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Design and synthesis of the radiation pattern of the linear antenna arrays with parasitic monopole elements using a Dolph-Tchebychev method

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ABSTRACT : *The objective of this article is the synthesis of the radiation pattern of a linear antenna arrays with parasitic elements, where the radiated elements are monopoles. The developed method of synthesis is based on the method of Dolph-Chebyshev. This allows us to determine the values of the reactive loads to connect to the parasitic elements so that the spatial distribution of the radiated power by the array satisfies the constraints which we set. The obtained results using a CST microwave studio are compared with the same array but with nonuniform feed. It is shown that the implementation using an effective technique of synthesis allows access to the levels of performances close to the antenna arrays with nonuniform feed.*

KEYWORDS: *Antenna arrays, parasitic elements, radiation pattern*

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I. INTRODUCTION

With the fast development of wireless technology rising the demand for communication capacity, strict requirements have been raised and attached to the modern wireless communication system. As one of the most important components, antennas in the wireless communication systems are desired not only to integrate multifunction but also to have a low size to save space and cost [1, 2]. Specifically, to cope with the ever-increasing demand for capacity, a high-gain intelligent antenna array is always expected. This array is capable of steering its beam toward desired directions while simultaneously placing nulls toward undesired directions of interference, thereby enhancing the signal-to-noise ratio of the desired signal [1].

Many emerging radio technologies require a significant effort on antenna miniaturization while keeping an acceptable performance in terms of bandwidth, directivity, and efficiency. Such technologies are the Internet of Things (IoT), wireless sensors, Wireless Power Transfer (WPT), and low-power wireless communications. The effect of the antenna gain (efficiency and directivity) on far-field Power Transfer Efficiency (PTE) can be easily seen from the Friis transmission formula. Furthermore, it is demonstrated that using directive antennas also improves the PTE in the near-field region [3].

Switched beam arrays can give higher gain than single elements and can be used to improve the performance of small communication base stations and terminals. In addition, the Body Area Network (BAN) using communication channels between two body-mounted antennas can also benefit. In [4], the path gain of the antennas for two-body channels has been established, and the optimum antenna type was found to be a monopole antenna for these channels. In this on-body or other terminal and base station applications, beam switching can be used to increase gain and hence reduce link loss and battery consumption, or to reduce interference or multipath. The disk-loaded monopole antenna has the advantage that the height of the monopole antenna can be reduced significantly whilst still giving approximately the same performance as described in [4, 5].

Multielement antennas are widely used for years in wireless communications because of their potentialities in terms of high gain beam scanning and complex beam shaping. Most applications of radiating arrays concern very large panels (more than 20 wavelength sides) with several hundreds or thousands of elements because they are often dedicated to specific applications in the field of space or military missions. The high number of elements allows a high beam scan resolution for radar [6, 7] or a well-defined contour to optimize Equivalent Isotropic Radiated Power (EIRP) for beam shaping [6, 8].

Nevertheless, the need for moderate-size multielement antennas is growing because of the fast evolution of the consumer telecommunication market. To obtain a high data rate, an antenna gain increase is required. Moreover, as the devices including radiating elements must face a constant service evolution, multielement antennas with reconfiguration capabilities and the moderate gain would be of great interest to perpetuate telecommunications infrastructure for both end-users and operators (between 10-20 dB for a directive pattern).

Regardless of the multielement antenna size, one of the main difficulties to tackle consists in reaching the highest efficiency for the design and avoiding some phenomena like scan blindness, especially while couplings are strongly impacting the performances. Furthermore, electromagnetic performance optimization is a critical point to reduce the antenna cost, especially in the case of consumer applications.

Antennas with parasitic elements have been considered for years in the literature because they can be used for several applications where a trade-off between overall volume, cost, and performances is needed, as for consumer products. They are often a good opportunity to obtain a specific and fixed radiation objective, i.e., gain, polarization, radiation bandwidth, without introducing feed networks in the design as in a classical array [9-11]. They can be used to perform electronic beam steering with only one excited element with parasitic radiators including tunable reactive loads. Such a solution avoids the high cost and complexity related to a beamforming network and has especially been studied for multiple-input multiple-output (MIMO) systems [9, 12].

In this article, we propose the determinist method for designing linear antenna arrays with parasitic monopole elements. This proposed method, called Dolph-Tchebyshev method, allows us to minimize the level of the secondary lobes of the radiation pattern in the antenna arrays with parasitic elements.

