A Printed Monopole ESPAR Antenna for Truck-to-Truck Communications

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***Abstract*—Driver safety, traffic efficiency and green transportation can be significantly improved by Truck-to-Truck (T2T) communications. This paper proposes a 5.9 GHz Electronically Switched Parasitic Array Radiator (ESPAR) antenna that employs three printed monopoles as array elements. The antenna demonstrates a reconfigurable radiation pattern and compact dimensions that make it ideal for installing it in the side mirrors of a heavy duty vehicle (truck). By adjusting the voltage supply at two PIN diode switches, the antenna can operate in three different states and provide three different radiation patterns (one quasi-omni, two directive beams) to the T2T link user. An ESPAR antenna prototype is manufactured and experimentally characterized, demonstrating a good agreement between simulation and experimental results. The proposed antenna exhibits a satisfying impedance matching and a considerable gain enhancement in the two opposite directions when the antenna operates in the directive mode. An interesting investigation is also performed on the exact location of the antenna inside the truck side mirror.**

Keywords—ESPAR antenna; Truck-to-Truck communications; reconfigurable pattern; PIN diode; printed monopole

I. Introduction

Truck-to-Truck (T2T) communications play a crucial role in the area of vehicular communications and Intelligent Transportation Systems (ITS), mainly because they are able to decrease traffic congestion, reduce the number of accidents and optimize truck platooning. Truck platooning offers a cost-effective and an environmental-friendly transportation since it provides the ability to reduce fuel consumption and emissions [1][2]. In recent years, automotive applications employ more and more reconfigurable antennas [3].

The ability of an antenna array to adapt its radiation beam according to the noise environment (and steer it towards a desired direction or remove it from the direction of a noise source) can be considered highly preferable in vehicular communications [4]. In addition, it would be desirable for an automotive antenna to be compact in order to have no impact in the vehicle's design, avoid causing additional air drag or be installed in relatively small spaces (e.g. truck side mirror). An ESPAR antenna [5]-[8] can meet both aforementioned specifications. Furthermore, the single active array element corresponds to a single RF chain, a simple feeding network and uncomplicated control circuitry, and thus, it considerably decreases antenna complexity and cost.

II. Printed ESPAR Antenna Design Aspects

The design modeling of the proposed antenna is performed in CST 3D electromagnetic solver [9]. An accurate illustration of the antenna arrangement is shown in Fig. 1, along with the main parameters of the design. The ESPAR antenna is formed by three printed monopole radiators (one active, two parasitic) that are printed on a RO4725-JXR dielectric substrate (ε_r = 2.55, h = 0.78 mm).

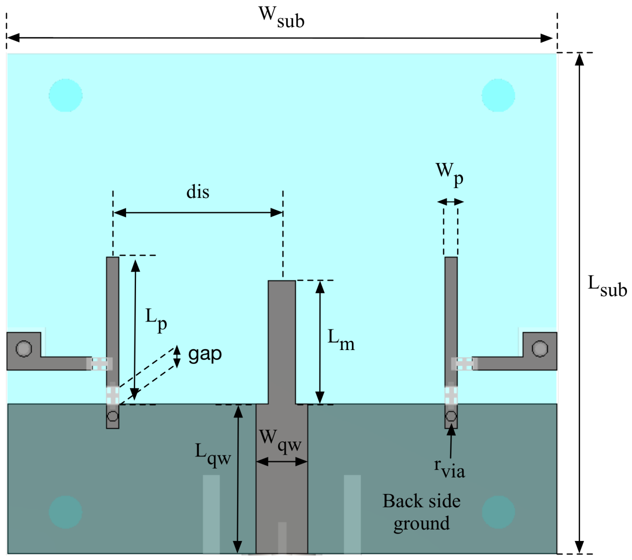


Fig. 1. The "front-view" layout of the antenna as it is illustrated in CST.

