Beamforming of an E-shaped Linear Array for WLAN Systems Applying PSO Algorithm with Restrictive Approach

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***Abstract*— This paper presents a four-element linear array composed of E-shaped microstrip antennas designed to switched-beam application in WLAN systems. Particle Swarm Optimization (PSO) algorithm is applied to optimize the amplitude of the excitation currents applied to each array radiator aiming to yield four distinct beams with 25 dB suppression of sidelobes. For this application, it has been verified the necessity of a constraint of power applied to each radiator in the PSO optimization in order to improve the algorithm convergence and to achieve only feasible solutions which satisfy the imposed constraints.**

***Keywords*— E-shaped microstrip antenna, linear array, Particle Swarm Optimization, switched-beam, beamforming, sidelobe level control.**

I. Introduction

Population-based algorithms such as Genetic Algorithm (GA), Particle Swarm and Invasion Weed Optimization (PSO, IWO) have large application in Electromagnetics [1]–[3]. Comparing GA with PSO, the PSO algorithm has a simpler implementation based on few equations which control and evaluate the optimization process.

The Particle Swarm algorithm has been used in several applications which require characteristics as beamforming, beamsteering and high performance. In [4], the particle swarm optimization applied for beamforming design of 10, 14 and 20-element linear array is described. In [5], a PSO algorithm combined with Numerical Electromagnetics Code (NEC) to produce the design curves of optimized log-periodic dipole arrays is presented. The algorithm is also applied on an innovative method to reach optimal radiation pattern of adaptive linear arrays by using phase-only disturbance in [6]. An interesting approach is presented in [7], where a broadband MEMS RHCP/LHCP reconfigurable E-shaped patch array is optimized by PSO and a 20% S_{11}-AR bandwidth was obtained using this technique. S_{11}-AR bandwidth stands for the range of frequency in which $S_{11} \leq -10\,\text{dB}$ overlaps AR $\leq 3\,\text{dB}$. In [8] and [9], E-shaped patches are applied in a 2x2 array for digital TV signal in C-Band (4.4 - 5.0 GHz) and in a performance comparison with omni-directional quarter wave monopole antenna, rectangular and triangular patch linear arrays for wireless broadcast, where the E-shaped antenna reached the best overall performance. E-shaped patches are also applied in circular polarization such as in [10], where a modified patch is developed for WLAN application.

This paper applies the Particle Swarm algorithm to synthesize four beams of a four-element array which composes a switched-beam system with suppression of sidelobe level (SLL). In order to avoid bad convergence, an approach is presented to achieve the best performance of this array. The synthesized beams considering no restriction of minimum power by array element and an approach taking into account this constraint are compared and the importance of the latter for this application is verified.

In the following sections, a brief discussion about the E-shaped patch and details about the array design with this antenna type are presented in Section II. Further, the PSO algorithm is discussed in Section III, where the main equations applied in this optimization method are shown. In addition, Section IV describes the parameters and approaches assumed for this implementation. Finally, Sections V and VI present the synthesized beams for the four-element array and some final considerations, respectively.

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II. Four-Element Array

The antenna array has been designed to provide the coverage of a $60°$ sectored cell. It is composed of E-shaped patch antennas and operates at 2.4 GHz, suitable for applications in WLAN systems.

A. E-shaped Patch Antenna

A standard microstrip antenna design consists of only one radiator element (patch) to radiate electromagnetic waves. A layer with a small thickness in relation to the operating wavelength is inserted into the model to separate the ground plane and the patch. The radiator element may take any geometric form, although the canonical shapes - such as rectangle, ellipse, circle and triangle - have been frequently used in microstrip antenna designs [11]. However, these patch shapes yield narrow operating band.

Various techniques have been developed to enable the operation in larger bandwidth than the canonical geometries, such as the E-shaped patch [12]. This kind of antenna has a rectangular geometry with addition of two parallel slits, which produce the excitation of two modes of operation. For the antenna in the upper operating mode (highest frequency), the slits have minor influence on the current density. Thus, only the central part of the antenna is responsible for most of the radiated energy. In the lower frequency mode, the slits start to contribute significantly in the behavior of the current density, modifying the way it flows on the patch.

