RSS-Based DoA Estimation Using ESPAR Antenna for V2X Applications in 802.11p Frequency Band

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***Abstract*— In this paper, we have proposed direction-of-arrival (DoA) estimation of incoming signals for V2X applications in 802.11p frequency band, based on recording of received signal strength (RSS) at electronically steerable parasitic array radiator (ESPAR) antenna's output port. The motivation of the work was to prove that ESPAR antenna used to increase connectivity and security in V2X communication can be also used for DoA estimation. The numerical simulation results show that for every proposed radiation pattern we can obtain acceptable DoA estimation results, even with radiation pattern without strong maximum and deep minimum.**

***Index Terms*— Switched-beam antenna, reconfigurable antenna, steerable antenna, electronically steerable parasitic array radiator (ESPAR) antenna, DoA Estimation, received signal strength (RSS).**

I. INTRODUCTION

Electronically steerable parasitic array radiator (ESPAR) antenna [1]-[4] is a simple yet powerful concept that enables beam steering capabilities in wireless sensor network (WSN) nodes that rely on inexpensive radio transceivers and energy-efficient microcontrollers. Such antennas have a single radiating element in the middle, which is connected to a radio frequency (RF) transceiver output, and a number of passive (also referred to as parasitic) elements that surround it being placed on a circumference with equal distances among them. Because every passive element is connected to a variable reactance, one can form a directional radiation pattern by setting appropriate reactance values electronically. Moreover, can change the direction of the main antenna beam electronically by changing these values.

Among various ESPAR antenna concepts already available in the literature for the 2.4 GHz frequency band, the design using single-pole, double-throw (SPDT) switches, that enable connecting passive elements' ends to the ground or leaving them open and can be controlled from digital input output (DIO) ports, seems to be particularly interesting [3], [4]. Using such simplified and energy-efficient beam steering concept, one can control the main beam from a simple and inexpensive microcontroller connected to the SPDT switches and provide direction-of-arrival (DoA) estimation capability with single degree accuracy to a WSN node [5], which can be used to increase the connectivity of the whole network [6], [7]. It has been shown that relying solely on received signal strength (RSS) values recorded at ESPAR antenna output one can estimate DoA of unknown signals impinging the antenna with 2° precision, being the maximum estimation error, for signal-to-noise ratio (SNR) equal to 20 dB [4], [5].

ESPAR antenna concepts proposed so far in the available literature for vehicle-to-everything (V2X) wireless communication in the 802.11p frequency band [8]-[11] address only connectivity improvement, which is the case in interference-rich and multipath environments when the influence of unwanted signals can be reduced by dynamically setting appropriate radiation pattern reconfiguration. However, in order to better address V2X communication security issues, like early detection of denial of service (DoS), spoofing or jamming attacks in complex scenarios [12], [13], one could utilize information about DoA of incoming 802.11p RF signals. Such information may be used to verify location of 802.11p nodes taking part in information exchange, which is especially important during over-the-air (OTA) software update scenarios particularly vulnerable to cybersecurity attacks [14].

As demonstrated in 2.4 GHz band, RSS values recorded at the antenna output allows for DoA estimation with good accuracy using ESPAR antennas with simplified beam steering when a sufficient number of unique directional radiation patterns is available [3]-[5]. Recently proposed ESPAR antenna design with simplified beam steering based on UltraCMOS SPDT switches utilized to operate at 5.89 GHz center frequency for IEEE 802.11p V2X applications [11] can produce a number of unique radiation patterns in 12 directions within the horizontal plane.

In this paper, we investigate how radiation patterns generated by 5.89 GHz ESPAR antenna proposed in [11] for V2X applications in 802.11p frequency band can be used together with DoA estimation algorithms that rely solely on RSS values recorded at the antenna output. As a result, by providing DoA estimation functionality to V2X application in 802.11p frequency band it will be possible to develop new countermeasures to possible cybersecurity attacks on 802.11p V2X communication nodes and particularly during OTA software update scenarios.

