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Synthesis of Antenna Arrays with Parasitic Elements for Interference Rejection using a LMS Method

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***Abstract:** The objective of this paper is to design a parasitic antenna array capable of rejecting interfering signals and directing its main lobe towards the wanted signal. The designed antenna is a linear array consisting of an active monopole and fourteen parasitic monopoles. The method used is LMS, making it possible to calculate the values of the reactive loads to be connected to the ports of the parasitic elements so that the radiation patterns satisfies the fixed constraints. The simulation results in CST-MWS (Computer Simulation Tool Microwave Studio software) of the radiation patterns show an energy level of less than -0.71 dB in the direction of the interference and a gain greater than 5 dB in the direction of the wanted signal. Thus, this technique will make it possible to design directional antennas, with low energy consumption and interference rejection.*

***Keywords:** Antenna Arrays, Parasitic Elements, Synthesis, Radiation Pattern, CST-MWS, LMS*

I. INTRODUCTION

The field of telecommunications has been experiencing unprecedented growth for several decades, and various services are offered by many wireless communication operators [1]. This has considerably increased the number of users, and consequently, a reduction in the capacity of the telecommunication network due to the increase in the number of interferers [2]. New telecommunications systems must be able to include a large number of functionalities to meet needs, to make several standards coexist on the same antenna, to reduce interference with other users, to improve transmission throughput, to avoid fading phenomena, to ensure better efficiency in signal reception [3].

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In this context, the antennas will be strongly solicited for the formation of directional [4, 5] and reconfigurable [6] beams. To obtain these directional beams, the most widespread solutions, independently of reflector antennas, are those based on phased antenna arrays [7]. Their principle is based on the use of phase shifters which adjust the amplitude and argument of the supply current of each element in order to obtain an antenna capable of adapting to changing environmental conditions by adjusting their radiation characteristic [8]. The synthesis problem consists in determining the currents likely to radiate, at a great distance, a field having certain properties given in advance. Given the variety of problems that can arise, it is deduced that there is not a general method of synthesis applicable to all cases; but on the contrary a large number of specific methods grouped into two main classes, namely: analytical methods such as Fourier [9], Woodward-Lawson [10], Dolph-Tchebycheff [11], Schelkunoff [12] ….etc. and stochastic methods such as Root-MUSIC [13], genetic algorithm [14], neural networks [15], LMS (stochastic gradient algorithm) [16] etc. Nevertheless, one of the major problems with these systems (phased antenna arrays) lies in the large number of elements required, naturally leading to high energy consumption, a complex beamforming circuit, and a cost that seems prohibitive for applications not affecting the aeronautics, space or military sectors [17]. To propose alternatives to these identified locks, the scientific community [18-20] has for several years shown great interest in antenna solutions derived from phased arrays, namely, antenna arrays with parasitic elements [21]. Antenna arrays with parasitic elements have been the subject of numerous publications [22-24] and are usually integrated into consumer communication systems. They make it possible to obtain an optimized radiation pattern [23, 25]. They can be used to perform electronic beam steering with a single excited element and parasitic elements with tunable reactive loads [26, 27]. Most of the work in the literature [28, 29] has focused on the use of phased arrays for directional beamforming and interference rejection. The rapid development of mobile telecommunications in recent years requires communicating systems that are less bulky and have low energy consumption. Hence the use of the antenna array with parasitic elements [21], the use of which for the formation of directional beams and the rejection of interference remains a major challenge, especially since only one element is powered and the others are powered by coupling effect.

It is in this perspective that the present study was conducted and aims at the design of an antenna having a radiation pattern with holes (minimum energy) in the direction of interference and a main lobe directed towards the useful signal. In this paper, we use the stochastic synthesis method based on the LMS algorithm for the synthesis of a linear array of parasitic element antennas; very efficient method for the synthesis of phased antenna arrays [30-32]. This method makes it possible to obtain a radiation diagram with a main lobe oriented towards the direction of the useful signal and to minimize the level of the side lobes in the direction of interference, by simultaneous action on the reactive loads jx_i connected to the ports of the parasitic elements.

