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Concentric circular antenna array synthesis for side lobe suppression using moth flame optimization

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A R T I C L E I N F O

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A B S T R A C T

This paper presents an accurate approach for Concentric Circular Antenna Array (CCAA) synthesis to improve the far-field radiation characteristics of the antenna using a meta-heuristic optimization technique called Moth Flame Optimization (MFO). The far-field radiation pattern improves with lower Side Lobe Level (SLL) which is essential for the reduction of interference in the entire side lobe regions. MFO algorithm is a recently proposed evolutionary algorithm which is applied to determine the optimum sets of current excitation weights and to find the optimal inter-element spacing between the array elements in the 3-rings structure of CCAA design. In this context, the design examples of two 3-ring CCAAs, one having the set of 4, 6, 8 elements and the other having the set of 8, 10, 12 elements, with and without centre element, are presented by optimizing the array parameters. The results obtained by using MFO algorithm based approach show a considerable improvement of SLL with respect to that of the uniform array pattern and those of the approaches reported in the recent literature.

1. Introduction

An accurate design and synthesis of antenna array have a significant role in modern-day communication systems. Many research works on the design and synthesis of antenna arrays have been carried out over the past few decades to improve the radiation pattern characteristics. The radiation pattern depends on the antenna array parameters like the geometrical configuration of the array, inter-element spacing and current excitation weights of the array elements. The increasing traffic in the electromagnetic environment has prompted to design the antenna array with a lower sidelobe level (SLL) and narrow First Null Beamwidth (FNBW). A low SLL is required to avoid the interference with the other system operating in the same frequency band [3]. On the other hand, a narrow FNBW is required for higher directivity which is essential for long distance communication. However, the design of antenna array with low SLL and narrow FNBW is challenging because an array with a lower SLL does not produce a narrow FNBW and vice-versa [1–3], i.e., the performance cannot be improved simultaneously maintaining both the criterion of the antenna array design.

A CCAA consists of some concentric circular rings, and each ring contains a specific number of antennas. The CCAAs are widely used in many high-performance radio systems, like radar, sonar, air and space navigation, underground propagation etc. Extensive research on circular antenna array (CAA) and CCAA synthesis have been reported in [4–15]. The CCAA synthesis can be achieved by optimizing the current excitation weights and the inter-element spacing between the array elements in 3-rings of CCAA structure.

Various evolutionary algorithms such as Evolutionary Programming (EP) [8] have been used for the synthesis and design of CCAA. Dib et al. [10] used Biography Based Optimization (BBO) algorithm for the design of non-uniform CCAA. Sharaqa et al. applied Firefly Algorithm (FA) in CCAA synthesis in [11]. FA has achieved a promising result as compared to those of the results reported in [8,10]. Dib et al. [9] have applied Symbiotic Organisms Search (SOS) method for SLL reduction in the design of CCAA. SOS is nature inspired optimization technique which is inspired by the interaction strategies between different organisms in an ecosystem. Various heuristic search evolutionary algorithm techniques are also used in the different electronic circuits modelling for the solution of complex, nonlinear, irregular and non-differentiable optimization problems [17–19].

In this paper, the constraints of non-uniform CCAA design have been considered by using MFO algorithm. The constraints are:

- Reduce sidelobe levels,
- Imposing nulls at all the peaks of side lobes in the radiation pattern,
- The lower value of FNBW to improve the directivity of the radiation pattern.

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The primary objective of this paper is to design a non-uniform CCAA with the lowest SLL value while maintaining a narrow FNBW by using MFO algorithm. MFO was first mathematically modelled by Mirjalili [20]. In this paper, the current excitation weights of all the array elements and the inter-element spacing are optimally calculated by using MFO, and the best results are reported in this paper. The MFO based approach shows a useful and comprehensive set of results and confirms the superiority of the algorithm over EP [8], BBO [10], FA [11] and SOS [9] for CCAA design.

The rest part of the paper is arranged as follows: Section 2 presents the design equation and the cost function evaluation of CCAA. Section 3 presents a brief discussion of the applied algorithm. Comparative simulation results are presented in Section 4. Finally, Section 5 concludes the paper.

2. Design equation

The design of an antenna array mainly depends on the geometrical configuration of the array. The elements of a CCAA are arranged in such a way that all the elements are configured in multiple concentric circular rings, which differ in radii and number of elements. The general configuration of CCAA with M concentric circular rings, where the mth ($m = 1, 2, \ldots, M$) ring has a radius r_m and the corresponding number of elements N_m is shown in Fig. 1.

If all the array elements in the rings are considered to be the isotropic source, then the radiation pattern of this array can be written in term of its array factor only.

Referring to Fig. 1, the array factor $AF(\theta,\phi,I)$ for the CCAA may be written as (1) [12].

$$AF(\theta,\phi,I) = \sum_{m=1}^{M}\sum_{n=1}^{N} I_{mn}\exp[j(kr_m\sin\theta\cos(\phi-\phi_{mn}) + \alpha_{mn})] \tag{1}$$

where I_{mn} denotes the current excitation of the nth element in the mth ring. $k = \frac{2\pi}{\lambda}$, is the signal wavelength. θ Symbolises the elevation angle from the positive z-axis and ϕ symbolises the azimuth angle from the positive x-axis. The angle ϕ_{mn} is the element to element angular separation measured from the positive x-axis. As elements in each ring are assumed to be uniformly distributed so,

$$\phi_{mn} = 2\pi\left(\frac{n}{N_m}\right);m = 1,2,...,M;n = 1,2,...,N_m. \tag{2}$$

