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Cuckoo Search Optimization for Linear Antenna Arrays Synthesis

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Abstract: A recently developed metaheuristic optimization algorithm, the Cuckoo search algorithm, is used in this paper for the synthesis of symmetric uniformly spaced linear microstrip antennas array. Cuckoo search is based on the breeding strategy of Cuckoos augmented by a Levy flight behaviour found in the foraging habits of other species.

This metaheuristic is tested on amplitude only pattern synthesis and amplitude and phase pattern synthesis. In both case, the objective, is to determinate the optimal excitations element that produce a synthesized radiation pattern within given bounds specified by a pattern mask

Keywords: Microstrip antenna array, Cuckoo search, Synthesis, Optimization.

1 Introduction

The microstrip antennas have characteristics which make them ideal for several applications. These antennas are low profile, conformable to planar and nonplanar surfaces, simple and inexpensive to manufacture using modern printed-circuit technology. They are also mechanically robust when mounted on rigid surfaces [1].

One of the major advantages of microstrip antennas is the simplicity of array construction. The radiating elements may be etched jointly with the feed network as an integrated structure leading to a very compact and low cost design. [2].

The potential advantages of the use of array, rather than of only single elements, is that the major lobe direction and sidelobe level of radiation pattern are controllable and are function of the magnitude and the phase of the excitation current and the position of each array element.

Finding these parameters to yield a desired radiation pattern is the mean concern in the pattern array synthesis. In this domain several analytical and numerical techniques were developed (Binomial, Dolph-Techybecheff, Taylor, dynamic programming and steepest descent…) [3]. Nowadays, several researches on antenna array are being carried out using various optimization

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techniques to solve electromagnetic problems due to their robustness and easy adaptivity [4].

A new nature-inspired evolutionary algorithm called Cuckoo search, was recently used for the synthesis of linear isotropic antenna Array with minimum side lobe level (SLL) and/or nulls control [5, 6].

In this paper, we use Cuckoo search for the synthesis of linear microstrip antenna array to determinate the optimal excitations elements that produce a synthesized radiation pattern within given bounds specified by a pattern mask.

2 Cuckoo Search

2.1 Cuckoo breeding behaviour

CS is based on the breeding strategy of some cuckoos species augmented by a Levy flight behaviour found in the foraging habits of other animal species.

Cuckoos are brood parasite, they lay their eggs in other bird's nests and leave the host birds to incubate and rear their offspring.

When the Cuckoo nestling hatches, it instinctively pushes the other eggs and nestlings out of the nest. This reproductive strategy can be extremely costly for foster parents [7], which leads to strong host adaptations to detect and reject foreign eggs or to simply abandon their nests and build new ones. As a consequence, Female cuckoos developed counter-adaptations: host-egg mimicry to overcome host defence strategies [8].

2.2 Levy flights

It is an open question how animals find food in dynamic natural environments where they possess little or no knowledge of where resources are located. Foraging theory predicts that Lévy flight movements optimize the success of resources' random searches [9].

In recent years, biologists have discovered that Lévy flights describe foraging patterns in a number of species of animals and insects [10, 11].

Lévy flights are a particular class of random walks. A random walk is a formalization of the intuitive idea of taking successive steps, each in a random direction. The statistical distributions of displacement lengths and changes of direction, describe the stochastic process. In particular, Lévy random walk models involve a uniform distribution for the turning angles and a Lévy-stable distribution for the move or flight step length [12].

Lévy flights are characterized by the existence of rare but extremely large steps, alternating between sequences of many short-length jumps and the same sites are revisited much less frequently than in patterns described by other process.

2.3 Cuckoo search algorithm

Cuckoo Search (CS) algorithm is a population-based algorithm, in a way similar to GA. Where solutions are represented by eggs in host's nests and the cuckoo eggs represent the new solutions, the aim is to use the new and potentially better solutions (cuckoos) to replace the not-so-good solutions in the nests. The CS is based on three idealized rules [13]:

1. Each cuckoo lays one egg at a time, and dumps it in a randomly chosen nest;
2. The best nests with high quality of eggs (solutions) will carry over to the next generations;
3. The number of available host nests is fixed, and a host can discover an alien egg with probability $P_a \in [0,1]$. In this case, the host bird can either throw the egg away or abandon the nest to build a completely new nest in a new location.

The third assumptions can be approximated as the fraction P_a of the n nests is replaced by new nests (new random solutions). The quality or fitness of a solution can be defined in a similar way to the fitness function in genetic algorithms [13].