II. MATERIALS AND METHODS

1.1. Material and geometry of the parasitic array

The antenna designed is a linear array **(figure 1)** consisting of a ground plane, a central element (active monopole) connected the RF port and fourteen unpowered monopole (parasitic elements) and connected to the reactive loads jx_i. These parasitic elements located on either side of the central element, are fed by mutual coupling effect and occupy the positions $(0, y_i)$ such as:

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

The ground plane is made of copper of dimension $400 \times 25 \times 0.35\ mm^3$, of relative permeability 0.9999. It is placed on an FR4-Epoxy substrate of relative permittivity 4.4. The spacing between the monopoles of length 27.8mm and radius 0.691mm is 0.4λ (λ is the wavelength). The current $I_{i \in N}$ which flows in each monopole induces currents in the others fed or not. The designed parasitic array is modeled by the parameter $[S]$, the admittance matrix $[S]$ $[Y]$ or the impedance matrix $[Z]$

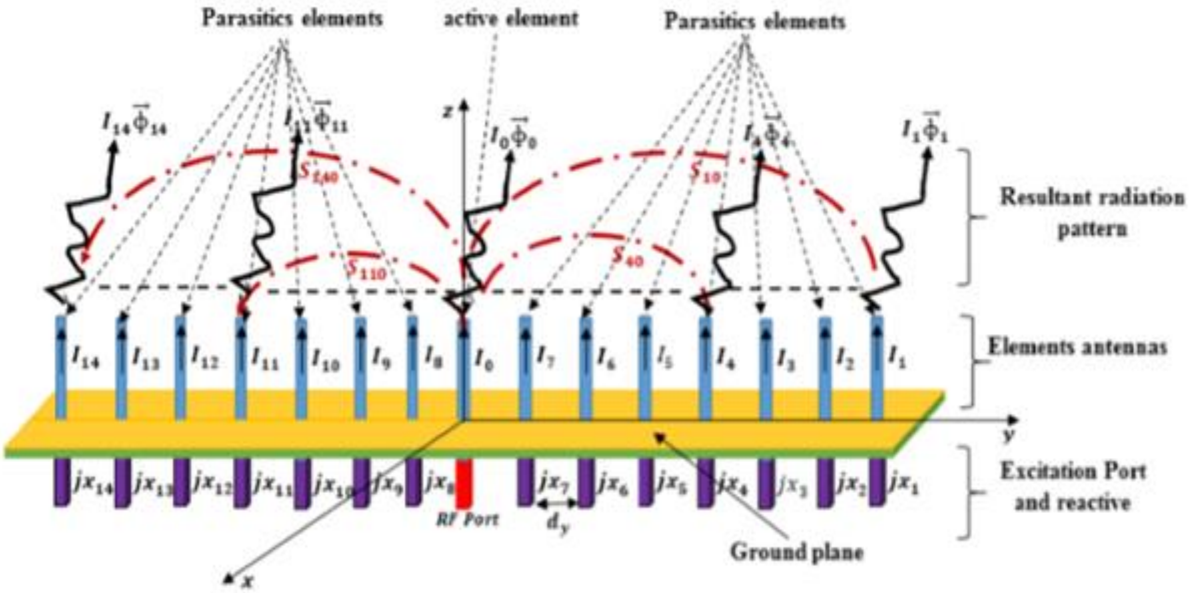

Figure 1: Geometry of the Parasitic Array

2-1. Synthesis Method

The resolution of the synthesis problem consists in finding the set of reactive loads allowing to have a radiation pattern having holes in the direction of the interferences and a main lobe directed towards the useful signal. The resulting radiation pattern $\Phi(\theta,\varphi)$ is the algebraic sum of all the weighted elementary radiation patterns $\vec{\Phi}i(\theta,\varphi)$ by currents I_i

$$\Phi(\theta,\varphi) = \vec{\Phi}i(\theta,\varphi) \sum_{i=0}^{14} I_i e^{j(ikd_y \sin\theta\cos\varphi} \qquad (1)$$

(θ,φ) is the observed angular direction and $k = \frac{2\pi}{\lambda}$ is the wave number

$$I = YV \qquad (2)$$

$V = [0...0 \quad V_0 \quad 0...0]^T - XI$ is the excitation vector,

$X = diag[Z_0 \quad jx_1 \quad ...... \quad jx_{14}]$, $Z_0 = 50\Omega$ and

$I = [I_0 \quad I_1 \quad ... \quad I_{14}]^T$

An appropriate synthesis algorithm will make it possible to determine the values of jx_i and by deduction those of the inductors L_i and the capacitors C_i to be connected to the parasitic elements according to the relations:

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$$L_i = \frac{jx_i}{\omega} \quad and \quad C_i = -\frac{1}{jx_i\omega} \tag{3}$$

$$\omega = 2 * pi * f_0 \quad \text{and} \quad f_0 = 2.4GHz$$

Figure 2 is a flowchart summarizing the different steps of the developed LMS synthesis method. The first step consists in the extraction of the input parameters (impedance matrix, elementary radiation diagrams, coupling matrix) by an analysis of the antenna array. For this, the antenna is modeled with the CST MWS software. The second step consists in injecting these data as input parameters of the synthesis tool developed under the matlab environment, to satisfy a radiation objective. The synthesis tool provides the reactive loads to be connected to the parasitic elements and the resulting radiation diagram. A verification step can be performed to validate the synthesis. This phase consists of inserting the inductors and capacitors at the ports of the simulated structure.

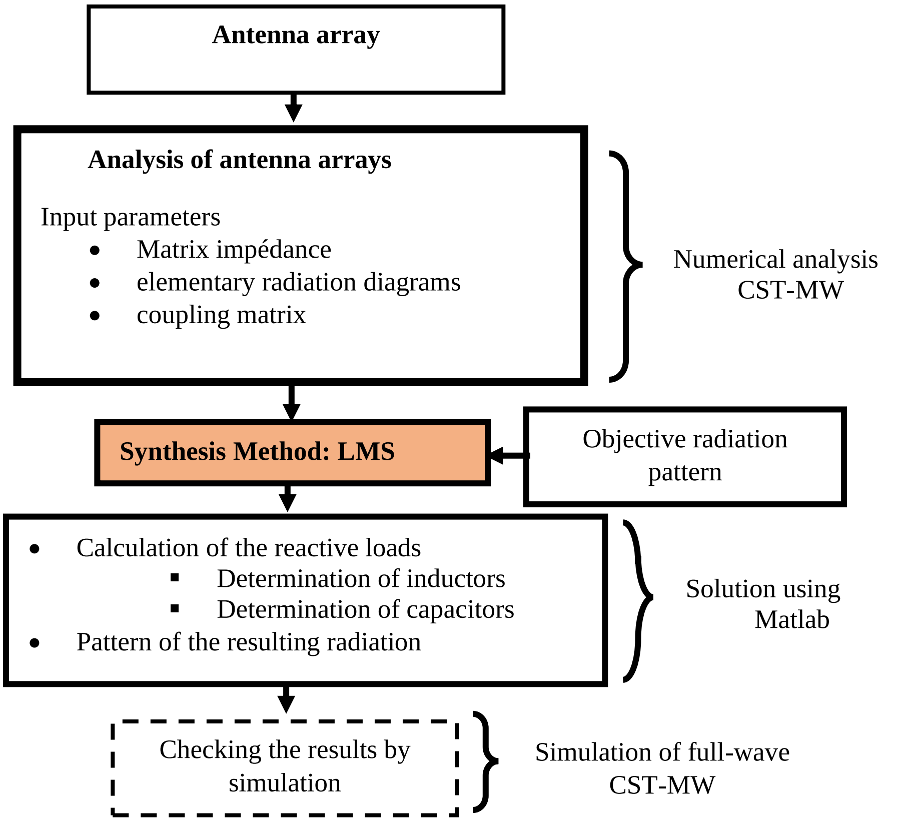

Figure 2. Flow chart of the developed LMS synthesis method method.

The LMS algorithm developed by Widrow and Hoffest based on the gradient method calculates and updates the weights recursively. The optimal weights $w(n+1)$ at time n + 1 are calculated according to the recurrence relation (4) such that they minimize the root mean square error between the antenna output and the reference signal $d(n)$ [27].

