The Communicative Vehicle:
Multiple Antennas in a Chassis Antenna Cavity

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***Abstract*—The number of antennas mounted on vehicles keeps growing. Antennas in hidden modules will replace or supplement antennas in shark-fin modules. Chassis antenna cavities were recently proposed as large antenna modules, which can be built, and concealed, inside the vehicle chassis. Recent results of multiple antennas inside a chassis antenna cavity are presented. An inverted-F antenna and a conical monopole antenna are compared, based on measurements performed in an anechoic chamber. Measurements suggest that the position of the antenna inside the cavity has a significant influence on the gain pattern. Further measurements of frequency sweeps are needed, but prior to that exchangeable cavity bases are required.**

I. INTRODUCTION

Technological advancements changed the understanding of vehicles tremendously in the past decade. Cars are no longer seen as steerable combustion engines, but as communicating, moving nodes in the internet of things [1]. Demand for vehicular communication systems will further grow with automated driving. Infotainment systems for passengers in the back seat are already widely used. Self-driving cars also free the person in the “driver” seat from performing tedious tasks. No longer bound to steer the vehicle, passengers desire infotainment systems for relaxing, or that the vehicle functions as a mobile office space. The demand of future car owners will be reliable, high-throughput connections to the internet.

On the other hand the car itself communicates with its surroundings, be it other vehicles or road side units strategically placed by a regulatory body. Vehicles employ a large number of antennas to gather sensor information, such as automotive radar and tire monitoring systems. Connected vehicles share their sensor information and planned trajectories [2]. Even more so, vehicles help each other drive, as is the case in platooning. Critical information is forwarded to vehicles, which might not have received the original message due to channel conditions - for example via tall vehicle relaying [3].

Like for handsets (smartphones, tables, laptops, etc.), hardware that enables mobile communication will result in diverse software solutions for a variety of problems. The high demand for phone apps shows, that providing sufficient communication hardware results in solutions, which could not be considered in development a priori. These developments require a significant growth of wireless communication hardware on-board vehicles. The bottleneck of automotive communication systems are the antennas. Antennas have to be placed on the outside of the vehicle, as radiation is blocked by the conductive metal chassis and metalized windows. Other communication hardware, such as amplifiers, filters, mixers, cables, etc., can be stored on the inside. The current design paradigm is, that antennas should not interfere with the vehicles aesthetic appearance, i.e. they should be concealed, covered or hidden.

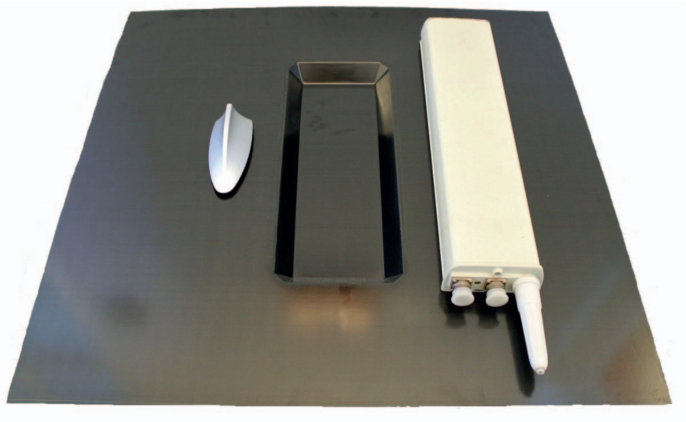


Fig. 1. From left to right: automotive shark-fin antenna module, chassis antenna cavity and base-station antenna.

Hidden automotive antennas are therefore under consideration for a variety of different positions on the vehicle. Television and radio antennas are mounted in an aperture in the car roof in [4]. [5] considers a stacked assembly of an antenna for the Global Positioning System (GPS) and an antenna for Satellite Digital Audio Radio (SDARS) hidden in a small cavity in the car roof. An antenna under a bezel at the rear end of the car roof for WLAN and mobile telephony is developed and measured in [6]. For truck-to-truck communication an antenna in the truck’s side-mirrors is considered [7]. Platooning is an important application for truck-to-truck antennas. A spiral antenna metalized conformaly onto the side-mirror housing is presented in [8].

