Accurate PPCC-Based DoA Estimation Using Multiple Calibration Planes for WSN Nodes Equipped with ESPAR Antennas

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***Abstract* — In this paper, we have introduced a new direction-of-arrival (DoA) estimation method, which relies on received signal strength (RSS) values measured at the output port of electronically steerable parasitic array radiator (ESPAR) antenna and uses the power pattern cross-correlation (PPCC) estimator. In the method, we have successfully incorporated measurements of ESPAR antenna's radiation patterns performed at multiple calibration planes within the PPCC estimator in a way easily implementable in wireless sensor network (WSN) nodes equipped with ESPAR antennas. Performed anechoic chamber measurements of our ESPAR antenna prototype indicate that the proposed approach provides much lower DoA estimation errors in a wide span of incoming signal elevation angles than other methods currently available in the literature, which makes the concept applicable in practical WSN deployment scenarios.**

***Keywords* — switched-beam antenna, electronically steerable parasitic array radiator (ESPAR) antenna, direction-of-arrival (DoA), multiplane calibration method, received signal strength (RSS), wireless sensor network (WSN).**

I. INTRODUCTION

Direction-of-Arrival (DoA) estimation is frequently used to enhance wireless sensor network (WSN) nodes capabilities. It can be used, together with beam steering, to increase WSN systems' functionality [1], [2], or to improve its key parameters, such as connectivity, coverage and energy efficiency of the whole network [3], [4]. However, due to high costs and energy consumption, the most popular DoA estimation relying on digital beamforming involving many digital signal processing (DSP) units cannot easily be applied in WSN nodes. Therefore, one has to consider simpler and more energy efficient switched beam antenna concept with a dedicated DoA estimation algorithm [3].

Electronically steerable parasitic array radiator (ESPAR) antenna, first proposed in [5], is a one-port device, in which a single active element is surrounded by a number of passive elements having its ends connected to variable reactances. By changing values of the reactances electronically, it is possible to form a directional main beam and change its direction. As a result, by rotating the main beam around an ESPAR antenna having six parasitic elements and by applying MUltiple SIgnal Classification (MUSIC) algorithm to signal samples recorded at its output port, it has been possible to estimate DoA of a signal impinging the antenna with 3° precision [6]. However, due to complicated beam steering method involving a DSP unit, necessity of accurate phase synchronization during signal measurements and high computational cost of eigendecomposition required by MUSIC algorithm, such an approach has never been applied in simple and inexpensive WSN nodes [7].

Recently developed ESPAR antenna concepts, which rely on simplified steering concept to rotate the main directional beam, can successfully be integrated with WSN nodes [7], [8]. Additionally, by implementing power pattern cross-correlation (PPCC) algorithm that employs antenna's radiation patterns measured in an anechoic chamber during the calibration phase, one can estimate DoA of a signal impinging the antenna with 2° precision based solely on received signal strength (RSS) values recorded at ESPAR antenna output port for different directional radiation patterns [7]-[9].

One of the most serious deficiencies of PPCC-based DoA estimation lies in its inability to produce accurate results for different elevation angles [10]. Due to the calibration procedure in PPCC method, in which radiation patterns of an ESPAR antenna are usually measured in the horizontal plane only (i.e. for $\theta = 90°$), calculation of correlation coefficient between RSS values gathered for the actual DoA estimation and previously measured patterns may cause errors when elevation angle of an unknown incoming signal is different than $\theta = 90°$. It means that in practical deployment scenarios, in which height differences between WSN nodes installed within the environment are comparable or greater than distances among them, the system might suffer from inaccurate DoA measurements.

Although low DoA estimation accuracy for incoming signals' elevation angles different than 90° can have serious impact in practical WSN applications, not many publications addressing this effect are available in the literature. To increase the overall accuracy, authors in [10] have proposed to measure radiation patterns of an ESPAR antenna in two horizontal planes, i.e. for elevation angles $\theta_{90} = 90°$ and $\theta_{45} = 45°$, during the initial calibration phase. As a result, the proposed modification of PPCC algorithm allows one to estimate DoA of a signal impinging the antenna with similar precisions in elevation planes ranging from $\theta = 90°$ to $\theta = 50°$.