$$w(n+1) = w(n) + \mu x(n)e(n) \tag{4}$$

$$y(n) = w^T(n)x(n) \tag{5}$$

$$e(n) = d(n) - y(n) \tag{6}$$

Where μ the adaptation is step $x(n)$ and is the input signal vector

III. RESULTATS

Using the CST MW software, we obtain the geometric and radio data of the designed network. The excitation of the elements was done using discrete ports and the inter-element distance is par to favor the coupling [28, 29]. The simulation was done in the considerations where the network receives three narrowband signals of 2.5GHz frequency, a useful signal and two interfering signals. Incoming signal power is 20dBw and 10dBw respectively for wanted and interference signals. The direction of incidence of the useful signal is denoted S_utile while those of the interferers are Interf_1 and Interf_2. We are interested in two synthesis scenarios: scenario 1 (S _ useful = 35°; Interf _1 = 0° Interf _ 2 = 60°) and scenario 2 (S _ useful = 62°; Interf _1 = 15° Interf _ 2 = 120°). For each of these scenarios, $\mu = 0.002$ [30]. Table 2 gives the weighting coefficients (excitations) for the phased network considered as the reference network and the reactive loads for the network with parasitic elements, obtained by the LMS method. The values of the inductances/capacitances are deduced from the reactive functions and presented in the same table.

Table 2: Excitations synthesized by LMS of the phased array and the parasitic array for scenarios 1 and 2: scenario 1: S _ useful = 35°, Interf _1 = 0°, Interf _ 2 = 60° and scenario 2: S _ useful = 62°, Interf _1 = 15°, Interf _ 2 = 120°

	Phased array					**Parasitic array**					
	S _ useful = 35° *Interf _1* = 0° *Interf _ 2* = 60°		*S _ useful* = 62 *Interf _1* = 15 *Interf _ 2* = 120		/	*S _ useful* = 35° *Interf _1* = 0° *Interf _ 2* = 60°			*S _ useful* = 62 *Interf _1* = 15 *Interf _ 2* = 120		
	μ = 0.05		μ = 0.05		/	μ = 0.05			μ = 0.05		
	weighting w_i		weighting w_i		/	reactive loads			reactive loads		
#i	Amplitude (mv)	Phase (degree)	Amplitude (mv)	Phase (degree)	/	jx_i	$c_i\,(pF)$	$L_i\,(nH)$	jx_i	$c_i\,(pF)$	$L_i\,(nH)$
1	0.1718	19.0522	0.170	-52.8344	/	202.93	0.3137		30.3152	2.1	/
2	0.1801	-102.172	0.1781	-15.3312	/	146.957	0.4332		187.553	/	11.94
3	0.1762	142.249	0.1368	-77.2076	/	272.533		17.35	288.063	0.221	/
4	0.1754	22.3771	0.1686	218.9841	/	22.4624		14.3	202.475	/	12.89
5	0.1773	-94.2962	0.1746	147.8611	/	263.066	0.2242		12.0549	5.281	/
6	0.1734	147.5745	0.1845	85.0503	/	83.7246		5.33	156.034	0.408	/
7	0.1768	29.0382	0.1807	24.9522	/	short-circuit			short-circuit		
8	0.1801	-88.0592	0.1684	-45.9541	/	active element: V_0=1V			active element: V_0=1V		
9	0.1842	134.7223	0.1766	121.6292	/	short-circuit			short-circuit		
10	0.1678	-106.655	0.1863	181.5854	/	388.182	0.164		153.781	/	9.79
11	0.1837	13.2854	0.11747	-113.528	/	59.8473		3.81	251.6284	0.253	/
12	0.1701	127.0408	0.1693	-45.8051	/	288.063	0.221		265.150	/	16.88
13	0.1804	-109.389	0.1869	23.3076	/	45.71		2.91	90.6866	0.702	/
14	0.1754	1.6427	0.1816	80.8369	/	286.33		18.24	117.671	0.541	/
15	0.1754	126.5650	0.1716	150.2917		146.754	0.4338		244.258	/	15.55

