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Optimal Synthesis of Concentric Circular Antenna Arrays Using Political Optimizer

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ABSTRACT

In this study, political optimizer (PO) which has entered the literature as a novel socio-inspired meta-heuristic method is used to improve radiation properties of concentric circular antenna arrays (CCAAs) in the far field such as wireless communication of smart grids and Internet of things. The radiation pattern of far field is improved by reducing the sidelobe level (SLL), which is the most important parameter of the antenna radiation pattern. By reducing SLL, unwanted signals and interferences in the same frequency band are suppressed. PO is a novel global optimization method which is based on the multi-phased process of politics. The inter-element spacing and amplitude coefficients of concentric circular antenna array elements are determined optimally by PO algorithm to obtain a radiation pattern with a lower SLL value. To show the flexibility and performance of the proposed algorithm, three-ring CCAAs with different numbers of elements (4, 6, 8 elements and 8, 10, 12 elements) without and with the center element are synthesized. SLL values obtained by PO algorithm are compared with other recent optimization methods in the literature. The results obtained with PO algorithm in all comparisons show that it reached a lower SLL value than other optimization methods.

KEYWORDS

Antenna array synthesis; Concentric circular antenna array; Meta-heuristic optimization algorithms; Political optimizer; Sidelobe level; Wireless communication

1. INTRODUCTION

Antenna arrays are the most important parts used in sending and receiving electromagnetic waves in wireless communication systems [1]. In many practical applications of antenna arrays, the elements are of common type and the distance between them is determined equally spaced [2]. The antenna radiation patterns are depending on the array parameters such as the geometric structure of the arrays, the amplitude excitation, phase and position of the array elements [3]. Today, with the rapid development in communication technologies, electromagnetic pollution in the environment has increased. In this case, it has revealed the necessity of optimum designing the antenna arrays, one of the most important structures of the communication systems, to be unaffected by other interference and unwanted signals in the environment. When designing this type of antenna arrays, the most important parameter is the sidelobe level (SLL) and this SLL value is desired to be very low [4]. Thus, unwanted interference and noise from other systems are suppressed. On the other hand, another parameter of the radiation pattern is the first null beam width (FNBW). A narrow FNBW is required for higher directivity antenna arrays in order to establish long-distance communication. However, it is quite difficult to obtain the radiation patterns with low SLL and narrow FNBW. Therefore, in this study, FNBW is taken as a constant and it was aimed to find the SLL values lower.

Antenna arrays took names such as linear, elliptical, circular, concentric circular according to their geometrical configuration. In the antenna arrays, especially the concentric circular antenna arrays (CCAAs) have been used in many wireless communication systems such as sonar [3], defense [5] and satellite communication [6] in recent years. The CCAA consists of many concentric circles with different numbers of elements and radii. CCAAs have many different advantages, compared to other antenna arrays. These advantages are that the radiation patterns can cover the entire area, invariant azimuth-angle coverage, increasing channel capacity and they do not have edge element, they are not much affected by the mutual coupling.

Meta-heuristic optimization methods have become very popular in the last decade and applied to many different electromagnetic problems. Mandal *et al.* [4] proposed a particle swarm optimization (PSO) with constriction factor and inertia weight approach (PSOCFIWA) to solve the optimal SLL achievement problem of CCAAs. Guney *et al.* [5] implemented backtracking search optimization algorithm (BSA) for the synthesis of CCAAs with the

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low SLLs at a fixed beam width. Sharaqa and Dib [7] have applied firefly algorithm (FA) to reduce the SLL of circular and concentric antenna arrays. Cat swarm optimization (CSO) is used to design circular and concentric antenna arrays [8]. Dib and Sharaqa [9] adopted biogeography-based optimization (BBO) algorithm for SLL reduction. Ram *et al.* [10] proposed a hybrid method to improve the directivity of time-modulated CCAAs. An optimal diagonal loading technique is used to investigate the performance of CCAA beamformers [11]. Ram *et al.* [12] proposed an Opposition-based BAT algorithm to design the optimal CCAA with improved radiation characteristics. Dragonfly algorithm (DA) is a nature-inspired optimization technique and it is used in the design of CCAAs to get low side lobes [13]. Das *et al.* [14] proposed a moth flame optimization (MFO) method to improve the radiation pattern of the CCAAs. Symbiotic organisms search (SOS) is utilized to reduce the SLL of CCAA radiation patterns [15]. Sun *et al.* [16] implemented a Cuckoo search-based hybrid approach to synthesize radiation beam patterns of CCAAs. Differential evolution algorithm with wavelet mutation has been used successfully for the radiation pattern synthesis for circular geometry of antenna arrays such as time-modulated half symmetric circular array and time-modulated CCAA [17]. Sahoo and Mandal [18] proposed swarm intelligence-based methods such as bacterial foraging optimization, standard PSO, and craziness-based PSO (CRPSO) technique to minimize the SLL of CCAAs. Comprehensive learning PSO has been utilized to improve the performance of high-altitude platform CCAAs [19]. Das *et al.* [20] used grey wolf optimization (GWO) to synthesize time-modulated linear antenna arrays and CCAAs. Ant lion optimization (ALO) is proposed to suppress the SLL of CCAAs [21]. Liang *et al.* [22] proposed a joint sidelobe suppression approach by using variation chicken swarm optimization (VPCSO) to design CCAAs. SOS is used for the synthesis of phase-only reconfigurable CCAAs [23]. Hybrid gravitational search algorithm (GSA) and PSO is utilized to obtain lower SLL of CCAAs [6]. Prabhakar and Satyanarayana have implemented salp swarm whale optimization Algorithm (SSWOA) for sidelobe pattern synthesis of conformal antenna arrays [24]. Jamunaa *et al.* [25] proposed MFO for the synthesis of flat-top/pencil beam pair of dual-beam reconfigurable CCAAs. Social group optimization algorithm (SGOA) is used to produce radiation pattern with SLL as low as possible [26]. Das *et al.* [27] proposed a social spider algorithm (SSA) and modified SSA to improve the far-field radiation pattern of CCAAs. Slime mold algorithm (SMA) is applied for optimal synthesis of thinned CCAAs [28]. For circular antenna arrays (CAA); Das *et al.* [29] proposed krill herd optimization (KHO) for optimal compact time-modulated CAAs, Durmus [30] proposed salp swarm optimization (SSA) for optimal CAAs, and Das *et al.* [31] proposed GWO for optimal time-modulated CAAs. Therefore, the meta-heuristic methods can be easily applied to many different problems thanks to its flexible and simple structure. Since the CCAA design problem has a very complex structure, using meta-heuristic methods with different paradigms that have just emerged in the literature, a radiation pattern with a narrower FNBW and lower SLL can be obtained.