II. ESPAR ANTENNA FOR V2X APPLICATIONS IN 802.11P FREQUENCY BAND

The original ESPAR antenna design dedicated for V2X applications has been proposed and described in detail in [11]. The same design of the antenna will be used to evaluate RSS-based DoA estimation performance. For the sake of

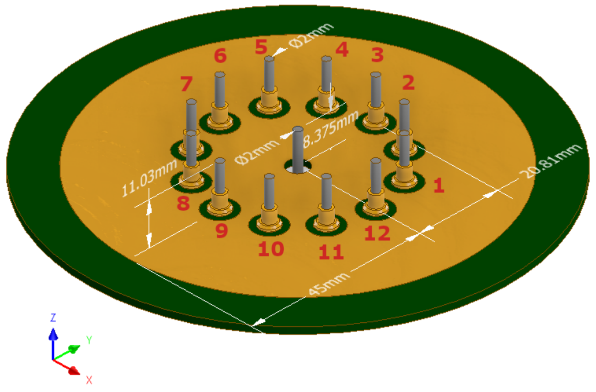

Fig. 1. ESPAR antenna design for 802.11p frequency band optimised for V2X application (as described in [11]).

clarity of the paper, the concept of the antenna will be only briefly presented below.

The base of the designed antenna, as presented in Fig. 1, is a 1.55 mm thick FR4 substrate with top layer metallization as the ground plane for monopoles and bottom layer metallization for switching circuits. The proposed antenna uses thirteen radiating elements: one active monopole fed by an SMA connector surrounded by twelve parasitic elements connected to the PE42424 SPDT switches. The switching circuit was designed in a way that allows changing the load of the parasitic element between short circuit or open circuit to the ground. In this design, parasitic elements shorten to the ground act as directors while elements left open become reflectors. Due to simplicity of the proposed beam steering method, it is possible to form and steer the antenna radiation pattern by any microcontroller with 12 digital output ports.

Each considered ESPAR antenna configuration can be denoted by the corresponding steering vector [4] that defines the combination of passive elements acting as reflectors and directors: $V^n_{\mathrm{max}} = [v_1\ v_2\ \ldots\ v_s\ \ldots\ v_{12}]$ where v_s denotes the state of each passive element: $v_s = 1$ for s-th passive element acting as reflector and $v_s = 0$ for director, while n stands for radiation pattern number. It is associated with a direction, for which the radiation pattern is supposed to have the maximum value in the horizontal plane, equal to φ^n_{max}.

The antenna was simulated in FEKO electromagnetic simulation software for five different configurations: from three to seven neighboring parasitic elements set as directors. The proposed configurations generate diverse radiation patterns that cover various V2X communication scenarios. For all these configurations the antenna was well matched to 50 Ohm (reflection coefficient below -19 dB) in whole 802.11p frequency band [11].

Radiation pattern horizontal cuts, scaled in dBi, for the five considered directional radiation patterns determined by their corresponding steering vectors are shown in Fig. 2. Each configuration provides unique radiation pattern shapes among which the maximum gain in horizontal plane, equal to 2.05 dBi, has been obtained for the configuration with five directors and seven reflectors (steering vector $V^1_{\mathrm{max\text{-}D5R7}}$). For each steering vector V^1_{max} defined in Fig. 2, the reference

