Low Side-lobe Beam-pattern Synthesis: Thinning of a Large Concentric Circular Antenna Array Using Wavelet Mutation Based Seeker Optimization Algorithm

Rajesh Bera[1], Durbadal Mandal[2], Rajib Kar[2], Sakti P. Ghoshal[3]

Abstract - **In this paper, Seeker Optimization Algorithm with Wavelet Mutation (SOAWM), which represents a recent approach in electromagnetic for optimization problems, is applied for optimal thinning of large multiple concentric circular ring array of uniformly excited isotropic and non-isotropic antenna elements which can produce directive beam with maximum reduced Side Lobe Level (SLL). The synthesis of a Concentric Circular Antenna Array (CCAA) of nine-ring with central element feeding is reflected in this paper. The simulation results show that the number of antenna array elements can be brought down from 279 to 113 for isotropic elements and 94 for non-isotropic elements with simultaneous reduction in SLL of around -22 dB with closely fixed First Null Beam Width (FNBW). Particle Swarm Optimization (PSO), Differential Evolution (DE) and basic Seeker Optimization Algorithm (SOA) as well are also adopted to compare the results of above wavelet mutation based algorithm.**

Keywords - **Concentric Circular Antenna Array; Particle Swarm Optimization; Seeker Optimization Algorithm; Thinning; Side-lobe Level; First Null Beam Width.**

I. INTRODUCTION

Concentric circular antenna array (CCAA) [1-11] that comprises many concentric circular rings of different radius has many advantages compared with other planar array geometries like linear array and rectangular array. CCAA has become widespread in wireless and mobile communications and have been applied extensively to radar, sonar and satellite communications systems [12–14] due to its flexibility in beam pattern synthesis, spreading coverage area, efficient spectrum utilization, less mutual coupling sensitivity, increasing channel capacity and the frequency invariant characteristics. Array elements in Uniform CCA (UCCA) [15] are uniformly excited and the spacing between two adjacent elements in each ring is kept fixed to half of the wavelength. The SLL drop is about -17.5 dB in the UCCA with uniform excitations. The reduction of SLL is the key issue when considering the design of CCAA. Array thinning is one of the simplest methods of optimizing array geometry to achieve this goal of SLL reduction.

Thinning [16-19] is the process of removing (switching OFF) antenna elements systematically from uniformly spaced array without a significant degradation in performance. In this procedure, all the elements have any of two situations; “ON” (excited) or “OFF” (detached). The main objective of thinning is to minimize the array elements with maximum reduced SLL while preserving the similar narrow beam-width as for fully populated array.

Classical optimization techniques have several drawbacks when optimizing discrete variables because they require continuous as well as differentiable cost functions. So, highly non-linear, discrete and non-differential array factors of antenna arrays are difficult to handle using classical methods. Initial solutions are randomly selected using classical techniques. With the increasing of the number of solution variable or solution space, initial solutions become highly sensitive. This is one of the major disadvantages using classical methods. Also, a particular classical approach may not be suitable for solving several problems. So, it is necessary to design a strong and proficient method of optimization. Various evolutionary optimization methods are there such as Particle Swarm Optimization (PSO) [20-22], Genetic Algorithm (GA) [14], Differential Evolution (DE) [23], Seeker Optimization Algorithm (SOA) [24-26] etc. for optimization of complex, highly nonlinear, discontinuous and non-differentiable array factor of antenna array, which do not suffer from above disadvantages.

The evolution process involving mutation operation takes an important role for maintaining the diversity from one generation to the next generation of the population. By setting a larger searching space using mutation operation, the solution space to be more widely explored in the early stage of the search. In the later stage of the search, it is more likely to obtain a fine-tuned near-global solution by setting a smaller searching space. This requirement can be achieved by Wavelet [27-29] which is a tool to model seismic signals by combining dilations and translations of a simple, oscillatory function (mother Wavelet) of a finite duration. Its properties enable us to improve further the optimization performance of SOA through mutation. Thus, SOAWM, a new variant of SOA associated with wavelet mutation (WM) is used in this work. SOAWM not only produces near-global solution, but provides a much faster convergence than SOA. In addition, WM helps to achieve better solution stability. Thus, SOAWM

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[1] Rajesh Bera is with the Department of Electronics and Communication Engineering, Madanapalle Institute of Technology & Science, Andhra Pradesh, India-517325, E-mail: rajeshkiit12@gmail.com

[2] Durbadal Mandal and Rajib Kar are with the Department of Electronics and Communication Engineering, National Institute of Technology Durgapur, West Bengal, India-713209, E-mail: durbadal.bittu@gmail.com, rajibkarece@gmail.com

[3] Sakti P. Ghoshal is with the Department of Electrical Engineering, National Institute of Technology Durgapur, West Bengal, India-713209, E-mail: spghoshalnitdgp@gmail.com

would have the near-global optimized set of current excitations for the synthesis of CCAA.

In this work, Particle Swarm Optimization (PSO) [20-22], Differential Evolution (DE) [23], Seeker Optimization Algorithm (SOA) [24-26] and its modified version with Wavelet mutation (SOAWM) [27-29] are adopted for optimal thinning of CCAA. The paper is organized as follows. Section II explains the array factor of the CCAA. Formulation of cost function is also discussed in this section. Brief introductions for the PSO, DE, SOA and SOAWM are presented in section III. Simulation results and discussion of synthesized array are presented in section IV. Finally section V explains the conclusions of the paper with possible extensions.

II. DESIGN EQUATION AND OBJECTIVE FUNCTION

General array configuration of CCAA with M concentric rings is shown in Fig. 1, where r_m is the radius of the mth (m = 1, 2,…, M) ring and the corresponding number of element is N_m.