Recently, Qamar Askari introduced the political optimizer (PO) as a novel socio-inspired method to solve optimization problems. The proposed meta-heuristic method is an algorithm inspired by different political stages such as party change, election campaign, election district allocation, inter-party election, and parliamentary affairs. The PO algorithm has been successfully applied to 50 benchmark problems and compared with 15 optimization algorithms in [32]. Since the PO algorithm is a very new optimization method, it has not been used in the electromagnetics optimization problem, and particularly antenna array synthesis.

In this manuscript, a novel meta-heuristic optimization technique, PO algorithm, is used to synthesis of CCAAs with lower SLL for the first time. The inter-element spacing and current amplitude values of the array elements are optimally determined by using PO algorithm to the optimal design of CCAA. Four different states of CCAA are examined to indicate the performance and effectiveness of the PO method. These are 4, 6, and 8 element without and with center element CCAA and the other is 8, 10, and 12 element without and with center element CCAA. The results achieved by PO are compared with those of the present methods such as BBO [9], DA [13], CSO [8], FA [7], MFO [14], SOS [15], sequential quadratic programming (SQP) [9], and evolutionary programming (EP) [4].

The rest of the article is arranged as follows: the optimal synthesis problem formulation of the CCAA is given in Section 2. Information about the proposed PO algorithm is given in Section 3. The simulation results by using PO are given comparatively in Section 4. Finally, Section 5 concludes the article.

2. PROBLEM FORMULATION

A CCAA can have a different number of elements, radii, and rings. The configuration of CCAA with M rings which have different r_m radii on the x–y plane is shown

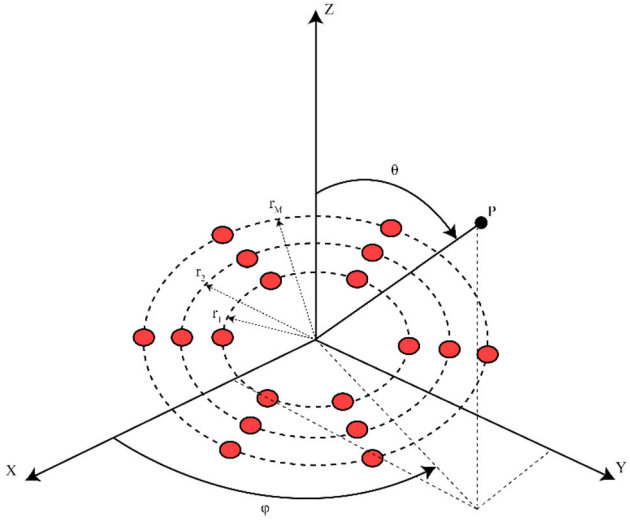


Figure 1: The structure of the concentric circular antenna array

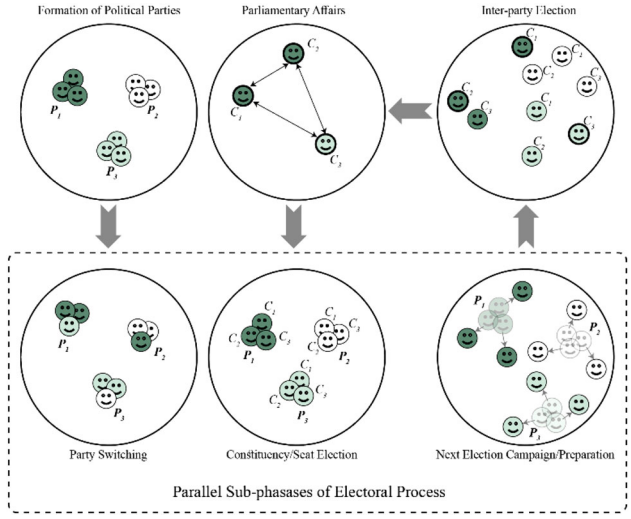


Figure 2: Visualization of multi-staged political process of PO

in Figure 1. There are N_m isotropic array elements in each ring of CCAA. Assuming that all array elements are isotropic sources, the array factor of a CCAA can be written as [1]

$$AF(\theta,\varphi) = I_{\text{center}} + \sum_{(m=1)}^{M} \sum_{(n=1)}^{N} \times I_m n \cdot e^{j(kr_m sin(\theta) cos(\varphi-\varphi_{mn})+\alpha_{mn})} \quad (1)$$

$$\varphi_{mn} = \frac{2\pi n}{N_m} \quad (2)$$

$$\alpha_{mn} = -kr_m \sin(\theta_0)\cos(\varphi_0 - \varphi_{mn}) \quad (3)$$

where I_{mn} is the amplitude coefficients of the nth element in the mth ring. The number of waves of the array factor is indicated by k. α_{mn} is the phase of the nth element in the mth ring. φ and θ represent the elevation and azimuth angels, respectively. For all examples in this paper, φ_0 value is set to 0° so that the main beam peak can be directed in the x direction and θ value is set to 90°.

