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DESIGN OF A FULLY DIGITAL CONTROLLED RECONFIGURABLE SWITCHED BEAM CONCENTRIC RING ARRAY ANTENNA USING FIREFLY AND PARTICLE SWARM OPTIMIZATION ALGORITHM

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Abstract—Reconfigurable antenna arrays are often capable of radiating multiple patterns by modifying the excitation phases of the elements. In this paper a method based on Firefly Algorithm (FA) has been proposed to obtain dual radiation pattern from a concentric ring array of isotropic elements, by finding out two different combinations of states for the switches, which are assumed to be connected with the rings of the array, along with optimum set of 4-bit radial amplitude and 5-bit radial phase distributions of the array elements for the specific switch combinations. The optimum excitations of the array elements in terms of discrete amplitudes and discrete phase, and the different switch combinations for the specific excitations are computed using Firefly Algorithm. To illustrate the effectiveness of Firefly Algorithm, the two beam pairs have been computed by the same procedure from the same array, using Particle Swarm Optimization (PSO) algorithm, without changing their design criteria. Results clearly show the superiority of the Firefly Algorithm over Particle Swarm Optimization to handle the proposed problem.

1. INTRODUCTION

Reconfigurable antenna arrays received considerable interest in recent times because of their ability to radiate multiple patterns from a single antenna array, which are often required in communication and radar related applications. Generally multiple radiation patterns are obtained by switching between the excitation phases distributions of

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the elements while sharing common amplitude distributions. Several methods of generating multiple patterns from a single antenna arrays appeared in the literature [1–11].

Bucci et al. [1] proposed the method of projection to synthesize reconfigurable array antennas with asymmetrical pencil and flat-top beam patterns using common amplitude and varying phase distributions. Design of phase-differentiated multiple pattern antenna arrays based on simulated annealing algorithm have been described by Diaz et al. [2]. Durr et al. proposed a phase only pattern synthesis method to generate multiple radiations of pre-fixed amplitude distribution with modified Woodward-Lawson technique [3]. The design of a phase-differentiated reconfigurable array [4] using particle swarm optimization in angle domain has been described by Gies and Rahmat-Samii. Synthesis of continuous phase-only reconfigurable array was described in [5]. Mahanti et al. [6] synthesized fully digital controlled reconfigurable linear array antennas while maintaining a Fixed Dynamic Range Ratio. Vaitheeswaran obtained multiple radiation patterns from a linear antenna array based on finding an optimum set of element-perturbed position in a constrained position range using generalized generation gap steady state genetic algorithm (G3-GA) [7]. Dual radiation patterns from a concentric ring array have been reported in [8–10]. In [8], three different beam-pairs — pencil/pencil, pencil/flat-top and flat-top/flat-top has been achieved by modifying the 5-bit discrete radial phase distribution of the array elements while sharing a common 4-bit radial amplitude distribution among the elements using Gravitational Search Algorithm (GSA). Discrete phase only reconfigurable antenna array to generate dual beam by finding out an optimum set of discrete phase of the array elements using differential evolution algorithm has been reported in [11].

In this paper, we proposed a technique to generate dual radiation patterns from a concentric ring array [12–24] with desired design specifications, based on finding the two optimum combinations of the states of the switches, which are assumed to be connected with the rings of the array, along with an optimum set of 4-bit radial amplitude and 5-bit radial phase distributions of the array elements. The proposed method has been applied to generate two different beam pair: a pencil/pencil beam-pair and a pencil/flat-top beam-pair in the vertical plane with specified values of side lobe level (SLL), first null beamwidth (FNBW), half-power beamwidth (HPBW) and ripple. The optimum values of discrete radial amplitudes, discrete radial phases and the optimum switching combinations required to generate the above mention beam-pairs, are computed using Firefly Algorithm

(FA) [25–27]. To illustrate the effectiveness of Firefly Algorithm, the two beam pairs have been separately generated by the same method form the same array using Particle Swarm Optimization (PSO) [27–29] algorithm, without changing their design criteria. Results clearly show the effectiveness of FA over PSO to compute the two different beam-pairs using the proposed method.

