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RESEARCH PAPER

Design of non-uniform concentric circular antenna arrays with optimal sidelobe level reduction using biogeography-based optimization

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This paper presents the design of non-uniform concentric circular antenna arrays (CCAAs) of isotropic radiators with optimum sidelobe level (SLL) reduction. The biogeography-based optimization (BBO) method is used to determine an optimum set of excitation amplitudes that provide a radiation pattern with optimum SLL reduction with the constraint of a fixed major lobe beamwidth. The BBO method represents a new global evolutionary algorithm for optimization problems in electromagnetics. It is shown that the BBO results provide an SLL reduction that is comparable to that obtained using well-known algorithms, such as the particle swarm optimization (PSO), genetic algorithm (GA), and evolutionary programming (EP). Moreover, BBO results are compared with those obtained using the Matlab function Fmincon which uses a sequential quadratic programming (SQP) method. The comparison shows that the design of non-uniformly excited CCAAs using the SQP method provides a SLL reduction that is better than that obtained using global stochastic optimization methods, indicating that global optimization techniques might not really be needed in this problem.

Keywords: Antenna arrays, Circular arrays, Optimization methods, Biogeography-based optimization

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I. INTRODUCTION

Antenna arrays are widely used in different wireless communications applications. To provide a very directive pattern, it is necessary that the fields from the array elements add constructively in some desired directions and add destructively in other directions. Thus, recently, the design of antenna arrays with minimum side lobes level (SLLs) has been a subject of much interest in the literature. Among the different types of antenna arrays, concentric circular antenna arrays (CCAAs) have become more popular in mobile and wireless communications [1]. For the design of CCAAs, one has to adequately choose the total number of antennas in the array, their positions on the circles, the circles radii, and the feeding current (amplitudes and phases) of the antenna elements. In general, the circular array optimization problem is more complicated than the linear array optimization [2–8]. Recently, different well-known evolutionary optimization techniques such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Invasive Weed Optimization (IWO), Differential Evolution (DE), Evolutionary Programming (EP), Firefly Algorithm (FA), Bee Colony Algorithms, and Teaching–Learning-Based Optimization (TLBO), have been used in the synthesis of CCAAs [2–15].

In this paper, the newly proposed global optimization method – the biogeography-based optimization (BBO) [16, 17] is used to determine an optimum set of weights for non-uniform CCAAs that provide a radiation pattern with minimum SLL for a fixed major lobe beamwidth. Moreover, the Matlab function Fmincon, which is based on the sequential quadratic programming (SQP) method, is used to perform the same design. It is shown that the results obtained using Fmincon are generally better than those obtained using the BBO and other global evolutionary methods.

BBO is a new algorithm to solve an optimization problem [16, 17]. BBO is based on the science of biogeography, which is the nature's way of distributing species. It is modeled after the immigration and emigration of species between islands in search of more friendly habitats. BBO has already proven itself as a valuable optimization technique compared to other already developed techniques. Recently, the BBO has been successfully applied in optimal power flow problems [18–21]. In the electromagnetic area, BBO has been applied to the optimal design of Yagi–Uda antenna [22], the calculation of the resonant frequencies of rectangular and circular microstrip patch antennas [23, 24], antenna arrays synthesis [25–30], and the design of multi-stub matching networks

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[31]. Here, BBO is further applied to design CCAAs with minimum SLLs.

This paper is divided as follows: in Section II, the geometry and the array factor for the non-uniform CCAA are presented. In Section III, the fitness (or cost) function is given. In Section IV, the BBO algorithm is briefly described; the reader can consult the references cited above for full details of the BBO algorithm, and [32] to obtain the basic BBO Matlab codes, and finally, design examples are presented in Section V.

