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Research Article

Enhancing Parasitic Interference Directional Antennas with Multiple Director Elements

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The Swedish Institute of Computer Science Parasitic Interference Directional Antenna (SPIDA) is an electrically switched directional antenna that uses switched beamforming techniques to shape the antenna radiation pattern focusing the transmitted power in a given direction, increasing the maximum gain, and simultaneously reducing interference in other directions. This work extends the use of the SPIDA antenna, showing that using multiple director elements results in an improved performance in terms of maximum gain, narrower Half Power Beamwidth (HPBW), and a lower module of the S_{11} parameter. Measurements show that using three directors improves the maximum gain about 1.4 dB (6.8 dBi for the single director element antenna against 8.2 dBi for the antenna with three directors); the input impedance matching was also improved, obtaining a module of S_{11} parameter of -9.8 dB at the central frequency (f_c = 2.4525 GHz) against -7.5 dB for the antenna with a single director element. Finally, new intermediate directions of transmission can be achieved by using two successive director elements, where the power is focused in the bisectrix of the angle formed by the two directors. This converts a six-sector antenna like the SPIDA into a twelve-sector antenna without changing the hardware.

1. Introduction

In the last decades lots of new applications have emerged thanks to the availability of small devices capable of wireless communications, which allows sensing, processing, and communicating multiple physical variables or interacting with the physical world with a very low power consumption. These devices are expected to be of low cost and small size and to reach years of autonomy with small batteries, conforming large Wireless Sensor Networks (WSNs) with low operational and maintenance costs.

The IEEE 802.15.4 protocol is nowadays the most widely accepted standard in the 2.4 GHz ISM band for WSN. For the last decade most of the effort was in the development and optimization of wireless communication protocols. In comparison, the effort to improve the antenna of the WSN nodes has been very small, which could have helped the achievement of lower power consumptions and better efficiency. Many of the commercial nodes come with integrated omnidirectional antennas which radiate the energy in a suboptimal way. Improving the antenna may provide better gain and SNR without increasing the overall irradiated power or may extend the battery lifetime, if the output power is reduced, keeping the distance range and the received signal strength. Another advantage of improving the antenna is that it may reduce the interference with other nodes by concentrating the radiated power in a certain direction, thus reducing the congestion that is known to be a common problem in multihop WSNs [1].

Also, directional antennas have been proposed as an alternative to increase the security in WSN [2].

One of the prominent ways to optimize an antenna is using dynamic beamforming. These techniques enable the increase of the antenna gain in some directions selected electronically on demand for each transmission [3, 4].

An example of this kind of antennas is the SPIDA antenna [5], which is an electrically switched directional antenna designed for WSN. This antenna has the advantage of having a low cost and an easy fabrication process, and also it has a very small size that makes it very convenient to use in large scale deployments.

In this work, the simulation stage, the building, and characterization of a SPIDA antenna in the 2.4 GHz ISM band are described. During this process the use of multiple director elements to enable a complete new set of beam patterns for this antenna was explored. With the use of the professional electromagnetic simulation tool Computer Simulation Technology (CST) (https://www.cst.com/.), the first steps of the performance analysis were made. Finally the SPIDA antenna with three directors was built and characterized, verifying in this way the predicted improvements with respect to the reference design antenna with only one director.

The main contributions of this work are (i) a complete characterization, simulation, and measurement of the reference design (single director element), including radiation pattern and S_{11} parameter, the last one missing in the bibliography; (ii) assessment of different configurations, by means of simulations, analyzing the resulting performance in terms of maximum gain in the main direction, Half Power Beamwidth (HPBW), and S_{11} parameter; and (iii) measurement of the three director elements configuration, identified as an equivalent to the reference but with improved performance, to confirm the simulation results.

The rest of this document is organized as follows. In Section 2 the main characteristics of the SPIDA antennas are introduced and the innovative idea of using multiple elements as directors is presented. In Section 3 the simulations and the results for different configurations are described. Section 4 describes the fabrication and characterization of the antenna and finally, in Section 5, the conclusions are summarized.

2. SPIDA Antenna

SPIDA antenna is a kind of antenna that allows us to perform switched beamforming [5–7]. Being able of controlling the beam direction dynamically is a very useful feature for wireless communication systems, also present in a similar kind of antennas based in this case in Electronically Steerable Passive Array Radiators (ESPAR) [8–10]. Comparing SPIDA antennas with ESPAR ones, the first are simpler and cheaper to fabricate, which represents an important advantage.