The basic steps of CS are described in the following pseudo code [13]:

```
begin
        Objective function $f(X),\ X = (x_1, x_2, ..., x_d)$
        Generate initial population of n host nests $X_i\ (i = 1, 2, ..., n)$
while (t < MaxGeneration) or (stop criterion)
        Get a cuckoo randomly by Levy flights
        evaluate its quality/fitness $F_i$
        Choose a nest among n (say, j) randomly
if ($F_i > F_j$),
        replace j by the new solution;
end
        A fraction (pa) of worse nests
        are abandoned and new ones are built;
        Keep the best solutions
        (or nests with quality solutions);
        Rank the solutions and find the current best
end while
        Post process results and visualization
end
```

When generating new solutions $X^{(t+1)}$ for a cuckoo *i*, a Lévy flight is performed using the following equation:

$$X_i^{(t+1)} = X_i^{(t)} + \alpha \otimes Lévy(\lambda), \tag{1}$$

where α (α > 0) represents a step size. This step size should be related to the scales of problem the algorithm is trying to solve.

The product ⊗ means entry-wise multiplications. Lévy flights essentially provide a random walk while their random steps are drawn from a Levy distribution for large steps.

$$Lévy \sim u = t^{-\lambda}, \quad (1 < \lambda \le 3). \tag{2}$$

It is worth pointing out that, in the real world, if a cuckoo's egg is very similar to a host's eggs, then this cuckoo's egg is less likely to be discovered, thus the fitness should be related to the difference in solutions. Therefore, it is a good idea to do a random walk in a biased way with some random step sizes.

There are a few ways for generation of steps of the Lévy flights, but one of the most efficient and yet straightforward ways is to use the so-called Mantegna algorithm for a symmetric Lévy stable distribution. Here 'symmetric' means that the steps can be positive and negative [14].

In Mantegna's algorithm, the step length s can be calculated by

$$S = \frac{u}{|y|^{1/\beta}}, \tag{3}$$

where $0 < \beta \le 2$ is an index, and *u* and *v* are stochastic variables drawn from normal distributions. That is

$$u\text{\textasciitilde}\mathrm{N}(0,\sigma_u^2), \quad v\text{\textasciitilde}\mathrm{N}(0,\sigma_v^2), \tag{4}$$

$$\sigma_u = \left\{ \frac{\Gamma(1+\beta)\sin\frac{\pi\beta}{2}}{\Gamma\left[\frac{1+\beta}{2}\right]\beta \cdot 2^{(\beta-1)/2}} \right\}^{\frac{1}{\beta}}, \quad \sigma_v = 1. \tag{5}$$

Here Γ(z) is the Gamma function

$$\Gamma(x) = \int_0^\infty t^{z-1} \mathrm{e}^{-t}\, \mathrm{d}t. \tag{6}$$

3 Synthesis of Linear Antenna Arrays

We consider a linear array of *2N* identical rectangular microstrip symmetrically and equally spaced along *x*-axis as is shown in Fig. 1. Here its element *i* is located at x_i with inter-spacing of $d = 0.25\lambda$, λ is wavelength.

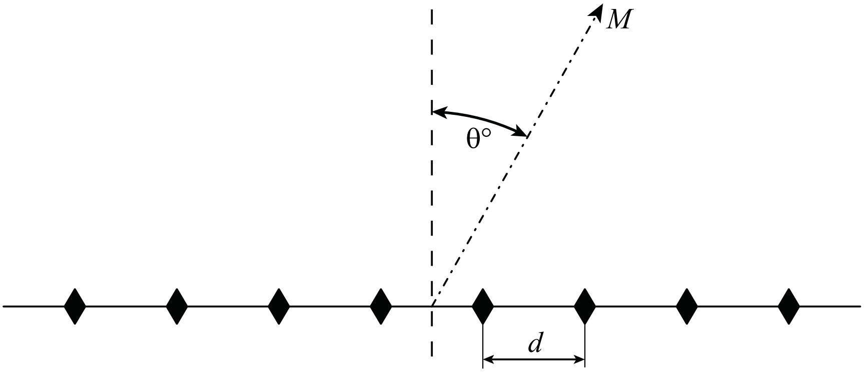

Fig. 1 – *Linear antenna array.*

The Far field pattern of this linear array is described by

$$F_s(\theta) = \frac{f(\theta)}{F_{s\max}} \sum_{i=1}^{N} a_i \cos(k_0 X_i \sin\theta + \psi_i), \tag{7}$$

$$X_i = (i - 1/2)d, \quad \text{where } i = 1,\ldots,N, \tag{8}$$

where, θ is the scanning angle from broadside, $f(\theta)$ element pattern, $k = 2\pi/\lambda$, represents the wave number, λ is wavelength, x_i is the distance between position of the i^{th} element and the array centre, and a_i and ψ_i are respectively the excitation amplitude and phase of the i^{th} element.