The rest of the paper is organized as follows: Section II presents the geometry of the structure, the flow chart of the synthesis method is presented in section III, numerical results and discussion are given in section IV. Finally, section V provides the conclusion.

II. GEOMETRY OF THE STRUCTURE

The geometry of the antenna arrays with parasitic elements is shown in Figure 1. The array is consisted of fourteen parasitic elements and fifteen identical monopoles with the same length. Monopoles are quarter-wavelength copper wire antennas with radius $a = 0{,}691\, mm$, arranged in parallel and in a lateral coupling configuration on a mass layout of rectangular shape copper. The active element, connected to a source RF (RF port) of the tension V_0, is located at the position (0, 0) which is the center of the plan of mass. In the meantime, the parasitic elements (antenna's number from 1 to 14) are not fed, but is connected to reactive loads jx_i. The positions $(0, y_i)$ of parasitic elements are:

$$y_i = \begin{cases} (7-i)d_y & 8 \le i \le 14 \\ (8-i)d_y & 1 \le i \le 7. \end{cases}$$

The current $I_{i\epsilon N}$, which circulates in each elementary antenna of the arrays, induces the currents in all the others.

The antenna with parasitic elements is modeled by a matrix of impedance $[Z]$ of admittance $[Y]$ or coupling $[S]$ made up of the mutual impedances Z_{ij} and self-impedances Z_{ii} or the parameters of coupling S_{ij}, where $(i, j) \in N \times N$.

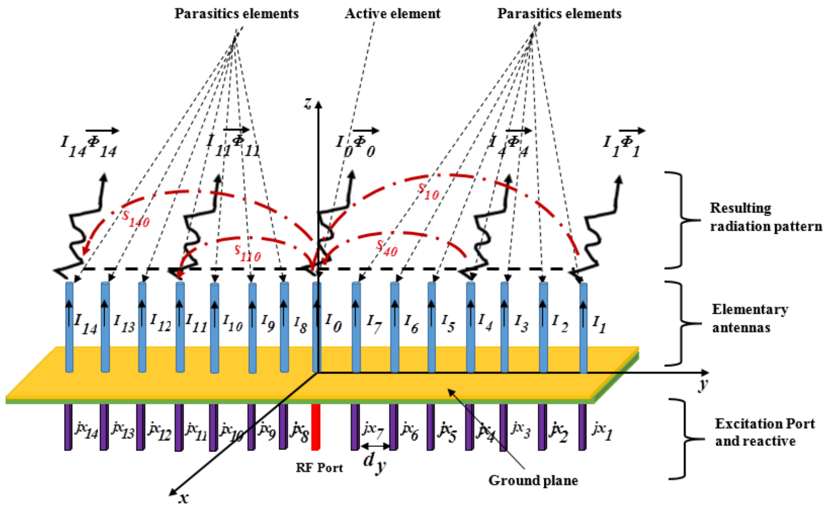

Figure 1. Geometry of the linear monopole array.

III. SYNTHESIS PROBLEM

The resolution of the problem of synthesis consists in finding the set of reactive loads jx_i which would help to carry out a radiation pattern diagram. The radiation pattern diagram of the antenna arrays $F(\theta,\varphi)$ in the angular direction (θ,φ), is the linear combination of all the contributions of n elementary diagrams $(\vec{\phi}_i)$ balanced of the weights I_i.

$$F(\theta,\varphi) = f(\theta,\varphi)\sum_{i=0}^{14} I_i e^{j(kd_y sin\theta cos\varphi)}, \quad (1)$$

where $f(\theta,\varphi\,)$ is the radiation pattern of an element and $(\theta,\varphi\,)$ is the observed angular direction.

$$\underline{I} = Y\underline{V}, \quad (2)$$

where $\underline{V} = [0\ldots0\ \ V_0\ \ 0\ldots0]^T - X\underline{I}$ is the vector of excitations, $X = diag[Z_0\ \ jx_1 \ldots\ldots\ldots\ldots jx_{14}]$, $Z_0 = 50\,\Omega$ and $\underline{I} = [I_0\ \ I_1 \ldots\ldots\ldots\ldots I_{14}]^T$.

The determination of these reactive functions jx_i can be obtained from an algorithm of synthesis compared to the objectives of predefined radiations. Thus, we deduce the values from inductances L_i and capacities C_i to be connected to the parasitic elements according to the relations:

$$L_i = \frac{jx_i}{\omega} \text{ and } C_i = -\frac{1}{jx_i\omega},$$

where $\omega = 2\pi f_0$ and $f_0 = 2.5\ GHz$.