The design goal of CCAA patterns is to achieve low SLL and fixed or narrower FNBW radiation patterns. For this purpose, the cost function can be defined as follows:

$$\text{CF}(\theta,\varphi) = w_1.F_1(\theta,\varphi) + w_2.F_2(\theta,\varphi) \quad (4)$$

$$F_1(\theta,\varphi) = [\text{AF}(\theta,\varphi_{\text{nul2}}) - \text{AF}(\theta,\varphi_{\text{nul1}})]^2 \quad (5)$$

$$F_2(\theta,\varphi) = \max\{\text{AF}(\theta,\varphi_{\text{sll1}})^2, \text{AF}(\theta,\varphi_{\text{sll2}})^2\} \quad (6)$$

where w_1 and w_2 are the weight factors. F_1 and F_2 are the functions used for suppressing SLL, and minimizing or fixed FNBW, respectively. FNBW is $\varphi_{\text{nul2}} - \varphi_{\text{nul1}} = 2\varphi_{\text{nul2}}$. φ_{sll2} and φ_{sll1} are the upper band (from φ_{nul2} to 180°), and the lower band (from $-180°$ to φ_{nul1}), respectively.

3. POLITICAL OPTIMIZER ALGORITHM

Political optimizer (PO) is a recent, novel, socio-inspired meta-heuristics algorithm that is used to solve global optimization problems. Algorithms inspired from natural processes can be divided into four main groups: physics-based, evolution-based, swarm-based, and human-behavior based.

In real life, politics can be considered as an optimization process. The PO algorithm, proposed by Askari *et al.* [32], the political system of a country thought as a reference-point and behavior of politicians tried to imitate. In Figure 2, multi-staged political process is visualized. Politics is an optimization process in two ways: everyone improves its reputation to win elections and parties are trying to increase the number of politicians in assembly to establish a government. PO has five stages including allocation of constituencies and formation of parties, party switching, election campaign, parliamentary affairs, and inter-party election. The first two stages just realized once as an initialization step and the rest of steps are iterated in a loop. Algorithm 1 expresses how stages of a political system are algorithmically modeled.

PO differs from the existing meta-heuristics in the following ways:

- PO has a recent position updating strategy based on mathematical modeling of the learning behavior of politicians in previous elections. This strategy is called a recent past-based position updating.
- One of the prominent features of the PO method is that a significant improvement has been achieved in

Algorithm 1. Main algorithm of PO.

Input: n (member size of parties, political parties, and constituencies), $\lambda_{\max}$(maximum rate of party switching), $T_{\max}$ (maximum number of iterations)
Output: final solution $P(T_{\max})$
Initialize P
Compute fitness of eachmember p_i^j
Compute the party leaders P^*
Compute the constituency winners C^*
$t = 1$;
$P(t-\mathbf{1}) = P$;
$f(P(t-\mathbf{1})) = f(P)$;
$\lambda = \lambda_{\max}$;
while $t <= T_{\max}$ **do**
  $P_{\text{temp}} = P$;
  $f(P_{\text{temp}}) = f(P)$;
  foreach $P_i \epsilon P$ do
    foreach $p_i^j \in Pi$ do
      $p_i^j = \text{ElectionCampaign}(p_i^j, p_i^j(t-1), p_i^*, c_j^*)$;
    end
  end
  PartySwitching(P,λ)
  /* Election */
  Compute fitness of each member p_i^j
  Compute the party leaders P^*
  Compute the constituency winners C^*
  ParliamentaryAffairs(C^*,P)
  $P(t-\mathbf{1}) = P$;
  $f(P(t-\mathbf{1})) = f(P)$;
  $\lambda = \lambda - \lambda_{\max}/T_{\max}$;
  $t = t + 1$;
End

Algorithm 2. ElectionCampaign $(p_i^j, p_i^j(t-1), p_i^*, c_j^*)$.

Result: $p_i^j(t+1)$
if $f(p_i^j(t)) <= f(p_i^j(t-1))$ **then**
  for $k = 1$ to d
    $m^* = p^*_{(i,k)}$
    $r =$ random[0,1]
    Update $p^*_{i,k}$ by party leader using Equation (7)
    $m^* = c^*_{(i,k)}$
    $r =$ random[0,1]
    Update $p^*_{(i,k)}(t+1)$ by constituency winner using Equation (7)
  end
else
  for k = 1 to d
    $m^* = p^*_{(i,k)}$
    $r =$ random[0,1]
    Update $p^*_{i,k}$ by party leader using Equation (8)
    $m^* = c^*_{(i,k)}$
    $r =$ random[0,1]
    Update $p^*_{(i,k)}(t+1)$ by constituency winner using Equation (8)
  end
End

Algorithm 3. PartySwitching (P,λ).

foreach $P_i \in P$
  foreach $p_i^j \in P_i$
    $sp =$ random[0,1]
    if $sp < \lambda$ **then**
      $r =$ random[0,1]
      Determine q by using Equation (9)
      Swap(p_r^q,p_i^j)
    end
  end
End

- the convergence speed thanks to its good exploration capability.
- The PO method is very successful in solving complex optimization problems with a large number of parameters.

3.1 Party and Constituency Formation

The structure with the total population number P is divided into n political entities. Each political party formation consists of n members. Each element of $\boldsymbol{p_i^j}$ is actually a candidate solution. In our case, d is the number of antenna parameters to be optimized. k denotes the parameter index of the solution. All party members can act as an election candidate and jth member of each party contests election from jth constituency Cj. The fittest member of a party is declared the party leader and the set of all the party leaders is represented by $P*$. Parliamentarians elected with most of the votes in their constituencies are indicated by $C*$.