Far field radiation pattern of a thinned CCAA in *x-y* plane may be written as [15]:

$$AF(\theta,I)=\sum_{m=1}^{M}\sum_{i=1}^{N_m} I_{mi}\exp\left[j\left(kr_m\sin\theta\cos(\phi-\phi_{mi})+\alpha_{mi}\right)\right] \tag{1}$$

where I_{mi} =Excitation amplitude of i^{th} element of m^{th} ring =

$$\begin{cases}1 & \text{on}\\ 0 & \text{off}\end{cases} \tag{2}$$

$k=2\pi/\lambda$; λ = signal wave-length. Eq. (1) may be written as a periodic function of θ with a period of 2π radian if the elevation angle ϕ = constant. So, the radiation pattern will be a broadside array pattern. The azimuth angle of the i^{th} element of the m^{th} ring is ϕ_{mi}. ϕ_{mi} and α_{mi} are also obtained from [12, 29] as:

$$\phi_{mi}=2\pi\left((i-1)/N_m\right) \tag{3}$$

$$\alpha_{mi}=-Kr_m\sin\theta_0\cos(\phi-\phi_{mi}) \tag{4}$$

where θ_0 is the value of θ where peak of the main lobe is attained in $\theta\in[-\pi,\pi]$. In order to antenna pattern synthesis, the most important parameter is to produce the objective function that is to be minimized. The objective function "Cost Function" (CF) may be written as Eq. (5):

$$CF=W_{F1}\times\frac{\left|AF(\theta_{msl1},I_{mi})+AF(\theta_{msl2},I_{mi})\right|}{\left|AF(\theta_0,I_{mi})\right|}+W_{F2}\times\left|\left(FNBW_{computed}-FNBW(I_{mi}=1)\right)\right| \tag{5}$$

$FNBW$ is the width between two first nulls on either side of the main beam. Cost function CF is computed only if $FNBW_{computed}<FNBW(I_{mi}=1)$ otherwise the solution is not retained. $W_{F1}\,(unitless)$ and $W_{F2}\,(radian^{-1})$ are the weighting factors. θ_{msl1} is the angle where the maximum SLL $\left(AF(\theta_{msl1},I_{mi})\right)$ is attained in the lower band and θ_{msl2} is the angle where the maximum SLL $\left(AF(\theta_{msl2},I_{mi})\right)$ is attained in the upper band. W_{F1} and W_{F2} are weighting constants to control the relative prominence of each term. $FNBW_{computed}$ and $FNBW(I_{mi}=1)$ refer to the computed FNBW for the non-uniform excitation case and for the uniform excitation case, respectively. In order to minimization of cost function value, the evolutionary optimization techniques are employed individually. So, the optimization of current excitation weights results in reductions in both SLL and FNBW. All the elements have same excitation phase of zero degree.

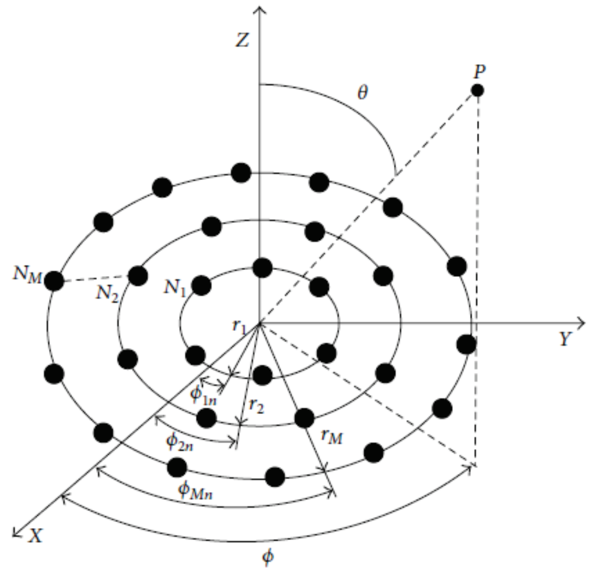

Fig. 1. Geometry of concentric circular antenna array (CCAA)

III. EVOLUTIONARY TECHNIQUES EMPLOYED

A. *Particle Swarm Optimization (PSO)*

PSO is a population-based stochastic optimization technique. The details of PSO are not given as some references on PSO are given in [20-22].

According to the following equation given below, velocities of the particles are modified in basic PSO

$$V_i^{(k+1)}=w*V_i^k+C_1*rand_1*\left(pbest_i^k-S_i^k\right)+C_2*rand_2*\left(gbest^k-S_i^k\right) \tag{6}$$

The searching positions of the particles in the solution space may be adjusted by the following equation:

$$S_i^{(k+1)}=S_i^k+V_i^{(k+1)} \tag{7}$$

B. *Differential Evolution (DE) Algorithm*

DE [23, 28] optimization technique was developed by Storn and Price in 1995. It is a scheme for generating trial parameter vectors and adds the weighted difference between two population vectors to a third one. D-dimensional parameter vectors (individuals) which encode the candidate solutions, are represented by Eq. (8)

$$\overrightarrow{x_{i,g}} = \{x_{1,i,g}, x_{2,i,g}, \ldots, x_{D,i,g}\}, \quad (8)$$

where i = 1, 2, 3,…, N_P. DE algorithm aims at evolving a population of N_P.

The initial population (at g=0) should cover the entire search space as much as possible by uniformly randomizing individuals within the search constrained by the prescribed minimum and maximum parameter bounds represented by $x_{\min}$ and $x_{\max}$ respectively as follow:

$$\vec{x}_{\min} = \{x_{1,\min}, \ldots, x_{D,\min}\}$$

$$\vec{x}_{\max} = \{x_{1,\max}, \ldots, x_{D,\max}\}.$$

For example, the initial value of the jth parameter of the ith vector

$$x_{j,i,0} = x_{j,\min} + rand(0,1) * (x_{j,\max} - x_{j,\min}) \quad (9)$$

where j = 1, 2, 3,…, D. *rand*(0,1), the random number generator, uniformly distributed from within the range [0,1]. DE enters a loop of evolutionary operations (mutation, crossover, and selection) after initialization. The steps of basic DE are given in [23].

