# Single-Anchor Indoor Localization Using ESPAR Antenna

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***Abstract*—In this letter, a new single-anchor indoor localization concept employing electronically steerable parasitic array radiator (ESPAR) antenna has been proposed. The new concept uses a simple fingerprinting algorithm adopted to work with directional main beam and narrow minimum radiation patterns of ESPAR antenna that scans 360° area around the base station, while the signal strength received from a mobile terminal is being recorded for each configuration. The letter describes the antenna design and necessary fingerprinting algorithm expansion and shows measurements of the proof-of-concept prototype performed within the experimental setup. Localization results obtained from indoor measurements indicate that the proposed concept can provide better results than the similar approach based on a switched-beam antenna introduced by Giorgetti *et al.* (*IEEE Commun. Lett.*, vol. 13, no. 1, pp. 58–60, Jan. 2009).**

***Index Terms*—Electronically steerable parasitic array radiator (ESPAR) antenna, fingerprinting, indoor localization, smart antenna, switched-beam antenna, wireless positioning system.**

## I. Introduction

The CONCEPT of single-anchor indoor localization introduced in [1] is an interesting and important idea enabling new application fields of wireless positioning systems (WPS). By using only one single 2.4-GHz base station (BS) equipped with a switched-beam antenna, one can determine the position of a mobile terminal. Relying on a single BS, instead of a set of reference nodes (RNs) installed across the area, one can significantly reduce WPS deployment costs. This approach might be particularly feasible in large indoor open spaces (i.e., warehouses, malls, concert halls, etc.) where installation costs of a WPS play an important role or in wireless sensor network (WSN) applications [2].

Although the system presented in [1] is a valuable concept introducing a practical implementation of a smart antenna in localization systems, the proposed switched-beam directional antenna has a complex construction as it is a sectorized antenna array with six active radiators assembled to form a semi-dodecahedron. Moreover, to increase the accuracy of the system, one should use higher-directivity radiators, e.g., antenna arrays as proposed in [3], and use more radiators in a switched-beam directional antenna. As a consequence, the antenna complexity will be even more challenging, and the final smart antenna size at 2.4 GHz may increase considerably.

In this letter, we propose to move the single-anchor indoor localization concept further by using a BS equipped with an electronically steerable parasitic array radiator (ESPAR) antenna. This representative of switched-beam antennas has one active element surrounded by a number of passive elements and enables 360° scan (with a discreet step) of a directional beam by a correct configuration of RF switches providing required load to the parasitic elements, e.g., close to open or short circuit [4], [5]. Due to its physical construction, ESPAR antennas' radiation patterns can easily be tuned to meet the specific requirements [5], [6]. Simple construction and ability to control main beam's direction make ESPAR antennas a popular choice in low-cost systems where determination of the direction of arrival (DoA) of incoming signal is required [6]. However, due to obvious limitations of DoA algorithms, at least two base stations equipped with ESPAR antennas are commonly used to find the position of a mobile terminal [4], [7].

Both, ESPAR antennas and those used in the single-anchor concept employing switched-beam directional antennas, provide 60-80° wide directional beam [1]–[5] used to estimate the direction of incoming signal. But the main advantage of ESPAR antennas, in the context of single-anchor indoor localization, is the ability of such configuration of RF switches providing the required load for all parasitic elements that in a consequence, one can obtain different, than the most commonly used directional main beam, radiation patterns. This approach was proposed in [5] to use narrow minimum radiation pattern to find the position of a mobile terminal.

In this letter, we demonstrate how single-anchor indoor localization concept can be advanced in terms of achievable accuracy by using a base station equipped with the designed ESPAR antenna and by employing both, directional main beam and narrow minimum, radiation patterns. Measurements of the prototype performed in a real-world scenario indicate that even for the proposed simple localization algorithm based on signal strength recorded in the BS, one can easily obtain levels of accuracy similar to the one for the most sophisticated algorithm presented in [1].