3.2 Election Campaign

Algorithm 2 shows the election campaign process which depicts the exploitation and exploration phases. These steps help parliamentary candidates to accelerate their work in the elections and to find optimum solutions in the solution space. In our case, the antenna parameters are adjusted to obtain better SLL. Learning from the previous election is determined by a recent past-based position updating strategy which is formulated by Equations (7) and (8). The suitability of possible solution candidates is assessed using Equations (7) and (8).

$$p_{i,k}^j(t+1) = \begin{cases} m^* + r(m^* - p_{i,k}^j(t)), \\ \text{if } p_{i,k}^j(t-1) \le p_{i,k}^j(t) \le m^* \\ or\ p_{i,k}^j(t-1) \ge p_{i,k}^j(t) \ge m^* \\ m^* + (2r-1)|m^* - p_{i,k}^j(t)|, \\ \text{if } p_{i,k}^j(t-1) \le m^* \le p_{i,k}^j(t) \\ or\ p_{i,k}^j(t-1) \ge m^* \ge p_{i,k}^j(t) \\ m^* + (2r-1)|m^* - p_{i,k}^j(t-1)|, \\ \text{if } m^* \le p_{i,k}^j(t-1) \le p_{i,k}^j(t) \\ or\ m^* \ge p_{i,k}^j(t-1) \ge p_{i,k}^j(t) \end{cases} \tag{7}$$

$$p_{i,k}^{j}(t+1)=\begin{cases} m^{*}+(2r-1)(m^{*}-p_{i,k}^{j}(t)), \\ \text{if } p_{i,k}^{j}(t-1)\le p_{i,k}^{j}(t)\le m^{*} \\ \text{or } p_{i,k}^{j}(t-1)\ge p_{i,k}^{j}(t)\ge m^{*} \\ p_{i,k}^{j}(t-1)+r(p_{i,k}^{j}(t)-p_{i,k}^{j}(t-1)), \\ \text{if } p_{i,k}^{j}(t-1)\le m^{*}\le p_{i,k}^{j}(t) \\ \text{or } p_{i,k}^{j}(t-1)\ge m^{*}\ge p_{i,k}^{j}(t) \\ m^{*}+(2r-1)|m^{*}-p_{i,k}^{j}(t-1)|, \\ \text{if } m^{*}\le p_{i,k}^{j}(t-1)\le p_{i,k}^{j}(t) \\ \text{or } m^{*}\ge p_{i,k}^{j}(t-1)\ge p_{i,k}^{j}(t) \end{cases} \tag{8}$$

3.3 Party Switching

The party-switching stage in politics proceeds with the campaign in the electoral area, but in the PO method, this process is run after the election campaign, as shown in Algorithm 3. The party-switching rate, called λ, is an adaptive parameter that starts from $\lambda_{\max}$ and drops to zero.

Each member $\boldsymbol{p_i^j}$ has the possibility to be selected in proportion to the λ value. The least eligible member in terms of $\boldsymbol{p_r^q}$ transitions to a randomly selected party. Using Equation (9), the q-value of the least appropriate member is calculated.

$$q=\text{argmax}\, f(\boldsymbol{p_r^j})1\le j\le n \tag{9}$$

3.4 Election

Election is a process in which winners are announced by evaluating the eligibility of all parliamentary candidates competing for being elected in a region. In our case, fitness of the candidates are calculated by the antenna parameters. The lower the SLL, the better the candidate. In Equation (10), $\boldsymbol{c_j^*}$ is the winner of the jth constituency (C_j):

$$q=\text{argmin}\, f(\boldsymbol{p_i^j})1\le i\le n$$
$$\boldsymbol{c_j^*}=\boldsymbol{p_q^j} \tag{10}$$

3.5 Parliamentary Affairs

Party leaders and constituency winners are determined using Equation (10). After the election process, with the announcement of the results, the efforts to establish a government begin. The government is formed after an inter-party election. The constituency winners and the party leaders are decided by Equation (10). If each parliamentarian $\boldsymbol{c_j^*}$ makes an improvement in the fitness value, its position is updated with reference to a randomly selected parliamentarian $\boldsymbol{c_r^*}$ in Algorithm 4.

Algorithm 4. ParliamentaryAffairs (C^*,P).

for $j=1$ to n
  $r=$ random[0,n], where $r\neq j$
  $a=$ random[0,1]
  $c_{\text{new}}^{*}=c_r^{*}+(2a-1)|c_r^{*}-c_j^{*}|$
  Calculate fitness of c_{new}^{*}
  if $f(c_{\text{new}}^{*})<=f(c_j^{*})$ **then**
    $c_j^{*}=c_{\text{new}}^{*}$
    $f(c_j^{*})=f(c_{\text{new}}^{*})$
    $i=$ party index of the winner of jth constituency $p_i^j=c_{\text{new}}^{*}$
    $f(p_i^j)=f(c_{\text{new}}^{*})$
  end
End

4. NUMERICAL RESULTS

PO algorithm optimally determined the inter-element spacing and amplitude values for the synthesis of three rings non-uniform CCAAs. In order to find the best result in the search space, the PO algorithm has been run 20 times with a computer with 2.8 Ghz i7 processor and 4GB RAM. The best values are obtained as a result of these iterations. The population size of PO and the number of maximum iterations are 30 and 1000, respectively, for all simulations.

PO algorithm is used to suppress SLL for CCAAs design with three rings. Experiments are limited with the design of symmetric CCAAs. In this context, CCAAs with $N_1=4, N_2=6, N_3=8$ and $N_1=8, N_2=10, N_3=12$ elements, which are the most common settings in the literature, have been discussed. There are two situations in all designs; these are CCAAs with and without central element.

In the experiments, for $N_1=4, N_2=6, N_3=8$ with center element, $N_1=8, N_2=10, N_3=12$ with center element and $N_1=8, N_2=10, N_3=12$ without center element cases, the distance between the elements in each ring used as 0.550λ, 0.606λ, 0.750λ from inside to outside. However, for the case $N_1=4, N_2=6, N_3=8$ without center element, the inter-element spacing of the rings are optimized by using PO as 0.493λ, 0.573λ, 0.762λ. In this study, the mutual coupling effect is not accounted.

