High-gain wideband and superdirective electronically-beam-switchable antenna for smart communication objects

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***Abstract*—This paper proposes the design of a high-gain, wideband, directive, and compact circular array composed of 5 symmetrical radiating elements (1 fed and 4 parasitic elements). The possibility to implement an electronically beam-switching capability over the horizontal plane is studied. Thanks to the superdirectivity principle, the proposed closely spaced parasitic antenna array achieves a maximum gain of 10 dBi steered in four directions on the horizontal plane and a minimum gain of 9 dBi in the whole horizontal plane. The proposed antenna achieves a stable gain > 9dBi in the frequency band 758-803 MHz, which is interesting for sub-GHz 5G applications.**

Index Terms—Beam-steering, beam-switching, electrically small antennas, superdirectivity, parasitic arrays.

I. Introduction

The rapid growth of compact and smart connected objects generates a need of increasingly small and performing antennas. Following the fundamental laws of physics [1], antenna miniaturization while conserving sufficient radiation and bandwidth performances is a challenge, especially for frequencies below 1 GHz where the wavelengths are large. In this paper, our interest is focused on the design of a high-gain wideband compact parasitic antenna array with electronically beam-switching capabilities in the horizontal plane. This antenna architecture has been optimized to work in the frequency band 753-803 MHz and offers new perspectives for the future sub-GHz wireless communication systems requiring spatial scanning and high-data rates for new services linked to IoT and 5G applications.

Classically, Electrically Steerable Passive Array Radiators (ESPAR) are used to achieve a directive and steerable radiation pattern on the antenna horizontal plane. ESPAR are designed generally considering circular arrays of parasitic radiating elements with the geometry of electrical compact monopoles over a half wavelength ground plane. The ground plane is often used to connect the electronic circuits to control the beam steering and bring the radiofrequency feeding of the antenna without affecting its radiation properties. Nevertheless, those ESPAR antennas have a maximum gain tilted from the horizontal plane due to the finite size of the ground plane [2]-[4]. Our recent work [5] has shown the opportunity to steer the radiation pattern of 9-elements dipole-like symmetrical ESPAR with a maximum gain in the horizontal plane using a floating ground plane. This particular ground plane, which is decoupled at radiofrequency, does not affect the radiation patterns of the symmetrical antenna and has been used to facilitate the integration of the electronic devices required to control the beam switching. Moreover, both beam steering capability and angular resolution of ESPAR in the literature are often constrained by the number of parasitic elements in the array. In classical architectures, each beam is formed by using a linear end-fire sub-array and the number of beams is equal to the number of parasitic elements. When high-directivity beam are required, this classical technique results in a lower gain in the horizontal plane at the intersection of two adjacent beams, especially for ESPAR with a small number of parasitic elements.

In this paper, a 5-element antenna array with beam-switching capability is optimized in the operation frequency bandwidth 758-803 MHz. The array is composed of 4 parasitic elements disposed in a circular geometry around a central fed element. Superdirectivity principle is used to optimize the complex impedance loads of the parasitic radiating elements strongly coupled to the array fed antenna [6] and to obtain a small-sized and directive radiating system. In the proposed architecture, symmetrical radiating elements are chosen to achieve a directive radiation with a maximum directivity and gain in the horizontal plane. To improve the beam steering resolution and achieve a gain higher than 9 dBi in the whole horizontal plane, the possibility to steer the beam with an angular step of 15° is considered and demonstrated using only four parasitic radiating elements.

The paper is organized as follows. In Section II, the geometry of the elementary radiating element of the array is firstly described, then the 5 elements array. Section III deals with antenna directivity optimization and beam steering capability at a single frequency (800 MHz). Then, in Section IV, an analysis of antenna radiation performances in the frequency bandwidth of interest (758-803 MHz) is performed. Finally, conclusions are drawn in Section V.

II. Description of Antenna Geometry

A. Single element description

The single element of the antenna array is a wideband dipolar wire-plate antenna described in Fig. 1. It consists of symmetrical double crossed elliptical shape metallic plates top loaded by two metallic circular “hats”. In order to lower the height of the antenna, the two “hats” are connected to each other by mean of four shorting wires. The antenna is fed at the center by an ideal balanced port. The two hats have a diameter of 66 mm ($0.18\lambda_0$) and the height of the antenna is 80 mm ($0.21\lambda_0$). Where λ_0 is the wavelength computed at 800 MHz.

