Pattern Reconfigurable Antenna With Four Directions Hidden in the Vehicle Roof

Gerald Artner*, Jerzy Kowalewski†, Christoph F. Mecklenbräuker* and Thomas Zwick†
*Technische Universität Wien, Institute of Telecommunications, Vienna, Austria
†Karlsruhe Institute of Technology, Institut für Hochfrequenztechnik und Elektronik, Karlsruhe, Germany

***Abstract*—Chassis integrated antenna cavities offer ten times the space of conventional automotive roof mounted antenna modules and can be fully concealed beneath the roofline. A pattern reconfigurable antenna for 2.6 GHz LTE is measured inside an automotive chassis cavity. The antenna can be electrically reconfigured to radiate towards the front, back, left or right side of the vehicle. Measurement results show that the antenna retains this ability when being hidden beneath the roof, proving that it is possible and feasible to hide antennas utilizing pattern diversity inside chassis cavities.**

***Index Terms*—chassis module, pattern reconfigurable antennas, concealed, hidden, vehicular, automotive, CFRP**

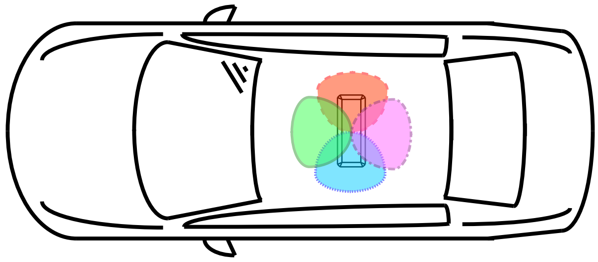


Fig. 1. A pattern reconfigurable antenna with a left, right, front and back state is concealed inside the chassis antenna cavity, exemplary location in a car roof.

I. Introduction

The preferred mounting position for many vehicular antennas is on the roof. The roof provides a large ground plane, allows omnidirectional radiation and isolation to the passengers. Antennas are concentrated in antenna modules, this allows the car manufacturer to reserve space on the vehicle prior to antenna development, and allows antenna design for the reserved space largely independent of vehicle development. The current state of the art is to consolidate a number of antennas in roof mounted automotive antenna modules, also referred to as shark-fins [1]–[4]. The number of included services has steadily increased in the last decade (LTE, GPS, C2C, SDARS, etc.), LTE and C2C are currently built with two antennas for MIMO [5]–[8], while the LTE standard allows for MIMO with eight antenna ports. However, roof mounted antenna modules can not significantly grow in size, as they disturb the aesthetic appearance of cars and influence their drag coefficient.

The appearance of vehicles is a major selling point and attaching large modules or a large number of small modules might not be desirable. A way to free more space for antennas is to conceal them, such that they do not influence the vehicles' design. Several hidden positions are considered: antennas placed on or behind windows [9] (radio) [10] (reconfigurable between FM and DAB) and [11] (C2C), bumpers [9] (GSM), an aperture in the roof [12] (FM, AM, TV, DAB), spoiler [13] (Wi-Fi) [14] (LTE, C2C) and side mirrors [15] (SDARS). It is also possible to use characteristic modes of vehicle parts such as chassis or mirrors [16].

One solution to hide antennas is to lower each into their own cavity in the vehicle roof. A patch antenna array for the 2.45 GHz ISM band inside a cavity is described in [17]. SDARS and GPS antennas are measured in [18] and an LTE antenna in [19]. The principle is also used in aviation [20]. However, all these cavities only contain the respective antennas and car manufacturers can not reserve space in the roof for every antenna's cavity. In [22] a cavity that can be integrated into a chassis with ten times the volume of roof mounted antenna modules was manufactured and measured for C2C applications. This chassis cavity can be manufactured as part of vehicle roofs, a prototype was even built from carbon-fiber reinfored polymer (CFRP), and operates in the whole frequency range currently required for antennas in shark-fin modules [23].

Pattern reconfigurable antennas can be changed between different radiation patterns and therefore utilize pattern diversity without the need for additional antennas. A variety of pattern reconfigurable antennas intended for shark-fin modules have recently been proposed including antennas for 2.45 GHz ISM band with a front/back and a left/right pattern [24], [25] an antenna for 2.6 GHz LTE reconfigurable between front/back and left/right [26] and a 2.6 GHz antenna that can be configured in four states - left, right, front and back [27].