An antenna cavity, built as part of a chassis, was recently proposed in [9]. The chassis antenna cavity is very large compared to other automotive antenna solutions. It is much larger than state of the art automotive “shark-fin” antenna modules, which are mounted on top of the roof [10]. Chassis antenna cavities allow automotive antenna modules to grow to

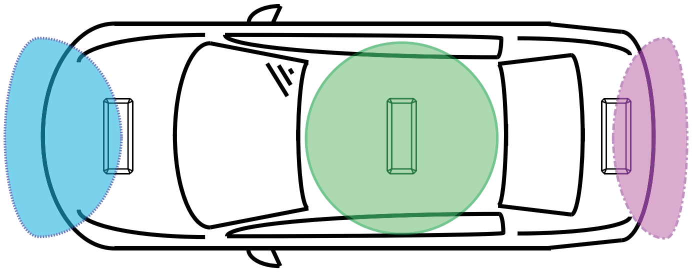
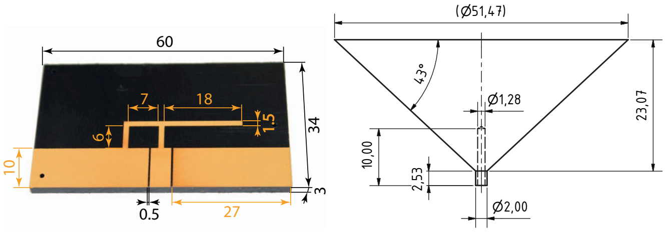


Fig. 2. Sketch of chassis antenna cavities located on the engine hood, car roof and trunk lid.



(a) (b)

Fig. 3. a) Inverted-F antenna for 2 GHz (Reprinted with permission from [13]; ©2016 IEEE.) and b) conical monopole antenna (Reprinted with permission from [17]; ©2017 IEEE.). All dimensions are in millimeter.

the size of base-station antennas. Fig. 1 compares the size of the chassis antenna cavity to a shark-fin module and a base station antenna. The chassis cavity enables a further increase in the number of automotive antennas. It also provides enough space to include parasitic antenna elements and structures to increase antenna isolation, such as ground plane slots or metal fences. While the LTE standard already allows for 8 antenna MIMO communication, shark-fin antenna modules currently only contain 2 MIMO antennas and these modules are not expected to significantly grow in size [10], [11]. As a possible remedy 2 conformal LTE antennas are built onto a shark-fin radome with LDS technology in [12].

A cavity prototype was built from Carbon Fiber Reinforced Polymer (CFRP) to show feasibility for airplanes, boats and electric cars [9]. For automotive applications the cavity can be built into the car chassis. Preferably the antenna cavity would then be positioned in the center of the car roof, as was proposed in [13]. Radiation from the roof is not obstructed by vehicle parts and omnidirectional radiation patterns are achievable. Additional antenna cavities can also be added at the roof ends, the trunk lid or the engine hood, to utilize spatial diversity (sketched in Fig. 2) and increase space for MIMO systems. In addition to the spatial diversity the antennas can use pattern diversity, with the antennas in the engine hood radiating towards the front, the ones in the trunk lid radiating towards the back and the antennas in the car roof having omnidirectional radiation patterns. Space in the hood is available for electric cars, where engines are no longer placed there. A spiral antenna in the trunk lid is already presented in [14]. Smart antenna systems are also feasible, as pattern reconfigurable antennas work inside chassis antenna cavities [15].

This paper presents the first measurements of multiple antennas inside the chassis antenna cavity. An inverted-F antenna for 2 GHz (mobile communication) and a wideband conical monopole antenna are investigated. Measurement results from an anechoic chamber are used to compare the performance of these antennas.

II. MULTIPLE ANTENNAS INSIDE A CHASSIS ANTENNA CAVITY

The investigated antenna cavity is developed for vehicular applications. The cavity has a rectangular shape with inclined walls, inner dimensions of $150 \times 500 \times 40\,\mathrm{mm}^3$ and outer dimensions of $220 \times 570\,\mathrm{mm}^2$. The cavity prototype is manufactured in the center of a $1 \times 1\,\mathrm{m}^2$ sheet, which acts as a large ground plane typically available on cars, such as the roof, trunk, doors, etc. [9]. Additional influences from specific locations on the vehicle can be obtained by simulation or from measurements on a whole car in later development stages. To show feasibility for electric cars, the antenna cavity is manufactured from Carbon Fiber Reinforced Polymer (CFRP). In the investigated frequency range the CFRP behaves like an isotropic conductor, which allows the application of CFRP for vehicular antennas [16].