Phase-shifting antennas are also widely used in communications systems, but their use of heavy signal processing techniques makes them inadequate for WSN. In [11], a phase shifting directional antenna for WSN is proposed, but this antenna requires custom hardware to manage the signal processing and cannot be used with regular sensor nodes. In this aspect, the SPIDA antenna takes the lead as it can be attached to any sensor node with six output pins available.

These dynamic beamforming features are a promising alternative to optimize WSNs. This is the reason why several researchers have been developing this area [12–15], and it is the main motivation of this work.

2.1. SPIDA Baseline Design. The original antenna proposed by Nilsson [6] has six parasitic elements; thus the legs are separated 60° forming a hexagon. Figure 1 shows a sketch of the constructed antenna. The overall size is such that in can be fitted in a cylinder with radius 52 *mm* and height 60 *mm*.

The antenna is composed of a planar structure in a symmetrical arrangement and a central vertical active element of 29.2 *mm*. Each of the six structures attached to the central hexagon is formed by a "leg" (that resembles the leg of a spider) with a vertical parasitic element. The length of this element is 27 *mm* and it can act either as a director, if it is left isolated (i.e., not connected), or as a reflector, if it is connected to ground. Each connection can be controlled electronically by a RF-switch that allows a microcontroller to manage dynamically the configuration of the antenna.

This antenna configuration has been characterized by other works, featuring approximately between 4 and 7 dBi in the principal direction with a 130° beamwidth [6, 13]. However, some important data, such as the S_{11} parameter, are missing in the corresponding reports. Thus, in this work a complete characterization is included, consisting in simulations and measurements.

2.2. SPIDA with Multiple Director Elements. Several works explored the use of SPIDA antennas for WSNs; initial efforts were in the antenna design itself [6], focusing, later, on solving problems not present in omnidirectional antennas, such as direction mismatch between main lobes of neighbor nodes during discovery phase. All these works were based on a six element SPIDA antenna with only one as a director. To the best of our knowledge, there is not any published report proposing the use of multiple director elements for this kind of antennas.

In this work different configurations were considered aiming to obtain higher gains in the main direction. Other aspects to study are how the adoption of multiple director elements affects the complete shape of the radiation pattern, and the input impedance matching.

Table 1 lists the eight different configurations considered, and Figure 2 depicts them graphically, where the direction of maximum gain is aligned with the horizontal axis (0°) for experiments 1, 2, 3, 4, and 5. For experiments 6 and 7, the direction of maximum gain is also aligned with the horizontal axis but equally high for 0° and 180°, and experiment 8 is omnidirectional. All these configurations were simulated in order to assess their performance. Section 3 describes the simulation results in detail. Among them, the most promising configuration (using three director elements) was measured and analyzed more deeply in Section 4.

3. Simulation

In order to assess the performance of the different configurations, the CST tool was used to simulate the antenna. This electromagnetic simulator was used to obtain the radiation pattern and the S_{11} parameter.

3.1. One Director (Conf. #1). This configuration, in which a single element acts as director, corresponds to the original configuration previously reported and is the reference design for comparison. From the simulated radiation pattern results, the maximum gain is 5.98 dBi with a HPBW of 129° and

Table 1: List of eight different configurations simulated with the location of the director element(s).

#	Description	Location
1	One director	0°
2	Two consecutive directors	30° and 330°
3	Three consecutive directors	0°, 60°, and 300°
4	Four consecutive directors	30°, 90°, 270°, and 330°
5	Five consecutive directors	0°, 60°, 120°, 240°, and 300°
6	Two opposed directors	0° and 180°
7	Four opposed directors	30°, 150°, 210°, and 330°
8	Six directors (all)	-

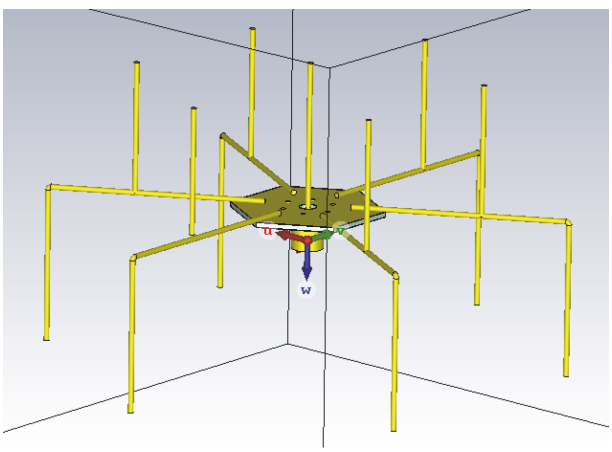


Figure 1: SPIDA antenna model in CST.