2. PROBLEM FORMULATION

In this problem a concentric ring array of isotropic elements have been considered. Two different radiation patterns are obtained from the single array under two different combinations of state of the switches, connected with the rings of the array. The optimum combinations of state of the switches and optimum discrete radial amplitude and radial phase of the array elements for the specific switch combinations, generates dual radiation pattern in the vertical plane. The two patterns share common amplitudes and phase distributions of the array elements and are differ only in the two different states of the switches. The state of a particular switch indicates the states of all the elements in a particular ring of the array associated with that switch. The "off" state of a particular switch is represented by making the excitation amplitude and phase both equals to 'zero' to all the elements of a ring associated with the switch. Similarly the "on" state of a switch is represented by making the excitation amplitude and phase of all the elements of a ring, associated with the switch, equals to the optimum values of discrete amplitude and discrete phase assigned for the ring.

The states of the switches are found out in terms of binary words. A 'zero' in the binary word reflects the "off" state and a 'one' reflects the "on" state. All the radial amplitudes are varied in the range of $0 \leq I_m \leq 1$ in steps of $1/2^4$ of a 4-bit digital attenuators and the radial phases are varied in the range of $-180^\circ \leq \varphi \leq 180^\circ$ in steps of $360^\circ/2^5$ or 11.25° of a 5-bit digital phase shifters.

The proposed method has been applied to generate two different beam pairs from a single concentric ring array of isotropic antennas. Two different cases comprising a pencil/pencil beam pair and a pencil/flat-top beam pair have been considered.

The free space far field pattern of the concentric ring array [15–18] as shown in Figure 1 on the x-y plane can be expressed as:

$$E(\theta, \varphi) = \sum_{m=1}^{M} \sum_{n=1}^{N_m} I_m e^{j[kr_m \sin\theta \cos(\varphi - \varphi_{mn}) + \phi_m]} \quad (1)$$

Normalized absolute power pattern $P(\theta, \varphi)$ in dB can be expressed as

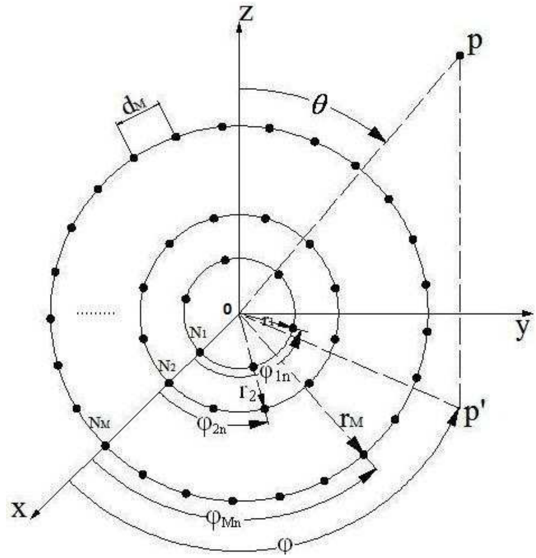

Figure 1. Concentric ring array of isotropic antennas in X-Y plane.

follows:

$$P(\theta,\varphi) = 10\log_{10}\left[\frac{|E(\theta,\varphi)|}{|E(\theta,\varphi)|_{\max}}\right]^2 = 20\log_{10}\left[\frac{|E(\theta,\varphi)|}{|E(\theta,\varphi)|_{\max}}\right] \quad (2)$$

where, M = number of concentric rings, N_m = number of isotropic elements in m-th ring, I_m = excitation amplitude of elements on m-th circular ring, d_m = interelement arc spacing of m-th circle, $r_m = N_m d_m/2\pi$ is the radius of the m-th ring, $\varphi_{mn} = 2n\pi/N_m$ is the angular position of mnth element with $1 \leq n \leq N_m$, θ, φ = polar, azimuth angle, λ = wave length, k = wave number = $2\pi/\lambda$, j = complex number, ϕ_m = excitation phase of elements on m-th ring.

