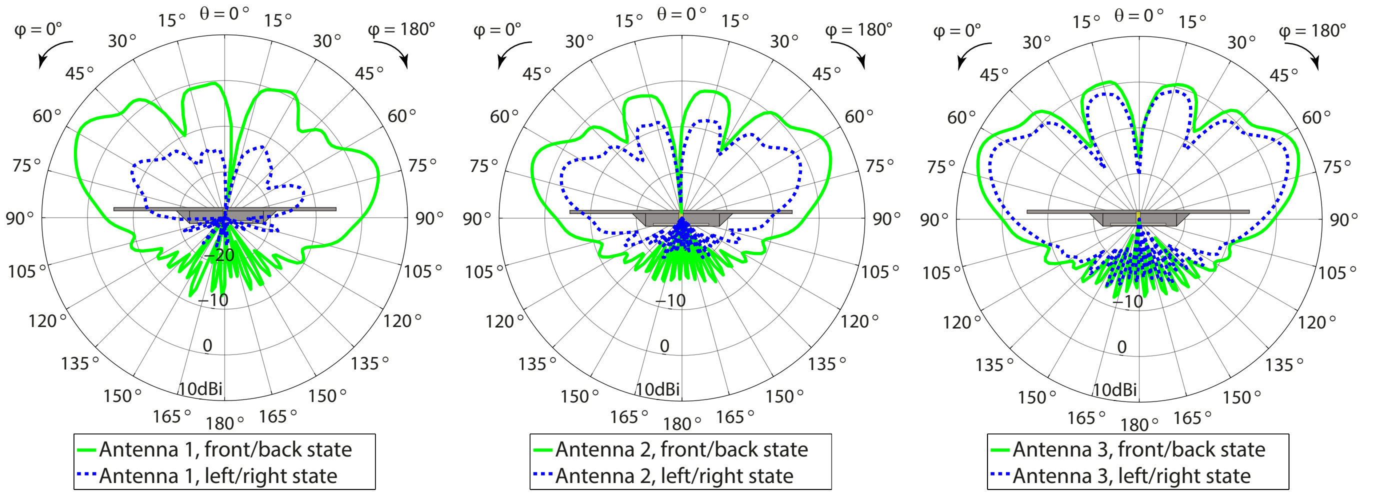
(a) (b) (c)

Fig. 5. Measured horizontal cuts of the gain patterns at 2.45 GHz for polar angle $\theta = 90°$ of a) antenna 1, b) antenna 2 and c) antenna 3. If the cavity is mounted on the vehicle according to Fig. 1, the left sides of the plots ($\varphi = 0°$) coincide with driving direction.

plane is a good performance, considering that the antennas are placed below the surface of a large ground plane. In front/back direction the pattern of the undesired state of antenna 1 has a null, resulting in a gain difference >10 dB between states in front/back direction (Fig. 5a). Switching antenna 1 into left/right state results in a gain increase of about 5 dB in left/right direction. Antenna 2 shows good overall performance. Results in Fig. 5b show that switching between the states results in a gain increase >5 dB in the horizontal plane for all four directions. As is evident in Fig. 5c antenna 3 offers the smallest gain difference between the two states in the horizontal plane. For most angles the difference in the gain patterns is close to 3 dB.