The best results obtained with PO method for all cases are compared with optimization methods such as EP [4], DA [13], BBO [9], FA [7], SQP [9], SOS [15], MFO [14],

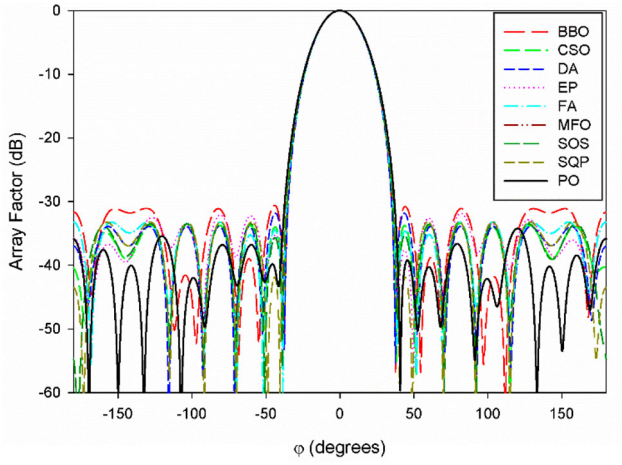


Figure 3: Radiation array pattern for CCAA having $N_1 = 4$, $N_2 = 6$, and $N_3 = 8$ without center element

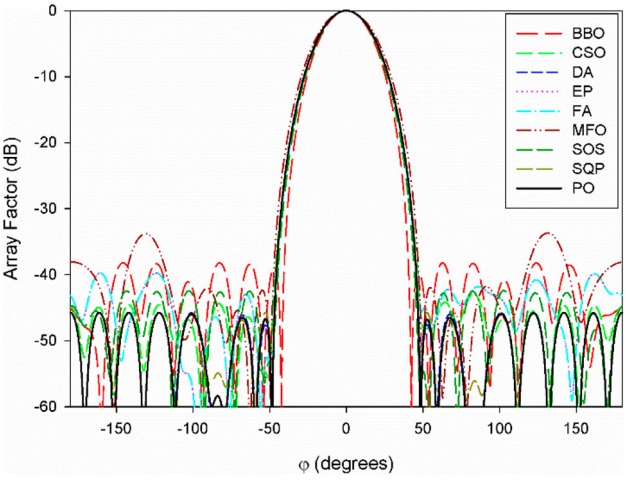


Figure 4: Radiation array pattern for CCAA having $N_1 = 4$, $N_2 = 6$, and $N_3 = 8$ with center element

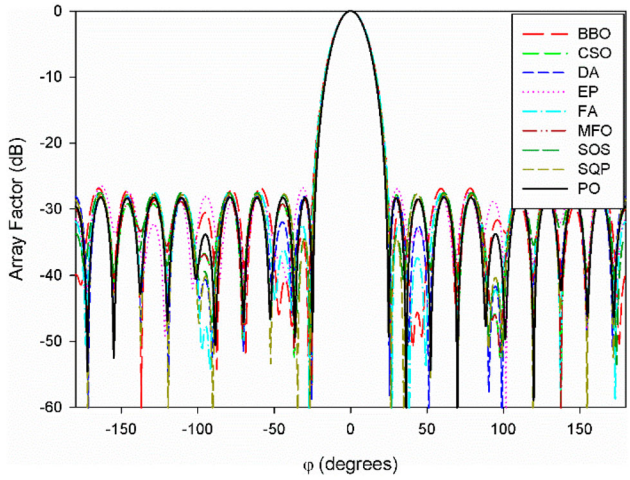


Figure 5: Radiation array pattern for CCAA having $N_1 = 8$, $N_2 = 10$, and $N_3 = 12$ without center element

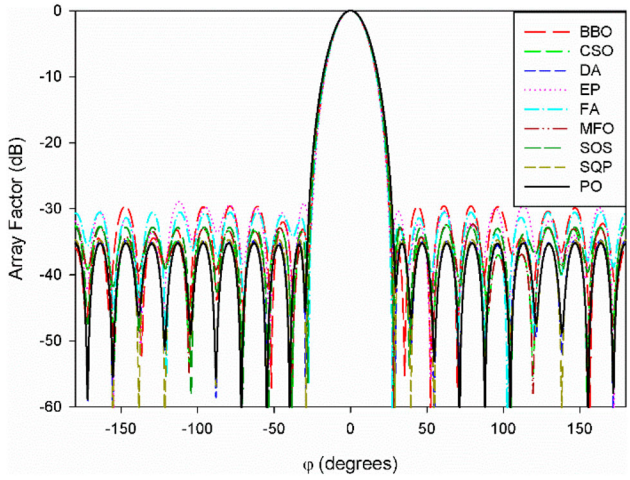


Figure 6: Radiation array pattern for CCAA having $N_1 = 8$, $N_2 = 10$, and $N_3 = 12$ with center element

and CSO [8]. The SLL results of PO and other metaheuristic algorithms for design CCAAs having $N_1 = 4$, $N_2 = 6$, $N_3 = 8$ and $N_1 = 8$, $N_2 = 10$, $N_3 = 12$ elements without and with the center element are given in Tables 1–4 comparatively. The radiation patterns obtained as a result of the amplitude coefficients given in Tables 1–4 are shown comparatively in Figures 3–6.

In Table 1, optimal amplitude values and SLL obtained for CAA having $N_1 = 4$, $N_2 = 6$, $N_3 = 8$ without center element are given. The SLL of BBO is -30.60 dB and becomes the worst in the comparison. However, the proposed PO obtained the best SLL value as -37.30 dB. The 2D visualization of the results given in Table 1 is shown in Figure 3. As can be clearly seen from Figure 3, the proposed PO method outperforms the comparison methods in terms of the lowest SLL value in all angles.

The optimum amplitude values and SLL obtained for CCAA having $N_1 = 4$, $N_2 = 6$, $N_3 = 8$ with center element are given in Table 2. The aim of design is to suppress the SLL values for optimal radiation. In Table 2 and Figure 4, it can be seen that the maximum SLL value of the proposed PO method is lower than the others.

In order to prove that the proposed PO methods flexibility and performance, CCAA having $N_1 = 8$, $N_2 = 10$, and $N_3 = 12$ with and without center element cases are also evaluated. In Table 3, the optimal amplitude values and SLL obtained for CCAA having $N_1 = 8$, $N_2 = 10$, $N_3 = 12$ without center element are tabulated. As shown in Table 3 and Figure 5, EP has the worst value and the proposed PO has the best value in terms of SLL.