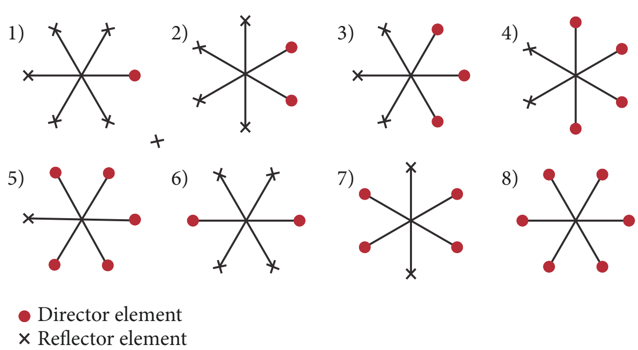


Figure 2: Eight different experiments, showing the location of the director and reflector element(s).

no side lobes, in agreement with previous reports (see the curve "Reference SPIDA" in Figure 3(a)). The front-to-back ratio (FTBR) is 21 dB and the S_{11} parameter varies from 2 GHz to 3 GHz as what the curve "Reference SPIDA" shows in Figure 3(b). These two curves are plotted together with the simulation results of other configurations for comparison purposes.

3.2. Two Consecutive Directors (Conf. #2). As shown in Figure 3(a), the radiation pattern in H plane of this configuration presents a good directivity with a HPBW of 87°, significantly narrower than the 129° from the reference design. The maximum gain is 7.70 dBi, 1.72 dB higher than the configuration with one director, but the FTBR is 9 dB, 12 dB lower than the reference design. Figure 3(b) shows the S_{11} parameter over the Smith Diagram (SD) when it varies from 2 GHz to 3 GHz. The S_{11} parameter in the central frequency of the IEEE 802.15.4 band 2.4525 GHz is -7.73 dB, about 4.00 dB lower than the reference design. According to these simulation results, this configuration outperforms the original one in maximum gain, presenting a narrow beamwidth which could be favorable in many scenarios, and having a better input impedance matching.

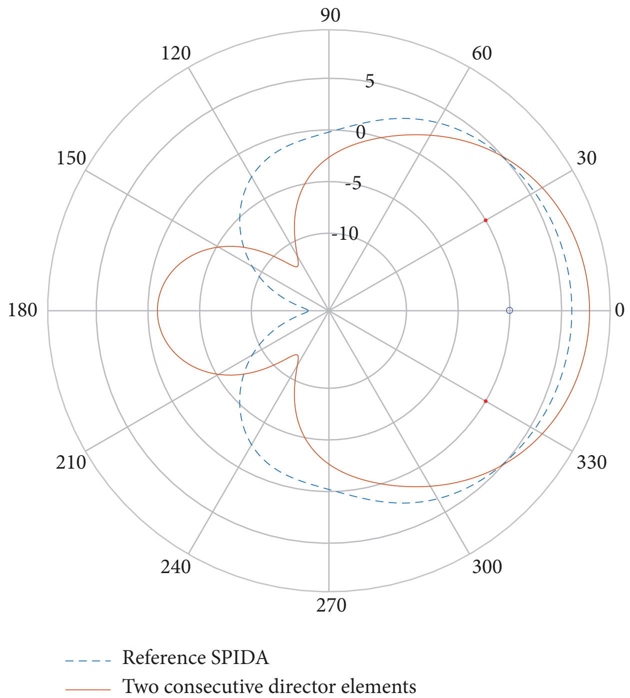
Another interesting characteristic of this configuration is that the main lobe direction is in the middle of the two directors, so with a six element antenna and using two consecutive directors it would be possible to direct the main beam in 12 different directions.

3.3. Three Consecutive Directors (Conf. #3). The radiation pattern in H plane of this configuration is shown in Figure 4(a). It can be observed that this configuration has an even better directivity than that for one and two consecutive directors, with a HPBW of 76° compared to the 129° of the original design. The maximum gain is also better than the corresponding one for one and two directors, achieving 8.35 dBi, 2.37 dB higher than the reference design. This configuration presents a backlobe resulting in a FTBR of 13 dB, lower than that in the reference design but better than that in the configuration with two directors. Figure 4(b) shows the radiation pattern in E plane; for the sake of brevity E plane is shown for this configuration only, since the others have very similar characteristics.