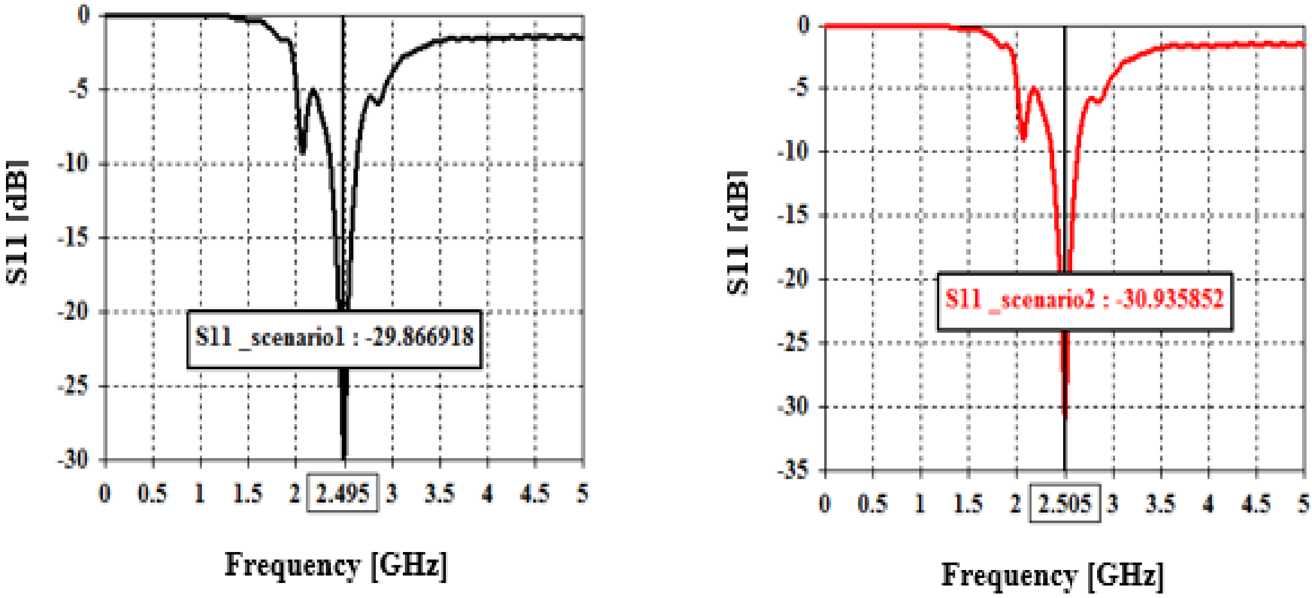

Figure 3: Coefficient of reflection: scenario *1(a) and scenario 2 (b)*

The curves of variation of the coefficient of reflection as a function of the frequency of the parasitic array operating in two different scenarios (scenario 1: S _ useful = 35°, Interf _1 = 0°, Interf _ 2 = 60° and scenario 2: S _ useful = 62°, Interf _1 = 15°, Interf _ 2 = 120°) are shown in Figure 3.

In scenario 1, we obtain in Figure 3a, an antenna which resonates at the 2.495 GHz frequency with a value of the coefficient of reflection equal to -29.866918dB.

In scenario 2, we obtain in Figure 3b, an antenna which resonates at the 2.505 GHz frequency with a value of the coefficient of reflection equal to -30.9335852dB.

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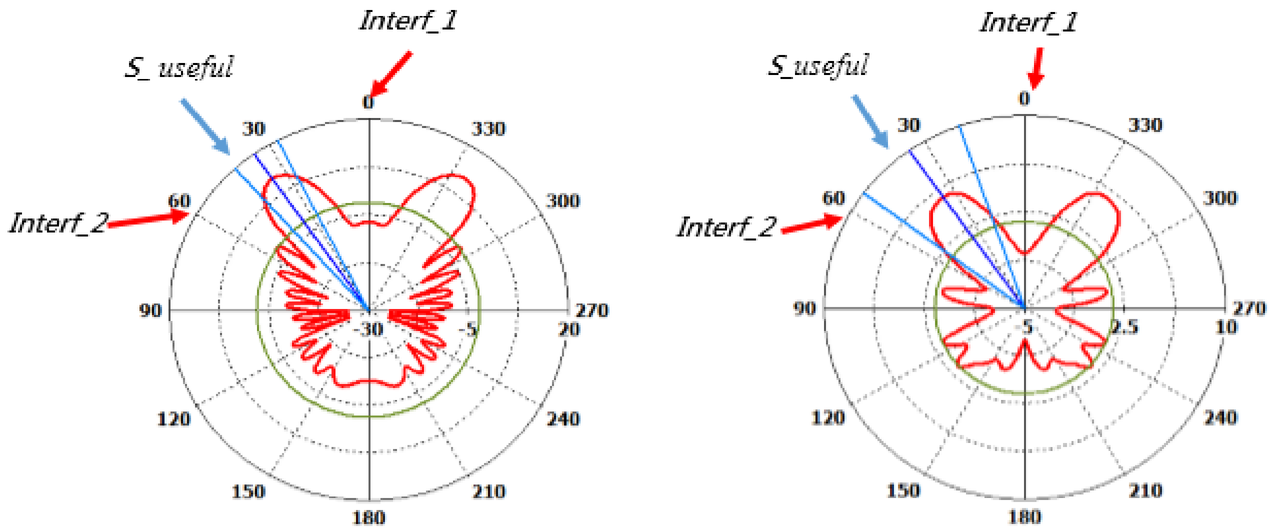