Table 1: Optimal amplitude values and SLL obtained for CCAA having $N_1 = 4, N_2 = 6, N_3 = 8$ without center element

Algorithm $\phi_{null2} = 52^o$	SLL (dB)	$I_{1,1}I_{1,2}I_{1,3}I_{1,4}$	$I_{2,1}I_{2,2}I_{2,3}I_{2,4}I_{2,5}I_{2,6}$	$I_{3,1}I_{3,2}I_{3,3}I_{3,4}I_{3,5}I_{3,6}I_{3,7}I_{3,8}$
PO	−37.30	0.4972 0.5878 0.4909 0.6153	0.5801 0.5586 0.8983 0.5649 0.5804 0.8895	0.4653 0.7313 0.4620 0.2672 0.4604 0.7365 0.4655 0.2433
BBO [9]	−30.60	0.3477 0.7950 0.3348 0.7975	0.5046 0.5078 1.0000 0.5171 0.5073 1.0000	0.5173 0.8248 0.5079 0.2251 0.5263 0.7986 0.5332 0.2260
CSO [8]	−33.39	0.0703 0.5675 0.0824 0.5491	0.3442 0.3516 0.8304 0.3463 0.3440 0.8596	0.4199 0.5768 0.4140 0.1919 0.4040 0.5928 0.4149 0.2097
DA [13]	−33.91	0.1390 0.673 0.15123 0.6732	0.4334 0.4284 0.9978 0.4210 0.4264 0.9999	0.4975 0.7080 0.4998 0.2296 0.4975 0.7399 0.4949 0.2290
EP [4]	−31.84	0.0496 0.3242 0.0283 0.3416	0.2114 0.1923 0.4901 0.1876 0.1994 0.5321	0.2555 0.3527 0.2450 0.1229 0.2294 0.3449 0.2400 0.1204
FA [7]	−33.20	0.1410 0.6770 0.1215 0.7025	0.4349 0.4084 0.9999 0.4076 0.4305 0.9999	0.4789 0.7366 0.4831 0.2542 0.4790 0.7172 0.4730 0.2352
MFO [14]	−36.84	0.8696 0.7969 0.9075 0.7528	0.6441 0.6758 0.8161 0.6599 0.6771 0.7870	0.5037 0.8125 0.4958 0.2756 0.4930 0.8334 0.4989 0.2813
SOS [15]	−33.47	0.0433 0.6712 0.0748 0.6489	0.3915 0.4036 1.0000 0.4141 0.4037 0.9999	0.4866 0.6634 0.5005 0.2437 0.4804 0.6897 0.4659 0.2401
SQP [9]	−33.16	0.0310 0.6669 0.0203 0.6701	0.3911 0.3886 1.0000 0.3831 0.3852 0.9998	0.4610 0.6812 0.4627 0.2542 0.4630 0.6642 0.4614 0.2501

Table 2: Optimal amplitude values and SLL obtained for CCAA having $N_1 = 4, N_2 = 6, N_3 = 8$ with center element

Algorithm $\phi_{null2} = 46^o$	SLL (dB)	$I_{1,1}I_{1,2}I_{1,3}I_{1,4}$	$I_{2,1}I_{2,2}I_{2,3}I_{2,4}I_{2,5}I_{2,6}$	$I_{3,1}I_{3,2}I_{3,3}I_{3,4}I_{3,5}I_{3,6}I_{3,7}I_{3,8}$	I_{center}
PO	−45.75	0.9861 0.9196 0.9896 0.9202	0.6828 0.6789 0.1046 0.6816 0.6845 0.1070	0.2722 0.3881 0.2726 0.0635 0.2725 0.3902 0.2716 0.0638	0.6802
BBO [9]	−38.20	0.7560 0.9983 0.7491 1.0000	0.7319 0.7228 0.7698 0.7307 0.7288 0.7394	0.5440 0.6968 0.5683 0.1953 0.5568 0.6848 0.5297 0.1801	0.4669
CSO [8]	−42.87	0.4719 0.4897 0.4805 0.4830	0.3430 0.3528 0.1096 0.3579 0.3483 0.1139	0.1531 0.2177 0.1539 0.0421 0.1586 0.2257 0.1576 0.0464	0.3320
DA [13]	−45.73	0.9905 0.9262 0.9961 0.9292	0.6859 0.6826 0.1041 0.6876 0.6890 0.1064	0.2734 0.3897 0.2741 0.0649 0.2731 0.3918 0.2717 0.0637	0.6878
EP [4]	−39.73	0.5477 0.5530 0.5890 0.5502	0.3830 0.3972 0.0999 0.4152 0.4051 0.0976	0.1730 0.2290 0.1734 0.0401 0.1750 0.2755 0.1717 0.0417	0.3770
FA [7]	−40.43	0.8029 0.9508 0.8087 0.9943	0.7228 0.7056 0.6025 0.7020 0.7262 0.5727	0.4732 0.6145 0.4837 0.1627 0.4748 0.6159 0.4648 0.1516	0.5142
MFO [14]	−42.93	0.3878 0.5541 0.3707 0.5288	0.8094 0.8214 0.7204 0.8183 0.8089 0.7100	0.3894 0.3864 0.4018 0.0041 0.4270 0.3832 0.4191 0.0019	0.7288
SOS [15]	−42.40	0.8722 0.9998 0.9026 1.0000	0.7095 0.7121 0.4203 0.7249 0.7276 0.4055	0.3928 0.5217 0.3991 0.1313 0.3939 0.5531 0.3885 0.1287	0.6111
SQP [9]	−42.40	0.9818 0.9129 0.9831 0.9111	0.6798 0.6751 0.1048 0.6756 0.6800 0.1076	0.2709 0.3865 0.2711 0.0621 0.2718 0.3885 0.2714 0.0638	0.6724

Table 4 gives the optimal amplitude values and SLL obtained for CCAA having $N_1 = 8$, $N_2 = 10$, $N_3 = 12$ with center element. Figure 6 is visualized by using the optimum amplitude values of the elements given in Table 4. SLL of the proposed PO is obtained as −35.20 dB.