II. GEOMETRY AND ARRAY FACTOR

Figure 1 shows the geometry of a CCAA with isotropic antenna elements placed on M rings lying in the x–y plane. In the x–y plane, the array factor for this CCAA is given as follows [1]:

$$AF(\phi) = I_{\text{center}} + \sum_{m=1}^{M}\sum_{n=1}^{N_m} I_{mn} \exp\{j[k\, r_m \cos(\phi - \phi_{mn}) + \alpha_{mn}]\}, \tag{1}$$

where

$$k = \frac{2\pi}{\lambda}, \tag{2}$$

$$\phi_{mn} = \frac{2\pi(n-1)}{N_m}. \tag{3}$$

In the above equations, I_{center} is the excitation amplitude of the center element, if any, that exists at the origin, r_m is the radius of the mth ring (where r_1 is the radius of the innermost ring), I_{mn} and α_{mn} represent the excitation amplitude and phase of the nth element in the mth ring, respectively; and N_m represents the number of elements in the mth ring. Moreover, ϕ_{mn} is the angular position of the nth element lying in the mth ring. It is clear from (3) that the antenna elements in each ring are assumed to be uniformly distributed. To direct the peak of the main beam in the ϕ_0 direction, the excitation phase is chosen to be [1]:

$$\alpha_{mn} = -k\, r_m \cos(\phi_0 - \phi_{mn}). \tag{4}$$

In our design problems, ϕ_0 is chosen to be 0, *i. e.*, the peak of the main beam is along the positive x direction.

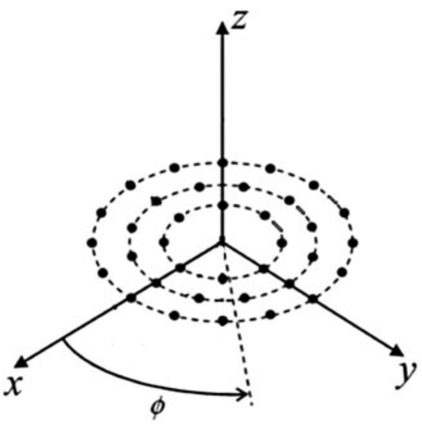

Fig. 1. Geometry of a CCAA with isotropic radiators.

III. FITNESS FUNCTION

In this paper, the goal is to design a CCAA with optimal SLLs reduction for a specific first null beamwidth (FNBW). Thus, the following fitness (objective) function is used [29]:

$$Fitness = (W_1F_1 + W_2F_2)/|AF_{max}|^2, \tag{5}$$

$$F_1 = |AF(\phi_{nu1})|^2 + |AF(\phi_{nu2})|^2, \tag{6}$$

$$F_2 = Max\{|AF(\phi_{ms1})|^2, |AF(\phi_{ms2})|^2\}, \tag{7}$$

where

ϕ_{nu} is the angle at a null. Here, the array factor is minimized at the two angles ϕ_{nu1} and ϕ_{nu2} defining the major lobe, i.e., the FNBW $= \phi_{nu2} - \phi_{nu1} = 2\phi_{nu2}$.

ϕ_{ms1} and ϕ_{ms2} are the angles where the maximum SLL is attained during the optimization process in the lower band (from -180° to ϕ_{nu1}) and the upper band (from ϕ_{nu2} to 180°), respectively. An increment of 1° is used in the optimization process. Thus, the function F_2 minimizes the maximum SLL around the major lobe.

Moreover, AF_{max} is the maximum value of the array factor, i.e., its value at ϕ_0. W_1 and W_2 are weighting factors which are chosen here to be 1 and 5, respectively. Thus, for the design of CCAA with minimum SLL, the optimization problem is to search for the current amplitudes (I_{mn} and I_{center} if a center element exists) that minimize the above fitness function.

IV. BIOGEOGRAPHY BASED OPTIMIZATION

Although the BBO algorithm is described elsewhere in the literature [16, 17], for the sake of completeness, it is described here briefly. BBO is a new evolutionary algorithm developed by Simon [16, 17]. BBO is a metaphor drawn from the science of biogeography which is specializing in studying the geographical distribution of living organisms. Mathematical biogeography models are based on the metaphor of extinction and migration of species between neighboring islands. An "island" is any habitat (area) that is geographically isolated from other habitats. Islands that are more suitable for habitation have a high "habitat suitability index" (HSI), which is treated as a dependent variable because it correlates with many factors such as rainfall, temperature, diversity of vegetation and topography, and so on. Another important BBO variable is the "suitability index variable" (SIV) which generally characterizes an island's habitability and is treated as an independent variable.