B. Array Design

The simulated array is composed of four elements along the x-axis. Such orientation has been adopted in order to produce a beam steering in the azimuth plane. Fig. 1 depicts the array structure and its orientation. The array structure

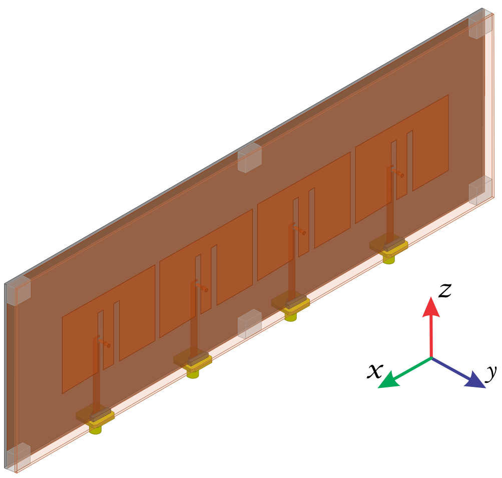

Fig. 1: Four-element array composed by E-shaped patches: orientation.

was optimized aiming at providing 200 MHz of bandwidth, which makes it suitable for different standards of wireless communications systems. Fig. 2 shows the dimensions of this optimized structure. The operating bandwidth obtained

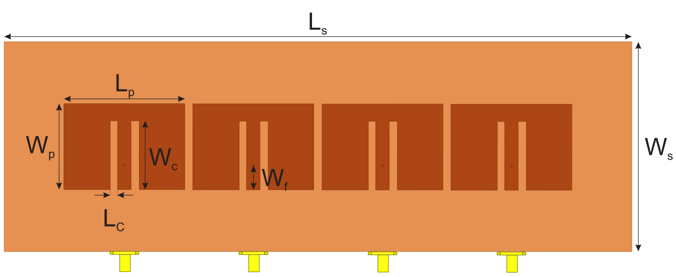

Fig. 2: Top View (all dimensions in millimeters): $L_p = 58.449$, $W_p = 41.695$, $L_c = 3.781$, $W_c = 33.499$, $W_f = 11.8$, $L_p = 304.362$ and $W_s = 101.77$.

in HFSS [13] for this designed array is equals to 215 MHz, which satisfies the design constraints. The reflection coefficient for each array element is depicted in Fig. 3. All elements achieve a value of reflection coefficient (Γ) below -20 dB at the operating frequency. This is important to validate the simulated structure and it likely guarantees the achievement of a reasonable performance by the prototype. Fig. 4 depicts the H and E-plane gain. These plots assume uniform excitation in every radiator ($I_i = 1\underline{/0°}$ A). The result for this case

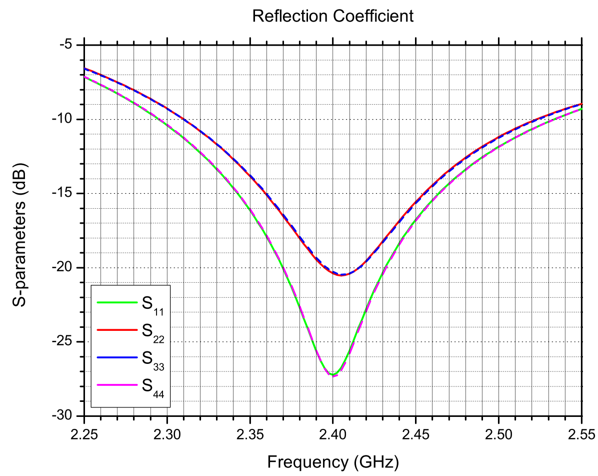

Fig. 3: Reflection coefficient for each array element: bandwidth equals to 8.95% approximately, considering the range of frequency which has $\Gamma \leq -10$ dB

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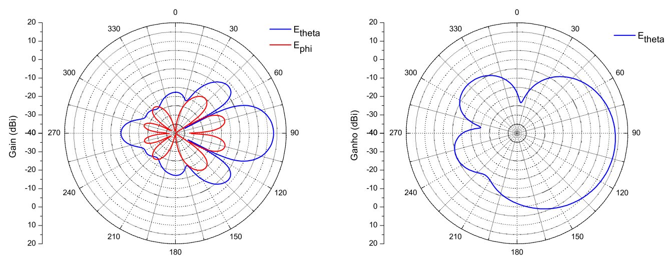


(a) H-plane ($\theta = 90°$) (b) E-plane ($\phi = 90°$)

Fig. 4: Radiation Pattern at 2.4 GHz for interelement spacing of 0.5 λ: (a) H-plane; (b) E-plane.