Measurements of single antennas inside the cavity are presented in [9], [13]. In this paper two antennas are simultaneously inserted into the cavity: an inverted-F antenna (IFA) for 2 GHz [13] and a wideband conical monopole antenna [17]. The antennas were measured inside the cavity in [13], but only a single antenna was placed inside the cavity and only in the cavity center. The inverted-F antenna is manufactured with Laser Direct Structuring (LDS), a technology used to manufacture Molded Interconnect Devices (MID). LDS has recently been used in a variety of antenna applications. A simple LDS dipole antenna is presented in [18]. IFAs in LDS technology are widely used for mobile phones [19]. [20] presents a 12-element LDS phased array for projectiles. The conical monopole antenna is a standard antenna design turned from brass. The cylindrical extension fits on the inner conductor of an SMA flange without the requirement for soldering. The antenna dimensions are depicted in Fig. 3

The antennas are measured inside the institute's anechoic chamber. The chamber is a near-field system and far-field results are obtained from a near-to-far-field transformation. The cavity with the antennas inside is mounted on an azimuth rotary stage. For first results the conical monopole antenna is placed in the cavity center and the IFA is placed off-center, as is depicted in Fig. 4. During measurements the antenna under test was connected via a coaxial cable routed through the cavity floor, the other antenna was terminated with a 50 Ω resistor.

Further measurements with multiple antennas inside the chassis antenna module are required. Simulations need to be validated by measurement to quantify the impact of antenna

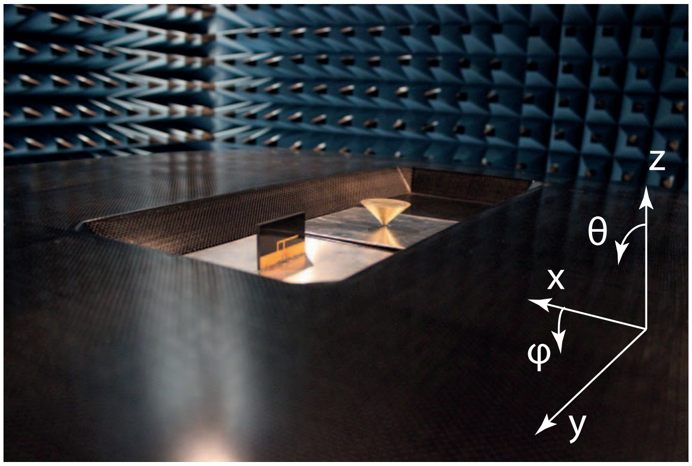


Fig. 4. An inverted-F antenna and a conical monopole antenna inside a chassis antenna cavity.

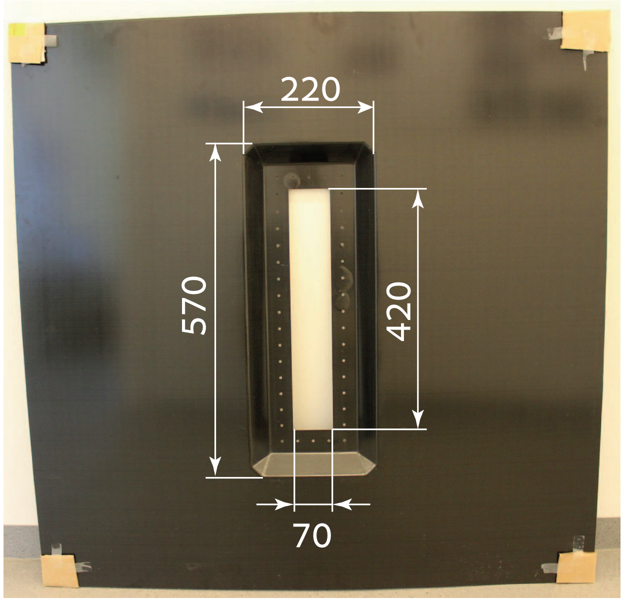


Fig. 5. A cavity prototype with floor cutout that allows measurements of multiple antenna systems and antennas on different positions.

placement on different positions in the cavity. However, a very practical problem arises when measuring several antennas inside a chassis antenna cavity. A coaxial cable needs to be routed through the cavity floor, in order to connect each antenna with a coaxial cable in the anechoic chamber. With too many antennas connected at different positions, the cavity floor needs an increasing number of holes. Exchangeable cavity bases are currently in development. The exchangeable aluminum plates can be laser-cut and allow placement of antennas at different locations and MIMO configurations inside the cavity. Before their application the influence of the exchangeable bases onto antenna measurements needs to be verified. Measurements of more advanced antenna setups will continue after verification. Fig. 5 shows a photograph of a CFRP cavity prototype cut by waterjet for exchangeable cavity bases. With the exchangeable bases the antennas are also fastened inside the cavity for drive tests. It should be noted, that this is only required during development. For mass-production the antennas and their locations are already fixed, and routing can be done with microstrip lines on printed circuit boards.