C. Seeker Optimization Algorithm (SOA)

SOA [24-26] is a population-based empirical search algorithm. A seeker population is used to obtain an optimal solution where each individual of this population is called a *seeker*. The total population is arbitrarily characterized into three subpopulations. These subpopulations search over several different domains of the search space. All the seekers in the same subpopulation constitute a neighbourhood. This neighbourhood represents the social component for the social sharing of information.

The steps of the SOA, as implemented for the solution of optimal synthesis of a thinned CCAA carried out in this work, are shown below [25]:

Step 1: Initialization

i) Number of rings=9, ii) Number of elements in each ring, iii) Inter-element spacing (λ/2) iv) Set number of maximum iteration cycles (100); v) Set maximum population number (120) of seeker strings, each having total number of current excitation weights (279 for this problem); vi) Set lower (0.0) and upper (1.0) limits of current excitation weights.

Step 2: Randomly and uniformly Initialization of the positions of the seekers.

Step 3: Setting time step t = 0

Step 4: Computation of the Cost Function CF for the initial locations. The initially best location is achieved among the population. Set current location as the personal historical best location for each seeker.

Step 5: Let t = t + 1.

Step 6: Neighbour of each seeker is selected.

Step 7: Search direction and step length is defined for each seeker.

Step 8: Updating the location of each seeker.

Step 9: Computation of CF for each seeker.

Step 10: Updating personal best location of each seeker and global best among the population.

Step 11: Subpopulations learn from each other.

Step 12: Repeating Step 5 to the maximum iteration cycles (stopping criterion).

Step 13: Deciding the best seeker corresponding to the outstanding optimum CF.

Step 14: Optimal set of current amplitude excitation weights are determined.

D. SOA with Wavelet Mutation (SOAWM)

(a) Basic wavelet theory: Is referred to [27-29].

(b) Association of Wavelet based Mutation with SOA (SOAWM)

It is proposed that every element of the particle of the population generated by SOA will mutate. Among the population, a randomly selected ith particle and its jth element (within the limits $[S_{j,\min}, S_{j,\max}]$) at the k^{th} iteration) $S_{i,j}^{(k)}$ will undergo mutation as given in the following equation

$$S_{i,j}^{(k)} = \begin{cases} S_{i,j}^{(k)} + \sigma \times (S_{j,\max} - S_{i,j}^{(k)}), & \text{if } \sigma > 0 \\ S_{i,j}^{(k)} + \sigma \times (S_{i,j}^{(k)} - S_{j,\min}), & \text{if } \sigma \le 0 \end{cases} \quad (10)$$

where $\sigma = \psi_{a,0}(x) = \frac{1}{\sqrt{a}}\psi(\frac{x}{a})$; Eq. (10) represents the new mutation strategy by which SOAWM differs from SOA; otherwise all other steps of SOA and SOAWM are the same.

A Morlet wavelet (mother wavelet) is defined in the following equation given in Eq. (11). It is also shown in Fig. 2.

$$\psi(x) = e^{\frac{-x^2}{2}} \cos(5x) \quad (11)$$

Thus,

$$\sigma = \frac{1}{\sqrt{a}} e^{\frac{-(\frac{x}{a})^2}{2}} \cos(5(\frac{x}{a})) . \quad (12)$$

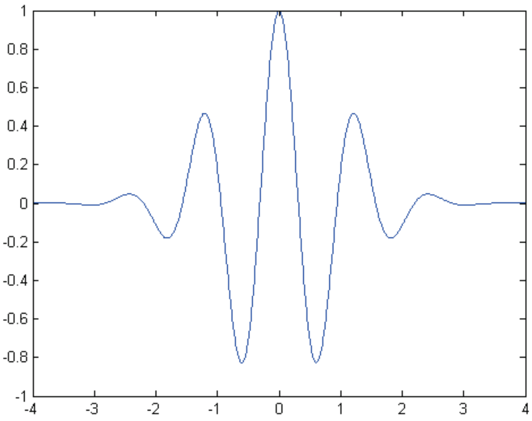

Fig. 2. Morlet wavelet

Fig. 3 shows the various dilated Morlet Wavelets for different values of parameter *a*. It is clear from the fig. 4 that the amplitude of $\psi_{a,0}(x)$ will be scaled down as the dilation parameter a increases. In order to enhance the searching performance in the fine tuning stage, this property will be utilized in mutation operation. x can be randomly generated from $[-2.5\times a,\ 2.5\times a]$ [27-29] as over 99% of the total energy of the mother wavelet function is contained in the interval [-2.5, 2.5]. Monotonic increasing function, a, with increase of k/K may be written as given in the following equation [27]

$$a = e^{-\ln(g_1)\times(1-\frac{k}{K})^{\xi_{\omega m}} + \ln(g_1)} \tag{13}$$

where $\xi_{\omega m}$ is the shape parameter and g_1 is the upper limit(=10000) of the parameter a. Thus, the value of a will increase monotonically from 1 to g_1 (=10000) as the iteration cycle k increases towards K (maximum iteration cycle). ξ_{wm} determines how fast a will increase towards g. A high value of ξ_{wm} is not preferred since a increases very fast, it may cause local search earlier before sufficient global search occurs, which will lead to much inferior optimal solution. So, ξ_{wm} is chosen more than 1; more details of the effect of ξ_{wm} on the variation of a are given in [27].

