Circular Antenna Array Synthesis Using Firefly Algorithm

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Received 25 September 2012; accepted 10 January 2013

ABSTRACT: In this article, the design of circular antenna arrays (CAAs) and concentric circular antenna arrays (CCAAs) of isotropic radiators with optimum side lobe level (SLL) reduction is studied. The newly proposed global evolutionary optimization method; namely, the firefly algorithm (FA) is used to determine an optimum set of weights and positions for CAAs, and an optimum set of weights for CCAAs, that provides a radiation pattern with optimum SLL reduction with the constraint of a fixed major lobe beamwidth. The FA represents a new algorithm for optimization problems in electromagnetics. It is shown that the FA results provide a SLL reduction that is better than that obtained using well-known algorithms, like the particle swarm optimization, genetic algorithm (GA), and evolutionary programming. Int J RF and Microwave CAE 00:000–000, 2013.

Keywords: antenna arrays; circular arrays; optimization techniques; firefly algorithm

I. INTRODUCTION

Antenna arrays are widely used in modern communication and radar systems [1, 2]. In contrast to linear antenna arrays [3–6], the radiation patterns of circular antenna arrays (CAAs) and concentric circular antenna arrays (CCAAs) inherently cover the entire space and the main lobe could be oriented in any desired direction. 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 has been a subject of very much interest in the literature. To accomplish this, different global evolutionary optimization techniques [e.g., particle swarm optimization (PSO), genetic algorithm (GA) and evolutionary programming (EP)] have been used in the synthesis of nonuniform CAAs and CCAAs [7–22]. In this article, the newly proposed global optimization method, firefly algorithm (FA) [23] is used to design nonuniform CAAs and CCAAs of isotropic radiators with optimum side lobe level (SLL) reduction. FA is based on the attractiveness and movements of fireflies [23, 24]. Recently, the FA has been successfully applied in the electromagnetics area, where it has been applied to the synthesis of antenna arrays [25–27]. In this article, for CAAs, FA is used to determine an optimum set of weights and positions that provide a radiation pattern with optimum SLL reduction with the constraint of a fixed major lobe beamwidth. On the other hand, for CCAAs, it is used to determine an optimum set of weights only that accomplishes the same objective of getting an optimum SLL reduction.

The rest of this artcile is organized as follows: In Section II, FA is briefly described. In Section III, the geometry and array factor for both the CAA and CCAA are presented. Moreover, the fitness function is given. Then, based on these models, in Section IV, numerical results are given and compared to the results obtained using other optimization methods. Finally, the article is concluded in Section V.

II. FA

FA is a new nature inspired algorithm developed by Yang [23, 24]. Several well-known optimization techniques; such as invasive weed optimization (IWO) [28], ant colony optimization (ACO) [29], PSO [30] and recently FA mimic insect behavior in problem modeling and solution. FA is based on the flashing light of fireflies which is produced by a process of bioluminescence. The objectives of flashing system in fireflies are to attract marrying partners, to attract potential victim, and to give a warning sign. The attractive process between fireflies is based on their light

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DOI 10.1002/mmce.20721
Published online in Wiley Online Library (wileyonlinelibrary.com).

intensity where fireflies move toward the brightest ones. FA employs this swarm behavior in optimization problem where the light intensity and location of firefly correspond to the fitness value and a set of solution to the optimized problem.

FA algorithm can be summarized and described as follows:

I. Create a set of solutions (location of n-fireflies in the d-dimensional search space) to the problem, where they are randomly selected within the search bound:

$$x_i = (x_{i1}, x_{i2}, \ldots, x_{id}) \quad \text{for} \quad i = 1, 2, \ldots, n \tag{1}$$

II. Calculate the fitness function $f\ (x_i)$ (Intensity (I_i)) of each solution (each firefly position) and sort the population from best (brightest) to worst (dimmest). For minimization problem:

$$I_i \propto 1/f(x_i) \tag{2}$$

III. Update fireflies' locations depending upon the attractiveness between the brighter one and the moving firefly where fireflies i (low intensity) are attracted toward other fireflies j that are more brighter (highest intensity) using the following formula:

$$x_i = x_i + \beta_o e^{-\gamma r_{ij}^2}(x_j - x_i) + \alpha(\text{rand} - 0.5) \tag{3}$$

$$r_{ij} = \|x_i - x_j\| = \left(\sum_{k=1}^{d}(x_{i,k} - x_{j,k})^2\right)^{0.5} \tag{4}$$

where x_i and x_j are fireflies locations, γ is the light absorption coefficient, β_o is the attractiveness coefficient, r_{ij} is the Cartesian distance between the two fireflies i and j, α is the randomization parameter, *rand* is a random number generator uniformly distributed in [0, 1]. The flow chart shown at the bottom of the left column summarizes the main steps in the FA.