The active printed monopole has two components (apart from the SMA connector): (a) a λ/4 microstrip transformer that transforms the 50 Ω impedance to the 37 Ω theoretical input impedance and (b) a printed λ/4 monopole. The beamforming capability of the ESPAR antenna is realized by positioning two parasitic elements (printed monopoles) close to the active element (λ/5) at opposite ends. The intense mutual coupling that is produced provides the pattern reconfigurability. This is accomplished by controlling which parasitic monopole is connected to the ground with two PIN diode switches (simple integration and fast switching). When the parasitic monopole is connected to the ground plane (by a platted via), it creates a reflector (L-shaped) that directs the beam to the opposite side. The two equivalent RLC circuits of the PIN diodes that are used in the CST simulation (Skyworks SMP1320-040LF) are extracted from the PIN diode data sheet [10].

A two-branch DC bias network is also integrated in the antenna design. This is essential in order to apply the required voltage to the two PIN diodes and alter their state. Moreover, two 18 nH chip inductors (Coilcraft 0302CS-18NXJLU) are placed at the start of the DC bias lines in order to prevent the RF current flow (RF chokes). The main dimensions of the antenna model are included in Table I in mm.

TABLE I. ESPAR ANTENNA DIMENSIONS

Parameter	***Description***	***Value (mm)***
t	thickness of the copper and the ground plane layers	0.035
L_m	length of the active printed monopole	7.4
W_m	width of the active printed monopole	1.65
L_p	length of the parasitic monopole	8.8
W_p	width of the parasitic monopole	0.7
L_{qw}	length of the λ/4 transformer	9.0
W_{qw}	width of the λ/4 transformer	3.1
dis	distance between the active and the parasitic elements	λ/5
gap	gap between the parasitic monopole and the grounding metal pad	1.0
r_{via}	radius of the platted via (through hole)	0.3

The ESPAR antenna was manufactured in UK (P+M Services Ltd.) and tested in Germany (VNA in IMST) and in Greece (far-field anechoic chamber in NTUA). A prototype of the 3-printed monopole ESPAR antenna is presented in Fig. 2. The components (SMA connector, PIN diodes, inductors, DC pins) were soldered by hand.

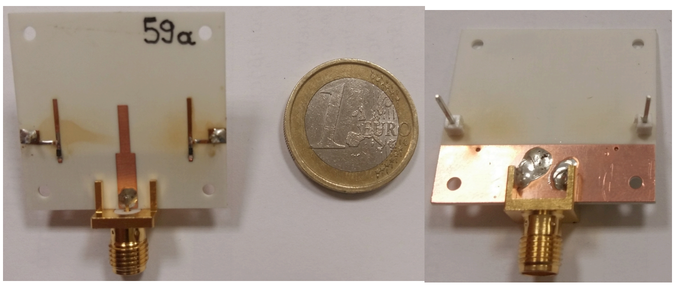


Fig. 2. Front and back side view of the prototype printed ESPAR antenna. The compact size of the antenna makes it an ideal candidate for installing it inside a truck side mirror.

III. ANTENNA PERFORMANCE

The two simulated gain patterns (omni and directive) of the printed ESPAR are plotted in Fig. 3 in blue and red color respectively, for the two principal planes. A considerable 3-4 dB gain enhancement is achieved between the two antenna switching states (OFF-OFF and ON-OFF). The OFF-OFF state presents a non-perfectly (quasi) omnidirectional pattern ("squeezed shape"), which is presumably caused by the planar structure of the antenna along this axis.