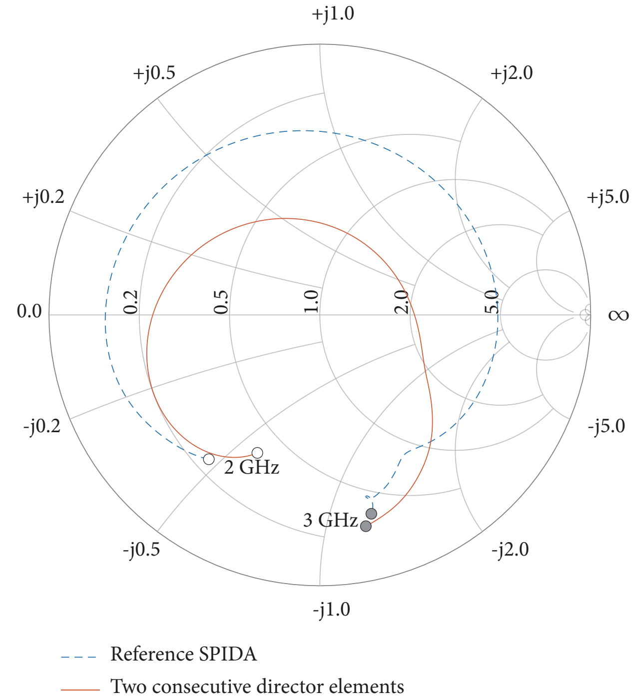
The S_{11} parameter is shown in Figure 4(c), which achieves -11.25 dB at 2.4525 GHz, outperforming previous configurations.

The main lobe direction is aligned with the central director element (of the three used director elements), allowing the directional transmission in any of the original six directions, but with these improved characteristics.

These simulation results so far show that using two and three directors can focus the main beam to 12 different directions with better performance, in terms of gain, directivity, and impedance matching, than the original configuration using only one director. An aspect to consider in these configurations is that the FTBR is lower than the reference design, resulting in the radiation of more energy in the opposite direction.



(a) Polar radiation pattern in H plane



(b) S_{11} parameter

FIGURE 3: Two consecutive director elements (conf. #2).