III. FLOW CHART OF THE SYNTHESIS METHOD

Figure 2 presents the flow chart of the method of synthesis developed for the antenna arrays with parasitic elements. It summarizes the various stages of the method of synthesis. The first stage consists of carrying out a multiport analysis of the antenna by a successive excitation of all the elements in order to extract the matrix from coupling $[S]$ and the elementary radiations diagrams given in the real environment. Then a gauge of radiation is defined by the values of desired directivities. These data are then injected as parameters of entry in a solvor developed under the Matlab environment. It provides the complex weights associated with the reactive functions to be connected to the parasitic elements, and then calculates the resulting radiation pattern diagram associated with the configuration. A stage of checking can be carried out to validate the synthesis. This stage consists of introducing the reactive loads on the ports of the structure simulated within the simulator, a full-wave CST-MWS.

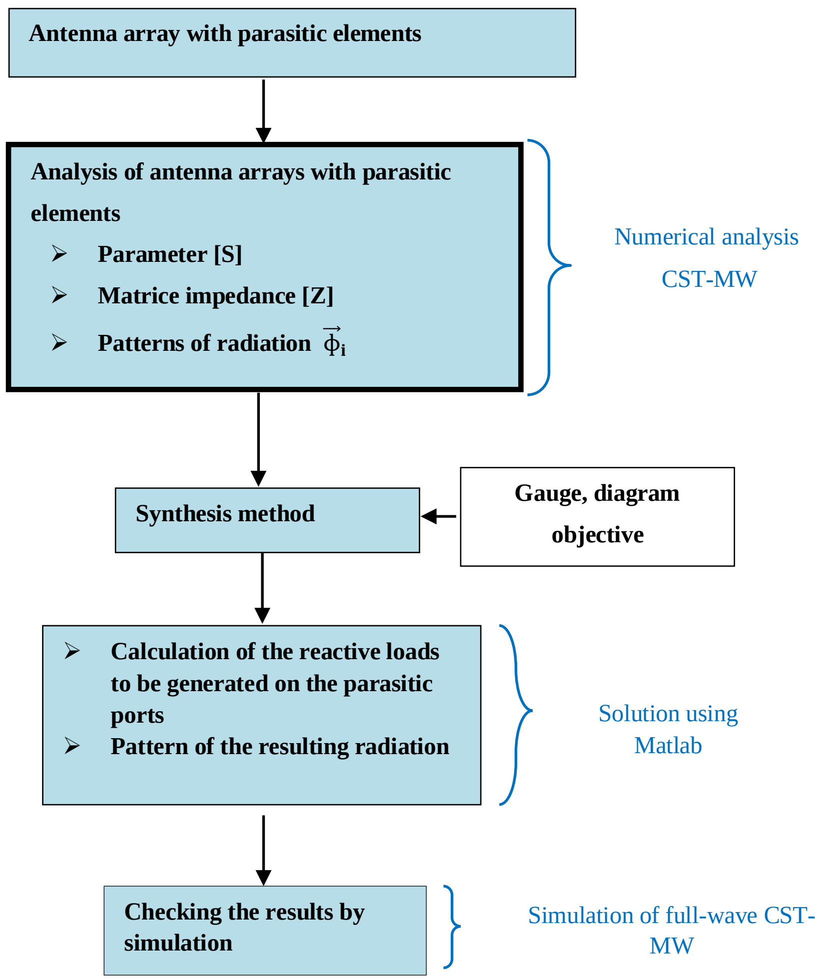

Figure 2. Flow chart of the developed synthesis method.

Elements	Ray of elements (mm)	Length of elements (mm)	Position of array elements: $d_y = 0.4\lambda$
#0	0.691	27.8	$(0, 0)$
#i	0.691	27.8	$\left(0, y_i = \begin{cases} (7-i)d_y & 8 \le i \le 14 \\ (8-i)d_y & 1 \le i \le 7 \end{cases}\right)$
❖ Plan of mass			
Name	Relative permittivity	Relative Permeability	Dimension
Copper	1	0.9999	$400 \times 25 \times 0.035 mm^3$
❖ Substrate			
Name	Relative permittivity	Relative Permeability	Dimension
FR-4 epoxy	4.3	1	$400 \times 25 \times 1.6 mm^3$

Table 1. The geometrical and radioelectric data of the designed array in CST-MW at the work frequency $f = 2.5\ GHz$.