Define the fitness function $f(x)$;
Set the input parameters of the firefly algorithm such as:
  Maximum generation (*Max Generation*) (number of iteration cycles);
  Population size (n) (number of fireflies);
  Number of variables (d) (the d-dimensional search space);
  The light absorption coefficient (γ) (between 0 and infinity, *default* = 1);
  The attractiveness coefficient (β_o) (between 0 and 1, *default* = 0.2);
  The randomization parameter (α) (between 0 and 1, *default* = 0.25);
For $i = 1$ to n
    $x_i = rand\ (x_{i1}, x_{i2}, \ldots, x_{id})$; Create a set of random solutions to the problem.
    $f(x_i)$; Calculate the fitness function.
End
  Sort the solutions from best to worst (brightest to dimmest).
For *counter* = 1 to *Max Generation*
  For $i = 1$ to n
    For $j = 1$ to n
      $r_{ij} = |x_i - x_j| = (\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2)^{0.5}$
        If Intensity (i) > Intensity (j)
          $x_i = x_i + \beta_o\ e^{-\gamma r_{ij}^2}\ (x_j - x_i) + \alpha\ (rand - 0.5)$
        End
    End
  End
  For $i = 1$ to n
    $f(x_i)$; Calculate the fitness function for the new fireflies' locations.
  End
  Sort the solutions from best to worst (brightest to dimmest).
End

III. GEOMETRY AND ARRAY FACTOR

A. CAA

Figure 1 shows the geometry of a CAA with N isotropic antenna elements placed nonuniformly on a ring (of radius a) lying in the x–y plane ($\theta = 90°$). As isotropic radiators are assumed, the radiation pattern of this array can be described by its array factor, which is given as follows [1]:

$$AF(\theta, \phi) = \sum_{n=1}^{N} I_n\ \exp(j[ka\ \sin(\theta)\cos(\phi - \phi_n) + \alpha_n]) \tag{5}$$

where

$$ka = \frac{2\pi}{\lambda}a = \sum_{i=1}^{N} d_i \tag{6}$$

$$\phi_n = \frac{2\pi \sum_{i=1}^{n} d_i}{ka} \tag{7}$$

$$\alpha_n = -k\ a\ \sin(\theta_o)\ \cos(\phi_o - \phi_n) \tag{8}$$

In the above equations, I_n and α_n represent the excitation amplitude and phase of the nth element. Moreover, d_n represents the arc separation (in terms of wavelength) between element n and element n–1 (d_1 being the arc distance between the first ($n = 1$) and last ($n = N$) elements), ϕ_n is the angular position of the nth element in the x–y plane, ϕ is the azimuth angle measured from the positive

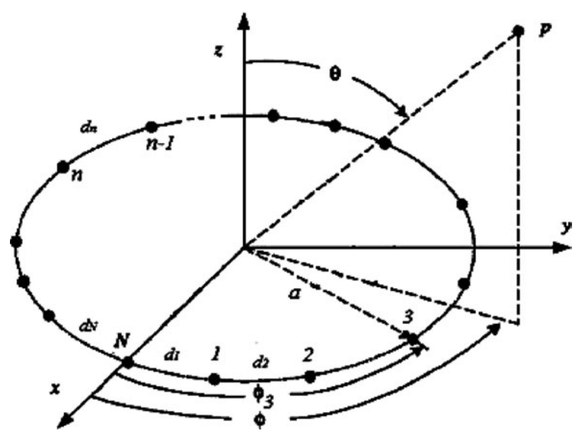

Figure 1 Geometry of a nonuniform circular antenna array with N isotropic antennas.

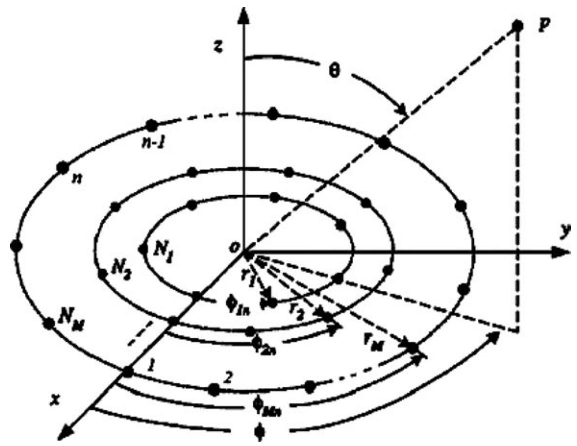

Figure 2 Geometry of a CCAA with isotropic radiators.

x-axis, θ is the elevation angle measured from the positive z-axis [in our examples, we consider the array factor in the x–y plane ($\theta = 90°$)], and θ_o and ϕ_o are the direction of the main beam. Here, θ_o and ϕ_o are chosen to be 90° and 0°, respectively, *i.e.,* the peak of the main beam is directed along the positive x-axis.