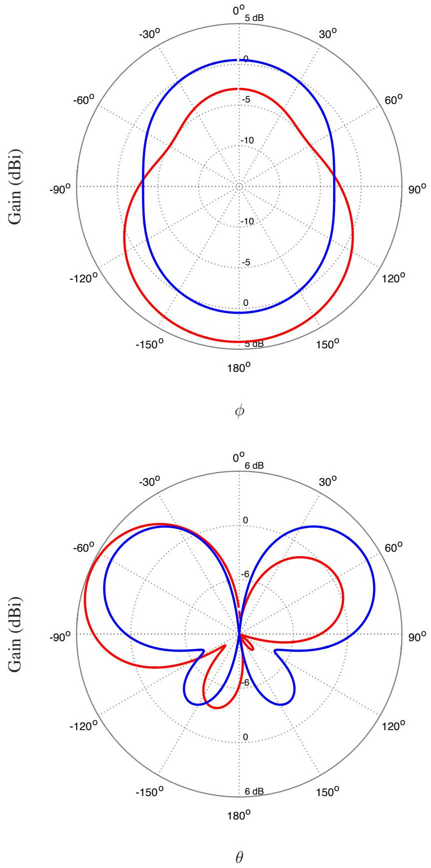


Fig. 3. The simulated 5.9 GHz gain radiation patterns of the antenna at the H plane (top) and the E plane (bottom)

The simulated and measured return loss responses (S_{11}), for the two main operating modes of OFF-OFF and ON-OFF, are presented in Fig. 4, exhibiting a clear agreement and a good design symmetry. The simulated S_{11} for the OFF-ON mode is not plotted since it is exactly the same as the ON-OFF mode (because of the design symmetry). The simulated S_{11} results that are presented in Fig. 4 demonstrate a sufficient reflection coefficient (both states below -14 dB at 5.9 GHz) and an adequate impedance bandwidth (both over 8%). The two reflection coefficients results for the two antenna states have a small deviation due to the different parasitics loading and its effect on the antenna's input impedance. The measured S_{11} parameters for both operating modes exhibit as well a satisfactory impedance matching and an adequate -10 dB bandwidth (above 9%).

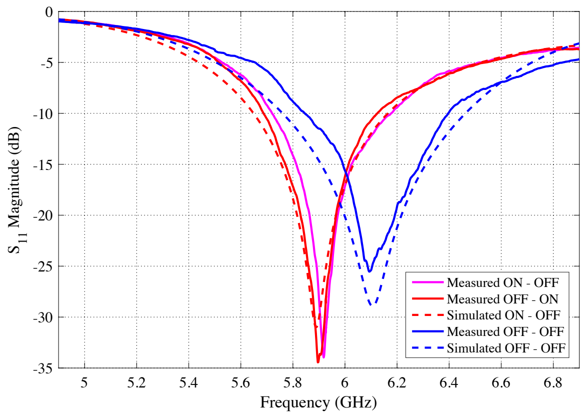


Fig. 4. The simulated and the measured return loss (S_{11}) for the OFF-OFF and ON-OFF operating modes of the printed ESPAR.

Figure 5 (top) illustrates the two measured gain patterns (OFF-OFF, ON-OFF) at the H plane for the 5.9 GHz. A significant 3 dB gain increase between the two operating modes can be observed. This quasi-omni behavior of the OFF-OFF state is additionally distorted (10 dB decrease) at φ = -90° due to the presence of the RF coaxial cable and the SMA adapter. In Fig. 5 (bottom), the two antenna gain patterns are plotted at the E plane.

IV. Antenna Integration

A. Beamforming Demonstration

Following the verification of the antenna's performance that was presented in the previous section, a second prototype printed ESPAR antenna was fabricated in order to perform a few combinational tests using two ESPARs and demonstrate the beamforming capability of the proposed radiator. Specifically, the demonstration was carried out in an indoor environment (inside the Telecommunications Systems Lab of University of Piraeus) using a PNA N5221A Network Analyzer. As it is shown in Fig. 6, the two printed ESPARs were mounted on two antenna tripods at the same height with a specific separation distance between them (1.5 m). The required alignment was executed by using a self-leveling laser device. The S_{21} parameter is measured for various ON-OFF combinations of the antenna system (i.e. both ESPARs omni, one ESPAR pointing the other, both ESPARs pointing each other etc.). Fig. 7 illustrates the S_{21} versus frequency results from the beamforming demonstration.