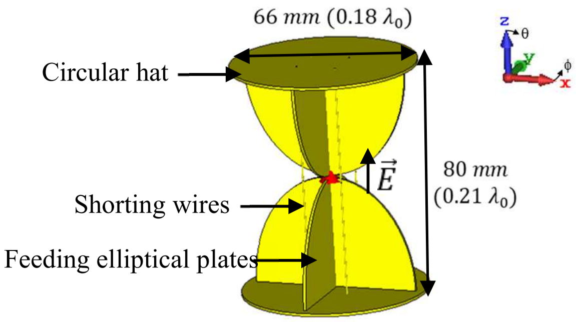

Fig. 1. Single element Dipolar wire-plate antenna.

As shown in Fig. 2-a, the single element antenna achieves a wideband frequency response with -10 dB frequency bandwidth of 27 % in the band 730-962 MHz. The compact antenna has a symmetrical dipolar-shape radiation pattern with a gain of 1.7 dBi and an efficiency close to 100% (Fig. 2-b). As shown in [5], the symmetrical radiation pattern of the single element is important to establish a directive radiation pattern, with a maximum directivity in the horizontal plane when the antenna is combined to other elements in the ESPAR geometry.

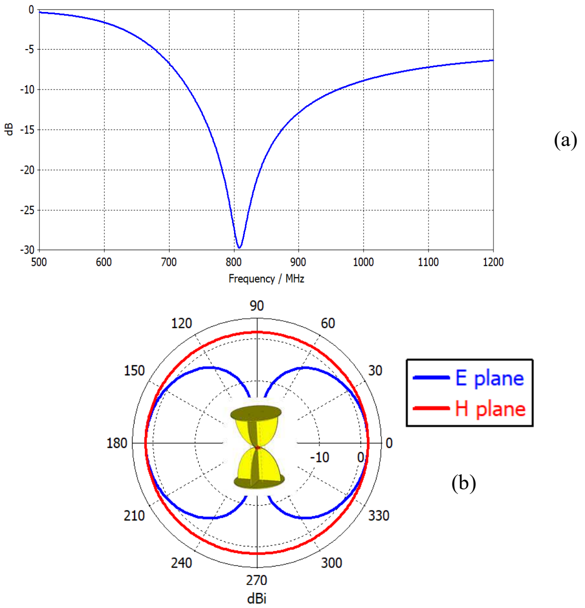

Fig. 2. (a) Frequency response of the single antenna and (b) radiation patterns in E- and H-planes.

B. *Five-element array description*

The wideband single element described previously is used to build the small-size 5-element circular array shown in Fig. 3. The antenna located at the center of the array is the only one fed. The other antennas are parasitic and loaded with optimized complex impedance loads. These loads are computed using the procedure presented [6] to achieve a directive beam in the direction of interest ($\phi = 0°, \theta = 90°$). The parasitic antennas are spaced by 0.2 λ_0 from the central antenna. Two adjacent parasitic antennas are spaced by $0.28\lambda_0$. The designed array is low profile with a height of 80 mm (0.2 λ_0) and a diameter of 216 mm (0.57 λ_0).

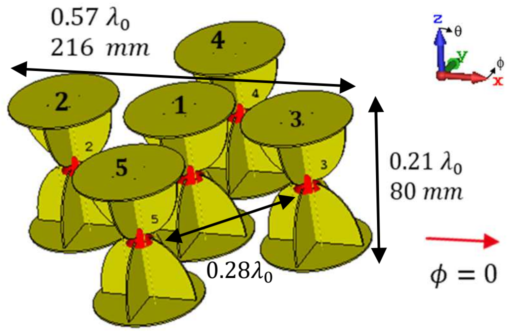

Fig. 3. Schematic view of the 5-element circular array.