B. CCAA

Figure 2 shows the geometry of a CCAA with isotropic antenna elements placed on M rings lying in the x–y plane. The array factor for this CCAA is given as follows [1]:

$$AF(\theta, \phi) = I_{\text{center}} + \sum\nolimits_{m=1}^{M} \sum\nolimits_{n=1}^{N_m} I_{mn} \times \exp\{j[k\, r_m \, \sin(\theta)\, \cos(\phi - \phi_{mn}) + \alpha_{mn}]\} \quad (9)$$

where

$$k = \frac{2\pi}{\lambda} \quad (10)$$

$$\phi_{mn} = \frac{2\pi(n-1)}{N_m} \quad (11)$$

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 (11) that the antenna elements in each ring are assumed to be uniformly distributed. To direct the peak of the main beam in the (θ_o, ϕ_o) direction, the excitation phase is chosen to be [1]:

$$\alpha_{mn} = -kr_m \, \sin(\theta_o) \, \cos(\phi_o - \phi_{mn}) \quad (12)$$

As stated previously, θ_o and ϕ_o are chosen to be 90° and 0°, respectively.

C. Fitness Function

In antenna array problems, there are many parameters that can be used to evaluate the fitness (or cost) function such as gain, SLL, radiation pattern, and size. Here, the goal is to design arrays with minimum side lobes levels for a specific first null beamwidth (FNBW). Thus, the following fitness function is used:

$$\text{Fitness} = (W_1 F_1 + W_2 F_2)/|AF_{\max}|^2 \quad (13)$$

$$F_1 = |AF(\phi_{\text{nu1}})|^2 + |AF(\phi_{\text{nu2}})|^2 \quad (14)$$

$$F_2 = \max\{|AF(\phi_{\text{ms1}})|^2, |AF(\phi_{\text{ms2}})|^2\} \quad (15)$$

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, that is, FNBW $= \phi_{\text{nu2}} - \phi_{\text{nu1}} = 2\phi_{\text{nu2}}$. 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, that is, its value at (θ_o, ϕ_o). W_1 and W_2 are weighting factors which are chosen here to be unity for the CAA examples while they are 1 and 5, respectively, for CCAA examples. Thus, for the design of CAAs with minimum SLL, the optimization problem is to search for the current amplitudes (I_n's) and the arc distances between the elements (d_n's) that accomplish this. Conversely, for the design of CCAAs, the problem is to search for the current amplitudes (I_{mn}'s and I_{center} if a center element exists) only that minimize the maximum SLL.

IV. NUMERICAL RESULTS

A. Eight Elements CAA

An eight-element CAA is optimized using FA. The FA code is run for 20 independent times. Table I shows the

TABLE I Weights and Spacings for the Optimized $N = 8$ CAA

$\phi_{\text{nu2}} = 34°$	$[d_1, d_2, d_3, \ldots, d_8]$ in λ's $[I_1, I_2, I_3, \ldots, I_8]$	Max SLL (dB)
FA	[0.3377, 0.8274, 0.8575, 0.6306, 0.8538, 0.7092, 0.2499, 0.1895] $\Rightarrow \sum = 4.6556$ [0.8251, 0.7018, 0.9962, 0.9964, 0.4933, 0.5697, 0.4228, 0.1669]	−13.0 dB
GA [7]	[0.1739, 0.3144, 0.662, 0.7425, 0.6297, 0.8969, 0.4633, 0.5267] $\Rightarrow \sum = 4.4094$ [0.3289, 0.2537, 0.7849, 1.0, 0.9171, 0.5183, 0.6176, 0.4612]	−9.81 dB
PSO [8]	[0.3590, 0.5756, 0.2494, 0.7638, 0.6025, 0.8311, 0.7809, 0.3308] $\Rightarrow \sum = 4.4931$ [0.7765, 0.3928, 0.6069, 0.8446, 1.0000, 0.7015, 0.9321, 0.3583]	−10.8 dB
Uniform	[0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5] $\Rightarrow \sum = 4.0$ [1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0]	−4.17 dB

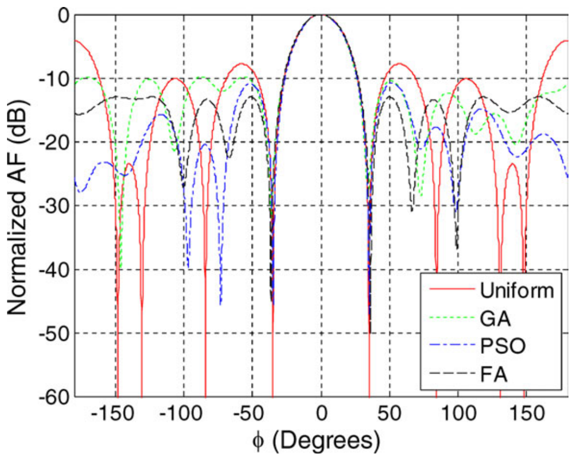

Figure 3 Radiation pattern for the optimized $N = 8$ CAA. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