When both antennas operate in omni-mode, S_{21} is around -45 dB (at 5.9 GHz), which is expected according to the Friis Transmission Equation for a distance of 1.5 m. S_{21} increases by 3.5 dB when one of the two ESPARs focuses its beam towards the other. An 8 dB increase is noticed when both ESPARs focus their beams to each other. S_{21} decreases by 6 dB when both ESPARs focus their beams to the opposite direction.

B. Truck Side Mirror Integration

The next step was to include a left side truck mirror in our measurements and investigate its effect on the antenna's performance. This is absolutely crucial in order to make the correct selection of the antenna's exact location inside the side

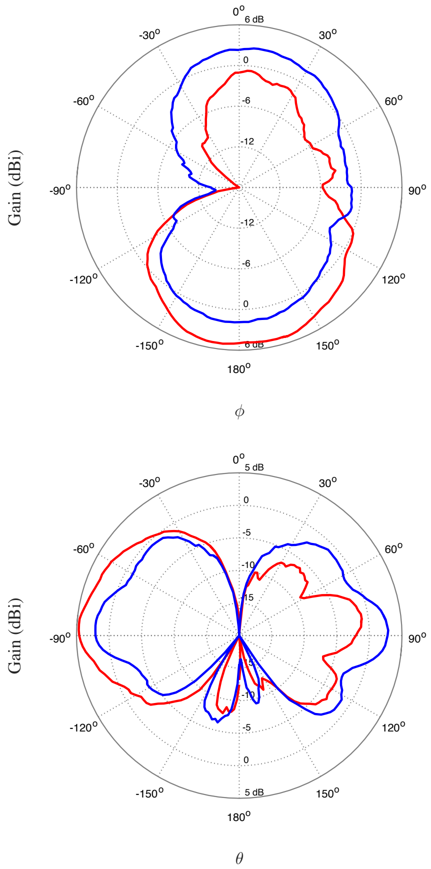


Fig. 5. The measured gain patterns on the H (top) and the E (bottom) plane at 5.9 GHz. The radiation pattern of the OFF-OFF state is quasi-omnidirectional.

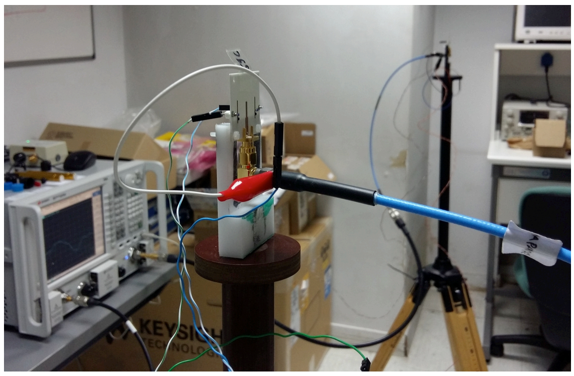


Fig. 6. The two printed ESPAR antennas mounted at the same height with a 1.5 m distance between them. Both antennas are connected to the PNA with long RF cables that were calibrated before the test.

mirror. There are three basic candidate locations for the antenna's installation: two big gap spaces in the main body of the mirror and a smaller space in the hollow plastic upper arm of the mirror. Firstly, as it is illustrated in Fig. 8(a), one of the two 5.9 GHz ESPARs was allocated behind the upper gap space that is available in the mirror structure. Consequently, the ESPAR was positioned behind the lower gap space and finally, it was allocated beside the plastic cover of the mirror's arm (Fig. 8(b).