IV. NUMERICAL RESULTS AND DISCUSSION

Using a CST microwave studio, we obtain the geometrical and radioelectric data of the designed array. The excitation of the elements is made using discrete ports and the distance of the inter-elements is fixed by $d_y = 0.4\lambda$ to support the coupling [13]. Here, the parameter SSL_{max} , which is the maximum relationship of the level between the main lobe and the secondary lobe, is fixed at 5 dB. Table 1 presents the geometrical and radioelectric data of the designed array at the work frequency $f = 2.5\ GHz$. It shows the followings: (1) the rays and the lengths of the elementary elements including their various positions in the array, and (2) the dimensions, the permeability, the permittivity of the plan of mass and the FR-4 epoxy substrate.

Table 2 gives the weighting coefficients (excitations) for the array with nonuniform feed and the reactive loads for the array with parasitic elements, obtained by the Chebyshev method. The reactive functions are translated by values of inductances or capacities, presented in the two last columns of the same table.

Element #i	Linear antenna arrays with nonuniform feed : $d_y = 0.4\lambda$	Linear antenna arrays with parasitic elements : $d_y = 0.4\lambda$		
	Excitations with Dolph-Chebyshev method $d_y = 0.4\lambda, \varphi = 90^0, SSL_{max} = 5\ dB, N = 15$	Reactive loads with Dolph-Chebyshev method $d_y = 0.4\lambda, \varphi = 90^0, SSL_{max} = 5\ dB, N = 15$		
	Values of excitation a_i in volt	jx_i	Inductance L_i in nH	Capacity C_i in pF
#0	0.1116	Active element: $V_0 = 1\ V$, $Z_g = 31.698732 - j0.20836738\ \Omega$		
#1	1.0000		///	24.219
#2	0.0987		///	22.589
#3	0.1025		///	23.921
#4	0.1057		///	23.696
#5	0.1083		///	23.332
#6	0.1101		///	23.623
#7	0.1112		2.10	///
#8	0.1112		2.10	///
#9	0.1101		///	23.623
#10	0.1083		///	23.332
#11	0.1057		///	23.696
#12	0.1025		///	23.9221
#13	0.0987		///	22.589
#14	1.0000		///	24.219

Table 2. Excitations of the antenna's elements array with nonuniform feed and reactive loads of the elements of the array with parasitic elements using a Dolph-Tchebyshev method. Parameters used are $d_y = 0.4\lambda,\ \varphi = 90^0$, $SSL_{max} = 5\ dB,\ N = 15$, and $f = 2.5\ GHz$.

Figure 3 presents the coefficient of reflection of an antenna array with the parasitic elements where the port of the active element is surrounded by 14 monopoles which are connected to the active loads. We note that the coefficient of reflection obtained by the synthesis at the frequency f=2.5 GHz is -31.1382 dB with a bandwidth of 278.17 MHz ranging from 2.3609 to 2.6391 GHz. This shows that the designed antenna is well adapted for an impedance $Z_g = 31.698732 - j0.20836738\ \Omega$.

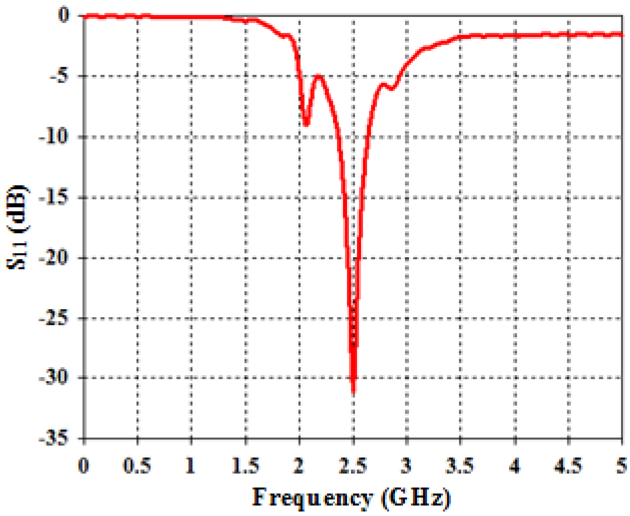

Figure 3. Coefficient of reflection of an antenna array with parasitic elements.

Figure 4 presents the radiation pattern of the linear antenna arrays at 15 radiated elements with nonuniform feed in polar coordinates by using the Dolph-Chebyshev method. It is seen that this radiation pattern exists within the limits imposed with a difference between the level of the secondary lobes and the main lobe of 4.5786 dB for an aperture of 6.1 degrees.