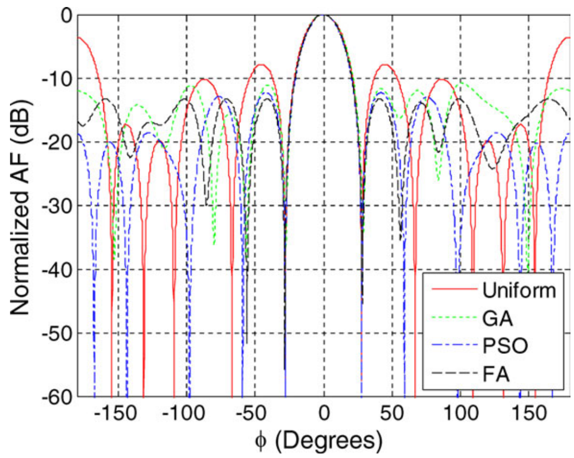

Figure 4 Radiation pattern for the optimized $N = 10$ CAA. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

best results obtained using FA. ''Best results'' are defined as the ones that provide a radiation pattern with the best maximum SLL reduction. Moreover, results obtained using other optimization techniques are included in the same table. Figure 3 shows the radiation patterns of the FA, GA [7] and PSO [8] as compared to uniform CAA. The maximum SLL obtained using the FA is −13 dB. It should be noted that this value is better than those obtained using GA [7] and PSO [8]. Specifically, the maximum SLLs obtained using GA and PSO were −9.81 nd −10.8 dB, respectively. It is worth mentioning that a uniform circular array with the same number of elements and $\lambda/2$ element-to-element spacing has a maximum SLL of −4.17 dB.

B. 10 Elements CAA

In this example, a 10-element CAA is optimized using FA. The best results are listed in Table II in comparison with GA and PSO techniques. Figure 4 shows the radiation pattern obtained by the FA, GA and PSO as compared to a uniform CAA. The maximum SLL obtained using FA is −13.31 dB, while that obtained using the GA [7], PSO [8], and the uniform array is −10.85, −12.31, and −3.6 dB, respectively. It can be noted that the FA gives slightly better maximum SLL.

C. 12 Elements CAA

Similar to the previous examples, Table III shows the FA results for 12 elements CAA, while Figure 5 shows a comparison between the array factors obtained using the different optimization methods as compared to a uniform array. The maximum SLLs obtained using the FA, GA [7], and PSO [8] methods are −14.21, −11.79, and −13.68 dB, respectively.

From the above examples, it is clear that the FA results are somewhat better than those obtained using the well-known GA and PSO techniques. This shows the effectiveness of the FA in solving antenna array problems.

D. CCAA with $N_1 = 4$, $N_2 = 6$, $N_3 = 8$.

In this example (and the following ones), it is assumed that the CCAA is composed of three 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 [9]. CCAAs with and

TABLE II Weights and Spacings for the Optimized $N = 10$ CAA

$\phi_{nu2} = 27°$	$[d_1, d_2, d_3, \ldots, d_{10}]$ in λ's $[I_1, I_2, I_3, \ldots, I_{10}]$	Max SLL (dB)
FA	[0.3810, 0.7453, 0.2668, 0.3142, 1.0000, 0.6032, 0.9706, 0.5713, 0.8800, 0.3376] $\Rightarrow \sum =$ 6.0700 [0.7081, 0.2682, 0.3713, 0.4100, 0.8800, 0.9665, 0.4165, 0.5813, 0.7494, 0.5403]	−13.3 dB
GA [7]	[0.3641, 0.4512, 0.275, 1.6373, 0.6902, 0.9415, 0.4657, 0.2898, 0.6456, 0.3282] $\Rightarrow \sum =$ 6.0886 [0.9545, 0.4283, 0.3392, 0.9074, 0.8086, 0.4533, 0.5634, 0.6015, 0.7045, 0.5948]	−10.85 dB
PSO [8]	[0.3170, 0.9654, 0.3859, 0.9654, 0.3185, 0.3164, 0.9657, 0.3862, 0.9650, 0.3174] $\Rightarrow \sum =$ 5.9029 [1.0000, 0.7529, 0.7519, 1.0000, 0.5062, 1.0000, 0.7501, 0.7524, 1.0000, 0.5067]	−12.31 dB
Uniform	[0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5] $\Rightarrow \sum = 5.0$ [1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0]	−3.6 dB