In this case, the synthesis problem consists in determining the vectors $[a_1, a_2,\ldots,a_i]$ and $[\psi_1, \psi_2, \ldots, \psi_i]$, amplitude and phases coefficients of excitation current that produces a radiation pattern $Fs(\theta)$ that is closest to the desired pattern specified by the pattern model as illustrated in Fig. 2. The relation between the synthesis problem and the optimization method is define by the fitness function; the fitness function we have adopted is given as [15]

$$C_{fitness} = \sum_{\theta} L(\theta), \tag{9}$$

where:

$$L(\theta) = \frac{k(\theta) + |k(\theta)|}{2}, \tag{10}$$

$$k(\theta) = \left(M_{\max}(\theta) - |F_s(\theta)|\right)\left(M_{\min}(\theta) - |F_s(\theta)|\right). \tag{11}$$

Here, $M_{\min}$ and $M_{\max}$ represent the minimum and the maximum shaping region, respectively (Fig. 2), and $L(\theta)$ does not equal to 0 only if $|F(\theta)|$ is situated inside the shaping region.

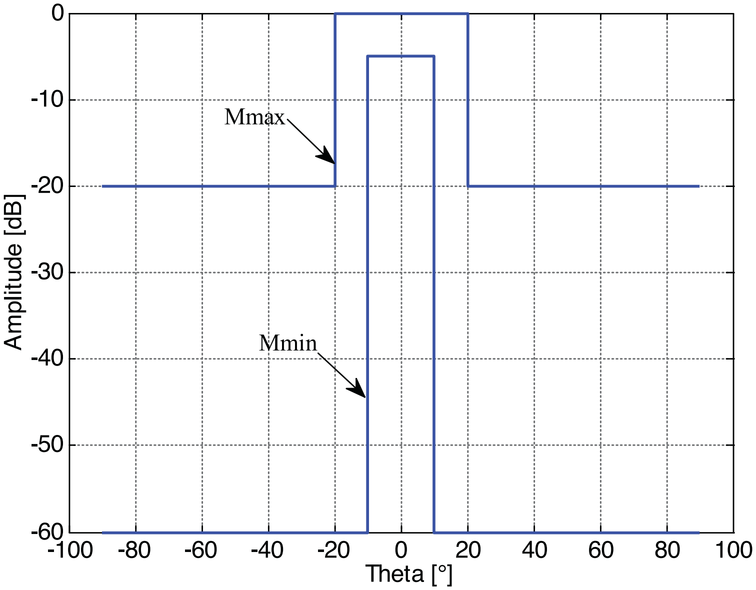

Fig. 2 – *Desired pattern shape.*

4 Numerical Results

In order to evaluate the performance of CS for the shaped beam pattern synthesis of a linear array, two cases of synthesis are considered. Amplitude only pattern synthesis and amplitude and phase pattern synthesis. In the both cases, a symmetric uniformly spaced (half wavelength inter element spacing) linear array of rectangular microstrip antennas with 0.906cm width and 1.186cm long working at the frequency of 10GHz is used.

In the optimization process, the number of nest (population size) is 50 and the fraction probability, P_a (discovery rate) is 0.25.
The mask of the desired pattern is shown in Fig. 3. And it is defined by:

$$M_{\min} = \begin{cases} 0\,\mathrm{dB}, & \text{for } -20° \le \theta \le 20°; \\ -20\,\mathrm{dB}, & \text{elsewhere}; \end{cases} \tag{12}$$

$$M_{\max} = \begin{cases} -5\,\mathrm{dB}, & \text{for } -10° \le \theta \le 10°; \\ -60\,\mathrm{dB}, & \text{elsewhere}. \end{cases} \tag{13}$$

In the case of the amplitude only pattern synthesis, all the elements of the array have the same phase excitation ($\psi_i = 0$ in (7)), the synthesis problem consists in determining the vectors $[a_1, a_2, \ldots, a_i]$ amplitude coefficients of the courant excitation.