According to Figures 3–6 and Tables 1–4, it can be clearly seen that the all SLL results obtained by PO are better than those of EP [4], DA [13], BBO [9], FA [7], SQP [9], SOS [15], MFO [14], and CSO [8]. The SLL value obtained by PO as a result of the synthesis of CCAA with the total number of elements of 18 for both cases (without and with center element) are −37.30 and −45.75 dB, respectively. In addition, for CCAA having 30 elements, the outcomes of PO in terms of SLL are −28.25 and −35.20 dB without and with center element cases, respectively. The suppression of SLL in antenna arrays is very important to prevent interference from systems operating in the same frequency band. Therefore, the presence of the central element enabled better SLL values to be obtained.

The convergence curve of the PO algorithm obtained for non-uniform CCAA design for both cases with and without center elements is shown in Figure 7. The computation time of PO algorithm varies between 51 and 58 s depending on the element numbers used in the rings.

All simulation results of PO algorithm for CCAA designs with lower SLL are compared with the well-known optimization algorithms. As a result of comparisons with other meta-heuristic methods, the performance in terms of SLL suppression of the PO algorithm is very impressive

Table 3: Optimal amplitude values and SLL obtained for CCAA having $N_1 = 8, N_2 = 10, N_3 = 12$ without center element

Algorithm $\phi_{null2} = 28^o$	SLL (dB)	$I_{1,1}I_{1,2}I_{1,3}I_{1,4}I_{1,5}I_{1,6}I_{1,7}I_{1,8}$	$I_{2,1}I_{2,2}I_{2,3}I_{2,4}I_{2,5}I_{2,6}I_{2,7}I_{2,8}I_{2,9}I_{2,10}$	$I_{3,1}I_{3,2}I_{3,3}I_{3,4}I_{3,5}I_{3,6}I_{3,7}I_{3,8}I_{3,9}I_{3,10}I_{3,11}I_{3,12}$
PO	−28.25	0.7058 0.2764 0.6833 0.6505 0.6824 0.2526 0.7078 0.8076	0.6547 0.0861 0.1174 0.5257 0.4812 0.4693 0.1630 0.1286 0.6045 0.5284	0.3718 0.3901 0.9997 0.3249 0.3444 0.4798 0.3803 0.2737 0.9998 0.3444 0.4008 0.4909
BBO [9]	−26.83	0.6957 0.3821 0.7366 0.9184 0.8001 0.2855 0.7184 0.9670	0.6631 0.1436 0.2588 0.6330 0.6310 0.6184 0.2104 0.1214 0.7737 0.5634	0.4075 0.3080 1.0000 0.2797 0.3986 0.5384 0.3191 0.3241 0.9751 0.3741 0.3804 0.6059
CSO [8]	−27.86	0.6739 0.3432 0.6771 0.8039 0.7780 0.2618 0.7627 0.7271	0.4706 0.1789 0.1448 0.5577 0.4837 0.6122 0.0510 0.0895 0.6417 0.4643	0.3747 0.2329 0.9529 0.2425 0.4582 0.4318 0.3656 0.3845 0.9701 0.4396 0.2581 0.4045
DA [13]	−28.15	0.7333 0.3098 0.7275 0.8021 0.7444 0.3016 0.7500 0.7824	0.5110 0.1976 0.1589 0.5479 0.4847 0.6092 0.1166 0.1535 0.5699 0.4838	0.3963 0.2488 0.9637 0.2897 0.3742 0.4556 0.3372 0.3510 0.9950 0.3099 0.3569 0.4499
EP [4]	−26.12	0.2886 0.1891 0.3336 0.5458 0.3895 0.1000 0.2866 0.2242	0.1378 0.1036 0.1000 0.4048 0.2686 0.309 0.1000 0.1000 0.1696 0.1595	0.1183 0.1144 0.4708 0.1685 0.2090 0.2566 0.2200 0.1000 0.4229 0.1273 0.1020 0.2419
FA [7]	−27.49	0.7716 0.3013 0.7299 0.8924 0.7641 0.3044 0.7999 0.9354	0.5686 0.2124 0.1958 0.5901 0.5647 0.6322 0.1498 0.1660 0.6379 0.5444	0.4125 0.2457 0.9673 0.2516 0.3827 0.4854 0.3444 0.3209 0.9734 0.3290 0.3651 0.5044
MFO [14]	−27.92	0.6751 0.3437 0.6788 0.8048 0.7787 0.2633 0.7641 0.7287	0.4717 0.1793 0.1452 0.5590 0.4846 0.6128 0.0518 0.0904 0.6420 0.4660	0.3755 0.2337 0.9535 0.2428 0.4588 0.4323 0.3670 0.3858 0.9707 0.4398 0.2589 0.4046
SOS [15]	−27.51	0.7272 0.2027 0.7132 0.7764 0.6652 0.3052 0.6754 0.8210	0.5748 0.1225 0.0582 0.6055 0.5303 0.6102 0.0831 0.1484 0.6280 0.5918	0.4459 0.3050 0.9260 0.3879 0.3089 0.4550 0.3126 0.3476 0.9983 0.2882 0.4373 0.4990
SQP [9]	−27.74	0.6802 0.2215 0.7085 0.7993 0.7182 0.2220 0.6914 0.7489	0.5471 0.1255 0.1374 0.5816 0.5741 0.5904 0.1227 0.1123 0.5560 0.5608	0.3797 0.2825 0.9968 0.3036 0.3680 0.4846 0.3685 0.3295 0.9991 0.3096 0.3806 0.5030

Table 4: Optimal amplitude values and SLL obtained for CCAA having $N_1 = 8, N_2 = 10, N_3 = 12$ with center element.