TABLE III Weights and Spacings for the Optimized $N = 12$ CAA

$\phi_{nu2} = 23°$	$[d_1, d_2, d_3, \ldots, d_{12}]$ in λ's $[I_1, I_2, I_3, \ldots, I_{12}]$	Max SLL (dB)
FA	[0.3171, 0.8105, 0.5833, 0.7609, 0.8946, 0.4747, 0.9868, 0.2509, 0.2932, 0.7748, 0.6722, 0.3955] $\Rightarrow \sum = 7.2145$ [0.9175, 0.3153, 0.5814, 0.6311, 0.9629, 0.9903, 0.3297, 0.4345, 0.6820, 0.4397, 0.7151, 0.7605]	−14.21 dB
GA [7]	[0.4936, 0.4184, 1.4474, 0.7577, 0.4204, 0.5784, 0.4520, 0.8872, 0.7514, 0.4202, 0.4223, 0.7234] $\Rightarrow \sum = 7.7724$ [0.2064, 0.5461, 0.2246, 0.6486, 0.7212, 0.7993, 0.5277, 0.3485, 0.5125, 0.4475, 0.5233, 0.8553]	−11.97 dB
PSO [8]	[0.2569, 0.8509, 0.6607, 0.7057, 0.8540, 0.3734, 0.1609, 0.8321, 0.6464, 0.7079, 0.8330, 0.2682] $\Rightarrow \sum = 7.1501$ [0.9554, 0.6641, 0.7109, 0.7769, 1.0000, 1.0000, 0.3958, 0.7162, 0.6746, 0.7695, 0.9398, 0.6415]	−13.68 dB
Uniform	[0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5] $\Rightarrow \sum = 6.0$ [1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0]	−7.17 dB

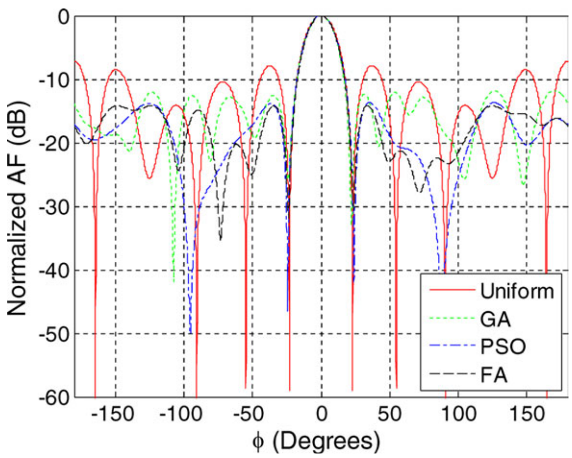

Figure 5 Radiation pattern for the optimized $N = 12$ CAA. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

without center element are investigated. The same examples were considered in [9] using the standard PSO [and its variant PSO with Constriction Factor and Inertia Weight Approach (PSOCFIWA)] and EP. It was found in [9] that the EP gave a maximum SLL that is less than that obtained by PSO and PSOCFIWA. Thus, FA results will be compared with EP results only.

FA code is run for 20 independent times. Tables IV and V show the best results obtained using FA for this CCAA with and without the central element, respectively. Figures 6 and 7 show the array factor obtained using the results in Tables IV and V, respectively. In Figure 6, the maximum SLL obtained using the FA is −33.2 dB. On the other hand, in Figure 7, the maximum SLL obtained using the FA is −40.42 dB. These values are compared to those obtained using EP [9].

It can be seen that the maximum SLL values obtained using FA are comparable to (or even better than) those obtained using EP. It should be also noted that the maximum SLL values obtained using FA are better than those obtained using PSO and PSOCFIWA [9]. From Tables IV and V, it can be seen that the uniform CCAA's with the same number of elements and $\lambda/2$ element-to-element spacing have maximum SLLs of −11.23 and −12.31 dB, respectively.

E. CCAA with $N_1 = 8$, $N_2 = 10$, $N_3 = 12$.

Tables VI and VII show the best results obtained using FA for this CCAA with and without the central element, respectively, along with the EP results from [9]. Figures 8 and 9 show the corresponding array factors. Again, the

TABLE IV Excitation Weights of Nonuniform CCAA with $N_1 = 4$, $N_2 = 6$, $N_3 = 8$ Without Central Element

$\phi_{nu2} = 46°$	$[I_{1,1}\ I_{1,2}\ I_{1,3}\ I_{1,4}\ ;\ I_{2,1}\ I_{2,2}\ I_{2,3}\ I_{2,4}\ I_{2,5}\ I_{2,6}\ ;\ I_{3,1}\ I_{3,2}\ I_{3,3}\ I_{3,4}\ I_{3,5}\ I_{3,6}\ I_{3,7}\ I_{3,8}]$	Max SLL (dB)
FA	[0.7025 0.1410 0.6770 0.1215; 0.9999 0.4349 0.4084 0.9999 0.4076 0.4305; 0.2352 0.4789 0.7366 0.4831 0.2542 0.4790 0.7172 0.4730]	−33.20
EP [9]	[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]	−31.84
Uniform	[1 1 1 1 ; 1 1 1 1 1 1; 1 1 1 1 1 1 1 1]	−11.23