A perfect balance between the exploration of new regions and the exploitation of the already sampled regions in the search space is expected in SOAWM. This balance, which critically affects the performance of the SOAWM, is governed by the right choices of the control parameters, e.g. the shape parameter of WM ($\xi_{\omega m}$), the swarm size (n_p) and the probability of mutation (p_m). Changing the parameter $\xi_{\omega m}$ will change the characteristics of the monotonic increasing function of WM.

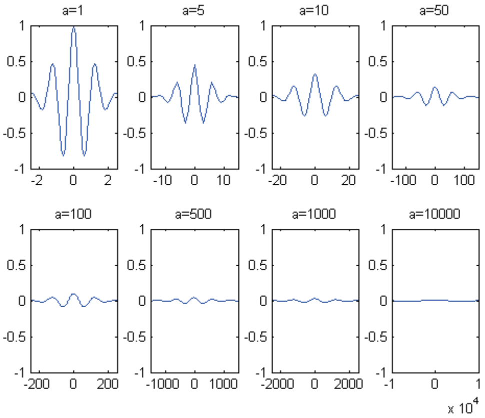

Fig. 3. Morlet wavelet dilated by different values of parameter a

Rigorous sensitivity analysis with respect to the dependence of a on (k/K), $\xi_{\omega m}$ and g_1 is performed to determine the individual best values of $\xi_{\omega m}$ and g_1. The individual best values of $\xi_{\omega m}$ and g_1 are 2.0 and 10000, respectively.

IV. SIMULATION RESULTS AND DISCUSSIONS

In the numerical analysis, we have considered CCAA of a fixed optimal inter-element spacing. Synthesis of CCAA is achieved by PSO, SOA, and SOAWM in this section. The ring radius of each ring in CCAA is defined by the product of the inequality constraint for the inter-element spacing, *d*, $\left(d\in\left[\lambda/2,\lambda\right]\right)$ and number of elements in that particular ring. $\phi_0 = 0^0$ is considered to maintain the main lobe starts from the origin for all the cases.

A large concentric circular antenna array of nine rings (N_1, N_2, ……., N_9) having (6, 12, 18, 25, 31, 37, 43, 50, 56) elements with central element feeding is considered for synthesis. The number of rings in the array is chosen arbitrarily to a large value (9 rings) because the total number of elements in the array has a great influence on the array pattern synthesis. FNBW/HPBW in the array pattern decreases with the increasing of the total number of elements in the array. Thus, the array directivity increases with the increasing in the number of elements. But, the SLL increases with the number of elements in the array. In order to reduce the SLL values, various evolutionary optimization techniques are applied for the optimal thinning of large CCAA.

Sometimes, the control parameters of PSO, DE and SOA techniques are quite sensitive. The parameter values should be carefully chosen which are shown in Table 1.

Fig. 4 shows the geometry of a 279-element concentric ring array of nine rings (N_1, N_2, ……., N_9) with central element feeding. Inter-element spacing in each ring is $d_m \cong \frac{\lambda}{2}$. So, the radius of ring *m* and the number of equally spaced elements in ring *m* can be obtained from Eqs. (14) and (15), respectively.

$$N_m = \frac{2\pi r_m}{d_m} = 2\pi m \tag{14}$$

$$r_m = m\times\frac{\lambda}{2} \tag{15}$$

The value N_m must be rounded up or down as the number of elements must be an integer. Table 2 lists the number of elements in each ring and radius of each ring for the uniform CCAA corresponding of Fig. 4. An individually generated set of optimal current excitations of synthesized CCAA using PSO, DE, SOA and SOAWM technique are shown in Tables 3-12.

A. Radiation Pattern Analysis of CCAA

Figs. 5-6 show the normalized absolute power patterns of optimized thinned arrays and uniformly excited arrays found by PSO, DE, SOA and SOAWM for 9-ring CCAA with central element feeding. It is observed that the number of antenna array elements can be brought down with simultaneous reduction in SLL is achieved after thinning; as compared to the fully populated array with fixed inter-element spacing, d≈λ/2.

As seen from Tables 7 and 12, SLL reduces to more than -21 dB for all algorithms, with respect to -17.4 dB for isotropic and -17.53 dB non-isotropic elements with uniform excitation and d= λ/2. Further, the above improvement is achieved with thinning percentage of 50.18%, 56.63%, 56.99% and 59.5% using PSO, DE, SOA, SOAWM, respectively for isotropic elements and central element feeding. Further, 54.12%, 62.01%, 62.36% and 66.31% elements turned off for PSO, DE, SOA, SOAWM, respectively for non-isotropic elements and central element feeding. Thinning is the ratio of the number of 'OFF' elements to the total number of elements in the array.

Thus, the thinned CCAA results in the reductions on SLL with simultaneous reductions in the number of effective antenna elements more than 50% as well, as compared to that of the fully populated array of same shape and size for both the cases of isotropic and non-isotropic elements.