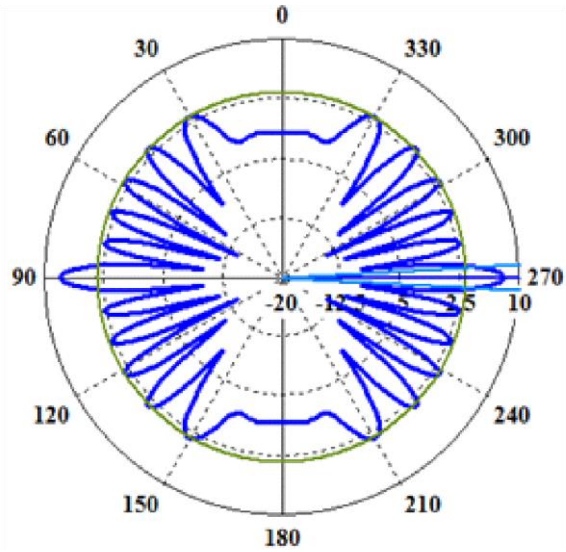

Figure 4. Radiation pattern of the linear antenna arrays at 15 radiated elements with nonuniform feed in polar coordinates by using the Dolph-Chebyshev method. Parameters used are $d_y = 0.4\lambda,\ SSL_{max} = 5\ dB,$ and $\varphi = 90^0$.

We present the radiation pattern of the linear antenna arrays at 15 radiated elements with one active element and 14 parasitic elements connected to reactive loads in polar coordinates in Fig. 5 using the method of Dolph-Tchebyshev. As shown in the figure, the radiation pattern exists within the limits imposed with a difference between the level of the secondary lobes and the main lobe of 4.894 dB for an aperture of 63.9 degrees.

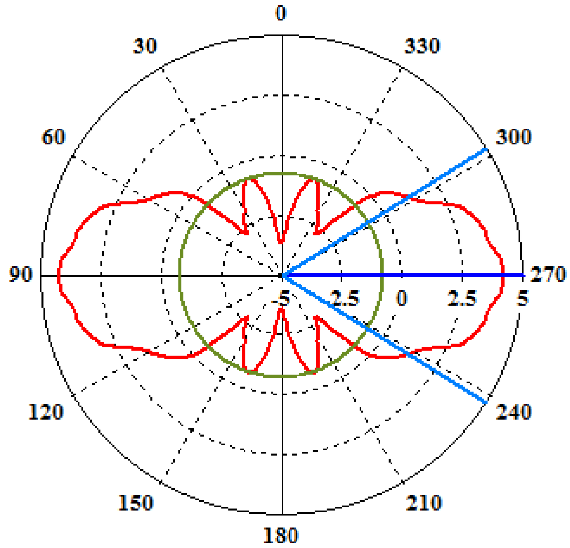

Figure 5. Radiation pattern of the linear antenna arrays at 15 elements with 14 parasitic elements in polar coordinates by using the Dolph-Chebyshev method. Parameters used are $d_y = 0.4\lambda$, $SSL_{max} = 5\ dB$, and $\varphi = 90^0$.

Table 3 presents a comparison of the radiation characteristics of the array with uniform feed and the array with parasitic elements synthesized by the method of Dolph-Chebyshev. We note here that the synthesis of the linear antenna arrays (with nonuniform feed or parasitic elements) by the method of Dolph-Tchebyshev allows to strongly reduce the maximum level of secondary lobes. The opening of the main lobe of an array with parasitic elements is broader than that of an array with nonuniform feed which presents several secondary lobes and a higher gain.

	linear antenna arrays with nonuniform feed	linear antenna arrays with parasitic elements
SSL_{max} (dB)	4,5786	4,894
Gain (dB)	7,93	4,18
Angle of aperture	6,1°	63,9°
Direction of the main lobe	90°	90°

Table 3. Comparison of the radiation characteristics of the array with nonuniform feed and the array with parasitic elements synthesized by the Dolph-Tchebyshev method.

V. CONCLUSION

In summary, we have studied the radiation characteristics of antennas array with parasitic elements using the Dolph-Chebyshev method. Specifically, the coefficient of reflection and the radiation patterns are simulated. We have compared the obtained results with the antenna array of nonuniform feed. We have shown that by feeding only one port in the antennas array, we can control the level of the secondary lobes by integrating the reactive loads into the ports of the parasitic elements. Thus, an antenna with parasitic elements is a possible solution for the strong consumption of energy that the antenna arrays with nonuniform feed produce.

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