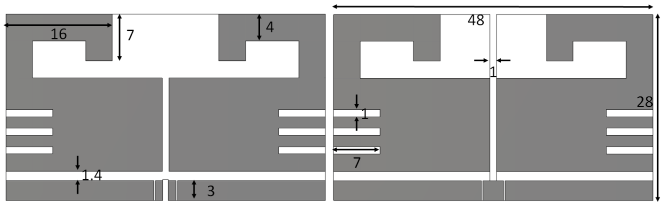
In this paper a pattern reconfigurable antenna for 2.6 GHz LTE [27], which can be electrically switched between four different states, is hidden in a CFRP chassis cavity. S-parameter measurements show good matching with a return loss better than 15 dB. Calibrated gain measurements show that reconfiguring between left, right, front and back radiation is possible from a position below the roofline. An exemplary mounting position on a car roof is depicted in Figure 1.

II. Pattern Reconfigurable Antenna for LTE

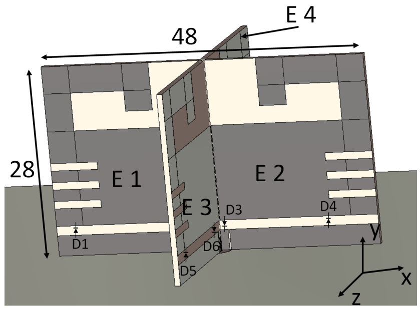
According to the study presented in [28], if automotive urban scenarios are considered, in most of the cases maximal three sub-channels with adequate signal-to-noise-ratio (SNR) exist. Thus it is possible to construct a system with a reduced number of antennas, which produce specific radiation patterns and switch between them. Therefore, the vastly utilized omni-directional antennas are replaced with reconfigurable antennas. The designed switchable radiation patterns should be optimized for these sub-channels and switch to the best pattern depending on the environment. Based on the study presented in [28], the highest eigenvalues of the channels are obtained if the radiation pattern is focused in the driving and the opposite direction, and orthogonal to the sides of the car. The goal of the presented antenna design is to realize an antenna covering these directions. Such a design is presented in [27]. This antenna covers all the named directions as presented in Figure 1 and shows good broadband matching important for proper function in LTE application.

The antenna consists of two orthogonal elements which are in turn composed of two radiating elements (see Figure 2a). The two orthogonal elements are connected mechanically by cutting vertical slot in the middle of both of them. The radiating elements are made of a patch like structure and an inverted-L element on the top. Thus a relatively broadband operation and compact construction is achieved (28 by 48 mm). The structure is printed on an 0.8 mm thick Rogers 5880 substrate (ε_r = 2.2). The antenna is placed vertically on a horizontal ground plane (see Figure 2b). Antenna feeding is realized through a short section of coplanar transmission which is connected to a coaxial connector placed in the ground plane. Use of a coplanar line enables proper feeding of the antenna and connection of the p-i-n diodes (in this design BAP64-02 diodes from NXP) crucial for state reconfiguration. Depending on the configuration of activated and deactivated diodes, a desired state can be chosen. If the element E 1 is connected to the feeding line through a diode D2 (not visible in the figure) and at the same time the element E 2 is shorted to the ground through diode D4, a directive beam in $-x$ direction is generated. At the same time all the other diodes should be off. The element E 2 then acts as a reflector due to the small distance between it and radiating element E 1. Thus, a strong coupling between both elements occurs, and the current is generated on the reflector element. By connecting the element E 2 to the ground (with diode D4) the currents on the reflector are reduced. As a result radiation to the back decreases and antenna's efficiency increases. The patterns in other four directions are generated in the same manner. The diodes are activated by applying either a positive or a negative DC bias to the antenna elements. The bias is fed through a 10 kΩ resistor used as RF choke.

The pattern should be switched to the other state as soon as signal drops below a given threshold. The observations made in other works of the group show that, if this mechanism is chosen, the number of switch cycles can be minimized. However an optimal state is not always chosen. If choosing the best state is considered it can be observed, using a ray-tracer based analysis, that statistically all the states would be used with almost the same frequency. Thus proving the applicability



(a) Layout of both antenna elements.