TABLE 1
CONTROL PARAMETERS OF ALGORITHMS

Parameters	PSO	DE	SOA	SOAWM
Population size	120	120	120	120
Iteration cycles	100	100	100	100
C_1 & C_2	1.5, 1.5	-	-	-
$v_i^{\min}$, $v_i^{\max}$	1, 10	-	-	-
$w_{\min}$, $w_{\max}$	0.4, 1.0	-	-	-
C_r	-	0.3	-	-
F	-	0.5	-	-
Δ	-	-	0.02	0.02
k_1, k_2, k_3	-	-	1.5, 2, 2	1.5, 2, 2
$\xi_{\omega m}$	-	-	-	0.2
g_1	-	-	-	10000
p_m	-	-	-	0.3

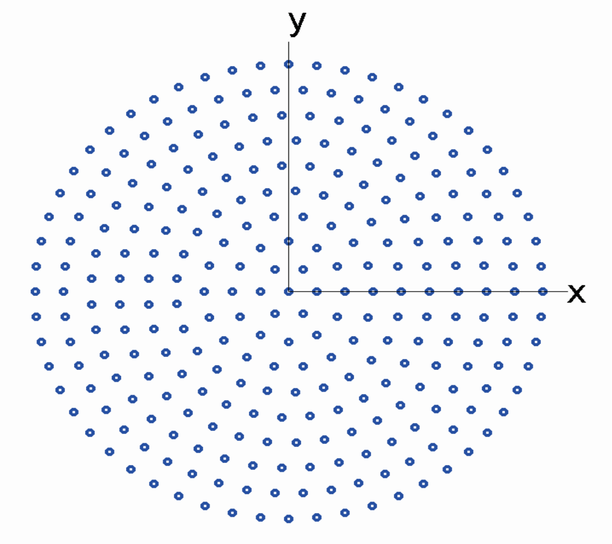

Fig. 4. Nine-ring CCAA with $d_m \approx \lambda/2$

TABLE 2
NUMBER OF ELEMENTS IN EACH RING AND CORRESPONDING RING RADIUS

M	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
N_m	6	12	18	25	31	37	43	50	56
$r_m(\lambda)$	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5

TABLE 3
DISTRIBUTIONS OF AMPLITUDES IN THINNED CCAA OF ISOTROPIC ELEMENTS USING PSO

Ring No.	Number of elements in each ring	Distribution of ON and OFF elements
central element	1	1
1	6	1 1 0 1 1 1
2	12	1 1 0 1 1 1 0 1 1 1 1 1
3	18	0 0 0 0 1 0 1 1 1 1 0 1 1 0 0 0 0 0
4	25	1 1 0 1 1 1 0 0 0 1 1 0 0 1 1 1 1 0 1 1 1 0 0 1 1
5	31	0 1 1 0 0 1 1 1 1 0 1 0 1 0 0 0 0 1 0 0 0 1 0 0 0 0 1 1 0 1 0
6	37	0 1 0 1 0 0 0 0 1 0 0 0 1 0 0 0 1 0 0 0 0 0 1 0 0 1 1 0 1 0 0 1 0 1 1 0 0
7	43	1 0 1 0 1 1 0 1 1 0 1 1 1 0 1 1 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 1 0 1 1 0 1 0 1 1 1 0
8	50	0 1 0 0 0 1 1 0 0 1 0 0 1 0 1 0 0 0 1 0 1 0 1 0 1 0 0 0 0 1 0 1 1 1 1 1 0 1 0 1 0 1 0 0 1 1 1 1 1 1
9	56	0 1 1 1 0 0 1 0 0 0 1 0 0 1 1 0 0 1 0 1 0 1 1 0 1 1 0 0 1 1 0 0 0 0 0 0 0 1 1 1 0 1 1 0 0 0 0 1 1 1 0 0 0 1 1 1

TABLE 4

DISTRIBUTIONS OF AMPLITUDES IN THINNED CCAA OF ISOTROPIC ELEMENTS USING DE

Ring No.	Number of elements in each ring	Distribution of ON and OFF elements
central element	1	1
1	6	1 1 1 0 1 0
2	12	1 0 0 0 0 1 0 1 0 1 1 0
3	18	0 0 1 0 0 1 1 1 1 0 0 1 1 0 1 1 1 1
4	25	0 0 0 0 0 0 1 1 1 1 1 0 1 1 1 0 0 0 1 0 0 1 1 1 0
5	31	0 0 1 1 0 0 1 1 0 0 1 0 1 1 1 0 1 0 1 0 1 0 0 0 1 1 0 0 0 0 0
6	37	1 0 1 1 1 0 0 1 0 1 0 0 0 1 1 1 0 1 1 1 1 0 0 0 0 0 0 1 1 0 0 1 0 1 1 0 0
7	43	1 0 1 0 0 0 0 0 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 0 0 0 0 1 0
8	50	0 1 0 0 1 1 0 1 0 0 0 0 1 1 1 0 0 1 1 0 1 0 1 0 0 0 0 1 1 1 1 0 0 0 0 1 0 0 1 0 0 0 1 1 1 0 1 0 0 0
9	56	0 1 1 0 0 1 0 1 0 0 1 0 0 0 0 1 1 0 0 0 0 0 1 0 0 0 1 1 1 0 0 0 1 1 1 0 1 1 1 0 1 0 1 0 0 1 1 1 0 1 0 1 0 1 0 0

TABLE 5

DISTRIBUTIONS OF AMPLITUDES IN THINNED CCAA OF ISOTROPIC ELEMENTS USING SOA

Ring No.	Number of elements in each ring	Distribution of ON and OFF elements
Central element	1	0
1	6	1 0 0 1 1 1
2	12	1 0 1 1 1 1 1 1 1 0 1 0
3	18	1 0 1 1 0 1 1 0 0 1 1 1 0 0 1 0 1 1
4	25	0 1 0 1 1 0 1 0 0 0 1 1 0 1 1 0 0 0 0 1 0 0 0 0 0
5	31	1 0 1 0 1 1 1 1 0 0 0 0 1 1 0 0 1 0 1 1 0 0 0 0 0 0 1 0 1 0 0
6	37	0 1 0 1 0 1 1 0 1 0 0 0 0 1 1 1 0 0 0 0 0 0 1 0 0 1 0 1 1 0 0 1 1 0 1 1 0
7	43	0 1 1 0 1 0 1 0 1 1 0 0 1 0 0 0 1 0 0 1 0 0 1 0 0 0 1 0 0 0 0 1 0 0 0 1 0 0 1 0 1 0 1
8	50	0 0 0 0 0 1 0 1 1 0 1 1 0 0 1 1 0 1 1 1 0 0 0 0 0 1 1 0 0 1 1 0 1 0 0 0 1 1 0 1 0 0 0 1 0 1 1 1 0 1
9	56	0 1 0 0 0 0 0 0 0 1 0 1 0 0 1 0 1 0 1 0 0 1 0 0 1 0 1 0 0 1 1 1 0 1 0 0 1 0 0 1 0 0 0 0 1 1 0 1 0 1 0 0 0 0 1 1