## II. Antenna Design and Realization

### A. ESPAR Antenna Design

The proposed design comprises 12 passive elements ESPAR antenna (Fig. 1) with one active monopole in the center of the

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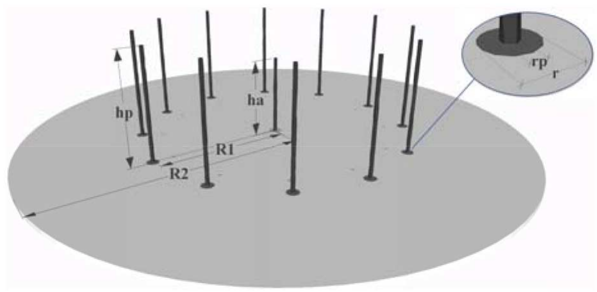


Fig. 1. Dimensions of the designed ESPAR antenna.

TABLE I
DESIGNED ESPAR ANTENNA'S PARAMETERS

| | | Parameter | | | | | |
|---|---|---|---|---|---|---|---|
| | | $h_a$ | $h_p$ | $R_1$ | $R_2$ | $r_p$ | $r$ |
| Size | *[mm]* | 26 | 37 | 48 | 86 | 1.2 | 4 |
| | *[λ]* | 0.21 | 0.30 | 0.38 | 0.69 | 0.01 | 0.03 |

ground plane being a top layer of the printed circuit board (PCB) base. The active element is fed by an SMA connector, while the parasitic elements can be connected to the ground or opened by the single-pole, single-throw (SPST) switches connected to the end of each of them at the bottom layer of the structure. Parasitic elements connected to the ground are referred to as reflectors because they reflect energy, while the opened elements are directors as the electromagnetic wave can pass through them. All switches are controlled by an external microcontroller, hence the actual configuration of the antenna can be denoted by the steering vector $V = [v_1, v_2, \ldots, v_{12}]$, where $v_n$ denotes the state of each parasitic element in Fig. 1: $v_n = 0$ for $n$th parasitic element connected to the ground and 1 for opened.

The antenna was designed and simulated in FEKO electromagnetic simulation software tool. The antenna design is based on those proposed in [4] and [5] and employs 1.55-mm-height FR4 laminate with top-layer metallization. In [4], the number of 12 parasitic elements was proven to be optimal with respect to the narrowest main lobe and the lowest backward radiation at the center frequency equal to 2.4 GHz, hence the same starting configuration was chosen, and then the antenna was optimized to obtain various radiation patterns (see Section II-B) and satisfactory input impedance matching for all parasitic elements configurations. The resulting antenna parameters are gathered in Table I.

### B. ESPAR Antenna Radiation Patterns for Single-Anchor Indoor Localization

Ability to provide a set of various radiation patterns of the ESPAR antenna by different SPST switches' configurations is the key factor enabling single-anchor indoor localization performed by a base station equipped with such an antenna. In this letter, two sets of unique radiation patterns were considered. The first set presents a classical approach to the directional properties of the ESPAR antenna and is directional main beam having 81° 3-dB beamwidth [see Fig. 2(a)]. Here, each radiation pattern is provided by opening four neighboring passive elements that are directors, while the others are reflectors shortened to the antenna ground, hence each of 12 possible steering vector

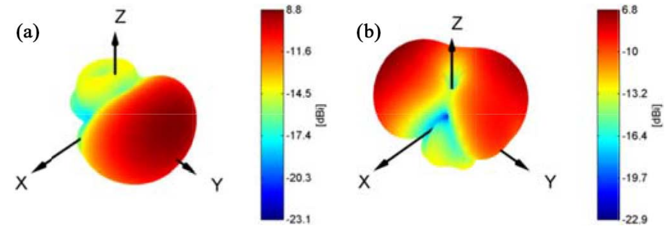


Fig. 2. Simulated 3-D radiation patterns for representatives of the two proposed ESPAR antenna radiation patterns sets: (a) directional main beam (almost 9 dBi in the radiation maximum); (b) narrow minimum (the minimum value close to −20 dBi).

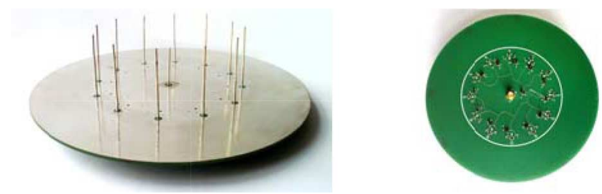

Fig. 3. Realized ESPAR antenna (top and bottom).