TABLE 2: Simulation results.

#	Description	Half Power Beamwidth (3 dB)	Maximum Gain	$\lvert S_{11}\rvert$ at 2.4525 GHz	FTBR
1	One director	129°	5.98 dBi	-3.73 dB	21dB
2	Two consecutive directors	87°	7.70 dBi	-7.73 dB	9 dB
3	Three consecutive directors	76°	8.35 dBi	-11.25 dB	13 dB
4	Four consecutive directors	137°	6.42 dBi	-11.94 dB	25 dB
5	Five consecutive directors	103°	5.65 dBi	-8.39 dB	-
6	Two opposed directors	70°	5.91 dBi	-8.70 dB	-
7	Four opposed directors	58°	7.40 dBi	-12.20 dB	-
8	Six directors (all)	Omni	3.90 dBi	-5.81 dB	-

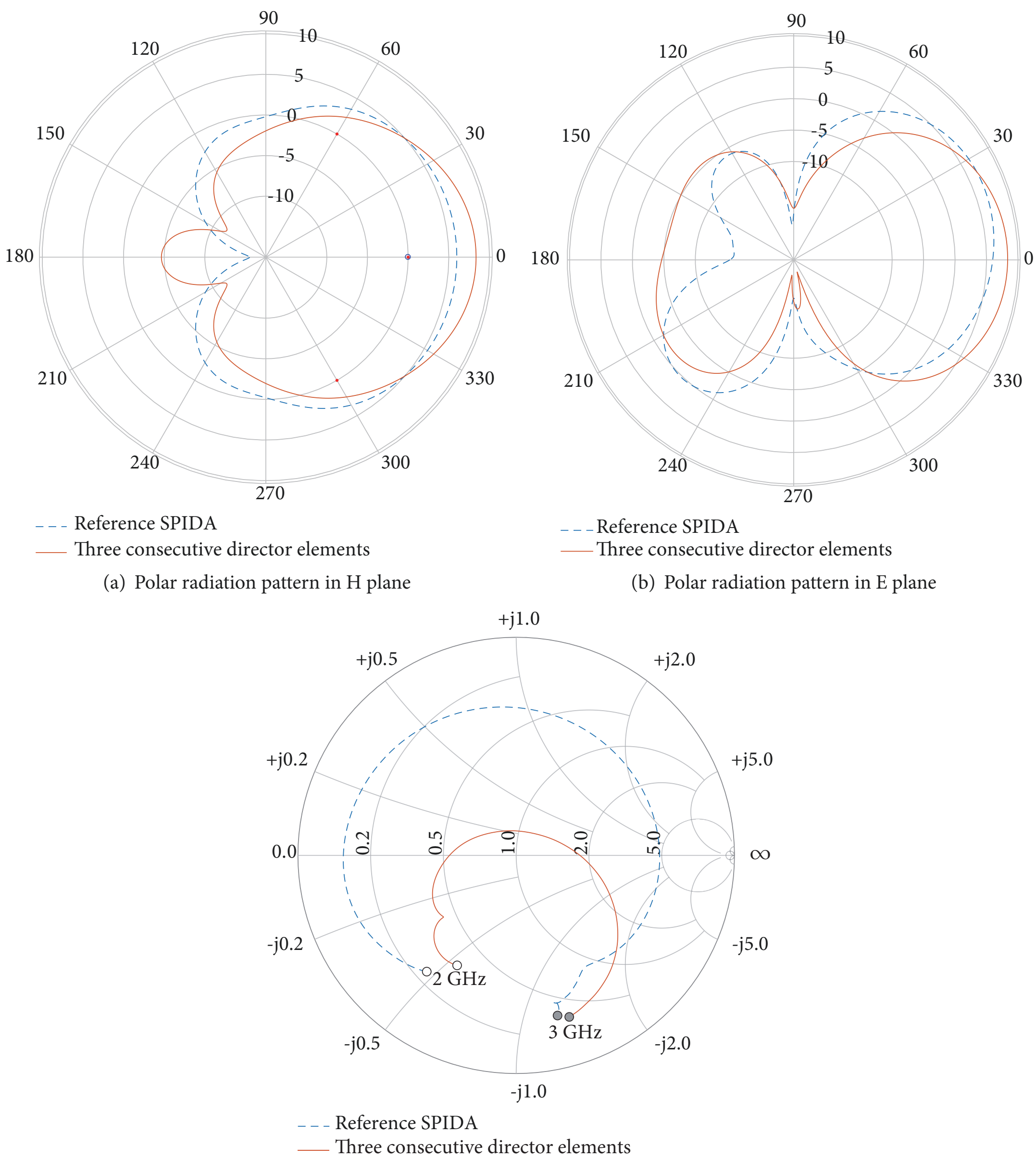
3.4. Four and Five Consecutive Directors (Confs. #4 and #5). The remaining configurations using consecutive directors, that is four and five (configurations #4 and #5, respectively), do not show improvements, in terms of maximum gain, over the two previous analyzed configurations, so these results are not plotted for the sake of brevity.