TABLE 6

DISTRIBUTIONS OF AMPLITUDES IN THINNED CCAA OF ISOTROPIC ELEMENTS USING SOAWM

Ring No.	Number of elements in each ring	Distribution of ON and OFF elements
Central element	1	0
1	6	1 1 0 1 1 1
2	12	0 0 0 0 0 0 1 0 0 0 1 1
3	18	1 0 1 0 0 0 0 1 0 1 1 0 0 1 1 0 0 0
4	25	0 1 0 1 0 0 0 0 1 1 1 0 0 1 0 1 0 0 1 0 0 1 1 1 0
5	31	1 0 0 0 1 0 0 0 0 0 1 1 0 0 0 0 1 1 0 1 1 0 0 1 1 0 1 0 1 1 0
6	37	0 0 1 0 1 0 0 0 1 0 0 1 1 0 1 1 1 1 1 0 0 0 0 0 0 1 0 1 1 0 1 0 0 0 0 0 0
7	43	1 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 1 1 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
8	50	1 0 0 0 0 0 1 0 1 0 0 0 0 1 0 1 1 0 1 1 0 0 0 1 1 1 1 0 0 0 0 0 1 0 1 0 1 1 1 0 0 0 1 1 0 0 0 0 1 0

9	56	0 1 1 1 1 1 0 1 0 0 0 0 0 0 1 1 1 0 1 1 0 0 1 1 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1 1 0 1 1 0 0 0 0 0 1 0 1 1 1 0 1 0

TABLE 7

PERFORMANCE RESULTS OF OPTIMIZED THINNED CCAA OF ISOTROPIC ELEMENTS USING EVOLUTIONARY ALGORITHMS

Parameters	Thinned array (PSO)	Thinned array (DE)	Thinned array (SOA)	Thinned array (SOAWM)	Fully populated array
SLL (in dB)	-20.37	-20.65	-21.04	-21.64	-17.40
FNBW (in degree)	15.844	15.916	15.988	15.844	14.762
Number of OFF elements	140	158	159	166	0
Number of ON elements	139	121	120	113	279

TABLE 8

DISTRIBUTIONS OF AMPLITUDES IN THINNED CCAA OF NON-ISOTROPIC ELEMENTS USING PSO

Ring No.	Number of elements in each ring	Distribution of ON and OFF elements
Central element	1	1
1	6	1 1 1 0 1 0
2	12	1 1 0 0 0 1 0 0 1 0 0 0
3	18	1 1 1 0 1 1 0 0 0 1 0 1 0 0 1 0 1 1
4	25	0 1 1 0 1 1 1 0 1 1 1 0 0 0 1 1 0 1 1 1 1 0 1 0 0
5	31	0 1 1 1 0 0 1 0 0 1 1 0 0 1 1 0 1 1 1 0 0 1 1 1 1 0 0 1 0 1 0
6	37	1 0 0 0 0 0 0 0 1 0 0 0 0 1 1 1 0 0 1 1 1 0 1 0 0 1 0 1 1 0 1 1 0 1 1 1 1
7	43	1 0 0 0 0 1 1 0 0 0 0 0 1 0 0 0 0 0 1 0 0 1 0 1 0 0 1 0 0 0 1 0 0 1 1 0 1 0 0 0 0 1 0
8	50	0 0 0 1 0 1 0 1 0 0 0 0 1 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 1 0 0 0 1 1 0 0 1 1 1 1 1 0 0 1 1 0 0

9	56	0 1 0 1 0 0 1 1 1 0 0 0 1 1 0 1 1 0 1 1 1 1 0 0 0 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 0 0 1 1 0 0 0 0 0 0 1 0 1 0 1 0

TABLE 9

DISTRIBUTIONS OF AMPLITUDES IN THINNED CCAA OF NON-ISOTROPIC ELEMENTS USING DE

Ring No.	Number of elements in each ring	Distribution of ON and OFF elements
central element	1	0
1	6	0 1 0 1 1 1
2	12	1 0 0 1 1 0 1 0 1 0 0 1
3	18	1 0 0 0 0 1 1 1 0 0 0 1 0 0 1 1 1 1
4	25	0 0 0 1 1 0 0 1 1 0 0 0 0 1 0 1 0 0 0 1 1 1 1 0 0
5	31	1 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 1 0
6	37	1 1 1 0 1 1 0 0 0 0 1 0 0 0 0 0 0 0 0 1 1 1 0 0 0 1 0 1 1 0 1 1 1 0 0 0 0
7	43	1 0 0 1 0 0 0 1 0 1 0 0 0 0 0 0 1 0 1 0 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 0 0 1 0 0 1
8	50	0 0 1 0 0 1 1 1 1 0 1 1 0 0 1 1 0 0 1 0 0 1 1 1 0 0 1 0 0 1 1 0 0 1 0 1 1 0 1 0 0 0 0 0 1 0 0 1 0 1
9	56	0 1 1 1 0 1 0 0 0 1 0 1 1 0 0 0 0 0 0 1 0 1 0 1 1 0 1 0 1 0 0 1 0 1 0 0 0 0 1 0 1 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0