TABLE V Excitation Weights of Nonuniform CCAA with $N_1 = 4$, $N_2 = 6$, $N_3 = 8$ with Central Element

$\phi_{nu2} = 52°$	$[I_{center}\ ;\ I_{1,1}\ I_{1,2}\ I_{1,3}\ I_{1,4}\ ;\ I_{2,1}\ I_{2,2}\ I_{2,3}\ I_{2,4}\ I_{2,5}\ I_{2,6}\ ;\ I_{3,1}\ I_{3,2}\ I_{3,3}\ I_{3,4}\ I_{3,5}\ I_{3,6}\ I_{3,7}\ I_{3,8}]$	Max SLL (dB)
FA	[0.5142; 0.9943 0.8029 0.9508 0.8087; 0.5727 0.7228 0.7056 0.6025 0.7020 0.7262; 0.1516 0.4732 0.6145 0.4837 0.1627 0.4748 0.6159 0.4648]	−40.43
EP [9]	[0.3770 ; 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]	−39.73
Uniform	[1; 1 1 1 1 ; 1 1 1 1 1 1; 1 1 1 1 1 1 1 1]	−12.31

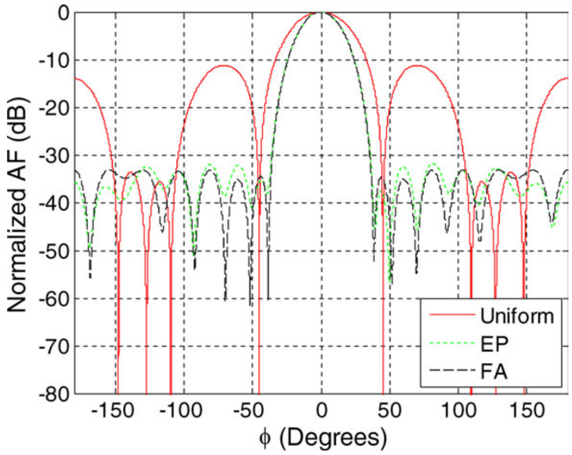

Figure 6 Radiation pattern for the CCAA using the results in Table IV. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

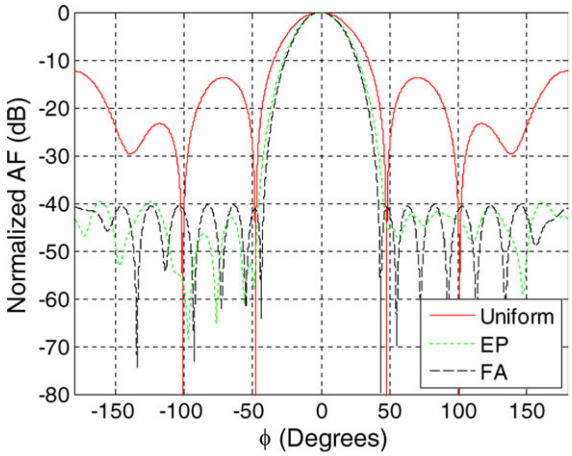

Figure 7 Radiation pattern for the CCAA using the results in Table V. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

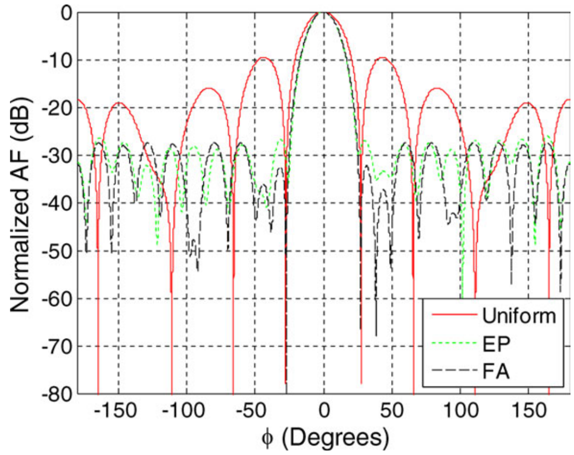

Figure 8 Radiation pattern for the CCAA using the results in Table VI. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

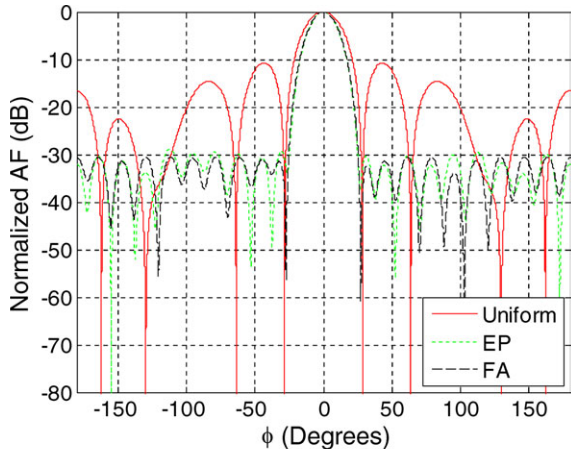

Figure 9 Radiation pattern for the CCAA using the results in Table VII. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE VI Excitation Weights of Nonuniform CCAA with $N_1 = 8$, $N_2 = 10$, $N_3 = 12$ Without Central Element