III. MEASUREMENT RESULTS

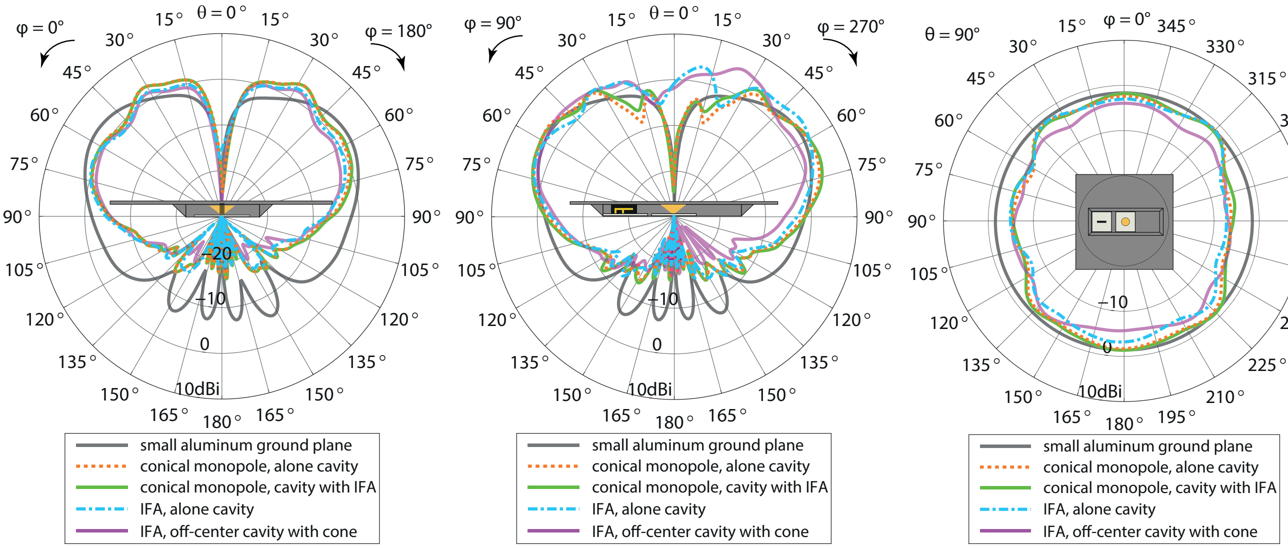
The antennas are investigated at two frequencies: 2 GHz the design frequency of the IFA, and at 5.9 GHz for dedicated short range communication for V2V communication. Measured gain patterns of the conical monopole antenna on a smaller, circular aluminum ground plane are shown for reference. The reference ground plane has a diameter of 300 mm and illustrates the influence of both the antenna cavity and the car roof acting as a larger ground plane.

Cuts of the measured gain patterns at 2 GHz are depicted in Fig. 6. Fig. 6a shows the vertical cuts at azimuth $\varphi = 0°$, Fig. 6b shows the vertical cuts for $\varphi = 90°$ and Fig. 6c shows the cut in the horizontal plane (polar angle $\theta = 90°$). Compared to patterns on the small aluminum ground plane, all patterns are tilted upwards, as is expected. Towards the short side of the cavity (Fig. 6a) the influence on the gain patterns is small and can be neglected. Gain of the IFA towards the direction of the conical monopole antenna is reduced by $1-5$ dB (Fig. 6b), which is both an influence of the IFA's off-center position in the cavity and the presence of the monopole antenna. The changes in patterns are also noticeable in the horizontal plane (Fig. 6c), but near-omnidirectional radiation is retained. No additional zeros are introduced into the gain pattern. Overall the pattern of the off-center IFA is changed more than the pattern of the monopole antenna. This hints, that changing the position of the antenna influences the pattern more, than the introduction of an additional antenna does. As noted in Sec. II the influence of the position in the cavity will be measured once exchangeable cavity bases are available.