3.5. Two and Four Opposed Directors (Confs. #6 and #7). Configurations using opposing directors could be interesting to be assessed, since these can be used to radiate simultaneously power in two opposite directions, in order to minimize the broadcast transmissions in linear deployments. The configuration #7 uses four opposed director elements. The resulting radiation pattern in H plane is shown in Figure 5(a). We observe that the power is actually radiated in two opposite directions, each one with a gain of 7.40 dBi (1.42 dB higher than the reference design). The S_{11} parameter is shown in Figure 5(b) presenting a value of -12.20 dB at 2.4525 GHz, about 8.47 dB lower than the reference design. The HPBW is 58°, being much narrower than the reference design.

The results obtained for two opposed directors (conf. #6) can be observed in Table 2; these are not better than the corresponding ones for conf. #7.

3.6. Six Directors (Conf. #8). A special case is the configuration with six director elements; obtaining an omnidirectional pattern with a gain of 3.9 dBi, it is 1.8 dBd, which shows an improvement in the radiation characteristics with respect to the dipole, being in this way a very good option as an omnidirectional antenna.

The use of a combination of directional antennas together with omnidirectional antennas has been proposed in some communication protocols [16–18], where the omnidirectional



(a) Polar radiation pattern in H plane

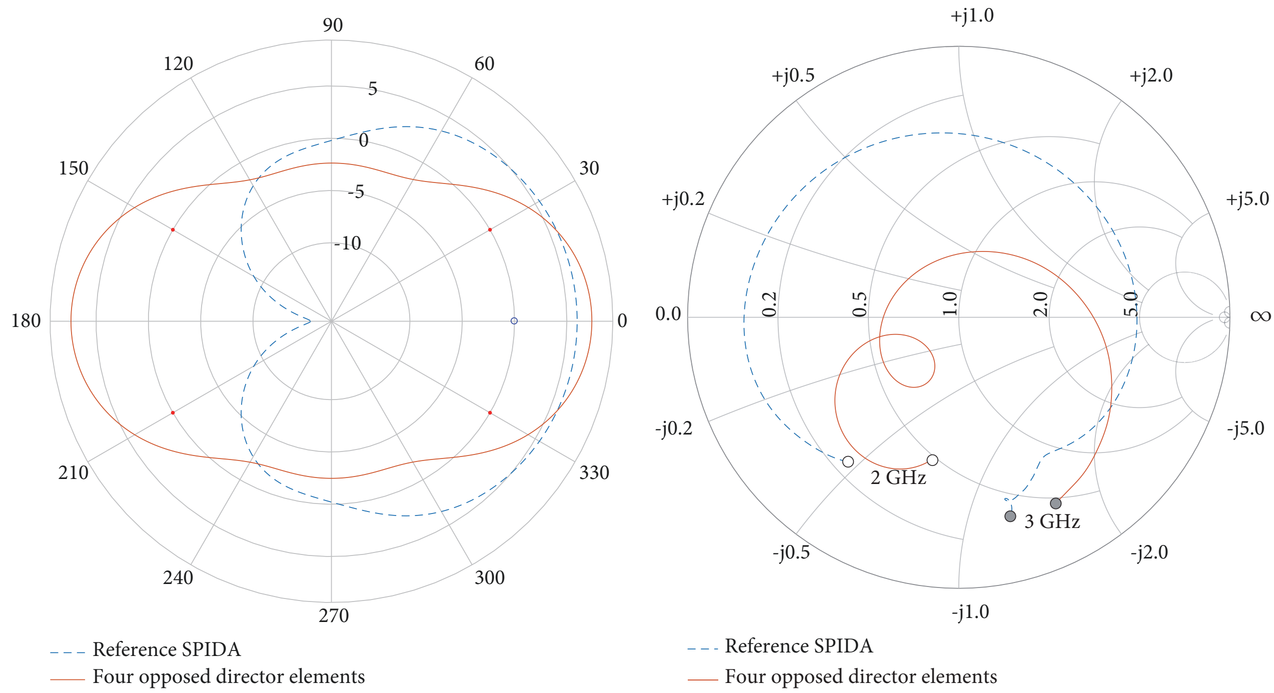
(b) Polar radiation pattern in E plane

(c) S_{11} parameter

Figure 4: Three consecutive director elements (conf. #3).

antenna is adopted for broadcast messages. The configuration with six directors can be adopted for obtaining omnidirectionality.

Table 2 summarizes the main performance parameters of the simulation for the different configurations of the SPIDA. All configurations using consecutive directors outperform the reference design in terms of input impedance matching. The configurations with two, three, and five consecutive directors (confs. #2, #3 and #5) present narrower beamwidth, while the configuration with four directors (conf. #4) has a wider beamwidth. In terms of maximum gain confs. #2, #3, and #4 outperform the reference design. Considering the FTBR, the reference antenna performs similar to the one with four consecutive directors, but better than the configurations with two and three consecutive director elements. Considering configurations with opposed directors, confs. #6 and #7 outperform the reference design in terms of input impedance matching and beam directivity in the desired directions, with conf. #7 having a higher maximum gain than the reference design and conf. #6 a lower one than it. These configurations have the potential to direct RF power to opposite directions with the benefit of enhanced performance. Also this antenna can be used as an omnidirectional one, with a better gain than a dipole. The final choice would depend on network design aspects, such as medium access protocols requirements and sensor nodes arrangement. Moreover, the increased RF power delivered to the air due to better impedance matching (achieved in all the



(a) Polar radiation pattern in H plane

(b) S_{11} parameter

FIGURE 5: Four opposed director elements (conf. #7).

cases) represents an important improvement to the energy efficiency of the system.

Measured and simulated values of S11 for the more interesting cases are shown in Figures 3(b), 4(c), 5(b), and 7. If we take the criterion for the impedance bandwidth of considering a VSWR lower than two (module of S11 in dB lower than -9.54 dB), the configuration with three director elements presents an impedance bandwidth of 310 MHz, from 2180 MHz to 2490 MHz. For the band used in the IEEE 802.15.4 standard (from 2400 MHz to 2483.5 MHz), the module of S11 in dB for this antenna configuration is always lower than -9.7 dB, satisfying the selected criterion. During the development of this research, it was observed that the gain, directivity, and impedance bandwidth of the reference antenna could be modified (and improved) by changing its geometry, in particular changing the distance between the parasitic and the active elements. But it is important to have in mind that the number of director elements in use in this antenna is selected dynamically, and any geometrical optimization of this antenna has a different impact in each of the possible configurations.

4. Fabrication and Characterization

From the simulation results analysis, it turns out that one very promising configuration to improve the performance of the reference design is using three directors. This particular configuration is quite useful for our general research in the WSN area, so we decided to measure the performance of this configuration.

4.1. Fabrication. Two antennas were fabricated in a fixed configuration: one with one director and another with three directors. The first antenna is used as a reference for comparison with the second configuration in which the SPIDA antenna uses multiple director elements. Both antennas were built following the dimensions provided by [5, 6] and using six "legs" and six parasitic elements.