For this case, we consider a symmetric uniformly spaced linier array of 2N = 12 rectangular microstrip with half wavelength spaced; The CS optimization results are show in the Fig. 3 where it is clear that there is no sidelobe that exceeds the specified values –20dB and the synthesized radiation diagram is contained in the desired pattern. Fig. 4 illustrates the evolution of the fitness function over the generations. The elements amplitude excitation required to achieve the desired pattern are shown in the **Table 1**.

Table 1
Obtained amplitude feed law.

Source	Amplitude
1	0.9993
2	0.6846
3	0.7354
4	0.0050
5	0.1241
6	0.0015

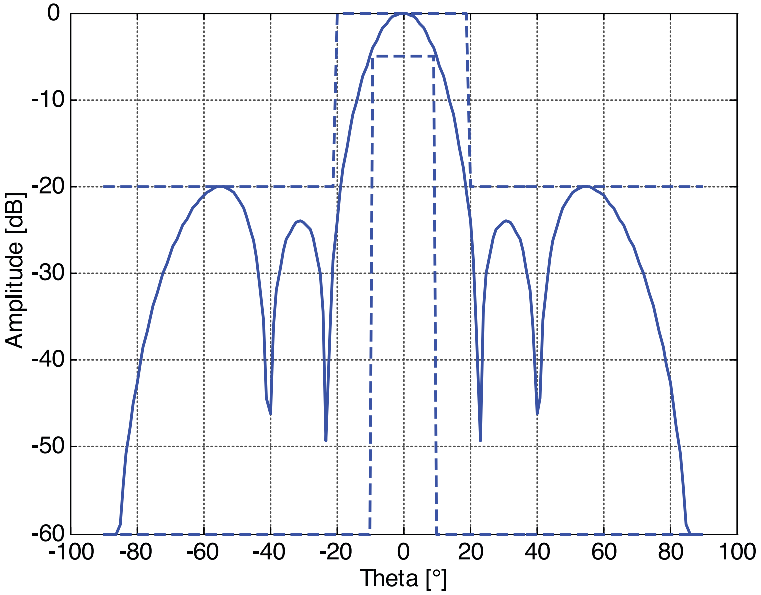

Fig. 3 – *Optimized radiation pattern of* 12 *elements symmetric linier obtained by amplitude only pattern synthesis* (*solid line*) *and the mask of desired pattern* (*dashed line*).

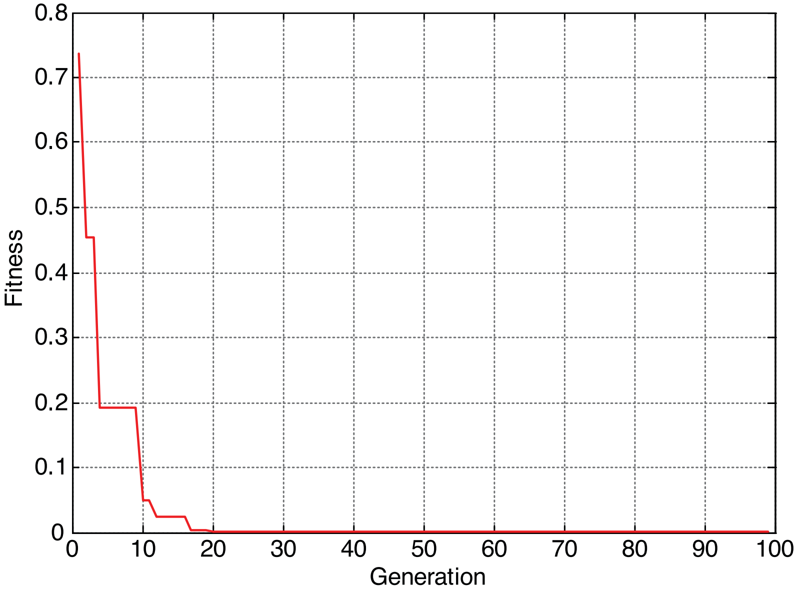

Fig. 4 – *Convergence curves for best fitness versus the number of iterations.*

In the second case, the CS is used for the optimization of amplitude and phase pattern synthesis of symmetric uniformly spaced linier array of 2N = 8 rectangular microstrip.