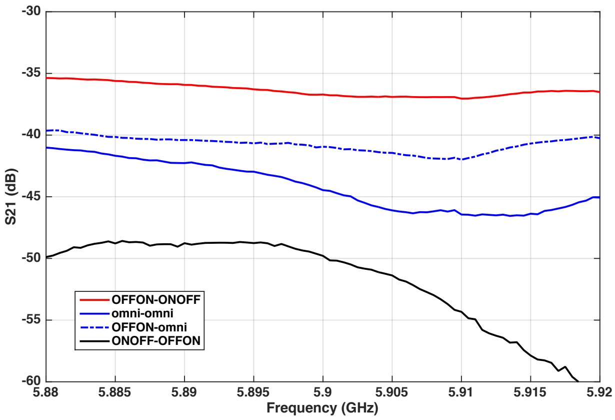
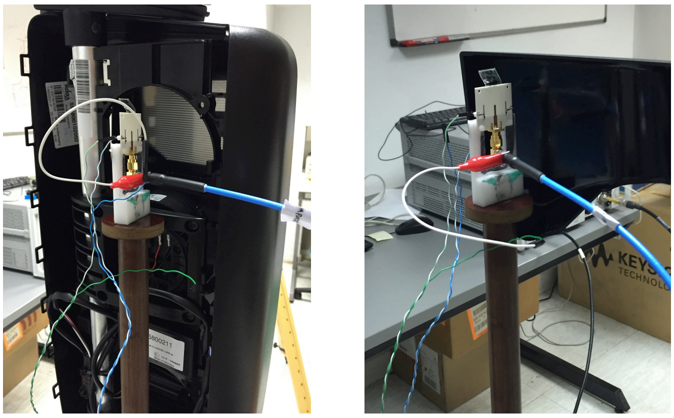


Fig. 7. The S_{21} response versus frequency for four different combinations of the two ESPAR antennas.



(a) (b)

Fig. 8. The printed ESPAR antenna mounted (a) next to to the upper space of the side mirror and (b) next to the plastic cover of the mirror upper arm.

The S_{21} measurements were repeated with the antenna system operating in the omnidirectional mode (both ESPARs in omni operating mode). Fig. 9 includes the comparison results. Specifically, when the antenna is positioned behind the lower and the upper gap space, the ESPAR's performance is significantly affected by the mirror, since S_{21} is decreased by 8 dB and by 9 dB respectively. This impact is mainly due to the dense metal stripes of the mirror heating mechanism. On the other hand, when the antenna is placed beside the plastic cover of the upper mirror arm, the effect can be considered negligible, since the two S_{21} responses (with and without the plastic cover, in blue color) have insignificant deviations.

V. CONCLUSION

The design of a novel 3-printed monopole ESPAR antenna (operating at 5.9 GHz) with a reconfigurable radiation pattern has been proposed for T2T communications in this paper. A good agreement between the simulated and the experimental results is indicated. A satisfactory impedance matching performance for the three main switching antenna states is observed. A considerable 3 dB gain increase is achieved when

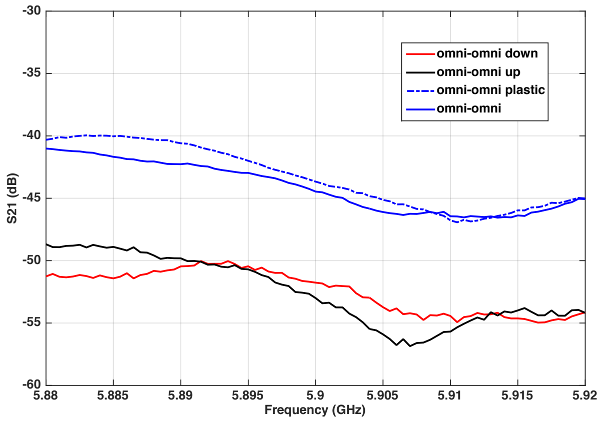


Fig. 9. The S_{21} response versus frequency comparison when the side mirror and the upper arm plastic cover are placed next to the antenna.

the ESPAR is switched to its directive mode (ON-OFF). Finally, an indoor antenna system S_{21} characterization is performed (using two ESPAR prototypes and a truck side mirror) in order to select the optimum location inside the mirror for the antenna's installation (plastic upper arm of the mirror).

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