is a broadside pattern in H-plane, reaching 13.14 dBi, and a tilted pattern in E-plane. This effect is a consequence of the thick air gap considered between the feeding and antenna substrate. The whole structure is composed by a FR4-Epoxy laminate, an air gap layer and a Taconic TLC-338 substrate. The feeding substrate height is 1.524 mm while the antenna substrate is 1.54 mm. The air gap height is 4.8 mm. This is the same height of each acrylic base, where the length is 10 mm. The material characteristics adopted for this simulation are: $\varepsilon_{r_{acrylic}} = 2.55$, $\sigma_{acrylic} = 0.009$; $\varepsilon_{r_{FR4}} = 4.4$, $\sigma_{FR4} = 0.02$, $\varepsilon_{r_{Taconic}} = 3.54$ and $\sigma_{Taconic} = 0.0034$ [14], [15].

III. Particle Swarm Optimization

The Particle Swarm Optimization (PSO) is an advanced computational technique based on the movement of a swarm in order to find the best solution defined by the fitness function during successive iterations. The analogy of a bee swarm searching for the highest concentration of flowers in a garden perfectly fits the idea of this optimization method [2]. The implementation of this algorithm is mainly dependent on three initial definitions. First, we need to define which parameters shall be optimized, such as complex weight or even the array geometry [16]–[18]. Next, the range of possible solutions is determined. And finally, the fitness function is defined, which is used to evaluate every iteration. These parameters should be defined carefully since they are adaptable to each application.

The algorithm is started by setting the velocity and location of each particle randomly. In the first iteration, the fitness function evaluates each particle position. A score is defined for each dimension (assuming an n-dimensional problem). The calculated score is set as its particle best solution (p_{best}). The best score among the swarm is set as global best solution (g_{best}).

In order to explore the solution space, the first step is to perform a systematically movement to each particle. This movement is based on the particle position in contrast to its best solution until the current iteration and to the swarm best solution. Equation (1) computes the velocity applied to the particle to induce the motion in the next iteration as

$$v_{k,n}^{i+1} = w_i * v_{k,n}^{i} + C_1 * \text{rand}(\cdot) * (p_{best(k,n)} - x_{k,n}) + \ldots \\ C_2 * \text{rand}(\cdot) * (g_{best(n)} - x_{k,n}), \quad (1)$$

where n denotes the n-th dimension of the k-th particle in the i-th iteration, v is the current velocity of the particle, w is the inertia coefficient, C_1 and C_2 are two positive numbers (cognitive and social acceleration constants). The function rand$(\cdot)$ generates a random number within 0 and 1 - which simulates the arbitrary movement of the swarm, and x stands to the present position.

By analyzing (1) it is possible to conclude the particle is attracted to its best memory (p_{best}) and by social influence (g_{best}). The intensity of this pull is given by $C_1 * \text{rand}(\cdot)$ and $C_2 * \text{rand}(\cdot)$. The farthest is the position from $p_{best,n}$ and $p_{best,n}$, the stronger is the pull and the faster is the acceleration towards this position. The closer is the position, the weaker is the pull and the slower is the acceleration towards this position. The inertial weight (w_i) applies a velocity to keep the original particle path.

Considering all velocities updated, the next step is to update the position of each particle based on

$$x_{k,n}^{i+1} = x_{k,n}^{i} + \Delta t * v_{k,n}^{i+1}, \quad (2)$$

assuming Δt as the elapsed time during iterations, usually adopted as 1.

Finally, the algorithm returns to the fitness evaluation. Every time a best p_{best} or g_{best} is reached, the scores and locations are updated. The whole process repeats until either a particle fits the requirements tested by the fitness function or a maximum number of iterations is reached.

IV. BEAMFORMING SYNTHESIS

The proposed Particle Swarm Optimization algorithm for this application synthesizes four excitation amplitudes accordingly to the defined constraint for sidelobe levels. In this application, SLL is set to 25 dB below the level of the main beam.

Considering such array covering a $60°$ sector of a cellular cell, four distinguished beams are required to yield efficiently coverage of such sectored area. The choice of the number of beams take into account the balance between stable performance during transmission and system requirements - as available bits for feedback information to set the chosen beamforming during the communication [19]. Consequently, four sets of excitation amplitudes should be provided by the optimization algorithm to radiate the required patterns.