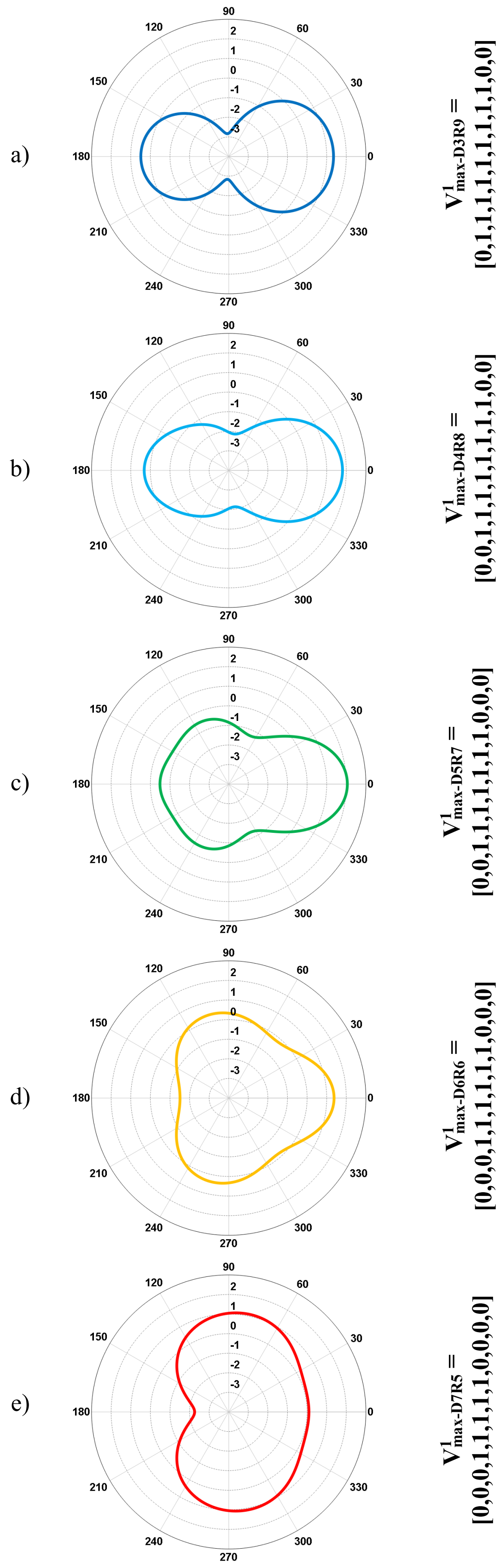

Fig. 2. Proposed 802.11p ESPAR antenna's radiation patterns in the horizontal plane for considered steering vectors (see text for explanations).

angle φ = 0° is assumed to be the direction pointed by the corresponding radiation pattern being the maximum gain direction in the symmetry plane, which means that $\varphi^{1}_{max} = 0°$. By applying a circular shift to the steering vector one obtains the radiation pattern shifted by 30° steps.

III. RSS-BASED DOA ESTIMATION FOR 802.11P FREQUENCY BAND ESPAR ANTENNA

To determine DoA of unknown signals impinging the proposed ESPAR antenna one can use power pattern cross-correlation (PPCC) algorithm. It relies on RSS values recorded at the antenna output port while directional radiation pattern of the antenna is constantly switched to point different directions in the horizontal plane. The PPCC method relies on an estimator [1], [3] and requires to measure all the radiation patterns in an anechoic chamber in the horizontal plane during the calibration process.

For a single directional radiation pattern $P(V^{n}_{max},\varphi)$ created using an appropriate steering vector V^{n}_{max}, the proposed ESPAR antenna provides 360° beam steering with 30° discrete step using the following N = 12 patterns in the horizontal plane $\{P(V^{1}_{max},\varphi), P(V^{2}_{max},\varphi), \ldots, P(V^{12}_{max},\varphi)\}$. To perform DoA estimation using PPCC method, one has to calculate cross-correlation coefficient Γ(φ) using the following formulae [1], [3]:

$$\Gamma(\varphi) = \frac{\sum_{n=1}^{12}\left(P(V^{n}_{max},\varphi)\,Y(V^{n}_{max})\right)}{\sqrt{\sum_{n=1}^{12} P(V^{n}_{max},\varphi)^2}\,\sqrt{\sum_{n=1}^{12} Y(V^{n}_{max})^2}} \qquad (1)$$

where $\{Y(V^{1}_{max}), Y(V^{2}_{max}), \ldots, Y(V^{12}_{max})\}$ are RSS values for the corresponding steering vectors recorded at the antenna output port during the actual DoA estimation process. It has been shown [3], that the estimated DoA angle $\hat{\varphi}$ corresponds to the highest value of the estimator Γ(φ) being a correlation coefficient between $\{Y(V^{1}_{max}), Y(V^{2}_{max}), \ldots, Y(V^{12}_{max})\}$ and $\{P(V^{1}_{max},\varphi), P(V^{2}_{max},\varphi), \ldots, P(V^{12}_{max},\varphi)\}$.