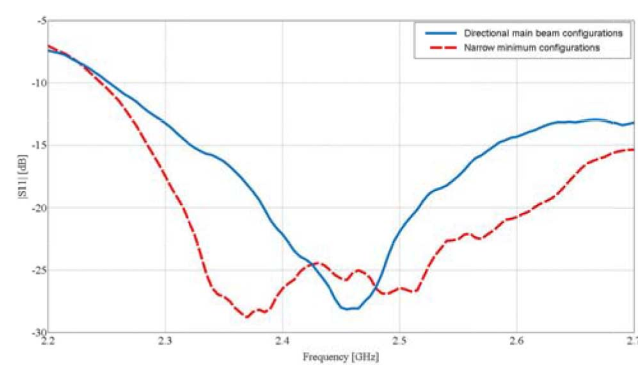


Fig. 4. Measurement results of the realized ESPAR antenna for directional main beam and narrow minimum configurations.

configurations can be obtained by circular shift of the steering vector $V_{\max} = [1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0]$.

The second set is based on considerations discussed in [5] where narrow minimum is proposed as a method of estimating the direction of the incoming signal. It has been found in the process of optimization of the antenna that one of the possibilities to obtain radiation pattern having unique minimum is to set the steering vector to $V_{\min} = [1, 0, 0, 0, 1, 0, 1, 1, 0, 1, 0, 1]$ [see Fig. 2(b)]. It means that to obtain radiation patterns having narrow minimum for all possible 12 directions, one has to apply circular shift to $V_{\min}$.

### C. Antenna Realization and Measurements

For realized ESPAR antenna, presented in Fig. 3, input impedance has been measured for two possible configurations. Results shown in Fig. 4 indicate that, in every case, input matching is satisfactory. Values better than −22 dB over the entire 2.4–2.5-GHz bandwidth obtained for all configurations allows one to use every configuration from the complete set of 24 radiation patterns while keeping the reflection losses at acceptable low level.

## III. Localization

### A. Localization Algorithm

To verify the concept of indoor localization by a single-anchor node equipped with the proposed ESPAR antenna and to compare the results to those already available in the literature [1], an adaptation of a simple fingerprinting algorithm [8] has been proposed in this section. The method allows one to estimate the position of a target directly, based on received signal strength (RSS) values recorded in an ESPAR antenna equipped node and previously measured RSS maps.

To determine the position of a mobile target using fingerprinting algorithm, two phases are required. During the training (offline) phase, location fingerprints are prepared, which in its standard implementation [8] are vectors of radio signal strength values measured for every base station and assigned to specified positions within the scene. In [1], it was proposed that in a case of a single-anchor indoor localization using a switched-beam directional antenna, one has to perform this operation for all six antenna radiation patterns. For realized ESPAR antenna, we propose to expand this approach and, for better clarity and generality, use the modification of the notation introduced in [8]. Assuming that the location fingerprint can be denoted as a vector $F = [\rho_1, \rho_2, \ldots, \rho_N]$, in a case of a base station equipped with the proposed ESPAR antenna, each element $\rho_i$ is an average RSS value measured by BS at a certain mobile target position $L = \{x, y\}$, where $x$ and $y$ are real-world coordinates, within the scene for the $i$th ESPAR antenna radiation pattern. For the proposed antenna configurations, $N = 24$, as 12 directional main-beam and 12 narrow minimum characteristics are considered. If we consider the total number of $l$ positions across the scene, after this phase, one will obtain a set of $l$ location fingerprints $\{F_1, F_2, \ldots, F_l\}$ together with a set of corresponding positions $\{L_1, L_2, \ldots, L_l\}$.

During the online phase, one can find the unknown position of a mobile target using fingerprinting algorithm and information gathered in the training (offline) phase. To this end, RSS values for all 24 ESPAR antenna radiation characteristics are measured by the base station receiving radio signals from a mobile target, and as a consequence, a sample vector $S = [s_1, s_2, \ldots, s_N]$ containing average RSS values can be created. It is worth noticing that ESPAR antenna radiation characteristics should be switched in exactly the same order as during the training phase. If we assume that each location fingerprint is expressed as $F_j = [\rho_1^j, \rho_2^j, \ldots, \rho_N^j]$, the simplest procedure to find mobile target position is to find the location fingerprint $F_k$ having the shortest distance to the sample vector $S$

$$\mathrm{Dist}(S, F_k) \leq \mathrm{Dist}\,(S, F_j)\,, \forall j \neq k. \quad (1)$$

Although many distance functions [8] and many variations of fingerprinting algorithm can be applied here [9], Euclidean distance function and K-Nearest Neighbor (KNN) regression algorithm [9] with $K = 1$ have been chosen to give a fair comparison to the results obtained for a BS equipped with the switched-beam directional antenna used in [1].