III. Directivity Optimization

A. *Spherical wave expansion optimization procedure*

The directivity of the 5-element array has been optimized in the direction $\phi = 0°, \theta = 90°$ using the synthesis procedure based on the spherical wave expansion theory [6]. Main steps of this method are summarized in Fig. 4.

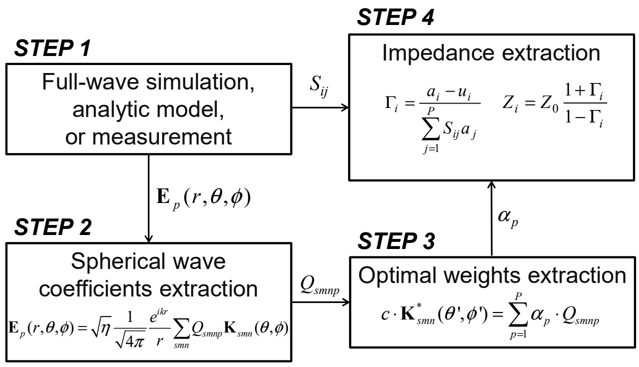

Fig. 4. Main steps of directivity optimization method.

Starting from the active radiation pattern of each element of the array ($\mathbf{E}_p(r,\theta,\varphi)$ in the STEP 1), the spherical wave coefficients are calculated (STEP 2). Then, solving a maximization problem the objective function is defined and a linear system is considered to calculate the optimal complex excitation coefficients associated to the array elements (STEP 3). Finally, using the complete scattering matrix, the equivalent parasitic complex loads are extracted (STEP 4).

B. *Single frequency radiation optimization at 800 MHz*

The directivity of the 5-element array has been optimized in the direction of interest at 800 MHz. The 3D radiation pattern and the associated optimized impedance loads computed with the procedure presented in the previous section are shown respectively in Fig. 5 and Table 1. A maximum directivity of 10 dBi and a maximum gain of 9.8 dBi are achieved in the end-fire direction with a half beam width of 67°.

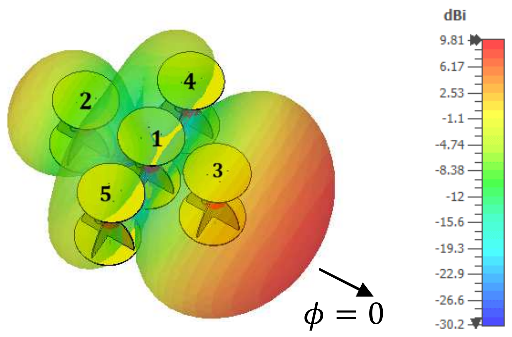

Fig. 5. 3D gain pattern optimized in the direction $\phi = 0°, \theta = 90°$.

We notice in Table 1 that the optimal load connected at the port 2 has a negative resistor, needed to enforce antenna's radiation in the optimized direction. Replacing this negative equivalent resistor by a 0 Ω resistor has a very slight effect. The beam is still shaped in the direction of interest with a drop of less than 0.1 dB on the gain and directivity, since the antenna array is not as sensitive (electrical distance of 0.28 λ_0 between two adjacent parasitic antennas). Optimal loads connected to the ports 4 and 5 are almost equal as the antenna geometry is symmetric. The difference is mainly due to computational error.

TABLE 1: OPTIMIZED LOADS FOR A MAXIMUM DIRECTIVITY AT 800 MHZ

Z	*R (Ω)*	*C/L*
Port 1	50	-
Port 2	-2.7	2 nH
Port 3	3.8	40.5 pF
Port 4	53	7.8 nH
Port 5	52	7.6 nH

Thanks to antenna symmetry, the same optimal set of loads can be used in permutations in order to achieve the optimized gain of 9.8 dBi in four different directions of the horizontal plane as shown in Fig. 6. Nevertheless, the antenna gain drops at 5 dBi at the intersection of two different beams in the horizontal plane. The classical method to avoid this significant drop is to increase the number of parasitic antennas of the array, which leads to increase the size of the ESPAR antenna. In the next paragraph, we propose another approach to solve this issue.