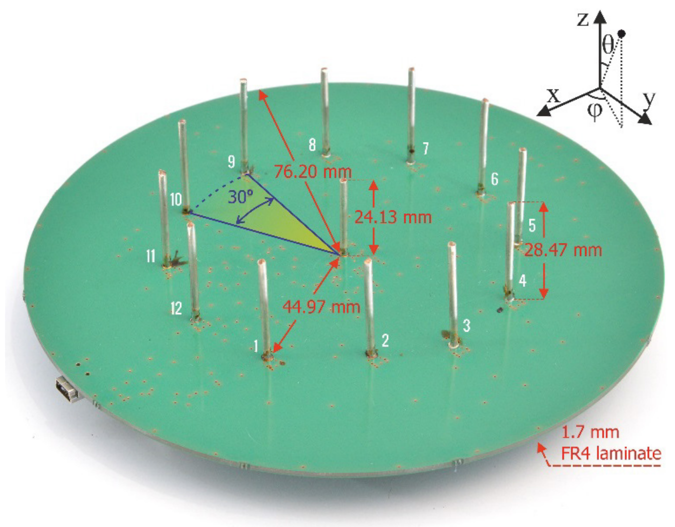

Fig. 1. Our ESPAR antenna fabricated using FR4 laminate, in which top layer metallization is the antenna's ground plane, together with numbering of its parasitic elements (see text for explanations).

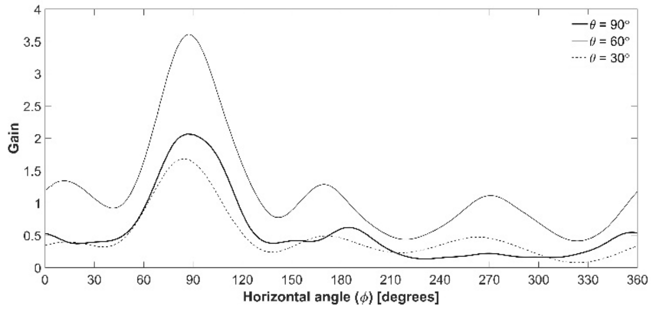

Fig. 2. The ESPAR antenna's radiation patterns for different elevation angles (see text for explanations).

In this paper, we present a new PPCC estimator that incorporates multiple calibration planes measurements to provide accurate DoA estimations for arbitrary elevation angles. The new formulation involves modified approach to PPCC-based estimation introduced in [8], hence it can easily be implemented in simple and inexpensive WSN nodes equipped with ESPAR antennas. Measurement results conduced in an anechoic chamber show that the proposed approach increase the overall accuracy of DoA estimation in a wide span of elevation angles.

II. ESPAR Antenna Design for WSN Applications

ESPAR antenna design suitable to be integrated with a WSN node in order to provide DoA estimation capability to the node has been proposed in [7], while its prototype providing accurate DoA estimation results in the horizontal plane has been described and demonstrated in [8]. The antenna, which has been optimized in [8] to work at 2.484 GHz and is presented in Fig. 1, has a single active monopole fed by an SMA connector that can be connected to WSN node radio frequency (RF) transceiver's output. The monopole is surrounded by twelve passive elements connected to the ground or opened by a corresponding single-pole, double-throw (SPDT) switch connected to the elements' ends at the bottom layer of the structure. When these digital SPDT switches are connected to WSN node's microcontroller digital input output (DIO) ports, the antenna's radiation pattern can be changed by setting the correct steering vector $V = [v_1, v_2, \cdots, v_{12}]$ in the microcontroller. If v_n is set to 0 it means that n-th parasitic element is connected to the ground and when is set to 1 it is opened.

The ESPAR antenna radiation patterns measured in an anechoic chamber for different elevation planes for directional main beam's direction aligned with y axis ($\varphi^1_{max} = 90°$), which has been obtained for $V^1_{max} = [1,1,1,1,1,0,0,0,0,0,0,0]$, are shown in Fig. 2. It is clearly visible that radiation patterns change differently across the horizontal plane for various elevation angles θ, which has to be taken into account in PPCC-based DoA estimation method to provide accurate results in a wide span of elevation angles.