Because in the proposed antenna five different directional radiation patterns are possible, which are formed using steering vectors $V^{n}_{max\text{-}D3R9}$, $V^{n}_{max\text{-}D4R8}$, $V^{n}_{max\text{-}D5R7}$, $V^{n}_{max\text{-}D6R6}$, $V^{n}_{max\text{-}D7R5}$, described in the previous section, 60 patterns in the horizontal plane can be created, namely $P(V^{n}_{max\text{-}D3R9},\varphi)$, $P(V^{n}_{max\text{-}D4R8},\varphi)$, $P(V^{n}_{max\text{-}D5R7},\varphi)$, $P(V^{n}_{max\text{-}D6R6},\varphi)$, $P(V^{n}_{max\text{-}D7R5},\varphi)$ for n ∈ ⟨1,12⟩. Consequently, for every set of 12 patterns cross-correlation coefficient Γ(φ) can be calculated using (1). For example, when steering vectors $\{V^{1}_{max\text{-}D3R9}, \ldots, V^{12}_{max\text{-}D3R9}\}$ is used one will obtain corresponding radiation patterns in the horizontal plane $\{P(V^{1}_{max\text{-}D3R9},\varphi), \ldots, P(V^{12}_{max\text{-}D3R9},\varphi)\}$ and to perform DoA estimation using PPCC method one will calculate cross-correlation coefficient Γ(φ) using (1) with $P(V^{n}_{max},\varphi)=P(V^{n}_{max\text{-}D3R9},\varphi)$ and $Y(V^{n}_{max})=Y(V^{n}_{max\text{-}D3R9})$ for all n.

IV. NUMERICAL SIMULATIONS

To verify the DoA estimation accuracy using PPCC algorithm for five different directional radiation patterns that can be produced in the proposed ESPAR antenna for V2X applications in 802.11p frequency band, numerical simulations were performed. To this end, for every considered steering vector, 12 corresponding antenna radiation patterns associated with 12 main beam directions were generated at 5.89 GHz center frequency of IEEE 802.11p standard with 1° angular step precision using the electromagnetic simulation software FEKO. As a result, five sets of radiation patterns, $P(V^{n}_{max\text{-}D3R9},\varphi)$, $P(V^{n}_{max\text{-}D4R8},\varphi)$, $P(V^{n}_{max\text{-}D5R7},\varphi)$, $P(V^{n}_{max\text{-}D6R6},\varphi)$, $P(V^{n}_{max\text{-}D7R5},\varphi)$ for n ∈ ⟨1,12⟩ have been created.

DoA estimation process has been conducted in Matlab program, in which unknown signal's directions have been set up with a discreet angular step equal to 5°, which results in 72 test directions $\varphi_t \in \{0°, 5°, \ldots, 355°\}$, while the power of the signal is equal to 10 dBm. Moreover, for every considered direction ten snapshots were generated and additive white Gaussian noise has been added to all recorded output power values to generate a specific signal-to-noise ratio (SNR). As a result, for each of the five sets of steering vectors $V^{n}_{max\text{-}D3R9}$, $V^{n}_{max\text{-}D4R8}$, $V^{n}_{max\text{-}D5R7}$, $V^{n}_{max\text{-}D6R6}$, $V^{n}_{max\text{-}D7R5}$, twelve output power values were recorded for every test direction.

TABLE I. DOA ESTIMATION ERRORS CALCULATED USING PPCC ALGORITHM FOR 5 DIFFERENT DIRECTIONAL RADIATION PATTERNS AVAILABLE IN THE PROPOSED 802.11P ESPAR ANTENNA (SEE TEXT FOR EXPLANATIONS).