### B. Localization Measurements

For the experiment, 2.4-GHz IEEE 802.15.4 compliant CC2430-based modules equipped with a standard Titanis 2.4-GHz Swivel SMA antenna and having output power set to 10 dBm were used in a mobile terminal. All measurements were done in a real environment (a computer laboratory) to build a proof-of-concept application. A base station equipped with the ESPAR antenna was placed in the center of the room, 3 m above the floor, while RSS measurements were collected from a mobile terminal placed at the height of 0.93 m across $4.5 \times 4.5$ m$^2$ area having 10 grid points in both directions, as shown in Fig. 5.

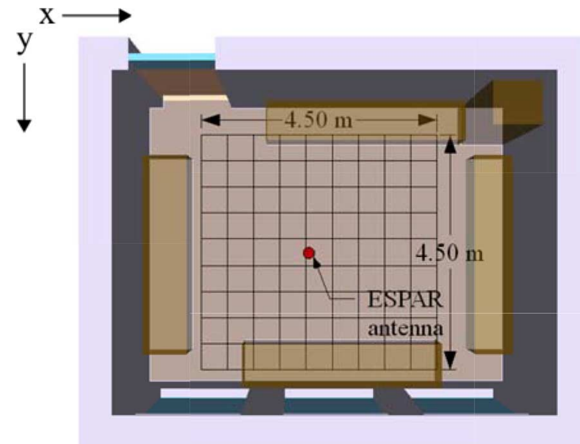


Fig. 5. Measurement area with 0.5 m mesh density and $10 \times 10$ grid points used in the experiment.

For every grid point, 24 measurements were conducted: 12 measurements for directional main beam, and 12 for narrow minimum configurations introduced in Section II-B, which corresponds to 360° area scanning for an ESPAR antenna with 12 passive elements. To ensure reliability of the results, 50 packets were sent in a single measurement for every configuration. The results of measurements are shown in Fig. 6, where the estimation of the received signal power for the whole measurement area and every considered ESPAR antenna configuration is presented. One can easily observe the strong influence of the environment, which is present in both configurations.

### C. Localization Results

To verify how a single base station equipped with the ESPAR antenna can be used to estimate the position of a mobile terminal, fingerprinting algorithm (see Section III-A) was implemented and applied to the data measured in the test area. To this end, measurement results were used to produce four sets of location fingerprints for the training (offline) phase having different mesh density as presented in Fig. 7. Localization errors obtained for all considered mesh densities are presented in Fig. 8 in a form of cumulative distribution function (CDF) together with average localization errors (see the inset in Fig. 8).

For the single-anchor indoor localization concept employing switched-beam directional antenna used in [1], average localization error was equal to 2.32 m when fingerprinting algorithm was used. One should note, however, that results presented in [1] were produced for the $6 \times 4$ measurement grid inside the $7.2 \times 8$-m$^2$ area. Because in [1] there is no detailed information about the grid size in each direction, based on the provided data and figures in [1], we have estimated that this grid size is between