Figure 4: Array radiation pattern: $S\_useful = 35°$; $Interf\_1 = 0°$ $Interf\_2 = 60°$ (a) Phased array; (b) Parasitic array

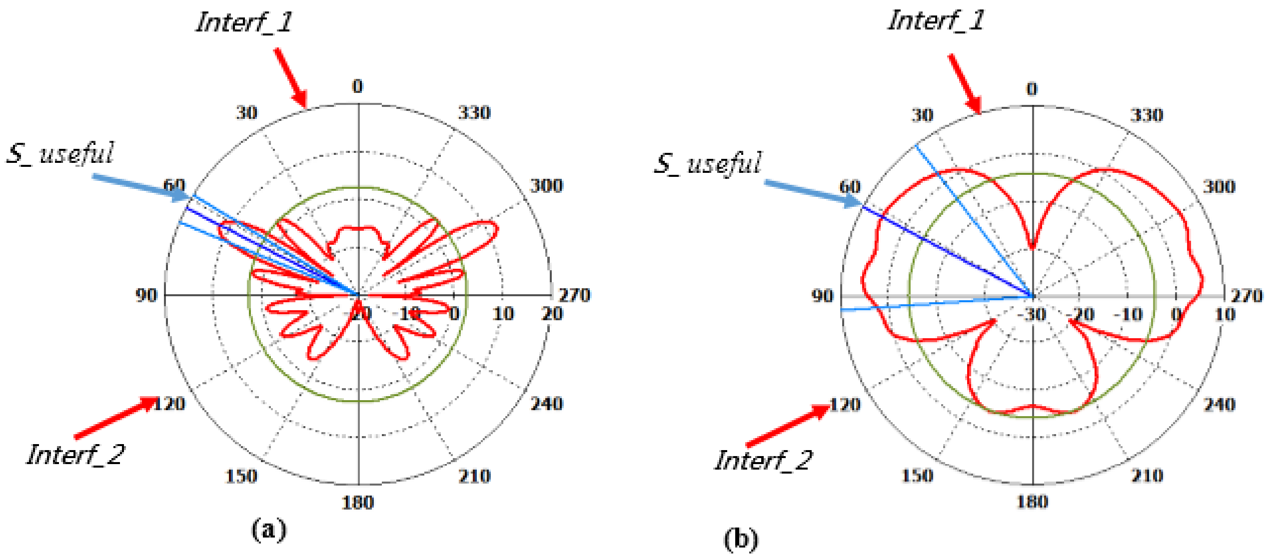

Figure 5: Array radiation pattern: $S\_useful = 62°$; $Interf\_1 = 15°$ $Interf\_2 = 120°$ (a) Phased array; (b) Parasitic array

Figure 4 represents the radiation diagrams of the phased array (a) and of the parasitic array (b) for a synthesis scenario where the useful signals and the two interferences arrive respectively under the angles of incidence of 35° ($S\_useful = 35°$), $0°$ ($Interf\_1 = 0°$) and $60°$($Interf\_2 = 60°$).

We obtain in Figure 4a a radiation diagram with a gain of 12.9 dB, an opening angle of 14.9°, a direction of the main lobe of 35.0°, a level of the lobe at 0° equal to -7 dB and a level of the lobe at 60° equals -13dB; and in Figure 4b a radiation pattern with a gain of 5.55 dB, an opening angle 34.2°, main lobe direction 35.0°, lobe level at -0° equal to -0.75 dB and lobe level at 60° equal to -1.25dB.

Figure 5 represents the radiation patterns of the phased array (a) and of the parasitic array (b) for a synthesis scenario where the useful signals and the two interferences arrive respectively under the angles of incidence of 62° ($S\_useful = 62°$), $15°$ ($Interf\_1 = 15°$) and $120°$($Interf\_2 = 120°$). We obtain in Figure 5a a radiation pattern with a gain of 11.9 dB, an opening angle of 9°, a direction of the main lobe of 63.0°, a level of the lobe at 15° equal to -6 dB and a level of the lobe at 120° equals -2dB; and in Figure 5b a radiation pattern with a gain of 5.43 dB, an opening angle 56.9°, main lobe direction 63.0°, a lobe level at -15° equal to -8 dB and a lobe level at 120° equal to -14.5dB.