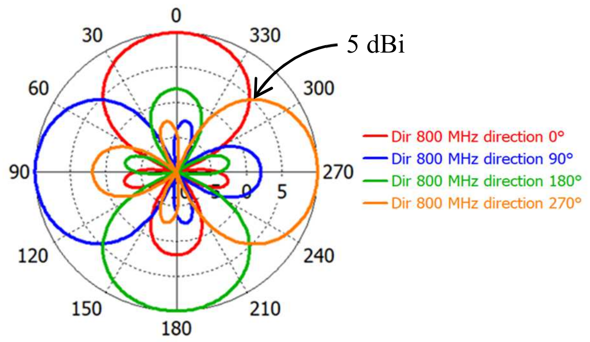

Fig. 6. Optimal gain pattern steered in 4 directions of the horizontal plane.

C. Beam switching capability improvement in the horizontal plane

In order to keep a sufficient gain in the whole horizontal plane, we propose to increase the number of optimization angles. Typically, using four different sets of loads leads to optimize antenna's directivity and gain with a step angle of 15° compared to 90° with one set of loads. This method leads to reduce significantly the drop of gain, and to guarantee a minimum gain of 9 dBi in the whole plane. The gain patterns are plotted in polar coordinates from ϕ =0° to ϕ =90° with a step of 15° in Fig. 7. As mentioned in the previous paragraph, the permutation of the four sets of loads computed at the directions 0°, 15°, 30° and 45° will lead to cover the entire horizontal plane, as the antenna geometry is symmetric.

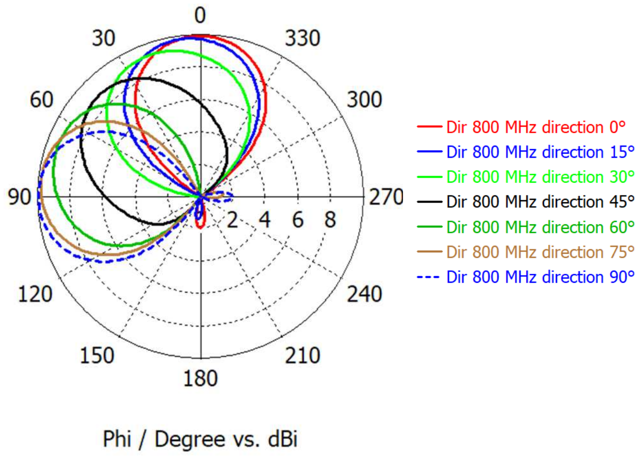

Fig. 7. Gain drop improvement in the horizontal plane with beam switching capability.

IV. WIDEBAND DIRECTIVITY OPTIMIZATION (758-803 MHZ)

In the previous section, a single frequency optimization at 800 MHz has been performed on the 5-element array. In this section, the same optimization method is applied with a step of 1 MHz from 758 MHz to 803 MHz to maximize antenna's directivity in the end-fire direction ($\phi = 0°, \theta = 90°$). Real and imaginary parts of the frequency dependent optimal impedance loads are respectively plotted in Fig.8-a and Fig.8-b.

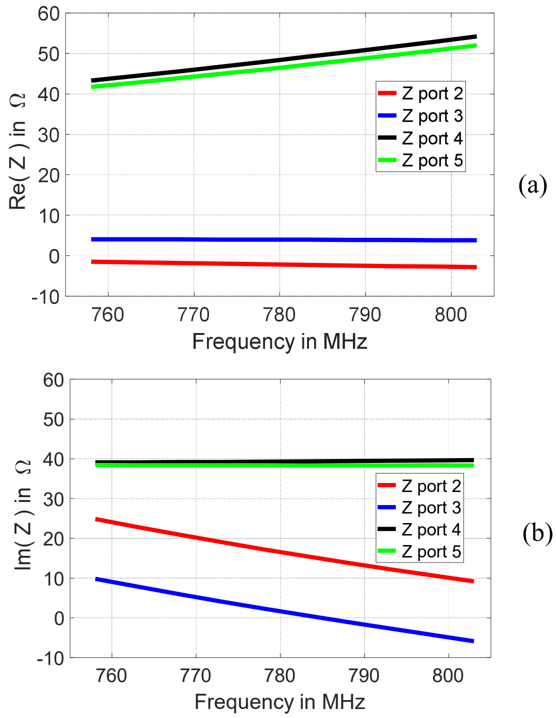

Fig. 8. (a) Real part and (b) imaginary part of the frequency dependent optimal impedance loads.