(b) Assembled antenna.

Fig. 2. Antenna model with added dimensions. All dimensions in millimeter.

of presented concept.

III. Chassis Antenna Cavity

The pattern reconfigurable antenna is hidden inside a chassis cavity [22]. The cavity has inclined walls and a size of $500 \times 150 \times 40\,\mathrm{mm}^3$, it can be manufactured as part of a vehicle's chassis. A typical mounting position in automotive applications would be in the roof, with the short length facing towards driving direction to leave roof space available for a panorama window (see Figure 1). The prototype of the chassis cavity is manufactured from carbon fiber reinforced polymer (CFRP), a material already used in the mass production of electric cars. The cavity is located in the center of a 2 mm thick sheet of CFRP with a size of $1000 \times 1000\,\mathrm{mm}^2$. The CFRP sheet models the influence of the vehicle roof, but car model specific influences such as roof curvature or pillars, are not considered. The prototype is manufactured as a single piece with the autoclave method from plain weave prepreg. Dimensions of the chassis module are depicted in Figure 3.

In the gigahertz range the woven CFRP behaves like a metallic ground plane. Measurements of monopole antennas for 2.45 GHz and 5.9 GHz on different CFRP ground planes show that the influence on the radiation pattern is negligible, while the efficiency is reduced by up to 23 % [21]. C2C antennas in a roof mounted antenna module are measured on a CFRP car roof in [7]. The chassis cavity is applicable in a wide frequency range including 2.6 GHz for the antenna described in Section II [23].

IV. Measurement Results

Calibrated gain measurements are performed in the anechoic chamber at Karlsruhe Institute of Technology (KIT). The CFRP prototype is mounted on the azimuth rotary column with an aluminum fixture. The antenna is placed in the center

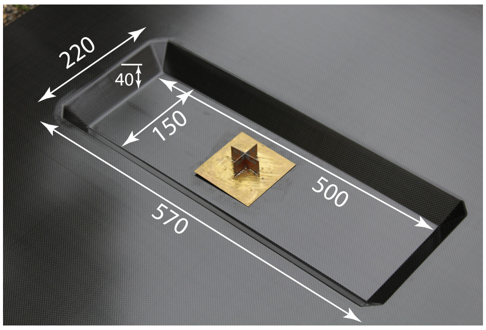


Fig. 3. Pattern reconfigurable antenna inside the CFRP chassis antenna cavity. All dimensions in millimeter.

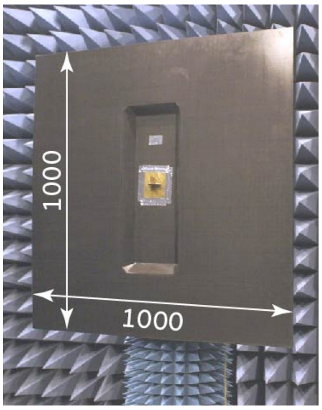


Fig. 4. Measurement setup inside the anechoic chamber at KIT. The chassis cavity with the AUT inside is mounted on an azimuth rotary stage.

of the cavity and attached to the cavity floor with conductive adhesive tape. Coaxial and DC cables of the antenna are routed through a hole in the floor of the cavity underneath the antenna. The cavity is not concealed with a protective cover, so that the results do not depend on an arbitrarily chosen material. The measurement setup is depicted in Figure 4.

The measured return loss of the antenna placed inside the chassis module is depicted in Figure 5. A return loss better than 15 dB is achieved in both states. Realized gain patterns at 2.6 GHz are depicted in Figures 6 and 7. As the whole setup is symmetric, measurement results are only presented for front and right directions. Overall the antenna shows good performance, and is able to switch between desired direction, even when positioned below the roofline.