Table 3 presents a comparison of the radiation characteristics of the phased array and the parasitic pattern synthesized by the LMS method.

Table 3. Comparison of the radiation characteristics of the phased array and the array with parasitic array synthesized by the LMS method (scenarios 1 and scenario 2)

$S\_useful = 35°$ $Interf\_1 = 0°$ $Interf\_2 = 60°$					
	gain	Main lobe direction	Lobe level at 0°	Lobe level at 60°	Angular width
phased array	12.1	35.0°	-7	-13.2	14.9°
parasitic array	5.55	35.2°	-0.75	-1.25	34.2°
$S\_useful = 62°$ $Interf\_1 = 15°$ $Interf\_2 = 120°$					
	gain	Main lobe direction	Lobe level at 15°	Lobe level at 120°	Angular width
phased array	11.9	63.0°	-6	-2	9°
parasitic array	5.43	63.8°	-8	-14.5	56.9°

IV. DISCUSSION

1.2. Parasitic array adaptability

In the present work, the results reveal that the value of the coefficient of reflection of our parasitic array is less than $-29\ dB$ whatever the scenario. These results show that the designed parasitic array is perfectly adapted. Results similar to ours are presented in [22]. These values of the coefficient of reflection less than $-29\ dB$ whatever the scenario and of the values of the reactive loads jx_i are in agreement with the work of [23]. In a similar logic, [32] attributes this adaptation to the inter-element distance whose value is 0.4λ, a value between 0.25λ and 0.5λ.

1.3. Rejection of the interfering signals

Our study globally indicates that the form of the parasitic array radiation pattern is almost identical to that obtained with the phased array synthesized by the LMS method. The results reveal that the radiation patterns present a high gain in the direction of the useful signal and a very low gain in the direction of the interferers whatever the type of array (phased array or array with parasitic elements) (Table 3). Similar results (shape of the radiation patterns) to ours for a phased array of 10 elements synthesized by the LMS method are presented in [33] where the gain is 0 dB in the direction of the useful signal and around -67 dB in the direction of the interferers. It can be noted that the interfering signals are more attenuated in [33] compared to our results where the gain in the direction of the interferers reaches -13.2dB. This is explained in [32] by not taking into account the inter-element coupling by [33]. Indeed these authors [33] worked in the consideration where the inter-element distance is large enough ($d > 0.5\lambda$) for the coupling phenomenon between the elements of array to be negligible. Moreover, the gain of $12.1dB$ obtained in the direction of the useful signal is clearly higher than the value $0\ dB$ presented in [33], which proves that our phased array is more directional. This improvement in directivity is justified by the number (15) of elements used. Indeed, it is demonstrated in [30] that the gain in the direction of the useful signal is better when the number of elements in the antenna array increases. The results reveal an average gain of $5.5\ dB$ in the direction of the useful signal for the parasitic array, a value less than $12.1dBi$ for the phased array. [23] justifies this degradation of the gain (and consequently the wider angular width) by the geometry of the parasitic array where only one element is fed and having neither reflectors nor directors. The direction of the main lobes for each scenario remains almost identical for phased array and parasitic array. Moreover, the two array present a level of the lobes in the direction of the interference which is substantially equal (Table 3). These results confirm the capacity of the parasitic array synthesized by the LMS method to reject the interference and to focus its main lobe in the direction of the useful signal.

V. CONCLUSION

This study made it possible to design a linear array of parasitic element antennas with the desired radiation pattern using the LMS method. On the one hand, the results highlighted the spatial distribution of radiated energy in two scenarios (scenarios 1 and 2). This allowed us to have an almost identical gain of 5.5 dB, and a lobe level in the direction of the interference of less than $-0.71dB$ for different scenarios presented. The analysis of the results shows a similarity between the different radiations patterns obtained compared to the phased array synthesized with the LMS method. These results can therefore serve as a scientific basis to guide the construction of a directional antenna, with low energy consumption and capable of rejecting interference.

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