BBO algorithm can be summarized and described in the following three steps:

(1) Create a set of solutions (parameters characterizing an island's habitability, $Habitat = [SIV_1, SIV_2, SIV_3, \ldots\ldots, SIV_N]$) to the problem, where they are randomly selected within the search bound, then calculate the value of the fitness function (suitability for habitation, $fitness(Habitat) = HSI = f(SIV_1, SIV_2, SIV_3, \ldots\ \ldots, SIV_N)$) which is found by evaluating the fitness function.

(2) Applying migration process: in the migration step, the immigration rate $\lambda = 1 - (S/S_{max})$ and the emigration rate $\mu = S/S_{max}$ of each solution (where S is the number of species in the habitat; and S_{max} is the maximum possible number of species), which are used to probabilistically share information between habitats with probability P_{mod} (known as the habitat modification probability), are calculated and applied as summarized in the following migration flow chart:

```
For $i = 1$ to $n$ (where $n$ is the number of islands)
    Select $H_i$ with probability $\alpha\ \lambda_i$
        If $H_i$ is selected
            For $j = 1$ to n
    Select $H_j$ with probability $\alpha\ \mu_j$
                If $H_j$ is selected
                    Randomly select an SIV from $H_j$
                    Replace the SIV in $H_i$ with the selected
                    SIV from $H_j$
                End
            End
        End
End
```

(3) Applying mutation process: the mutation step tends to increase the diversity among the population and gives the solutions the chance to improve their selves to the best. Performing mutation on a solution is done by replacing it with a new solution that is randomly generated. The following flow chart summarizes the mutation process:

```
For $i = 1$ to n
    For $j = 1$ to $N$ (where $N$ is the number of variables)
        Select SIV $H_i(j)$ with probability $\alpha\ P_m$ (Mutation
        Probability)
            If $H_i(j)$ is selected
                Replace $H_i(j)$ with a randomly generated
                SIV
            End
        End
End
```

V. RESULTS

Several examples with different number of antenna elements have been optimized using the BBO and SQP methods. It should be noted that the SQP method is not a stochastic method, and its results depend mainly on the initial estimate. In our implementation, the initial estimate is set to be a random vector using the rand function in Matlab. In a series of papers [2–8], Mandal *et al* applied several optimization methods (GA, EP and PSO and its variants) on the same problem studied here. In [6], it was shown that the minimum SLL is obtained using EP. Thus, for comparison purposes, the BBO and SQP results presented here will be compared with the EP results presented in [6]. In the design examples presented below, it is assumed that the CCAA is composed of 3 rings ($M = 3$). Moreover, in each ring, the inter-element spacing is assumed to be constant being 0.55λ, 0.606λ, and 0.75λ for the first, second, and third rings, respectively [6]. CCAAs with and without the center element are investigated.

In the BBO implementation, the following parameters are used: population size = 150, number of generations = 500, habitat modification probability = 1, mutation probability = 0.01 and elitism parameter = 2. The minimum and maximum allowable values for the variables (i.e., the

Table 1. Excitation weights of non-uniform CCAA with $N_1 = 4$, $N_2 = 6$, $N_3 = 8$ without central element.

	Max. SLL (dB)	$[I_{11}\ I_{12}\ I_{13}\ I_{14};\ I_{21}\ I_{22}\ I_{23}\ I_{24}\ I_{25}\ I_{26};\ I_{31}\ I_{32}\ I_{33}\ I_{34}\ I_{35}\ I_{36}\ I_{37}\ I_{38}]$
BBO	−30.6	[0.7975 0.3477 0.7950 0.3348; 1.0000 0.5046 0.5078 1.0000 0.5171 0.5073; 0.2260 0.5173 0.8248 0.5079 0.2251 0.5263 0.7986 0.5332]
SQP	−33.16	[0.6701 0.0310 0.6669 0.0203; 0.9998 0.3911 0.3886 1.0000 0.3831 0.3852; 0.2501 0.4610 0.6812 0.4627 0.2542 0.4630 0.6642 0.4614]
EP [6]	−31.84	[0.3416 0.0496 0.3242 0.0283; 0.5321 0.2114 0.1923 0.4901 0.1876 0.1994; 0.1204 0.2555 0.3527 0.2450 0.1229 0.2294 0.3449 0.2400]

Table 2. Excitation weights of non-uniform CCAA with $N_1 = 4$, $N_2 = 6$, $N_3 = 8$ with central element.