TABLE 10

DISTRIBUTIONS OF AMPLITUDES IN THINNED CCAA OF NON-ISOTROPIC ELEMENTS USING SOA

Ring No.	Number of elements in each ring	Distribution of ON and OFF elements
Central element	1	0
1	6	1 1 0 1 0 1
2	12	0 0 0 0 1 0 1 0 0 1 1 0

3	18	0 0 1 0 0 0 1 0 1 0 0 1 0 0 1 0 1 0
4	25	1 1 0 1 1 0 1 0 1 1 1 1 0 0 1 1 0 0 1 0 0 1 1 0 0
5	31	1 0 0 0 0 1 1 0 0 1 0 1 0 1 1 0 1 0 1 0 0 1 0 1 1 0 0 1 1 1 0
6	37	0 1 0 0 1 1 1 1 0 0 0 0 0 1 0 1 1 0 0 1 1 0 0 0 1 0 1 1 0 0 0 1 0 1 0 0 0
7	43	0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 1 0 0 0 0 0 0 0 1
8	50	1 0 1 1 0 0 1 0 0 0 1 0 1 1 0 0 0 1 0 1 1 0 0 0 1 0 1 1 0 0 0 1 0 1 0 0 0 0 1 0 0 1 0 1 0 0 0 1 1 0
9	56	1 0 1 0 0 0 0 0 0 1 0 1 0 1 0 1 0 0 0 1 0 1 0 0 1 1 1 1 1 1 1 0 1 1 0 1 0 1 1 0 0 1 0 0 0 1 1 1 0 1 0 0 1 0 0 0

TABLE 11

DISTRIBUTIONS OF AMPLITUDES IN THINNED CCAA OF NON-ISOTROPIC ELEMENTS USING SOAWM

Ring No.	Number of elements in each ring	Distribution of ON and OFF elements
Central element	1	1
1	6	1 1 1 1 1 0
2	12	0 0 1 0 0 0 1 0 1 0 0 0
3	18	1 0 0 1 0 0 1 0 1 1 0 1 0 0 0 1 1 0
4	25	0 1 1 1 0 1 1 0 0 1 0 0 0 1 1 0 0 1 0 1 0 1 1 0 1
5	31	1 1 0 0 0 0 0 1 0 0 1 0 1 0 0 0 0 1 1 0 1 0 1 0 1 0 1 0 0 1 0
6	37	1 0 1 0 0 1 0 0 0 1 1 0 0 1 0 1 1 0 1 0 1 0 1 0 0 0 0 1 1 0 0 0 1 1 0 0 0
7	43	0 0 1 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 1 0 0 0 0 1 0 0 1 0 0 0 1 0 0 0 1
8	50	0 0 0 0 0 0 0 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 0 0 0 0 0 1 0 1 0 0 0 1 1 0 0 0 1 1 0 0 1 0 0 0 0 1 0
9	56	0 0 1 1 0 0 0 1 0 0 0 0 0 0 1 1 0 0 0 0 0 1 0 0 1 0 1 0 0 0 1 0 0 1 0 1 0 1 0 0 1 1 1 0 0 1 0 0 0 0 0 0 0 0 1 0

TABLE 12

PERFORMANCE RESULTS OF OPTIMIZED THINNED CCAA OF NON-ISOTROPIC ELEMENTS USING EVOLUTIONARY ALGORITHMS

Parameters	Thinned array (PSO)	Thinned array (DE)	Thinned array (SOA)	Thinned array (SOAWM)	Fully populated array
SLL (in dB)	-20.65	-20.9	-21.99	-22.02	-17.53
FNBW (in degree)	16.204	15.772	15.844	15.916	14.762
Number of OFF elements	151	173	174	185	0
Number of ON elements	128	106	105	94	279

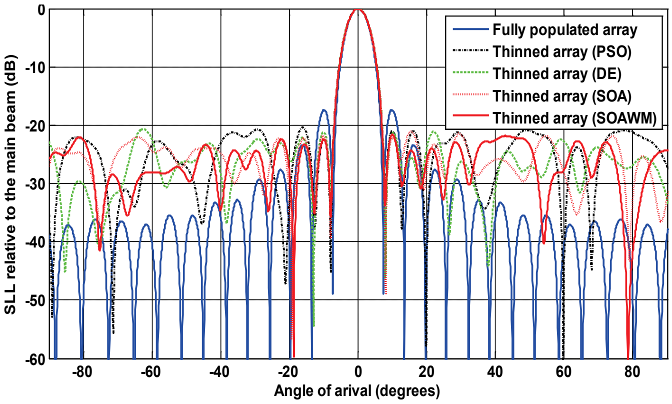

Fig. 5. Array patterns for nine-ring CCAA set with isotopic elements and central element feeding

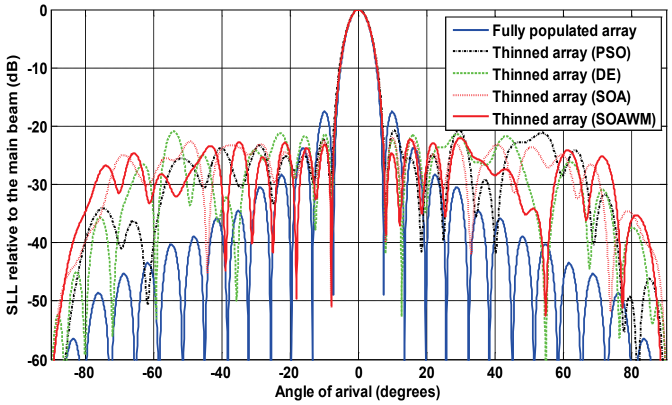

Fig. 6. Array patterns for nine-ring CCAA set with non-isotopic elements and central element feeding

B. *Convergence Profiles*

The convergence characteristics of PSO, DE, SOA and SOAWM are shown in Figs. 7-10, respectively, in terms of best fitness value (the minimum *CF* value) versus iteration cycle of each algorithm. All computations were done in MATLAB 7.5 on Intel (R) Core (TM) i5-4690 processor, 3.50 GHz with 4 GB RAM. The Figs. 7-10 shows the superiority of SOAWM for minimizing the cost function.