III. Accurate PPCC-Based DoA Estimation Using Multiple Calibration Planes

The PPCC algorithm, which has been proposed for DoA estimation in systems using ESPAR antennas in [9], is a simple yet effective method relying on cross-correlation coefficient $\Gamma(\varphi)$, which is calculated between antenna's radiation patterns measured beforehand in an anechoic chamber and RSS values recorded at the antenna output for different main beam directions during the actual DoA estimation. The cross-correlation coefficient, which the highest value corresponds to the estimated DoA angle $\hat{\varphi}$, for the considered ESPAR antenna has the following form [9]:

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

where $\{P(V^1_{max},\varphi), P(V^2_{max},\varphi), \ldots, P(V^{12}_{max},\varphi)\}$ are ESPAR antenna's radiation pattern values measured in the horizontal plane (i.e. $\theta = 90°$) in an anechoic chamber once, before the actual DoA estimation, with the angular step precision $\Delta\varphi$ for all corresponding steering vectors $\{V^1_{max}, V^2_{max}, \ldots, V^{12}_{max}\}$ and $\{Y(V^1_{max}), Y(V^2_{max}), \ldots, Y(V^{12}_{max})\}$ are output RSS values recorded for a signal impinging the antenna from an unknown direction during the actual DoA estimation process.

For signals impinging the antenna from directions other than $\theta = 90°$, one can expect lower DoA estimation accuracy [10]. This effect is caused by the calibration procedure involving, in the original implementation of PPCC algorithm in [9], ESPAR antenna's radiation patterns measured only in the horizontal plane. Because the radiation patterns change differently across the horizontal plane for various elevation angles θ, as shown in Fig. 2, a modification of PPCC algorithm involving two calibration planes (i.e. for $\theta_{90} = 90°$ and $\theta_{45} = 45°$ elevation angles) has been proposed to increase the overall estimation accuracy [10]. However, although the proposed modification increased the overall PPCC-based DoA estimation performance for arbitrary elevation angles, it provides acceptable results only when a signal impinging the antenna comes from elevation angles between $\theta = 90°$ and $\theta = 50°$.

To provide accurate DoA estimation results in a wide span of elevation angles one has to increase the number of possible calibration planes in a way that the resulting scheme can easily be implemented in simple and inexpensive WSN nodes. To this end, instead of two-step approach formulated in [10], we propose a PPCC-based estimator, which can easily be implemented in a WSN node's microcontroller, that incorporates multiple calibration planes measurements to provide accurate DoA estimations also for elevation angles lower than $\theta = 50°$.

Based on observations from [8], that in practical WSN implementations antenna's radiation patterns $P(V_{max}^n, \varphi)$ in (1) are in fact sets of discreet values $\boldsymbol{p}^n = [p_1^n, p_2^n, \cdots, p_I^n]^T$ measured in an anechoic chamber with the angular step precision $\Delta\varphi$, one can rewrite (1) in a vector form as [8]:

$$\boldsymbol{g} = \frac{\sum_{n=1}^{12}\left(\boldsymbol{p}^n\, Y(V_{max}^n)\right)}{\sqrt{\sum_{n=1}^{12}(\boldsymbol{p}^n \circ \boldsymbol{p}^n)}\ \sqrt{\sum_{n=1}^{12} Y(V_{max}^n)^2}} \qquad (2)$$

where the symbol '∘' stands for the Hadamard product, which can be implemented as element-wise multiplication of vectors, while $\boldsymbol{g} = [\Gamma(\varphi_1), \Gamma(\varphi_2), \cdots, \Gamma(\varphi_I)]^T$ is a vector of length I that contains correlation coefficient $\Gamma(\varphi)$ in a discretized form with elements corresponding to discretized values of φ in the vector $\boldsymbol{\varphi} = [\varphi_1, \varphi_2, \cdots, \varphi_I]^T$. Similarly to the original PPCC method, the estimated DoA angle $\hat{\varphi}$ is a value in the vector $\boldsymbol{\varphi}$ that corresponds to the highest value in $\boldsymbol{g}$ [8].

In order to implement multiple calibration planes measurements into the PPCC estimator (2), we propose to introduce the following vector associated with the corresponding steering vector V_{max}^n:

$$\boldsymbol{p}_\theta^n = \left[\, (\boldsymbol{p}_{\theta_1}^n)^T, (\boldsymbol{p}_{\theta_2}^n)^T, \cdots, (\boldsymbol{p}_{\theta_M}^n)^T \,\right]^T \qquad (3)$$

where each $\boldsymbol{p}_{\theta_m}^n$ vector contains ESPAR antenna's radiation pattern values measured at the elevation angle θ_m. It means that when the total number of M calibration planes is considered $\{\theta_1, \theta_2, \dots, \theta_M\}$, the length of the vector $\boldsymbol{p}_\theta^n$ is equal to $I * M$. Therefore, the resulting PPCC estimator involving multiple calibration planes will take the following form:

$$\boldsymbol{g}_\theta = \frac{\sum_{n=1}^{12}\left(\boldsymbol{p}_\theta^n\, Y(V_{max}^n)\right)}{\sqrt{\sum_{n=1}^{12}(\boldsymbol{p}_\theta^n \circ \boldsymbol{p}_\theta^n)\ \sqrt{\sum_{n=1}^{12} Y(V_{max}^n)^2}}} \qquad (4)$$

where $\boldsymbol{g}_\theta$ is a vector of length $I * M$ that contains correlation coefficient $\Gamma(\varphi)$ in a discretized form with elements corresponding to discretized values of φ in the vector $\boldsymbol{\varphi}_\theta = [\boldsymbol{\varphi}_{\theta_1}^T, \boldsymbol{\varphi}_{\theta_2}^T, \cdots, \boldsymbol{\varphi}_{\theta_M}^T]^T$, in which $\boldsymbol{\varphi}_{\theta_m} = \boldsymbol{\varphi}$ for every m. As a result, the estimated DoA angle in the multiple calibration plane approach is a value in the vector $\boldsymbol{\varphi}_\theta$ that now corresponds to the highest value in $\boldsymbol{g}_\theta$.

IV. Measurements

In order to verify the accuracy of the proposed PPCC-based DoA estimation algorithm, we have measured the considered ESPAR antenna in our $11.9 \times 5.6 \times 6.0\ m$ anechoic chamber at $2.484\ GHz$ with horizontal resolution $\Delta\varphi$ equal to 1°. To this end, twelve ESPAR antenna radiation patterns, which correspond to twelve main beam directions, have been measured in $M = 9$ calibration planes, namely $\{\theta_1 = 10°, \theta_2 = 20°, \dots, \theta_9 = 90°\}$. Additionally, the same radiation patterns were measured in $\theta_{90} = 90°$ and $\theta_{45} = 45°$ elevation planes to compare the obtained results with those already available in [10].

To examine DoA estimation accuracy, a signal generator within NI PXIe-5840 Vector Signal Transceiver has been used in the same anechoic chamber to generate $10\ dBm$ $2.484\ GHz$ BPSK test signal. For every RSS measurement, 10 snapshots were generated $8.0\ m$ from the ESPAR antenna and the signal has been received by the same NI PXIe-5840 unit connected to ESPAR antenna's output. Additionally, additive white Gaussian noise has been added to the received signal to generate signal-to-noise ratio (SNR) equal to $20dB$.

Signal's directions were set by rotating the receiving ESPAR antenna with a discreet angular step equal to 10° in both directions. In consequence, 36 test directions $\varphi_t \in \{0°, 10°, \dots, 350°\}$ were obtained for 9 elevation angles $\theta_t \in \{90°, 80°, 70°, 60°, 50°, 40°, 30°, 20°, 10°\}$. For every elevation angle θ_t and for every horizontal signal's direction φ_t, twelve RSS values have been recorded for all the main beam antenna configurations.

The results of the PPCC-based DoA estimation involving multiple calibration planes, presented in Fig. 3, indicate that absolute DoA estimations errors are lower than 6° for all signals impinging the antenna from directions ranging from $\theta = 90°$ to $\theta = 10°$, while the root-mean-square (RMS) error calculated from all 324 values in Fig. 3 equals 1.78. In fact, there are only a few (θ_t, φ_t) combinations for elevation angles $\theta_t \leq 30°$ where the maximum absolute error is larger than 4°.

Table 1. Comparison of DoA estimation errors obtained for the proposed PPCC-based algorithm involving multiple calibration planes together with methods available in the literature (see text for explanations).

θ_t	Calibration method in PPCC-based algorithm					
	The proposed multiple plane		Two-plane introduced [10]		The original single-plane [9]	
	RMS	prec.	RMS	prec.	RMS	prec.
10°	2.36°	5°	172°	180°	172°	180°
20°	1.67°	3°	3.14°	6°	3.59°	9°
30°	2.49°	6°	2.16°	6°	2.39°	7°
40°	1.63°	3°	1.52°	3°	2.42°	6°
50°	1.77°	4°	1.75°	4°	2.76°	7°
60°	1.40°	2°	2.59°	5°	2.73°	6°
70°	1.41°	3°	2.59°	5°	2.44°	5°
80°	1.27°	2°	1.84°	4°	1.84°	4°
90°	1.60°	3°	1.75°	5°	1.75°	5°