Algorithm $\phi_{null2} = 28^o$	SLL (dB)	$I_{1,1}I_{1,2}I_{1,3}I_{1,4}I_{1,5}I_{1,6}I_{1,7}I_{1,8}$	$I_{2,1}I_{2,2}I_{2,3}I_{2,4}I_{2,5}I_{2,6}I_{2,7}I_{2,8}I_{2,9}I_{2,10}$	$I_{3,1}I_{3,2}I_{3,3}I_{3,4}I_{3,5}I_{3,6}I_{3,7}I_{3,8}I_{3,9}I_{3,10}I_{3,11}I_{3,12}$	I_{center}
PO	−35.20	0.3867 0.9999 0.3811 0.8751 0.3406 1.0000 0.3451 0.8653	0.6299 0.0305 0.0255 0.6256 0.2249 0.6182 0.0098 0.0132 0.6176 0.2168	0.2823 0.2679 0.5452 0.2657 0.2850 0.1753 0.2788 0.2656 0.5255 0.2669 0.2743 0.1669	0.9481
BBO [9]	−29.61	0.6648 0.8292 0.6373 1.0000 0.5945 0.8948 0.5061 1.000	0.8204 0.0529 0.1067 0.8818 0.5429 0.7970 0.0846 0.000 0.8129 0.5600	0.4304 0.4370 0.9898 0.5142 0.3695 0.4323 0.3746 0.4201 0.9710 0.4175 0.4277 0.4745	0.7208
CSO [8]	−32.37	0.3522 0.6790 0.3002 0.5535 0.2998 0.7069 0.3734 0.7658	0.5586 0.0094 0.0249 0.3997 0.1955 0.3889 0.0243 0.0274 0.6129 0.2374	0.2335 0.2526 0.4757 0.1489 0.2343 0.1763 0.2177 0.1651 0.4915 0.3097 0.2273 0.1414	0.6082
DA [13]	−34.79	0.3814 1.0000 0.3930 0.9165 0.3910 0.9966 0.3776 0.8480	0.6043 0.0204 0.0390 0.6607 0.2502 0.6550 0.0290 0.0130 0.6100 0.2102	0.2706 0.2668 0.5700 0.2866 0.2978 0.1800 0.3090 0.2790 0.5585 0.2667 0.2831 0.1850	0.93400
EP [4]	−28.92	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	0.2750
FA [7]	−30.55	0.5631 0.7591 0.4567 0.6972 0.5239 0.6171 0.6279 0.9967	0.7551 0.0321 0.1155 0.5299 0.4027 0.4977 0.1285 0.0531 0.7114 0.3579	0.3824 0.3453 0.8170 0.2995 0.2844 0.3716 0.2866 0.2705 0.7644 0.3284 0.3990 0.3466	0.5199
MFO [14]	−32.88	0.3534 0.6802 0.3009 0.5543 0.3003 0.7081 0.3751 0.7669	0.5594 0.0105 0.0256 0.4012 0.1961 0.3901 0.0252 0.0288 0.6138 0.2390	0.2343 0.2545 0.4765 0.1498 0.2354 0.1770 0.2182 0.1663 0.4926 0.3111 0.2288 0.1420	0.6090
SOS [15]	−32.77	0.5128 0.9999 0.5347 0.9699 0.5246 0.9993 0.5313 0.9948	0.7888 0.0454 0.0978 0.6285 0.3094 0.7120 0.0442 0.0008 0.8066 0.3684	0.3440 0.3818 0.7780 0.2612 0.3821 0.3124 0.3594 0.3429 0.7892 0.4150 0.3454 0.2726	0.8628
SQP [9]	−34.70	0.3841 0.9919 0.4112 0.9154 0.4028 1.0000 0.3797 0.8538	0.6265 0.0170 0.0313 0.6672 0.2532 0.6587 0.0328 0.0192 0.6063 0.2222	0.2820 0.2794 0.5826 0.3003 0.2980 0.1906 0.3060 0.2900 0.5799 0.2619 0.2928 0.1924	0.9263

and it is quite useful for the solution of other optimization problems.

5. CONCLUSION

In this paper, PO which is a novel socio-inspired meta-heuristic method is used to achieve CCAAs radiation patterns with low SLLs. To appraise the flexibility and performance of the proposed method, three-ring CCAAs without and with center element are examined. The inter-element spacing and excitation amplitude of the CCAA rings are optimized successfully by PO. In conclusion, it can be said that PO can obtain superior SLL values for design CCAAs. PO algorithm is also successful at

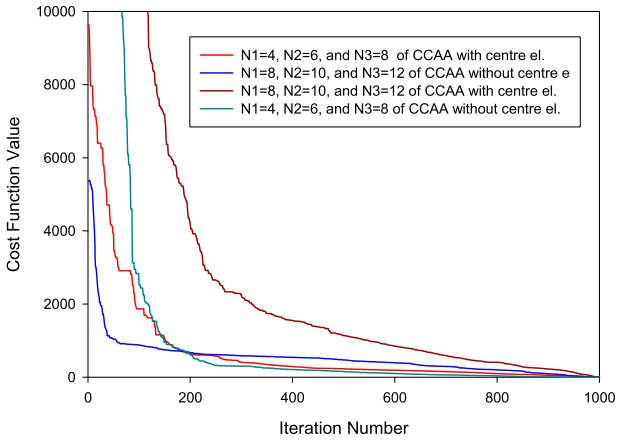


Figure 7: The convergence curve of PO for the synthesis of CCAAs

synthesizing CCAAs with a different number of array elements. It means that PO has a flexible optimization technique so and it can be easily applied to the other optimization problems. On the other hand, the results obtained by PO are compared with those of EP, FA, CSO, SQP, BBO, SOS, DA, and MFO in the literature. The results show that PO can achieve better SLL values than the other meta-heuristic optimization algorithms. These comparisons help to conclude that PO is a good alternative to the other optimization techniques for the antenna array synthesis problems such as asymmetric CCAA design. The mutual coupling effect and asymmetric design of CCAAs can also be considered in future works.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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