The fitness functions for the two beam pairs of case I and case II have been defined as follows:

$$Fitness1 = \sum_{j=1}^{3} k_j \left(P_{j,o}^{(p1)} - P_{j,d}^{(p1)}\right)^2 H(T1) + \sum_{j=1}^{3} w_j \left(P_{j,o}^{(p2)} - P_{j,d}^{(p2)}\right)^2 H(T2) \quad (3)$$

$$Fitness2 = \sum_{j=1}^{3} k_j \left(P_{j,o}^{(p1)} - P_{j,d}^{(p1)}\right)^2 H(T1) + \sum_{j=1}^{4} w_j \left(P_{j,o}^{(p2)} - P_{j,d}^{(p2)}\right)^2 H(T2) \quad (4)$$

where $Fitness1$ represents the fitness function for the pencil/pencil beam-pair, i.e., for case I and $Fitness2$ is for the pencil/flat-top beam-pair, i.e., for case II. The superscript *p1* is meant for the design specification of the *pattern 1* and the superscript *p2* is meant for the design specification of the *pattern 2* for both the cases.

$P_{j,o}$ and, $P_{j,d}$ represent respectively the obtained and desired values of the parameters for both the cases. The fourth term of second summation in Equation (4) is the ripple parameters for the flat-top beam of second case. The desired tolerance level of the ripple for the flat-top (sector) beam pattern of pencil/flat-top beam-pair in the coverage region $-12^\circ \leq \theta \leq 12^\circ$ is kept at 0.1 dB from the peak value of 0 dB.

H(T1) and *H(T2)* are Heaviside step functions defined as follows:

$$T1 = \left(P_{j,o}^{(p1)} - P_{j,d}^{(p1)}\right) \tag{5}$$

$$T2 = \left(P_{j,o}^{(p2)} - P_{j,d}^{(p2)}\right) \tag{6}$$

$$H(T1) = \begin{cases} 0, & \text{if } T1 < 0, \\ 1, & \text{if } T1 \geq 0 \end{cases} \tag{7}$$

$$H(T2) = \begin{cases} 0, & \text{if } T2 < 0, \\ 1, & \text{if } T2 \geq 0 \end{cases} \tag{8}$$

The weighting factors associated with each terms in Equation (3) have been made equals to 'one' i.e., $k_j = w_j = 1$ for all values of j. In Equation (4) the weighting factors associated with the first summation have been made equals to 'one' i.e., $k_j = 1$, for all values of j. The weighting factors associated with the second summation in Equation (4) has been defined as follows:

$$w_j = \begin{cases} 20\,, & \text{for } j = 4, \\ 1\,, & \text{otherwise} \end{cases} \tag{9}$$

For optimal synthesis of dual-beam concentric ring array the fitness functions of Equation (3) and Equation (4) have to be minimized based on the proposed method.

3. ALGORITHM DETAILS AND PARAMETRIC SETUP

This section describes the Firefly algorithm (FA) and the parametric setups for both FA and PSO [27–29] to obtain dual radiation pattern from the concentric ring array for both the cases.

3.1. Firefly Algorithm

Firefly algorithm is a swarm based optimization algorithm developed by Yang [25]. The algorithm relates the flashing characteristics of the fireflies with the objective function to be optimized. The idea of the algorithm was developed from the study of social behavior and the bioluminescent communication of fireflies [25–27]. The algorithm considered glowing fireflies as agents and they moved around the search space for finding out an optimum solution of a given problem. At a particular instant, each agent i.e., firefly is characterized by two parameters: its location (x) in the d-dimensional search space and its light intensity or brightness (I). The location of a firefly at a particular instant reflects a solution of an objective function, which is being optimized, and its brightness denotes the quality of that solution. Depending upon the types of problem, the intensity of flashing light from a firefly is determined by the fitness evolution of the objective function. In maximization problem, brightness is assume simply proportional to the value of the objective function [25–27] and in case of minimization problem, it is taken as inverse of the value of objective function. Each firefly is attracted towards every other "brighter" firefly in the population [25–27]. The location and the brightness of the fireflies are updated in the successive iterations of the algorithm. A fixed maximum number of iterations specify the termination condition of the algorithm and at the end of maximum iteration, the location of the brightest firefly in population gives the optimum solution of the problem and its brightness reflects the quality of the solution. The algorithm can be summarized as below:

Step 1: Generate initial locations of the fireflies:

Initialize the locations of n-number fireflies randomly in the d-dimensional search space within the search bound as below:

$$x_i = (x_{i1}, x_{i2}, \ldots, x_{id}) \quad \text{for } i = 1, 2, \ldots, n \tag{10}$$

Step 2: Compute the brightness of the fireflies:

Compute the brightness (I_i) of each firefly at current generation by fitness evolution at their current location.

for maximization problem,

$$I_i \propto f(x_i) \tag{11a}$$

for minimization problem,

$$I_i \propto {}^{1}\!/_{f(x_i)} \tag{11b}$$

Step 3: Rank the fireflies and compute current global best:

Rank the fireflies according to their brightness at current generation. Assign the location of the brightest firefly in the population as current global best (g_{best}) and the corresponding brightness as best fitness value at current generation.

Step 4: Update the location of the fireflies through their movement:

Move each firefly towards the "brighter" firefly [25–27] in the population at current generation and updates their locations for the next iteration of the algorithm depending upon the attractiveness between the "brighter" one and the moving firefly.

The movement of firefly i attracted towards another more attractive (brighter) firefly j in d-dimensional search space is computed as [25–27]:

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2} (x_i - x_j) + \alpha\varepsilon_i \tag{12}$$

where the product of β_0 and $e^{-\gamma r_{ij}^2}$ in Equation (12) denotes the attractiveness between the two fireflies i and j. γ is the light absorption coefficient in a given medium. r_{ij} is the Cartesian distance between the two fireflies i and j at x_i and x_j, and is computed as [25–27]:

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2} \tag{13}$$

Firefly algorithm does not allow the movement of the brightest firefly to any other direction at current generation. The algorithm holds the location of the brightest firefly at current generation, and rest of the fireflies changes there locations according to Equation (12). In this manner the algorithm gradually updates the global best (g_{best}) solution in the successive iterations of the algorithm.

β_0 is the attractiveness at $r = 0$. The third term Equation (12) is for introducing some randomization where α being the randomization parameter and ε_i is a vector of random numbers drawn from a Gaussian distribution or uniform distribution [25–27].

Step 5: Repeat from steps 2 to 4 until iteration reaches its maximum limit. Return the location of the best firefly (g_{best}) as the global solution and the corresponding brightness as the global fitness value of the objective function using firefly algorithm.

3.2. Details of Parametric Setup

A concentric ring array of ten rings is considered. The number of elements in each ring are taken as multiple of 7, i.e., $7m$, where m is the ring number. The inter-element distance d_m in each is considered as 0.5λ. The radius of the m-th ring of the array is determined from the expression $r_m = {}^{N_m d_m}/_{2\pi}$. From the expression of r_m it can be seen that, for $N_m = 7m$ and $d_m = 0.5\lambda$, all the rings are separated from each other by a minimum distance of 0.5λ which is helpful to avoid the effect of mutual coupling.