Gain pattern cuts for 5.9 GHz are depicted in Fig. 7. Results for the IFA are not included, as the IFA is not designed for 5.9 GHz. Again radiation below the horizontal plane ($\theta > 90°$) is decreased because of the larger ground plane size. This is a desired effect, as radiation towards the asphalt is generally unwanted. As is discussed in [13], the cavity causes additional zeros in the radiation pattern close to zenith. In Fig. 7b several additional zeros appear in the monopole antenna's gain pattern close to zenith $0° \leq \theta \leq 50°$, but their position does not significantly change with the introduction of the IFA. The influence of the IFA positioned next to the conical monopole antenna is quite small. The gain patterns are shifted by about 2 dB, but generally the shapes of the patterns inside the cavity are retained.

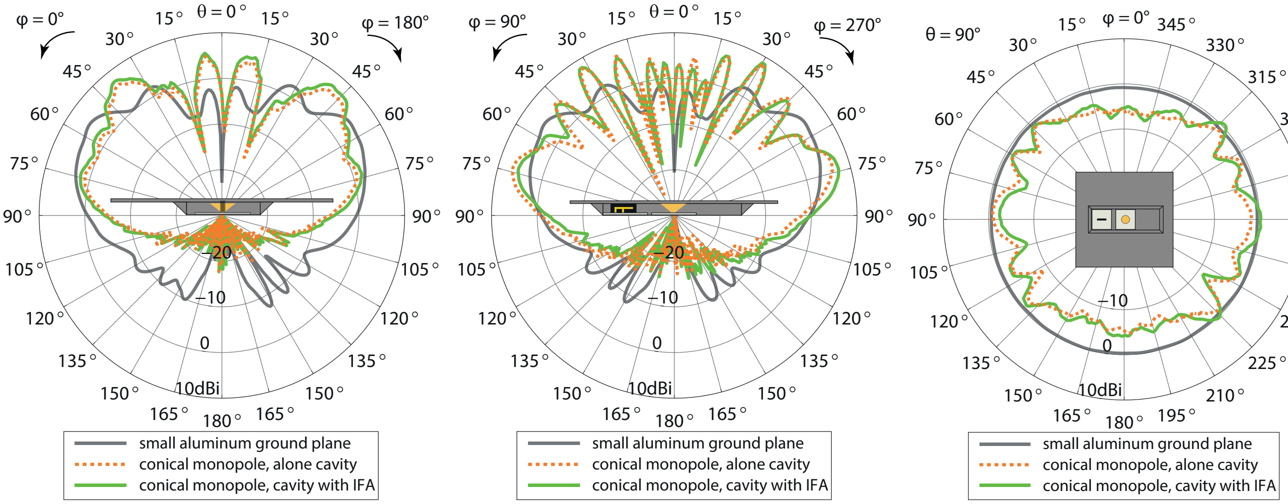
IV. CONCLUSION

A broadband conical monopole antenna and an inverted-F antenna are measured simultaneously inside a chassis antenna cavity. Influences on the gain pattern due to the IFA's off-



(a) (b) (c)

Fig. 6. Measured gain patterns at 2 GHz. a) vertical cuts for azimuth $\varphi = 0°$, b) vertical cuts for azimuth $\varphi = 90°$ and c) horizontal cuts for polar angle $\theta = 90°$. The pattern of the conical monopole antenna on a small circular aluminum ground plane is shown for reference.



(a) (b) (c)

Fig. 7. Measured gain patterns at 5.9 GHz. a) vertical cuts for azimuth $\varphi = 0°$, b) vertical cuts for azimuth $\varphi = 90°$ and c) horizontal cuts for polar angle $\theta = 90°$. The pattern of the conical monopole antenna on a small circular aluminum ground plane is shown for reference.

center position are noticeable. First measurements suggest, that the introduction of an additional antenna has a smaller influence on the gain pattern than positioning antennas off-center inside the cavity. Separating antennas inside the chassis antenna module is easier than in shark-fin modules, as more space is available for antenna design.

A full sweep of antenna positions is currently not possible, as too many holes in the cavity floor would influence measurements. Exchangeable cavity bases are currently in production, which will allow more flexible measurements of antennas inside chassis antenna cavities. This will allow the measurement of position sweeps inside the cavity, and the development of more sophisticated MIMO antenna assemblies.

Chassis antenna cavities enable significantly larger antenna modules for mass-produced cars. The extended hardware capabilities, of having several automotive antenna modules the size of base station antennas, enable new applications for vehicular communications - especially with regard to automatic and cooperative driving vehicles.

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