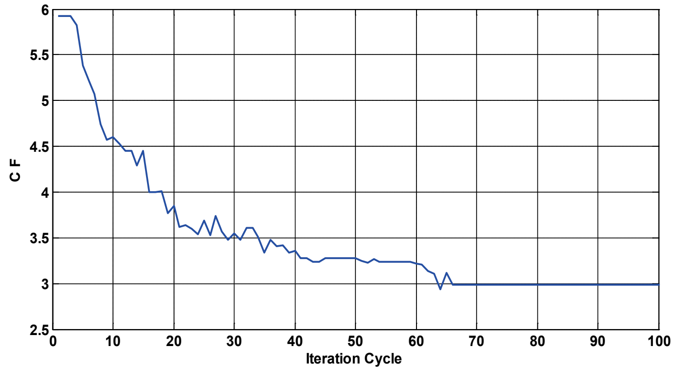

Fig. 7. Convergence profile for PSO in case of thinned nine-ring CCAA set with non-isotopic elements and central element feeding

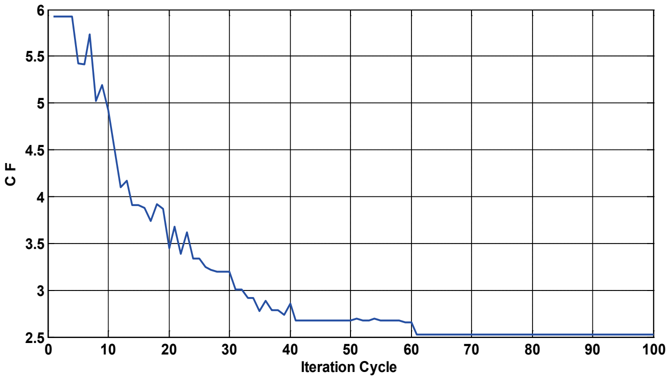

Fig. 8. Convergence profile for DE in case of thinned nine-ring CCAA set with non-isotopic elements and central element feeding

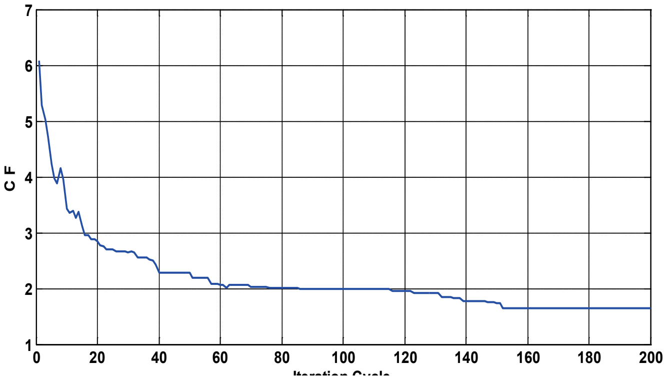

Fig. 9. Convergence profile for SOA in case of thinned nine-ring CCAA set with non-isotopic elements and central element feeding

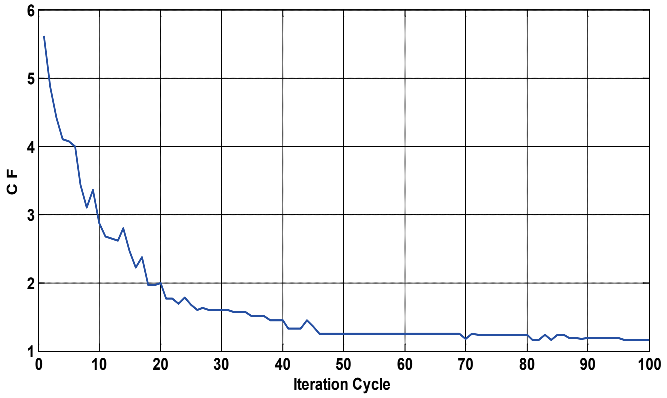

Fig. 10. Convergence profile for SOAWM in case of thinned nine-ring CCAA set with non-isotopic elements and central element feeding

V. CONCLUSIONS

This paper illustrates Particle Swarm Optimization (PSO), Differential Evolution (DE), a novel Seeker Optimization Algorithm (SOA) and its enhanced version, SOAWM for thinning of 9-ring Concentric Circular Antenna Arrays (CCAA) of isotropic elements and non-isotropic elements as well. The simulation results show that the number of antenna array elements can be brought down from 279 to 113 (Filled ratio 40.50%) for isotropic elements and 94 (Filled ratio 33.69%) for non-isotropic elements with a simultaneous drop in Side Lobe Level (SLL). So, SOAWM algorithm can efficiently handle the thinning of large CCAA of isotropic and non-isotropic elements with a reduction to 59.5% and 66.31% of the total elements, respectively, with a simultaneous reduction in maximum SLL of around -21.64 dB and -22.02 dB, respectively, by SOAWM.

SOAWM proves its better-searching ability compared with PSO, DE and SOA for the design of thinned CCAA in terms of the best converged solution and efficient SLL reduction. The other array parameters like FNBW of the synthesized array patterns are very close to the arrays of same shape and size. The comparison shows a significant improvement for SLL with a significant reduction in the number of elements which will reduce the cost of designing the antenna array substantially.

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