Int. J. Electron. Commun. (AEÜ) 68 (2014) 540–549

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Linear antenna array synthesis using cat swarm optimization

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ARTICLE INFO

Article history:
Received 1 January 2013
Accepted 30 December 2013

Keywords:
Linear antenna array
Cat swarm optimization
Particle swarm optimization
Side lobe level
Null control

ABSTRACT

Antenna arrays with high directivity and low side lobe levels need to be designed for increasing the efficiency of communication systems. A new evolutionary technique, cat swarm optimization (CSO), is proposed for the synthesis of linear antenna arrays. The CSO is a high performance computational method capable of solving linear and non-linear optimization problems. CSO is applied to optimize the antenna element positions for suppressing side lobe levels and for achieving nulls in desired directions. The steps involved in the problem formulation of the CSO are presented. Various design examples are considered and the obtained CSO based results are validated by comparing with the results obtained using particle swarm optimization (PSO) and ant colony optimization (ACO). The flexibility and ease of implementation of the CSO algorithm is evident from this analysis, showing the algorithm's usefulness in electromagnetic optimization problems.

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1. Introduction

Antenna arrays [1,2] are being widely used in wireless, satellite, mobile and radar communications systems. They help in improving the system performance by enhancing directivity, improving signal quality, extending system coverage and increasing spectrum efficiency. The performance of the communication system greatly depends on the efficient design of the antenna arrays. Systems with narrow first null beam width (FNBW) are desired for obtaining high directivity. On the other hand, systems need to maintain low side lobe level (SLL) to avoid interference with other systems operating in same frequency band. The above mentioned requirements of SLL and FNBW are in contrast to each other as arrays with narrow beam width generally do not produce lower side lobe levels and vice versa, i.e., the performance cannot be improved significantly for one aspect without degrading the other. In many applications it becomes necessary to sacrifice gain and beam width in order to achieve lower side lobe level. Also the increasing EM pollution has prompted the placing of nulls in undesired directions. So it is necessary to design the antenna array with low side lobe levels while maintaining fixed beam width and placing of nulls in undesired directions.

The radiation pattern of the antenna array depends on the structure of the array, distance between the elements and amplitude and phase excitation of individual elements. For the linear array geometry, suppressing side lobe levels and placing of nulls in desired directions can be achieved in two ways either by optimizing the spacing's between the element positions while maintaining uniform excitations, or by employing non uniform excitations of the elements while using periodic placement of antenna elements. Linear antenna array synthesis has been extensively studied from the past 5 decades. In order to optimize this type of electromagnetic design problems, evolutionary algorithms such as genetic algorithm (GA) [3–9], simulated annealing (SA) [10], particle swarm optimization (PSO) [11–18], ant colony optimization (ACO) [19] and invasive weed optimization (IWO) [20,21] have been successfully applied. All the above mentioned evolutionary algorithms have shown the capability of searching for global solution in electromagnetic optimization problems.

In this paper, a new optimization algorithm, cat swarm optimization (CSO) [22–24] is proposed for synthesis of linear antenna arrays. CSO is a high performance computational method, inspired from the natural behaviour of cats. It was introduced by Chu and Tsai in 2007 [22]. CSO has been successfully applied to different optimization problems in areas such as IIR system identification [23], clustering [25], etc. However, this is the first time that CSO is being proposed for electromagnetic applications. In this paper, CSO is used to optimize the spacing between the elements of the linear antenna array in order to produce a radiation pattern with minimum side lobe levels with nulls placed in desired directions.

The configuration of the linear array is discussed in Section 2. Section 3 presents a detailed description of CSO. Design examples and obtained radiation patterns are discussed in Section 4. The sensitivity of different parameters of CSO and PSO are discussed in Section 5. Section 6 gives a detailed analysis of the obtained results whereas Section 7 concludes the paper.

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http://dx.doi.org/10.1016/j.aeue.2013.12.012

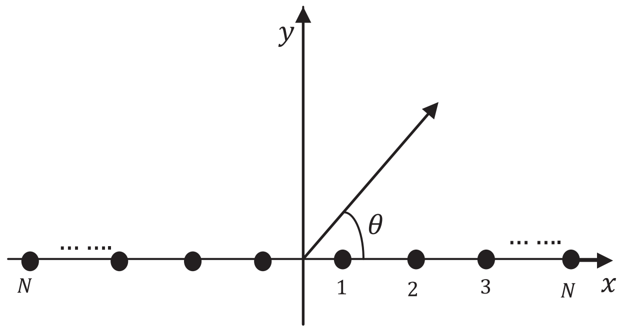

Fig. 1. Geometry of the symmetrically placed linear array.

2. Linear antenna array

The geometry of uniform linear antenna array with 2N elements placed symmetrically along x axis is considered and shown in Fig. 1.