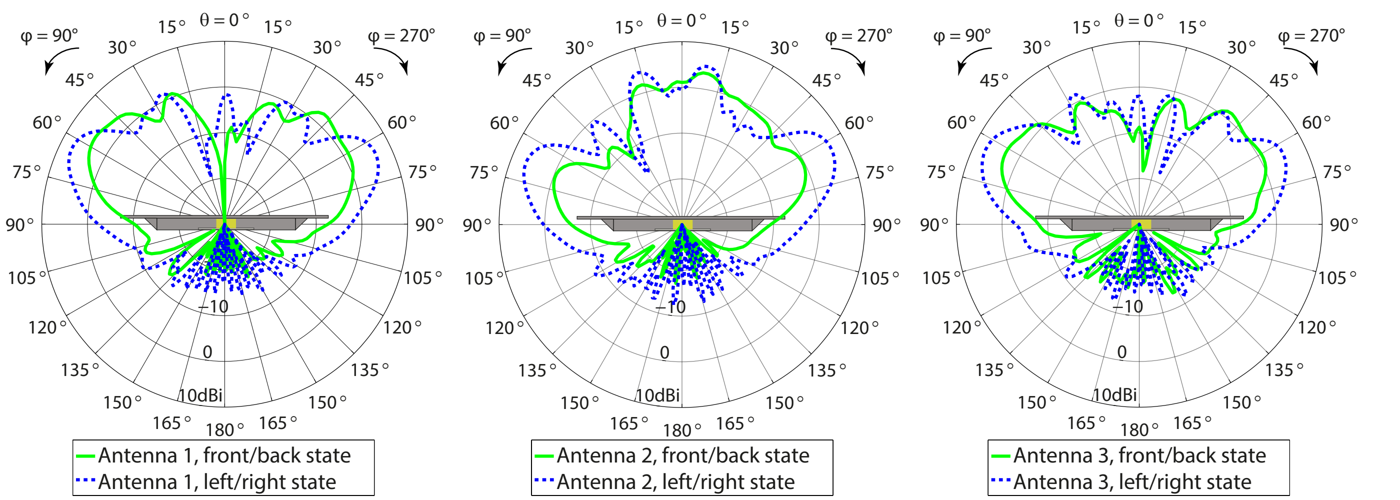
Analyzing all three plots in Fig. 5, the influence of the cavity on the radiation pattern can be observed. Without cavity the gain patterns in horizontal plane ($\theta = 90°$) have nearly elliptical form, and changing the state rotates the elliptical patterns by $90°$ (compare [13]–[15]). However, the patterns become flat in left and right directions ($\varphi = 60°$ to $120°$ and $\varphi = 240°$ to $300°$) when the antennas are embedded in the cavity. The exact angular values differ slightly between the three antennas, since their original patterns without cavity are also slightly different. Also a kind of step in gain (gain increase) is observed for the front/back state in the named angular ranges ($\varphi = 60°$ to $120°$ and $\varphi = 240°$ to $300°$); see Fig. 5. The form of the radiation patterns in the front/back directions remain nearly elliptical for all antennas, and thus corresponds very well with antenna placement on the car-roof. This difference between antennas mounted on the roof and concealed in the cavity can easily be explained by doing short geometrical analysis of the cavity. The chassis module is narrower in the driving direction (220 mm around 1.75 λ) and wider to left/right (570 mm around 4.5 λ) and the observed pattern changes correspond well with the cavity's corners.

The vertical gain pattern cuts are depicted in Fig. 6 and Fig. 7. Interfering reflections from the cavity walls cause additional nulls in the vertical patterns, but the cavity is designed such that the nulls appear close to zenith. In the vertical cuts at $\varphi = 90°$ the typical nulls at zenith ($\theta = 0°$) are observed for both states (see Fig. 6). However, if the vertical cut at $\varphi = 0°$ is considered, the null at zenith disappears for the left/right state (see Fig. 7). The field re-radiated at the long edge of the chassis module interferes constructively with field radiated from the antenna and erases the null at zenith. In applications where omnidirectional antennas are used this influence is of little concern. Typically vehicular antennas are



(a) (b) (c)

Fig. 6. Measured vertical cuts of the gain patterns at 2.45 GHz for azimuth $\varphi = 0°$ of a) antenna 1, b) antenna 2 and c) antenna 3. If the cavity is mounted on the vehicle according to Fig. 1, the $\varphi = 0°$ coincides with driving direction and $\varphi = 180°$ are the patterns towards the rear of the vehicle.



(a) (b) (c)

Fig. 7. Measured vertical cuts of the gain patterns at 2.45 GHz for azimuth $\varphi = 90°$ of a) antenna 1, b) antenna 2 and c) antenna 3. If the cavity is mounted on the vehicle according to Fig. 1, these cuts coincide with the left and right side of the vehicle.

monopole antennas, whose radiation patterns intrinsically have a null towards zenith.

Measurements in Fig. 6 confirm, that differences in antenna gain towards front and back are kept when placing the antennas inside the cavity. Among the three antennas, antenna 1 has the largest gain difference between states in the front/back direction of 15 dB. While in the left/right direction a difference between the states is only present for polar angles $\theta > 50°$. Antenna 2 shows good overall performance, with gain differences of about 5 dB. Antenna 3 has the smallest difference between states ≈ 3 dB.