Considering the real part of the impedance (Fig.8-a), we notice that a quite flat negative equivalent resistor about -3 Ω is expected on port 2 to achieve the maximum directivity in the direction of interest. This kind of resistor can be achieved with an active circuit and have to be carefully designed in order to avoid instabilities in antenna system [7]. The other equivalent resistors are positive and those of port 4 and 5 are very close as the antenna is symmetric. If we look at the imaginary parts of the optimal loads, we observe a particular behavior. Typically, at port 2 and 3, the imaginary part is decreasing with frequency. This means that two Non-Foster equivalent capacitances are required to achieve a broadband Superdirective antenna [8].

Antenna directivity and gain optimized in end-fire direction following the superdirectivity principle are plotted against frequency in Fig.9.

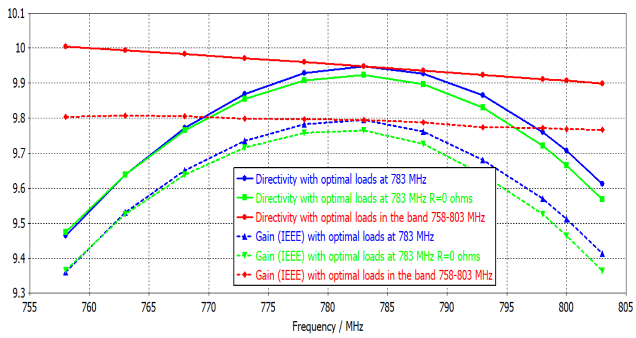

Fig. 9. 5-element array directivity and gain in the band 758-803 MHz.

The red curves correspond to radiation properties of the antenna loaded with the broadband optimal impedances shown in Fig.8. In this case, directivity and gain are almost flat in the band of interest and they are respectively close to 10 dBi and 9.8 dBi. The blue curves correspond to the case where the parasitic antennas are loaded with the optimal impedance computed at the central frequency of the considered frequency band 783MHz (Table 2). In this case, the antenna array achieves the maximum directivity and gain at 783 MHz and a drop of less than 1 dB is observed on the rest of the band. Finally, the green curves represent the case where the antenna is loaded with the optimal impedance computed at 783 MHz and the negative equivalent resistor is enforced to 0 Ω . We clearly observe that the negative resistor is not mandatory to achieve a gain higher than 9 dBi in our frequency band of interest. Meaning that the antenna array is not as sensitive, since the elements of the array are not so close ($0.2\lambda_0$).

TABLE 2: OPTIMIZED LOADS FOR A MAXIMUM DIRECTIVITY AT 783 MHZ

Z	*R (Ω)*	*C/L*
Port 1	50	-
Port 2	-2.2	3.1 nH
Port 3	4	0.1 nH
Port 4	49	8 nH
Port 5	47	7.8 nH

V. CONCLUSION

This work has proposed the design of a high gain wideband compact and directive antenna with beam switching capability for subGHz IoT and 5G applications. The use of balanced antennas with a controlled radiation pattern led us to consider the super directivity principle to achieve both small size and directive antenna with a low profile ($\lambda_0/5$ x $\lambda_0/2$). An approach consisting in increasing the number of optimization angles rather than the number of antennas in the array led us to reduce the drop of gain while switching the radiation pattern of a 5-element ESPAR in the horizontal plane without changing antenna geometry. Thanks to the symmetry of antenna architecture, a gain greater than 9 dBi is obtained over the entire horizontal plane using only four different sets of optimal loads (24 beams of 15° resolution). Finally, an analysis of the optimized radiation properties of the antenna array in the frequency band 758-803 MHz has shown a tradeoff between antenna properties and the complexity of the frequency dependent loads. Thanks to the low sensitivity of the antenna, a gain greater than 9 dBi can be achieved in the frequency band of interest with simple discrete component loads.

ACKNOWLEDGMENT

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