The vertical cut of the gain pattern in driving direction is depicted in Figure 6. The maximum gain in front direction is 3.5 dBi. The distinction in driving direction ($\varphi = 0°$) between the front and the right state is large with 10 dB. The difference between radiation to the front ($\varphi = 0°$) and back ($\varphi = 180°$) of the vehicle while the antenna is in front state is not so pronounced, but a difference of about 3 dB is still achieved. This means that the antenna radiates double the power towards the front of the vehicle when it is in front state, than it would in back state. Radiation to the front is good for polar angles $0° < \theta < 90°$. Of course radiation below horizon ($\theta > 90°$)

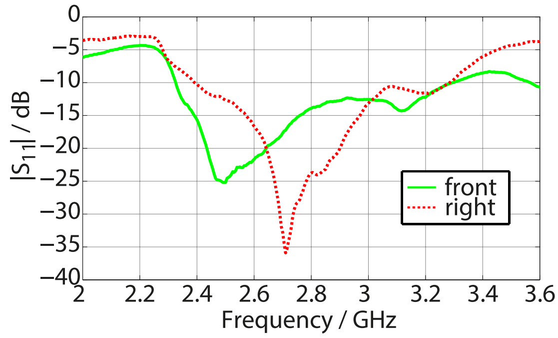


Fig. 5. Absolute value of the measured S-parameters of the AUT placed inside the CFRP chassis cavity.

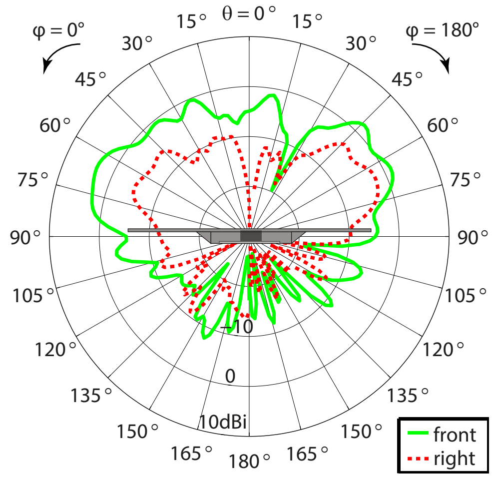


Fig. 6. Vertical cuts of the gain pattern for $\varphi = 0°$. Front direction shown on the left, back shown on the right.

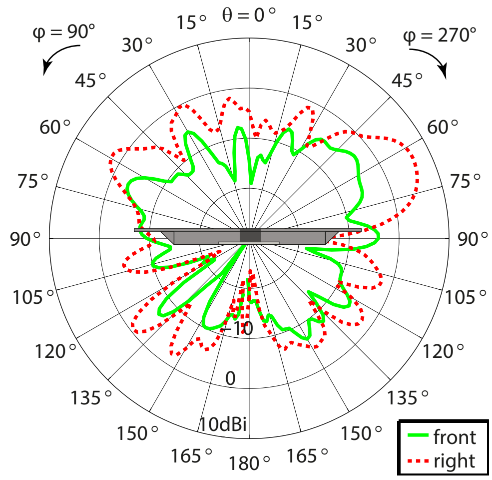


Fig. 7. Vertical cut of the gain pattern for $\varphi = 90°$.

is strongly reduced due to the large ground plane, resulting in good isolation to the car's passengers and electronics.

The vertical cut of the gain pattern for $\varphi = 90°$ (left and right of the car) is depicted in Figure 7. A maximum gain of 6.5 dBi is achieved in desired direction. Again the difference between desired state (right) and the front state is large (about 10 dB). The difference between radiation in the left and right direction with the antenna in right state (see Figure 7) is better than front/back with front direction selected (see Figure 6). The beam in the right direction is narrower considering the elevation cut, when compared to the beam to the front. The reason for this is probably the structure of the cavity. The dimension along the front-back axis is significantly smaller than the dimension along right-left axis. Thus, the field radiated from the antenna towards car's front is disturbed by the wall of the module, which is in the vicinity of the antenna (about 12 cm, which corresponds with one wavelength at design frequency). This problem could however be solved by adapting the design of the cavity and increasing gain along the car's front-back axis.

V. Conclusion

An automotive antenna for 2.6 GHz, which can be reconfigured to radiate in front, back, left or right direction, is hidden inside a chassis cavity. Measurements show that the antenna works properly even when placed below the roofline. The cavity has some influence on the gain pattern of the antenna (compare [27]). Radiation characteristics can be further improved by adapting the antenna design to the new mounting position or adapting the chassis cavity design to the antenna.

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