Declaring a favorable antenna is not meaningful without application. The antenna choice depends on the service and transmissions schemes. The presented antenna designs show that several strategies are achievable. While antenna 1 is a good choice to decrease the reception of interfering vehicles in the front and back, both states of antenna 3 offer near-omnidirectional radiation. This allows to use the antenna 3 in a given state most of the time, with the option to switch patterns to double the received power when necessary.

V. Conclusion

Pattern reconfigurable antennas for automotive wireless communication are concealed inside a chassis cavity and their performance is measured. The three antennas are reconfigurable between a front/back and a left/right radiation pattern, which are near-optimal for vehicular communication. Prototypes ranging from 3 dB to 15 dB gain difference between the reconfigurable states have been designed, manufactured, and measured. The influence of the chassis antenna module on the antennas is assessed quantitatively. The antennas function properly when placed in the cavity below the roof.

The design of extremely low-profile pattern-reconfigurable antennas for vehicular applications is hard, because of the presence of a large ground plane. By placing the antennas in a cavity, their height requirements are relaxed. This in return allows the use of inverted-F antennas (IFA) and (bent) monopole antennas, both of which excel on large ground planes. Pattern-reconfigurable antennas can be fully hidden in the vehicle roof with the use of a chassis antenna cavity.

A large antenna module suitable for concealing several antennas enables smart vehicular communication systems, which no longer are constrained by drag or aesthetic design limitations of the vehicle. This work proves the feasibility of smart, concealed, automotive antennas for services in the 2.4 GHz ISM band like WLAN and Bluetooth.

Due to the close proximity in frequency it can be expected that the concept is also applicable for automotive antennas for mobile telephony and car-to-car communication.

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References

[1] A. Pal, A. Mehta, D. Mirshekar-Syahkal and H. Nakano, "A Twelve-Beam Steering Low-Profile Patch Antenna With Shorting Vias for Vehicular Applications," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 8, 2017.

[2] 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 Conference on Antennas and Propagation in Wireless Communications (APWC)*, Palm Beach, Aruba, 2014.

[3] M. Gallo, S. Bruni and D. Zamberlan, "A Novel Fully Integrated Fin Antenna for Automotive Application," in *European Conference on Antennas and Propagation (EuCAP)*, The Hague, The Netherlands, 2014.

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

[5] N. Guan, H. Tayama, M. Ueyama, Y. Yoshijima and H. Chiba, "A Roof Automobile Module for LTE-MIMO Antennas," in *IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, Turin, Italy, 2015.

[6] G. Artner, J. Kowalewski, C. F. Mecklenbräuker and T. Zwick, "Pattern Reconfigurable Antenna With Four Directions Hidden in the Vehicle Roof," in *International Workshop on Antenna Technology (iWAT)*, Athens, Greece, 2017.

[7] G. Artner, R. Langwieser, R. Zemann and C. F. Mecklenbräuker, "Carbon Fiber Reinforced Polymer Integrated Antenna Module," in *IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, Cairns, Australia, 2016.

[8] 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 Society International Symposium (APSURSI)*, Orlando, Florida, 2013.

[9] N. Guan, H. Tayama, M. Ueyama, Y. Yamaguchi and H. Chiba, "An Invisible Vehicle Roof Antenna," in *IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, Cairns, Australia, 2016.

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

[11] T. Mahler, L. Reichardt, C. Heine, M. Pauli, T. Zwick, "Channel Based Design of Systems with Multiple Antennas," *Progress In Electromagnetics Research B*, vol. 64, pp. 63-81, 2015.

[12] T. Mahler, J. Kowalewski, B. Nuß, C. Richt, J. Mayer, T. Zwick, "Channel Measurement Based Antenna Synthesis for Mobile Automotive MIMO Communication Systems," *Progress In Electromagnetics Research B*, vol. 72, pp. 1-16, 2016.

[13] J. Kowalewski, T. Mahler, J. Mayer and T. Zwick, "A Miniaturized Pattern Reconfigurable Antenna for Automotive Applications," in *European Conference on Antennas and Propagation (EuCAP)*, Davos, Switzerland, 2016.