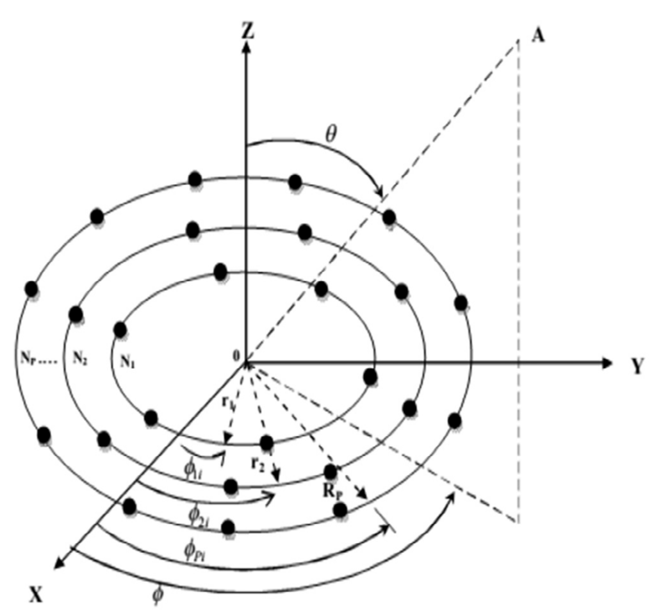

Fig. 1. Concentric circular antenna array structure.

The term α_{mn} is the phase difference between the individual elements in the array which is a function of angular separation ϕ_{mn} and ring radius r_m.

$$\alpha_{mn} = -kr_m\sin\theta_0\cos(\phi_0-\phi_{mn});m = 1,2,...,M;n = 1,2,...,N_m \tag{3}$$

where θ_0 and ϕ_0 are the values of θ and ϕ, respectively, where the peak of the main lobe is obtained. In this paper, $\theta_0 = 90°$ and $\phi_0 = 90°$.

In antenna array design, the directivity is a figure of merit. The directivity (D) measures the power density radiated by the array in the direction of its maximum emission to the power density of an ideal isotropic radiator which emits uniformly in all directions. Directivity is given in (4) [1].

$$D = \frac{|AF_0(\theta_0,\phi_0)|^2}{\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}|AF(\theta,\phi)|^2\sin\theta d\theta d\phi} \tag{4}$$

To obtain the desired radiation pattern the next step for the CCAA design is to formulate the Cost Function (CF) which is given in (5).

$$\begin{aligned} CF = {} & W_1 \times \frac{|AF(\theta_{ms1},I_{mn}) + AF(\theta_{ms2},I_{mn})|}{|AF(\theta_0,I_{mn})|} \\ & + W_2 \times \frac{|\prod_{\theta=-\pi}^{\pi} AF(\theta_{SLL\,Peaks},I_{mn})|}{|AF_{\max}|} \\ & + W_3 \times [FNBW_{Computed}-FNBW(I_{mn} = 1)] \end{aligned} \tag{5}$$

Here, W_1, W_2 and W_3 are the weighting factors; θ_0 is the value of θ where the crest of the main lobe is attained; θ_{ms1} is the angle of the maximum side lobe in the lower band; θ_{ms2} is the angle of the maximum side lobe in the upper band; I_{mn} is the current excitation amplitude weight of nth element in the mth ring. FNBW is the angular separation between the first null on each side of the primary beam. Thus, $\text{FNBW}_{\text{Computed}}$ and FNBW ($I_{mn} = 1$) refer to the computed FNBW for the non-uniform excitation and the FNBW value for the uniform excitation case, respectively. The third term in (5) is computed only if $\text{FNBW}_{\text{Computed}} > \text{FNBW}$ ($I_{mn} = 1$). The third term is used to improve the FNBW value as the narrowing of FNBW improves the directivity of the radiation pattern.

The second term in the right-hand side (RHS) of (5) is used for suppressing the SLL by imposing nulls at all the peaks of side lobes in the radiation pattern. These SLL peaks are represented as $AF(\theta_{SLL\,Peaks},I_{mn})$ within. $\theta \in [-\pi: \theta_{ms1},\theta_{ms2}: \pi]$. $|AF_{\max}|$ is the maximum value of AF. $\prod_{\theta=-\pi}^{\pi}$ represents the product of all the values of $AF(\theta_{SLL\,Peaks},I_{mn})$. So, the minimisation of CF means the maximum reduction of SLL and reduction of FNBW as far as possible. MFO algorithm controls the current excitation weights and inter-element spacing among the array elements in 3 different rings of CCAA structure to minimise the CF.

3. Evolutionary techniques employed

Evolutionary algorithms are characterised as stochastic and adaptive learning based to produce the intelligent optimization schemes. The optimization technique employed for this study is MFO [20–22]. The radiation pattern synthesis of CCAA design problem using MFO confirms the superiority of MFO over those of the recently reported literature like EP [8], BBO [10], FA [11] and SOS [9].

3.1. Moth-Flame Optimization (MFO) algorithm

Moths are fancy insects which come under the family of butterflies. It is observed that the moths converge towards the light. This behaviour of moths is modelled mathematically in MFO algorithm and is discussed in details in [20–22]. In MFO algorithm, the candidate solution is moths, and the positions of the moths in the search space are the problem's variables. Moths can fly in any dimensional space by changing their positional vector. The set of moths in MFO algorithm is