	Max. SLL (dB)	$[I_{center};\ I_{11}\ I_{12}\ I_{13}\ I_{14};\ I_{21}\ I_{22}\ I_{23}\ I_{24}\ I_{25}\ I_{26};\ I_{31}\ I_{32}\ I_{33}\ I_{34}\ I_{35}\ I_{36}\ I_{37}\ I_{38}]$
BBO	−38.2	[0.4669; 1.0000 0.7560 0.9983 0.7491; 0.7394 0.7319 0.7228 0.7698 0.7307 0.7288; 0.1801 0.5440 0.6968 0.5683 0.1953 0.5568 0.6848 0.5297]
SQP	−45.72	[0.6724; 0.9111 0.9818 0.9129 0.9831; 0.1076 0.6798 0.6751 0.1048 0.6756 0.6800; 0.0638 0.2709 0.3865 0.2711 0.0621 0.2718 0.3885 0.2714]
EP [6]	−39.73	[0.377; 0.5502 0.5477 0.5530 0.5890; 0.0976 0.3830 0.3972 0.0999 0.4152 0.4051; 0.0417 0.1730 0.2290 0.1734 0.0401 0.1750 0.2755 0.1717]

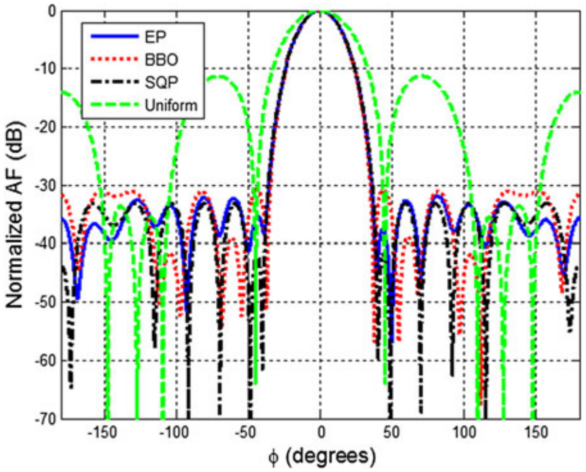

Fig. 2. Radiation pattern for Example 1 using the BBO, SQP, and EP results in Table 1 along with the radiation pattern of a uniform CCAA.

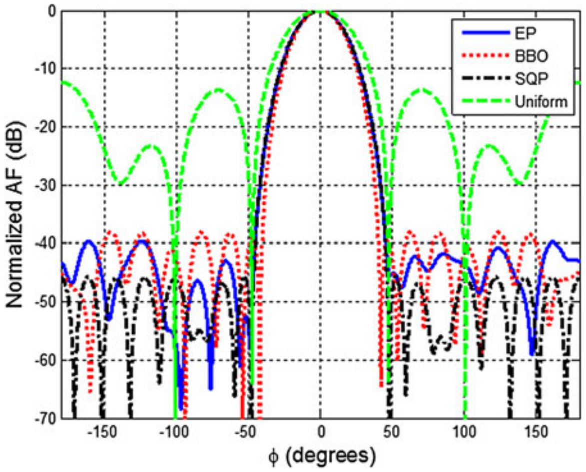

Fig. 3. Radiation pattern for Example 1 using the BBO, SQP, and EP results in Table 2 along with the radiation pattern of a uniform CCAA.

excitation amplitudes) are set to 0 and 1, respectively. The design examples are performed for a specific FNBW, which corresponds to a uniformly-fed CCAA with a uniform $\lambda/2$ element-spacing and the same number of elements. BBO and SQP codes are run for 20 independent times. Two examples are presented here:

Example 1: $N_1 = 4$, $N_2 = 6$, $N_3 = 8$.