	SNR [dB]	***mean***	***rms***	***std***	***precision***
$V^{n}_{max\text{-}D3R9}$	**0**	2.39°	2.73°	1.34°	5°
	5	2.01°	2.35°	1.22°	4°
	10	1.39°	1.62°	0.83°	3°
	15	0.79°	0.96°	0.56°	2°
	20	0.49°	0.70°	0.50°	1°
$V^{n}_{max\text{-}D4R8}$	**0**	2.08°	2.61°	1.59°	5°
	5	1.76°	2.23°	1.38°	5°
	10	1.19°	1.54°	0.97°	3°
	15	0.79°	1.06°	0.71°	2°
	20	0.26°	0.51°	0.44°	1°
$V^{n}_{max\text{-}D5R7}$	**0**	1.82°	2.37°	1.53°	5°
	5	1.61°	2.13°	1.41°	4°
	10	1.10°	1.51°	1.05°	3°
	15	0.65°	0.98°	0.73°	2°
	20	0.38°	0.61°	0.49°	1°
$V^{n}_{max\text{-}D6R6}$	**0**	2.22°	2.58°	1.31°	5°
	5	1.85°	2.17°	1.15°	4°
	10	1.28°	1.55°	0.88°	3°
	15	0.83°	1.04°	0.63°	2°
	20	0.50°	0.71°	0.50°	1°
$V^{n}_{max\text{-}D7R5}$	**0**	3.51°	4.11°	2.14°	7°
	5	3.00°	3.52°	1.85°	6°
	10	1.99°	2.37°	1.31°	4°
	15	1.18°	1.42°	0.79°	3°
	20	0.67°	0.83°	0.50°	2°

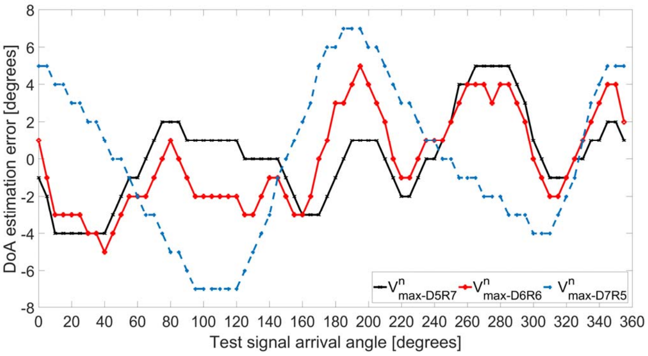

Fig. 3. DoA estimation error for three 802.11p ESPAR antenna radiation patterns. The results were obtained from numerical simulations using PPCC DoA estimation algorithm for SNR=0 dB (see text for explanations).

Results gathered in Table I and presented in Fig. 3 indicate that for all the considered ESPAR antenna radiation patterns the resulting PPCC algorithm provides acceptable DoA estimation accuracy even for very low SNR. The worst case is when ESPAR antenna radiation patterns are generated using seven directors, i.e. for steering vector $V^n_{max-D7R5}$, as it is the most omnidirectional pattern from all available ones. The best results, especially for very low SNRs, in terms of achievable root-mean-square (rms) values have been obtained for steering vector $V^n_{max-D5R7}$, which provides ESPAR antenna radiation patterns with the highest gain, monotonic decrease from the maximum value, and low side lobe level (SLL)[15].

It is worth noticing that although radiation patterns generated using steering vectors $V^n_{max-D6R6}$, i.e. by setting a half of the passive elements as directors and the other half as reflectors, do not show a strong maximum and deep minimum, they can still provide DoA estimation errors at acceptable levels. It means that by using such radiation patterns at receiver antenna during V2X communication it will be possible to determine DoA of incoming signals, while maintaining 802.11p connection quality at almost the same level.

V. CONCLUSIONS

In this article, using 802.11p ESPAR antenna along with RSS-based DoA estimation algorithms is proposed. Numerical simulations indicate that PPCC algorithm with selected radiation patterns provides DoA estimation accuracy with precision below 7°. Even using antenna configuration with moderate maximum and shallow minimum, when half of the passive elements are set as director and other half as reflector, provides error levels similar to configuration with the highest gain. The same configuration also can be used not only to determine DoA of incoming signals but also to maintain almost the same link quality during V2X communication in 802.11p frequency band in each direction. This article proves that regardless of the choice of proposed ESPAR antenna configurations we can obtain acceptable DoA estimation results along with good match to 50 Ohm and unique radiation patterns.

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