$\phi_{nu2} = 28°$	$[I_{1,1} \ldots I_{1,8}\ ;\ I_{2,1} \ldots I_{2,10}\ ;\ I_{3,1} \ldots I_{3,12}]$	Max SLL (dB)
FA	[0.9354 0.7716 0.3013 0.7299 0.8924 0.7641 0.3044 0.7999; 0.5444 0.5686 0.2124 0.1958 0.5901 0.5647 0.6322 0.1498 0.1660 0.6379; 0.5044 0.4125 0.2457 0.9673 0.2516 0.3827 0.4854 0.3444 0.3209 0.9734 0.3290 0.3651]	−27.49
EP [9]	[0.2242 0.2886 0.1891 0.3336 0.5458 0.3895 0.1000 0.2866; 0.1595 0.1378 0.1036 0.1000 0.4048 0.2686 0.3090 0.1000 0.1000 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]	−26.12
Uniform	[1 1 1 1 1 1 1 1 ; 1 1 1 1 1 1 1 1 1 1; 1 1 1 1 1 1 1 1 1 1 1 1]	−9.56

TABLE VII Excitation Weights of Nonuniform CCAA with $N_1 = 8$, $N_2 = 10$, $N_3 = 12$ with Central Element

$\phi_{nu2} = 28°$	$[I_{center}\ ;\ I_{1,1} \ldots I_{1,8}\ ;\ I_{2,1} \ldots I_{2,10}\ ;\ I_{3,1} \ldots I_{3,12}]$	Max. SLL (dB)
FA	[0.5199; 0.9967 0.5631 0.7591 0.4567 0.6972 0.5239 0.6171 0.6279; 0.3579 0.7551 0.0321 0.1155 0.5299 0.4027 0.4977 0.1285 0.0531 0.7114; 0.3466 0.3824 0.3453 0.8170 0.2995 0.2844 0.3716 0.2866 0.2705 0.7644 0.3284 0.3990]	−30.54
EP [9]	[0.2750; 0.2989 0.4102 0.3979 0.7325 0.3989 0.3813 0.2785 0.2628; 0.2300 0.0187 0.0464 0.5620 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]	−28.92
Uniform	[1; 1 1 1 1 1 1 1 1 ; 1 1 1 1 1 1 1 1 1 1; 1 1 1 1 1 1 1 1 1 1 1 1]	−10.77

newly proposed FA method proves to be an effective optimization technique with respect to designing nonuniform CCAAs with optimum SLL. Its results are as good as well-developed optimization techniques, like EP and PSO [9].

V. CONCLUSION

In this article, for the first time, the newly proposed FA was used to adjust the positions and the excitations of the antenna elements in a CAA, and the elements excitations in a CCAA to obtain better side lobe suppression. The obtained optimized array factor was compared to that obtained using other well-known optimization techniques (PSO, GA, and EP). Array factor patterns obtained from FA results outperform those presented in the literature.

ACKNOWLEDGMENT

This work was supported by the Deanship of Research at Jordan University of Science and Technology (JUST).