Tables 1 and 2 show the best results obtained using BBO and SQP for this CCAA with and without the central element, respectively. "Best results" are defined as the ones that give the smallest maximum SLL. The current amplitudes for the array elements are normalized such that $max(I) = 1$. As mentioned above, the same examples were considered in [6] using the standard PSO (and its variant Particle Swarm Optimization with Constriction Factor and Inertia Weight Approach (PSOCFIWA)) and EP. It was found in [6] that the EP gave a maximum SLL that is less than that obtained by PSO and PSOCFIWA. Thus, BBO and SQP results will be compared with EP results only.

Figures 2 and 3 show the array factor obtained using the results in Tables 1 and 2, respectively. In Fig. 2, the maximum SLL obtained using the BBO and SQP are −30.6 and −33.16 dB, respectively. On the other hand, in Fig. 3, the maximum SLL obtained using the BBO and SQP are −38.2 and −45.72 dB, respectively. These values are compared to those obtained using EP [6] in Tables 1 and 2. It can be seen that the maximum SLL values obtained using BBO are comparable to those obtained using EP. It should be also noted that the maximum SLL values obtained using BBO are better than those obtained using PSO and PSOCFIWA [6]. From Tables 1 and 2, it is interesting to note that the maximum SLL obtained using SQP is better than BBO and EP results. Thus, for this CCAA design problem, not only global optimization methods might not really be needed, but also as mentioned in [33]: "*the use of global optimization algorithms is not only a waste of computational resources, but can, indeed, prevent the attainment of the solution*". From Figs 2 and 3, it can be seen that the uniform circular arrays with the same number of elements and $\lambda/2$ element-to-element spacing have maximum SLLs of −11.23 and −12.31 dB, respectively.

Example 2: $N_1 = 8$, $N_2 = 10$, $N_3 = 12$.

Tables 3 and 4 show the best results obtained using BBO and SQP for this CCAA with and without the central element, respectively, along with the EP results from [6].

Figures 4 and 5 show the array factor obtained using the results in Tables 3 and 4, respectively. Again, the BBO method proves to be an effective optimization technique with respect to designing non-uniform CCAAs with optimum SLL. Its results are as good as well-developed optimization techniques, like EP and PSO [6], and GA [2]. From Tables 3 and 4, it is interesting to note that the maximum SLL obtained using SQP is better than BBO and EP results. This, again, indicates that global optimization methods might not really be needed in this CCAA design problem [33].

Table 3. Excitation weights of non-uniform CCAA with $N_1 = 8$, $N_2 = 10$, $N_3 = 12$ without central element.

	Max. SLL (dB)	$[I_{11} \ldots I_{18}; I_{21} \ldots I_{2,10}; I_{31} \ldots I_{3,12}]$
BBO	−26.83	[0.9670 0.6957 0.3821 0.7366 0.9184 0.8001 0.2855 0.7184; 0.5634 0.6631 0.1436 0.2588 0.6330 0.6310 0.6184 0.2104 0.1214 0.7737; 0.6059 0.4075 0.3080 1.0 0.2797 0.3986 0.5384 0.3191 0.3241 0.9751 0.3741 0.3804]
SQP	−27.74	[0.7489 0.6802 0.2215 0.7085 0.7993 0.7182 0.2220 0.6914; 0.5608 0.5471 0.1255 0.1374 0.5816 0.5741 0.5904 0.1227 0.1123 0.5560; 0.5030 0.3797 0.2825 0.9968 0.3036 0.3680 0.4846 0.3685 0.3295 0.9991 0.3096 0.3806]
EP [6]	−26.12	[0.2242 0.2886 0.1891 0.3336 0.5458 0.3895 0.1000 0.2866; 0.1595 0.1378 0.1036 0.10 0.4048 0.2686 0.3090 0.10 0.10 0.1696; 0.2419 0.1183 0.1144 0.4708 0.1685 0.2090 0.2566 0.2200 0.1000 0.4229 0.1273 0.1020]

Table 4. Excitation weights of non-uniform CCAA with $N_1 = 8$, $N_2 = 10$, $N_3 = 12$ with central element.