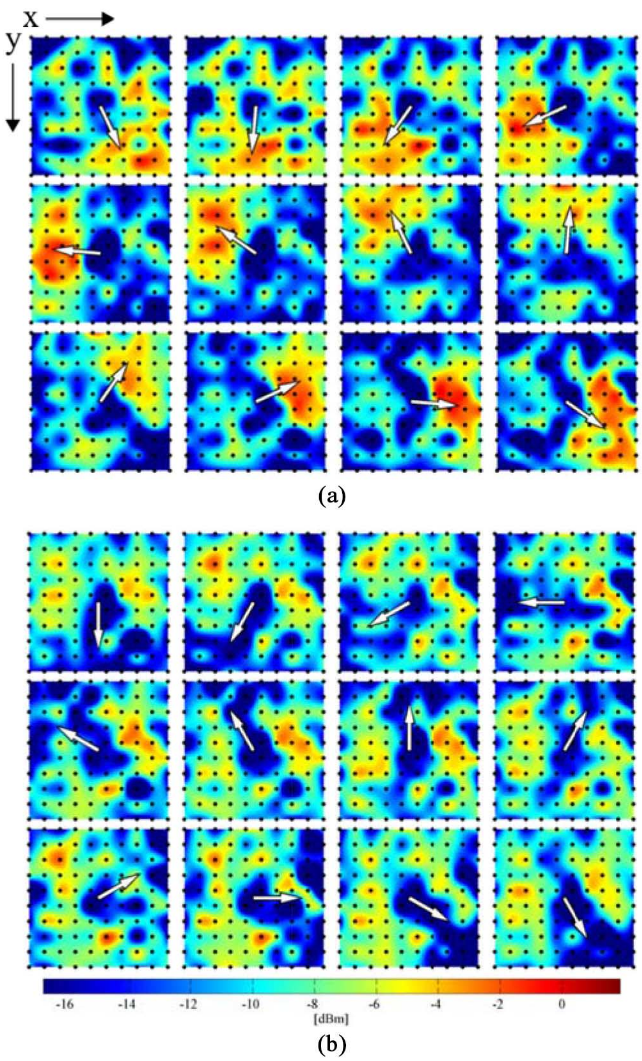


Fig. 6. Measurement results in a form of RSS maps for all 24 considered ESPAR antenna configurations. Black points are measurement grid points, while arrows show (a) the direction of main beam and (b) the orientation of narrow minimum in the respective configurations.

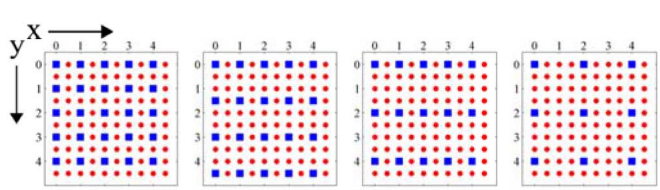


Fig. 7. Four fingerprinting maps in the proposed measurement setup. For every configuration, measurements performed at blue squares were used during the training phase, while those obtained at coordinates marked by red dots were used in the online phase to calculate mobile terminal's position.

$1.0 \times 1.5$ and $1.0 \times 2.0$ m$^2$. As it can easily be seen in Fig. 8, in every case, average localization errors are considerably (about 25%) lower for the proposed single-anchor indoor localization concept based on ESPAR antenna usage and easily reach the highest levels of accuracy (average localization error equal to 1.69 m) reported so far for the single-anchor indoor localization concept using a switched-beam antenna [1]. Additionally,

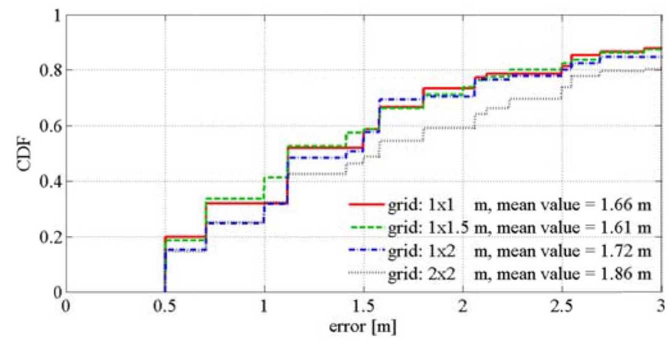


Fig. 8. Localization errors in a form of cumulative distribution function together with the corresponding mean values.

in Fig. 8, one can observe that the proposed concept works well also for coarser $2 \times 2$-m$^2$ grids.

## IV. Conclusion

In this letter, we have introduced a simple and cost effective concept of single-anchor indoor localization using ESPAR antenna. To this end, we have proposed an ESPAR antenna design optimized to work with directional main beam and narrow minimum radiation patterns that can be used in a base station working as a single-anchor indoor localization node. For the proposed concept, we have created a prototype and measured it in an office setup. Localization results indicate that by employing ESPAR antenna and a simple adaptation of the fingerprinting algorithm, one can achieve much better results than those obtained for the similar approach based on the switched-beam antenna introduced in [1].

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