The elements were made using copper wire of 1 mm^2 of section (the dielectric shield was removed). A central PCB hexagon was used to fix the legs and connect them to ground. This hexagon was made of standard two-layer 1.6 mm FR4 PCB board of 35 μm of copper thickness. Both copper layers of the hexagon were connected using vias of 1 mm^2 of section, welded with tin (the vias placement can be seen in Figure 6). A SMA connector was welded to the lower copper layer of the hexagon to feed the antenna through it. The active element of the antenna (the central element) was connected through the SMA connector to the central wire of the coaxial cable used to feed the antenna. A coaxial cable with SMA connectors was used to feed the antenna.

The hexagon was designed using CadSoft Eagle PCB Design Software and fabricated with a LPKF ProtoMat S63 circuit board plotter. The circuit board plotter features a resolution of 0.5 μm and an accuracy of ± 0.02 mm, allowing a very precise fabrication. This equipment enables the production of identical hexagons for the fabrication of these antennas, which facilitates the fabrication process repetitiveness.

The parasitic elements defined as directors were glued with silicone and the parasitic elements defined as reflectors were welded to its corresponding "legs" to ground (which

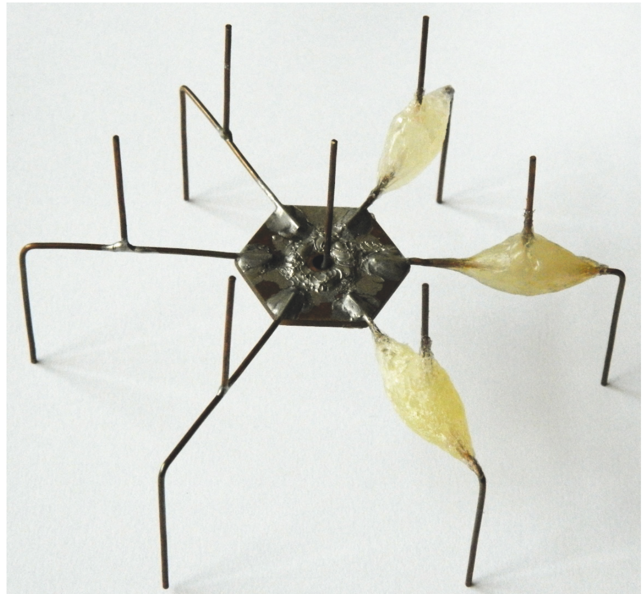


Figure 6: SPIDA antenna with three consecutive director elements.