	Max. SLL (dB)	$[I_{center}; I_{11} \ldots I_{18}; I_{21} \ldots I_{2,10}; I_{31} \ldots I_{3,12}]$
BBO	−29.61	[0.7208; 1.0 0.6648 0.8292 0.6373 1.0000 0.5945 0.8948 0.5061; 0.5600 0.8204 0.0529 0.1067 0.8818 0.5429 0.7970 0.0846 0 0.8129; 0.4745 0.4304 0.4370 0.9898 0.5142 0.3695 0.4323 0.3746 0.4201 0.9710 0.4175 0.4277]
SQP	−34.7	[0.9263; 0.8538 0.3841 0.9919 0.4112 0.9154 0.4028 1.0000 0.3797; 0.2222 0.6265 0.017 0.0313 0.6672 0.2532 0.6587 0.0328 0.0192 0.6063; 0.1924 0.2820 0.2794 0.5826 0.3003 0.2980 0.1906 0.3060 0.2900 0.5799 0.2619 0.2928]
EP [6]	−28.92	[0.2750; 0.2989 0.4102 0.3979 0.7325 0.3989 0.3813 0.2785 0.2628; 0.23 0.0187 0.0464 0.562 0.2875 0.5240 0.0855 0.0166 0.1763 0.1283; 0.1225 0.1932 0.5081 0.2903 0.2285 0.2227 0.2858 0.2278 0.4828 0.0957 0.1756 0.2082]

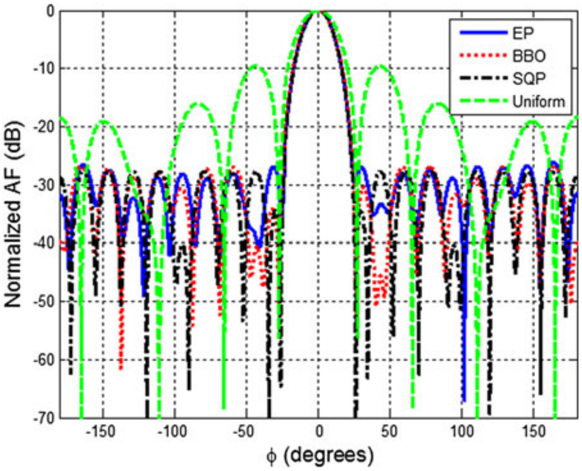

Fig. 4. Radiation pattern for Example 2 using the BBO, SQP, and EP results in Table 3 along with the radiation pattern of a uniform CCAA.

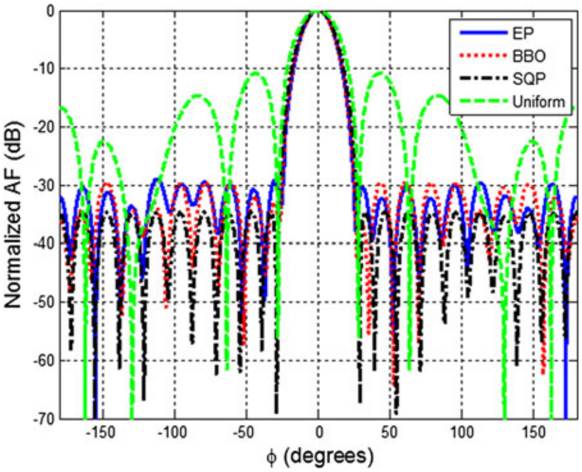

Fig. 5. Radiation pattern for Example 2 using the BBO, SQP, and EP results in Table 4 along with the radiation pattern of a uniform CCAA.

VI. CONCLUSIONS

In this paper, the BBO method was used to adjust the excitations of the antenna elements in a concentric circular array to obtain an optimum SLL. The obtained optimized array factor was compared to that obtained using other optimization techniques. Array factor patterns for the BBO-designed CCAAs are generally as good as those presented in the literature, which clearly shows the effectiveness of BBO. Moreover, the Matlab function Fmincon, which uses the SQP method, has been used to design the same arrays and has shown to give results that are better than those obtained using global stochastic optimization methods. This indicates that for the problem under consideration (i.e., the design of non-uniformly excited CCAA with optimum SLL), stochastic global optimization methods might not really be needed [33].

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