REFERENCES

1. C.A. Balanis, Antenna Theory: Analysis and Design, Wiley, New York, 1997.
2. C.A. Balanis, Modern Antenna Handbook, Wiley, New York, 2008.
3. A. Recioui, A. Azrar, H. Bentarzi, M. Dehmas, and M. Chalal, Synthesis of linear arrays with sidelobe reduction constraint using genetic algorithm, Int J Microwave Opt Technol 3 (2008), 524–530.
4. N. Dib, S. Goudos, and H. Muhsen, Application of Taguchi's optimization method and self-adaptive differential evolution to the synthesis of linear antenna arrays, Prog Electromagn Res 102 (2010), 159–180.
5. A.H. Hussein, H.H. Abdullah, A.M. Salem, S. Khamis, and M. Nasr, Optimum design of linear antenna arrays using a hybrid MoM/GA algorithm, IEEE Antennas Wireless Propag Lett 10 (2011), 1232–1235.
6. A. Sharaqa and N. Dib, Design of linear and circular antenna arrays using biogeography based optimization, Applied Electrical Engineering and Computing Technologies (AEECT), 2011 IEEE Jordan Conference on Amman, 2011, pp. 1–6.
7. M. Panduro, A. Mendez, R. Dominguez, and G. Romero, Design of non-uniform circular antenna arrays for side lobe reduction using the method of genetic algorithms, Int J Electron Commun (AEU) 60 (2006), 713–717.
8. M. Shihab, Y. Najjar, N. Dib, and M. Khodier, Design of non-uniform circular antenna arrays using particle swarm optimization, J Electr Eng 59 (2008), 216–220.
9. D. Mandal, S. Ghoshal, and A. Bhattacharjee, Design of concentric circular antenna array with central element feeding using particle swarm optimization with constriction factor and inertia weight approach and evolutionary programing technique, J Infrared Millimeter Terahertz Waves 31 (2010), 667–680.
10. G. Roy, S. Das, P. Chakraborty, and P. Suganthan, Design of non-uniform circular antenna arrays using a modified invasive weed optimization algorithm, IEEE Trans Antennas Propag 59 (2011), 110–118.
11. D. Mandal, S. Ghoshal, and A. Bhattacharjee, Application of evolutionary optimization techniques for finding the optimal set of concentric circular antenna array, Expert Syst Appl 38 (2011), 2942–2950.
12. P. Ghosh and S. Das, Synthesis of thinned planar concentric circular antenna arrays – a differential evolutionary approach, Prog Electromagn Research B 29 (2011), 63–82.
13. U. Singh and T.S. Kamal, Design of non-uniform circular antenna arrays using biogeography-based optimization, IET Microwaves Antennas Propag 5 (2011), 1365–1370.
14. N. Dib and A. Sharaqa, On the optimal design of non-uniform circular antenna arrays, J Appl Electromagn (JAE) 14 (2012), 42–59.
15. A. Chatterjee, G. Mahanti, A. Chakrabarty, and P. Mahapatra, Phase-only sidelobe reduction of a uniformly excited concentric ring array antenna using modified particle swarm optimization, Int J Microwave Opt Technol 6 (2011), 57–62.
16. R.L. Haupt, Optimized element spacing for low sidelobe concentric ring arrays, IEEE Trans Antenna Propag 56 (2008), 266–268.
17. L. Biller and G. Friedman, Optimization of radiation patterns for an array of concentric ring sources, IEEE Trans Audio Electroacoust 21 (1973), 57–61.
18. S.E. El-Khamy and A.A. Abou-Hashem, Efficient techniques of sampling circular aperture distributions for ring array synthesis, Fifteenth national radio science conference, Cairo, Egypt, 1998, B10/1–B10/9,.
19. G. Holtrup, A. Marguinaud, and J. Citerne, Synthesis of electronically steerable antenna arrays with elements on concentric rings with reduced sidelobes, Proceedings IEEE AP-S Symposium, Boston, MA, 3 (2001), 800–803.
20. A. Reyna, Marco A. Panduro, D.H. Covarrubias, and A. Mendez, Design of steerable concentric rings array for low side lobe level, Sci Iranica Trans D: Comput Sci Eng Electr Eng 19 (2012), 727–732.
21. M.A. Panduro, C.A. Brizuela, L.I. Balderas, and D.A. Acosta, A Comparison of genetic algorithms, particle swarm optimization and the differential evolution method for the design of scannable circular antenna arrays, Prog Electromagn Res B 13 (2009), 171–186.
22. A. Reyna, M.A. Panduro, and C. Bocio, Design of concentric ring antenna arrays for isoflux radiation in GEO satellites, IEICE Electron Express ELEX 8 (2011), 484–490.
23. X.S. Yang, Firefly algorithms for multimodal optimization, in O.Watanabe and T. Zeugmann, Eds., Stochastic Algorithms: Foundations and Appplications, Vol. 5792 of SAGA 2009, Lecture Notes in Computer Science, Springer, Berlin, Germany, 2009, pp. 169–178.
24. X.S. Yang, Firefly algorithm, stochastic test functions and design optimization, Int J Bio-Inspired Comput 2 (2010), 78–84.
25. M. Zaman and Md. Abdul Matin, Nonuniformly spaced linear antenna array design using firefly algorithm, Int J Microwave Sci Technol 2012 (2012), pp. 1–8.
26. B. Basu and G.K. Mahanti, Firefly and artificial bees colony algorithm for synthesis of scanned and broadside linear array antenna, Prog Electromagn Res B 32 (2011), 169–190.
27. A. Chatterjee, G.K. Mahanti, and A. Chatterjee, Design of a fully digital controlled reconfigurable switched beam concentric ring array antenna using firefly and particle swarm optimization algorithm, Prog Electromagn Res B 36 (2012), 113–131.
28. R. Mehrabian and C. Lucas, A novel numerical optimization algorithm inspired from weed colonization, Ecol Inform 1 (2006), 355–366.
29. M. Dorigo, M. Birattari, and T. Stutzle, Ant colony optimization, Comput Intell Mag IEEE 1 (2006), 28–39.
30. J. Kennedy and R. Eberhart, Particle swarm optimization, Proc. IEEE Int. Conf. Neural Networks, Perth, WA, 1995, pp. 1942–1948.

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