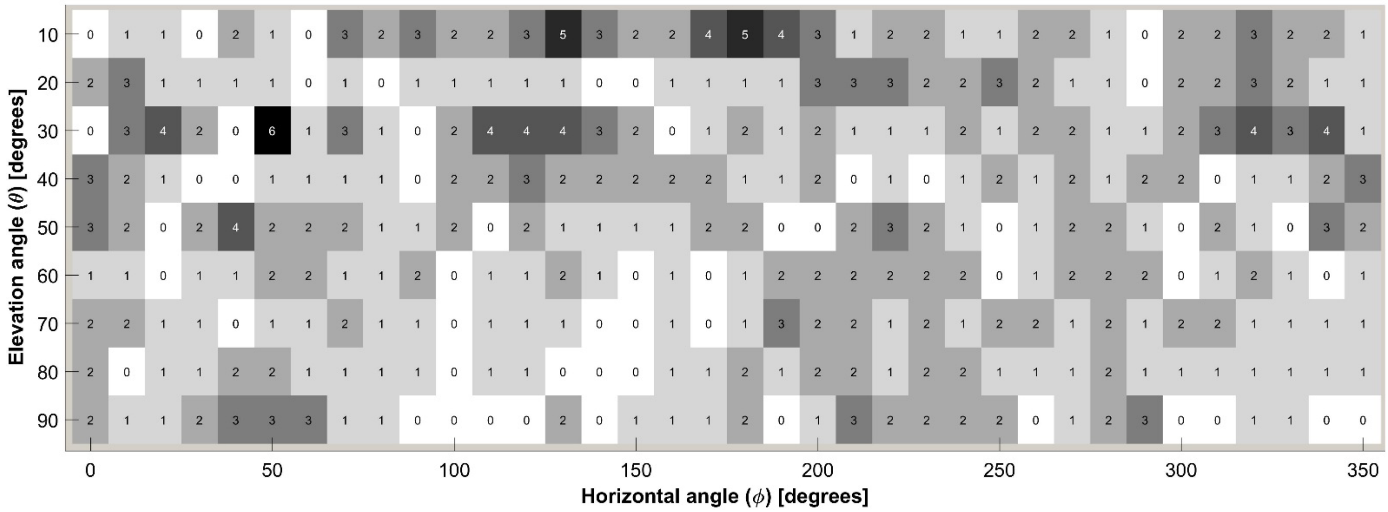

Fig. 3. Absolute values of DoA estimation errors obtained from measurements at SNR = 20 dB for horizontal and elevation angles used in the test measurements of the proposed PPCC-based DoA estimation algorithm involving multiple calibration planes (see text for explanations).

Comparison of the results obtained using the proposed approach with the results of the original single-plane calibration at $\theta_{90} = 90°$ introduced in [9], and also two-plane calibration proposed in [10], in which ESPAR antenna radiation patterns were measured at $\theta_{90} = 90°$ and $\theta_{45} = 45°$, are gathered in Tab.1. For each considered elevation angle θ_t, RMS error and precision, which after [6], [9] is the biggest absolute error value obtained during DoA estimations, have been calculated using available 36 test measurements for horizontal directions φ_t. It is clearly visible that the proposed approach provides higher accuracy, also in the horizontal plane $\theta = 90°$, while in the plane $\theta = 10°$ the multiple calibration plane method was the only one to provide acceptable results.

V. Conclusion

In this paper, we have introduced a new PPCC-based DoA estimation method for ESPAR antennas. The method relies on PPCC estimator, which in its original implementation involves single-plane calibration measurements in the horizontal (i.e. for $\theta = 90°$) plane only [9], that gradually loses its DoA estimation accuracy for other elevation angles (i.e. for $\theta < 90°$). In the proposed approach, necessary measurements of ESPAR antenna's radiation patterns can be performed at multiple calibration planes and then integrated within the PPCC estimator in a way easily implementable in WSN nodes equipped with ESPAR antennas. Anechoic chamber measurements of our ESPAR antenna prototype indicate that the proposed PPCC-based algorithm involving multiple calibration planes provides much lower DoA estimation errors in elevation planes between $\theta = 90°$ and $\theta = 10°$ than methods currently available in the literature. As a result, the multiple calibration plane method for PPCC-based DoA estimation of a signal impinging the antenna from different horizontal and elevation angles can successfully be used in applications, in which large differences in heights of WSN nodes installed at the deployment site are present.

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