Figs. 5 and 6 show the optimized radiation pattern and the convergence curve of the fitness function where it is clearly seen that the synthesized pattern is in good agreement with the desired pattern. **Table 2**, on the other hand**,** present the elements amplitudes and phases computed by the CS.

Table 2
Obtained amplitude and phase feed law.

Source	Amplitude	Phase (rad)
1	0.8321	3.3346
2	0.7104	2.8936
3	0.5309	3.6467
4	0.2193	2.6512

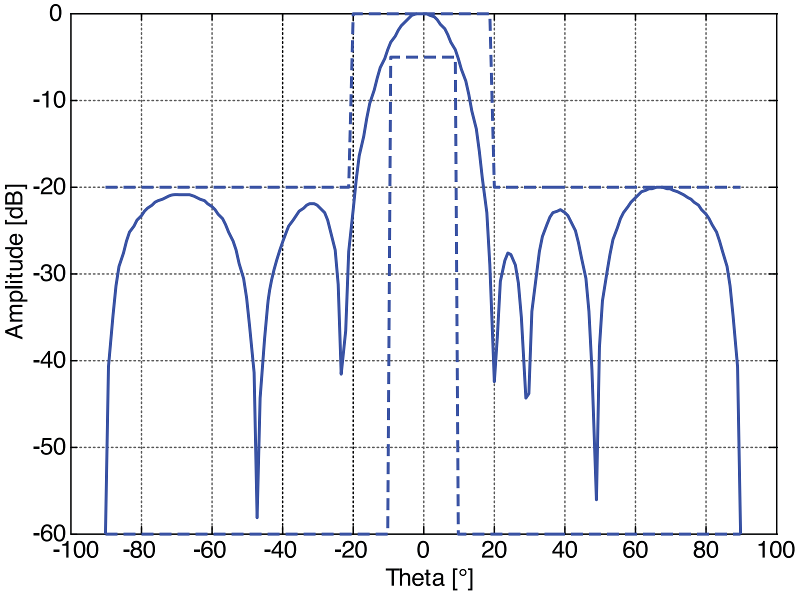

Fig. 5 – *Optimized radiation pattern of* 8 *elements symmetric linier obtained by amplitude and phase pattern synthesis* (*solid line*) *and the mask of desired pattern* (*dashed line*).

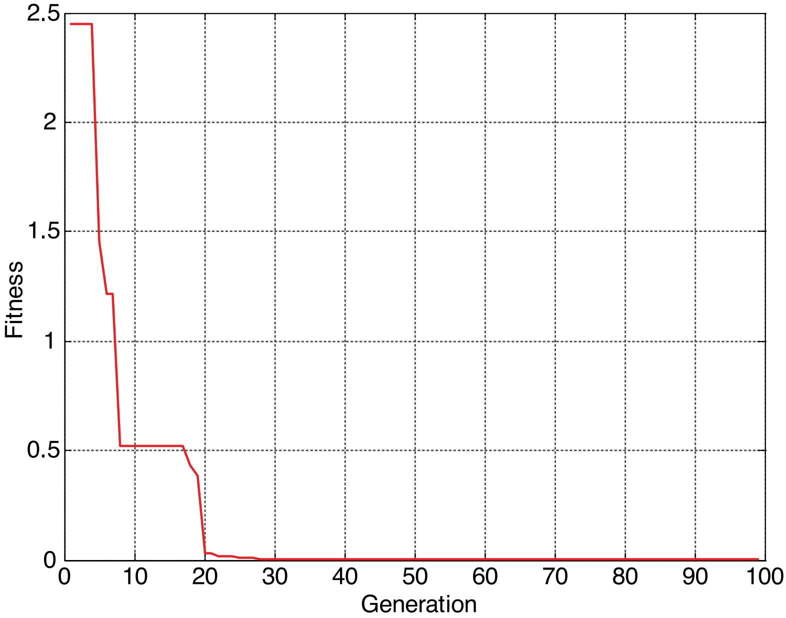

Fig. 6 – *Convergence curves for best fitness versus the number of iterations.*

4 Conclusion

In this work, we have used the cuckoo search for the synthesis and optimization of linear microstrip antennas array.

This metaheurstic was tested on amplitude only pattern synthesis and amplitude and phase pattern synthesis. The obtained results are satisfying and the algorithm achieves the desired goals with a good convergence.

The advantages of the cuckoo search are the simplicity in implementation and the fewer parameters to fine-tune in the algorithm.

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