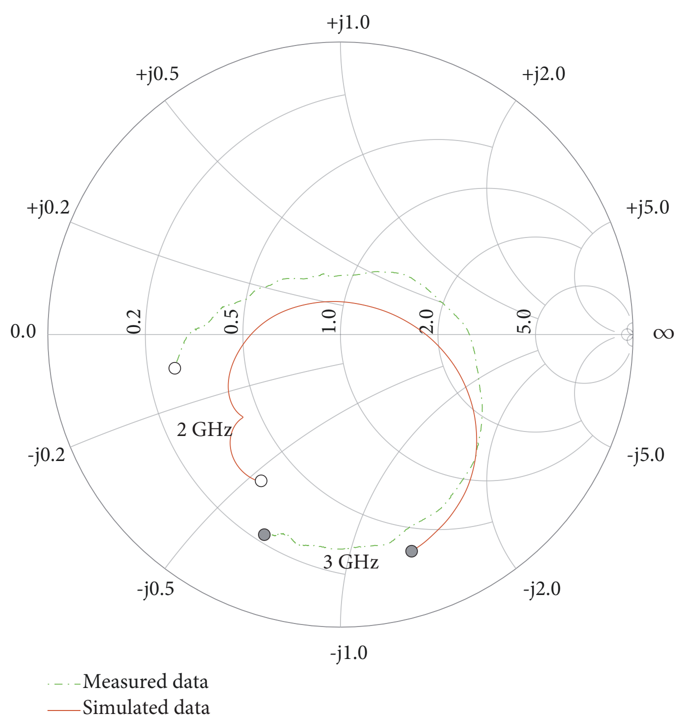


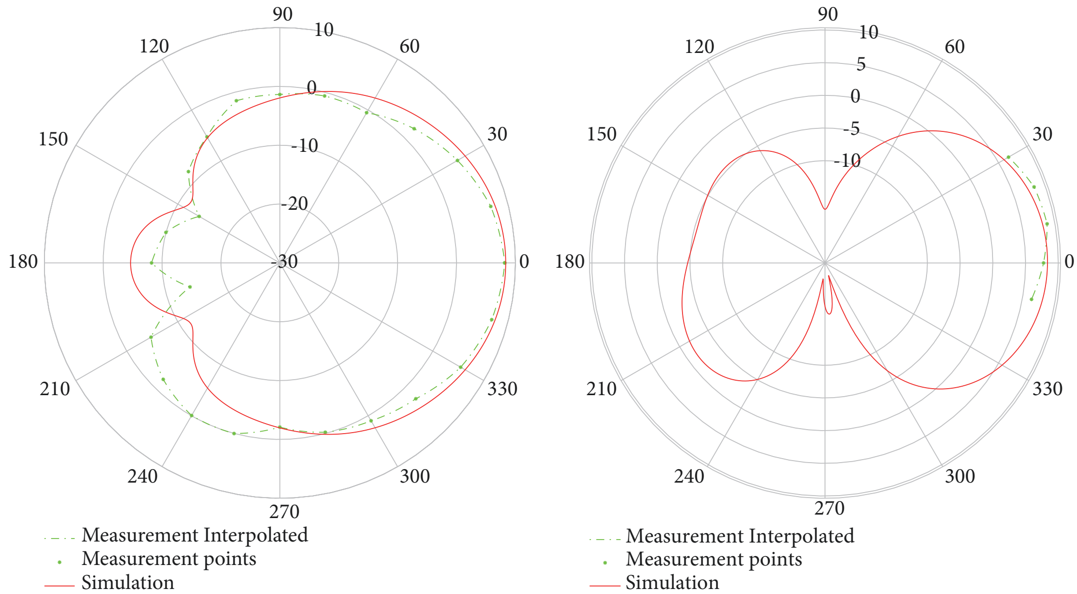
Figure 7: S_{11} parameter for the fabricated SPIDA antenna with three consecutive director elements.

are connected to the hexagon and through it to the cable shield). In a future work, switches will be inserted between the parasitic elements and its corresponding "leg" in order to have dynamic beamforming (controlled by their switches which are able to connect the parasitic element to the "leg" or not). According to chip manufacturer the typical switch attenuation is less than 1.6 dB.

Figure 6 shows a photography of the fabricated antenna with three directors.

4.2. Measurements and Results. For the characterization process a vectorial network analyzer (Rohde & Schwarz ZVB 8 Vector Network Analyzer, 300 kHz - 8 GHz), a RF generator (Agilent, E4438C, 250 kHz - 3 GHz, ESG Vector Signal Generator), and a spectrum analyzer (Agilent Technologies, EXA Signal Analyzer, N9010 A, 9 kHz - 7 GHz) were used.

During the antenna characterization the effort was concentrated on S_{11} parameter and the radiation pattern in the H and E planes for the case with three director elements. The



(a) Polar radiation pattern in H plane

(b) Polar radiation pattern in E plane

FIGURE 8: Fabricated SPIDA antenna with three consecutive director elements.

measurements obtained can be, respectively, seen in Figures 7 and 8. In these figures the measurements and the simulations are superimposed showing a good correspondence. The E plane was only measured in five points near 0°, as this is the area of interest for the WSN applications that we are considering, where all nodes are placed almost in the same horizontal plane.

For the SPIDA antenna with three director elements, a maximum gain of 8.2 dBi according to the measurements (8.35 dBi according to the simulations) was obtained, being 1.4 dB higher than the gain for the single director antenna taken as reference. A maximum gain of 8.2 dBi is a very good result, being a better gain than some previously reported results for similar antennas (e.g., in [6] (4.3 dBi), in [9] (5.1 dBi), and in [8] (8.08 dBi)).

According to the measurements, the HPBW for this antenna is 59° (76° according to the simulations) against 113° for the reference antenna (129° according to simulations).

The module of the S_{11} parameter according to the measurements for this antenna was -9.8 dB (-11.25 dB according to the simulations) against -7.5 dB for the reference antenna (-3.73 dB according to the simulations).

All these results show a very important improvement compared with the single director SPIDA antenna, which justify the use of three director elements instead of only one for this kind of antennas.

5. Conclusion

In this paper the advantages of using multiple director elements were discussed. An improved radiation pattern was obtained in this way, having an increase of the maximum gain of approximately 1.4 dB, 6.8 dBi for the single director element antenna against 8.2 dBi for the antenna with three director elements. Also the input impedance matching was improved having a module of S_{11} parameter of -9.8 dB at the central frequency (f_c = 2.4525 GHz) for the three directors antenna against -7.5 dB for the antenna with a single director. By considering multiple director elements it was also shown that the flexibility in the beam orientation can be duplicated (having twelve beam directions instead of only six). Also it was shown that the use of multiple director elements can be very useful for specific situations as broadcasting where omnidirectional radiation patterns are generally better.

Once the director elements are controlled dynamically by using switches, then a very flexible beamforming scheme is obtained which can improve the performance of a wireless sensor network significantly.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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