Ten particles are applied as possible solution for this specific problem. The position of each particle is given by a four-dimension space, where each dimension is an excitation amplitude. Each particle is evaluated by the fitness function at the beginning of each iteration. The maximum number of iterations is set to fifty. Thus, the optimal solution is reached either by fitting the established requirements or at the end of the fiftieth iteration. The fitness function applied for this problem is given by

$$\text{fitness} = \sum_{n,m=1}^{N,M} |\text{SLL}_{n,m} - (\text{E}_{max(\phi)} - \text{SLL})| \quad \text{(dB)}, \quad (3)$$

where N is the number of particles, M is the total number of sidelobes in the radiation pattern under evaluation, $\text{E}_{max(\phi)}$ is the maximum radiation of the major lobe pointing to ϕ and SLL is the desired sidelobe level.

The calculated scores indicate how far such particle is from the current (p_{best}) and (g_{best}). Therefore, the bigger is the score, the worse is the solution. The scores are also important to update particle (p_{best}) and global best (g_{best}) solution.

Applying invisible/reflecting walls approach [20], only particles inside the defined space of possible solutions are evaluated by the fitness function at each iteration. These particles out of boundaries have their velocities inverted, aiming to bring these particles back into the space of possibles solutions on the next iteration. The approach has the advantage of reducing the computational effort involved in the optimization, since only feasible solutions are evaluated.

An important step to yield coherent solutions when using particle swarm algorithm is to define the space of possible solutions carefully. Assuming normalized excitation currents, any value within 0 and 1 is theoretically valid and therefore a possible solution. Another important step is to define the parameters applied in (1). The inertial weight is linearly decreased throughout the optimization. Initially, the coefficient is set in 0.9. The minimum possible value for the inertial coefficient is 0.4 at the 50-th iteration. This variation is adopted firstly to provide a global exploration of the solution space and gradually modify this behavior to perform a exploration around the best position of each particle and around the global solution [21]. The equation used to linearly decrease inertial coefficient is

$$w_i = w_{\max} - (w_{max} - w_{min}) \frac{i}{i_{max}}, \quad (4)$$

where $w_{\max}$ is 0.9, $w_{\min}$ is equals to 0.4, $i_{\max}$ is defined as 50 and i is the i-th iteration. Coefficients C_1 and C_2 are assumed as 1.49, applied as in [22]. This value yields better convergence and show a good balance between nostalgia and social influence from the whole swarm. Even to improve convergence, the particle maximum velocity has been limited to the range of solution space.

The radiation pattern of each array element takes into account the effect of mutual coupling induced by the nearby elements. Applying this methodology, the resultant radiation pattern considered in the optimization reproduces a more realistic result compared to the one measured by using a prototype.

V. Results

The four sets of excitation currents have been synthesized for the directions given in Table I. The angles are all ϕ values in azimuth plane, considering $\theta = 90°$.

TABLE I: Beamforming directions of maximum.

Beamforming	ϕ
#1	72°
#2	84°
#3	96°
#4	108°

The excitation currents obtained using the PSO algorithm are present in Table II. The progressive phase shift is given by

$$\beta = 2\pi d \sin\theta \cos\phi_{apt} \quad \text{(radians)}, \tag{5}$$

assuming d equals to interelement spacing, θ equals to 90° and ϕ_{apt} defined by the beamforming direction given in Table I. The calculated phases are presented in Table III.

A. Optimization without power constraints

Analyzing the optimized amplitudes obtained without constraint of a minimum percentage of power in each array element, it is possible to state only two elements have significant amplitudes in the worst cases, such as in beams #3 and #4. These situations are not of interest when an antenna array is considered for a specific application, since the main goal is to achieve higher gain, to improve directivity and consequently to concentrate the radiation exclusively towards the directions of interest. In this application, elements with almost null feeding have a more significant impact on the resultant radiation pattern, since the array is composed of four elements. As a result, the main effect in the radiation pattern is a loss in directivity, just like is depicted in Fig. 5.

B. Optimization with power constraints

In order to create a constraint on the PSO algorithm to avoid the solution presented in Section V-A, the space of possible solution has been modified. Previously, the feasible space of normalized excitation amplitude was within 0 and 1. Alternatively, each array element shall be fed by at least 10% of the possible maximum power. Thus, each radiator must have at least an excitation amplitude of $\sqrt{0.1} = 0.3162$ A.

Throughout the optimization, whenever a particle has some of its amplitude excitation below this threshold value, this

TABLE II: Sets of excitation amplitudes for each synthesized beamforming.