The array factor (AF) in the azimuth plane [1,13] is

$$\mathrm{AF}(\theta) = 2\sum_{n=1}^{N} I_n \cos\left[kx_n \cos(\theta) + \varphi_n\right] \quad (1)$$

where $k = 2\pi/\lambda$ is the wave number, θ is the azimuth angle and I_n, φ_n and x_n are the excitation amplitude, phase and position of element n respectively.

Let us assume uniform amplitude and phase excitation for all elements, i.e., $I_n = 1$ and $\varphi_n = 0$.

$$\mathrm{AF}(\theta) = 2\sum_{n=1}^{N} \cos\left[kx_n \cos(\theta)\right] \quad (2)$$

The main aim is that to find the optimized positions of $x_1, x_2, \ldots, x_n$ of the corresponding elements to achieve desired radiation pattern with minimum side lobe levels and nulls at desired directions. In antenna arrays, proper placement of antenna elements is essential. Because, if the adjacent elements are placed closer, then it leads to mutual coupling effects or if they are placed too far, then it leads to grating lobes. Therefore, while solving this optimization problem, the following conditions [14] must be satisfied in order to overcome the disadvantages mentioned above.

$$|x_i - x_j| > 0.25\lambda \quad (3)$$

$$\min\{x_i\} > 0.125\lambda \quad i = 1, 2, \ldots, N. \quad i \neq j \quad (4)$$

3. Cat swarm optimization

CAT swarm optimization [22–24] is modelled by the identifying features of cat's behaviour. The features are termed as seeking mode and tracing mode. Cats spend most of the time resting but are always being alert by observing the surrounding environment. This behaviour is represented in seeking mode. Tracing mode is modelled as behaviour of cats while tracing targets. Cats spend a large amount of energy and move very quickly while chasing a target. In CSO, these two modes are mathematically modelled to solve different optimization problems.

3.1. Seeking mode

In seeking mode, the cat is in rest position while being alert. If it wants to move in rest position, the movement is very slow and careful after observing the surrounding environment. Some of the essential factors related to this mode are:

- *Seeking memory pool (SMP)*: It tells how many number of copies of cat to be produced in seeking mode.
- *Seeking range of the selected dimension (SRD)*: It tells how much range is varied for a selected dimension.
- *Counts of dimension to change (CDC)*: It tells how many number of dimensions to be mutated.

The steps involved in the seeking mode are:

(i) According to SMP, generate K copies of the ith cat.
(ii) One copy among K copies maintains the present position and $K-1$ copies undergo mutation. That is, for each copy, $K-1$ copies, randomly adds or subtracts SRD percents of the present position value based on CDC.
(iii) Calculate the fitness values of all the copies.
(iv) Based on the best fitness value, chose the best copy among K copies and replace the position of ith cat.

The flow chart of the seeking mode process is shown in Fig. 2.

3.2. Tracing mode

Tracing mode resembles the behaviour of swarm intelligence based PSO algorithm. In this mode cats trace the targets by changing the positions with their own velocities. The steps involved in this mode are as follows:

(i) Define the position and velocity of the ith cat in the N dimensional real valued solution space

$$X_i = [x_{ij}] \quad \text{where}\ j = 1, \ldots, N. \quad (5)$$

$$V_i = [v_{ij}] \quad \text{where} \quad j = 1, \ldots, N \quad (6)$$

(ii) Update the velocity and position for every dimension for ith cat from the following equations

$$V_{i+1,j} = \omega V_{i,j} + c_1 r_1 (p_{best} - X_{i,j}) \quad (7)$$

$$X_{i+1,j} = X_{i,j} + V_{i+1,j} \quad (8)$$

where p_{best} is the best position of the cat, ω is the inertia weight, c_1 is the acceleration constant and r_1 is random number in the range [0,1]. The flow chart of the tracing mode process is shown in Fig. 3.

3.3. Algorithm description

In CSO as discussed above, cats are dived in to two groups to achieve global solution. The cats are distributed to the two modes based on mixture ratio (MR). As we know most of the cats spend time in rest and observation position, i.e., in seeking mode. Therefore, MR is allocated a value such that less number of cats move to tracing mode. The steps involved in CSO are

(i) Initialize a finite number of cats in the N dimensional solution space with random positions.
(ii) Initialize the velocity of cats randomly.
(iii) Calculate the fitness value of each cat and pick the cat with best fitness and store the corresponding cat position into the memory as p_{best}.
(iv) According to MR, cats are randomly moved to seeking mode and tracing mode based on their flags.
(v) If flag of the ith cat is set to seeking mode, apply the cat to the seeking mode process; otherwise apply it to the tracing mode process.
(vi) After the process of two modes, evaluate the fitness of each modified cat and store the position of best cat as $p_{i,j}$.

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