[14] J. Kowalewski, J. Mayer, T. Mahler and T. Zwick, "A Compact Pattern Reconfigurable Antenna Utilizing Multiple Monopoles," in *International Workshop on Antenna Technology (iWAT)*, Cocoa Beach, Florida, 2016.

[15] J. Kowalewski, L. Keller-Bauer, T. Mahler, J. Mayer and T. Zwick, "Realization of a Compact Antenna with Reconfigurable Pattern for Multiple Antenna Systems," in *European Conference on Antennas and Propagation (EuCAP)*, Paris, France, 2017.

[16] L. Reichardt, T. Mahler, Y. L. Sit and T. Zwick, "Using a synthesis methodology for the design of automotive antenna systems," in *European Conference on Antennas and Propagation (EuCAP)*, Gothenburg, Sweden, pp. 1600-1604, 2013.

[17] D. Sievenpiper, H. J. Song, H. P. Hsu, G. Tangonan, R. Y. Loo and J. Schaffner, "MEMS-based switched diversity antenna at 2.3 GHz for automotive applications," in *International Symposium on Wireless Personal Multimedia Communications (WPMC)*, Honolulu, Hawaii, pp. 762-765, 2002.

[18] S. Senega, J. Kammerer and S. Lindenmeier, "Scan-phase antenna diversity for digital satellite radio (SDARS) in a single automotive side mirror," in *European Conference on Antennas and Propagation (EuCAP)*, The Hague, The Netherlands, pp. 3255-3259, 2014.

[19] R. J. Langley and J. C. Batchelor, "Hidden antennas for vehicles," *Electronics & Communication Engineering Journal*, vol. 14, no. 6, pp. 253-262, Dec 2002.

[20] M. Gallo, S. Bruni, M. Pannozzo, D. Zamberlan, R. Caso and P. Nepa, "Design and experimental validation of a windscreen patch array for C2C communications," in *IEEE Antennas and Propagation Society International Symposium (APSURSI)*, Orlando, Florida, 2013, pp. 2063-2064.

[21] M. Geissler, K. Scharwies and J. Christ, "Intelligent Antenna Systems for Cars," in *German Microwave Conference (GeMiC)*, Aachen, Germany, 2014.

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

[23] E. Gschwendtner and W. Wiesbeck, "Ultra-broadband car antennas for communications and navigation applications," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 8, pp. 2020-2027, Aug. 2003.

[24] L. Rufail and J. J. Laurin, "Aircraft Cavity-Backed Nonprotruding Wideband Antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 1108-1111, 2012.

[25] A. Kwoczek, Z. Raida, J. Láčík, M. Pokorny, J. Puskelý and P. Vágner, "Influence of car panorama glass roofs on Car2Car communication (poster)," in *IEEE Vehicular Networking Conference (VNC)*, Amsterdam, The Netherlands, pp. 246-251, 2011.

[26] J. Kowalewski, T. Mahler, L. Reichardt and T. Zwick, "Investigation of the Influence of Panoramic Roof on Mobile Telephony Antennas," in *European Conference on Antennas and Propagation (EuCAP)*, The Hague, The Netherlands, 2014, pp. 1062-1066.

[27] Y. Kim and E. K. Walton, "Effect of body gaps on conformal automotive antennas," *Electronics Letters*, vol. 40, no. 19, pp. 1161-1162, Sept 2004.

[28] B. D. Pell, E. Sulic, W. S. T. Rowe, K. Ghorbani and S. John, "Experimental Study of the Effect of Modern Automotive Paints on Vehicular Antennas," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 2, pp. 434-442, Feb. 2011.

[29] M. B. Diez, P. Plitt, W. Pascher and S. Lindenmeier, "Antenna placement and wave propagation for Car-to-Car communication," in *European Microwave Conference (EuMC)*, Paris, France, pp. 207-210, 2015.

[30] G. Artner, P. K. Gentner, J. Nicolics and C. F. Mecklenbräuker, "Carbon Fiber Reinforced Polymer with Shredded Fibers: Quasi-Isotropic Material Properties and Antenna Performance," *International Journal of Antennas and Propagation*, vol. 2017, Article ID 6152651, 11 pages, 2017. doi:10.1155/2017/6152651