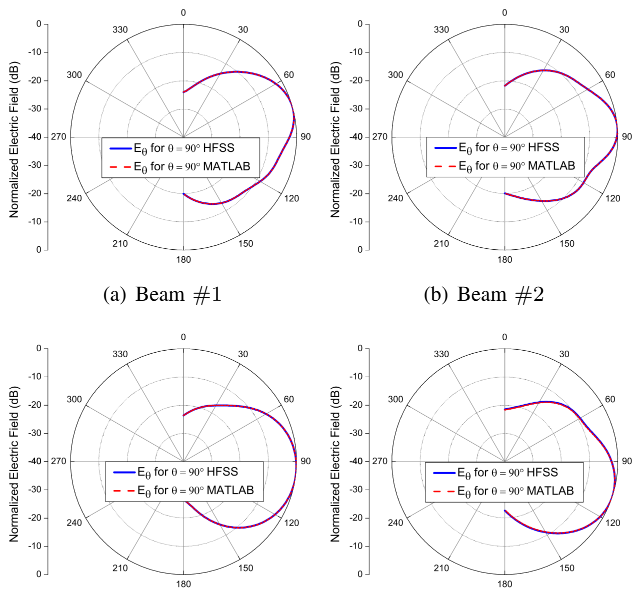
	Beams			
	without power constraints			
Element	#1	#2	#3	#4
1	0.0563	0.1748	0.0911	0.0568
2	0.1080	0.0683	0.7621	0.1835
3	0.2714	0.7059	0.3905	0.2988
4	0.5904	0.3180	0.0236	0.0030
	with power constraints			
1	0.3233	0.5304	0.4360	0.3597
2	0.8305	0.8097	0.8580	0.8557
3	0.9267	0.8565	0.8675	0.9762
4	0.3942	0.4080	0.3767	0.5214

TABLE III: Progressive phase shift for each synthesized beamforming.

Beamforming			
#1	#2	#3	#4
55.62°	18.81°	−18.81°	−55.62°

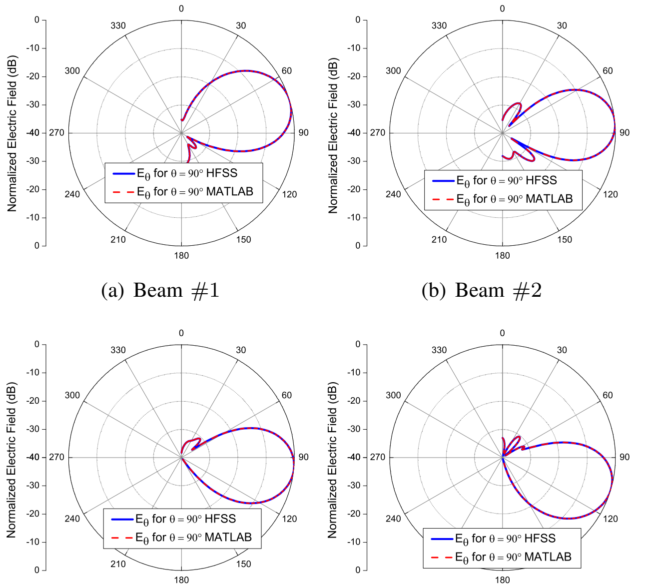
possible solution is not evaluated by the fitness function. In other words, the solution is discarded at this iteration.

As one can see in Table II, all the elements present excitation amplitudes greater than the defined lower boundary. Consequently, it is possible to verify an improvement on the synthesized beams, as depicted in Fig. 6. The main improvement when the minimum power constraint is taken into account is a greater directivity compared to the case without constraints. Consequently, a major lobe with narrower width is achieved, what is desirable for a four-element array. In addition, the requirement of sidelobes level below −25 dB has



(a) Beam #1 (b) Beam #2 (c) Beam #3 (d) Beam #4

Fig. 5: Radiation pattern for optimized excitation without a minimum power constraint for the array elements.



(a) Beam #1 (b) Beam #2

(c) Beam #3 (d) Beam #4

Fig. 6: Radiation pattern for optimized excitation with constraint of minimum power by array element.

been easily fulfilled, which means a greater lower boundary could be adopted for this scenario.

VI. Conclusions

The Particle Swarm Optimization is successfully applied in general problems, such as sidelobes level suppression and in application where a desired mask are required for the radiation pattern. Although, its implementation must consider some constraints in order to effectively achieve only feasible solutions. Applying the PSO algorithm to optimize the radiation pattern of an array, it can converge to some solutions where the contribution of each element does not provide a significant relevance to the total radiation, likewise depicted in Section V-A.

In order to avoid those problems, approaches like the one adopted in this paper should be considered in applications based on microstrip antenna arrays in order to achieve the best performance from PSO algorithm.

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