As the design problem is based on finding out the two optimum combinations of the state of the switches along with an optimum set of 4-bit radial amplitude and an optimum set of 5-bit radial phase for the array, the individual of the population for both FA and PSO are considered as follows:

$$P = [S_1\, S_2\, \ldots\, S_{2M}\;\; I_1\, I_2\, \ldots\, I_M\;\; \phi_1\, \phi_2\, \ldots\, \phi_M] \tag{14}$$

The limits of the variables are defined as follows:

$$0 \le S_m \le 1, \quad \text{for } m = 1, 2, \ldots, 2M \tag{15}$$

$$0 \le I_m \le 1, \quad \text{for } m = 1, 2, \ldots, M \tag{16}$$

$$-\pi \le \phi_m \le \pi, \quad \text{for } m = 1, 2, \ldots, M \tag{17}$$

where, M is the number of rings of the array, considered as 10.

The two combinations of the state of the switches are obtained by rounding off the S_m, and the 4-bit radial amplitudes and 5-bit radial phases are obtained by quantizing the amplitudes and phases to their significant levels. The other parametric setups of the FA and PSO, for the proposed problem are set based on the guidelines provided in [25–29] and are given in Table 1. The desired specification of the parameters $P_{j,d}$, required for obtaining dual radiation patterns for both the cases are given in Table 2 and Table 3, respectively.

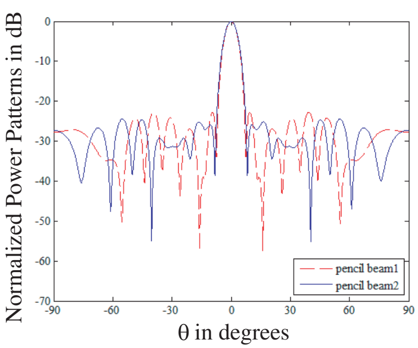

Figure 2. Dual radiation pattern of pencil/pencil beam pair (case I) computed using FA (shown in $\varphi = 0^\circ$ plane).

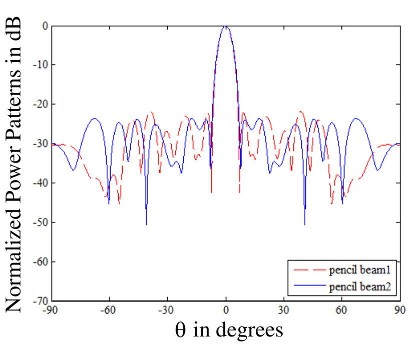

Figure 3. Dual radiation pattern of pencil/pencil beam pair (case I) computed using PSO (shown in $\varphi = 0^\circ$ plane).

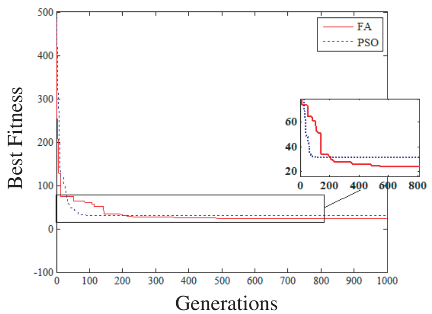

Figure 4. Convergences of FA and PSO for the minimization of the fitness function of case I.

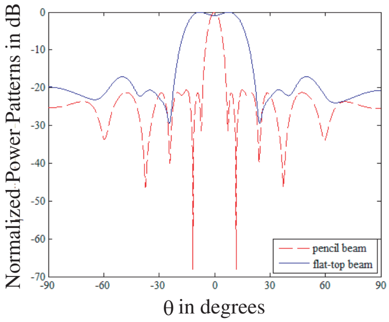

Figure 5. Dual radiation pattern of pencil/flat-top beam pair (case II) computed using FA (shown in $\varphi = 0°$ plane).

Table 1. Parametric setup of the FA and PSO.

FA		**PSO**	
Parameters	**Value**	**Parameters**	**Value**
number of fireflies	35	Swarm size	35
β_0	0.20	$C1$	2.0
γ	0.25	$C2$	2.0
α	1	Time-varying inertia weight (w)	Decreases linearly from 0.9 to 0.4
− − −	− − −	$v_{d,\max}$ (maximum allowed velocity for each particle on dth dimension)	$0.9r_d$ (r_d is the difference between the maximum and minimum possible values of decision variables on dth dimension)
Search space dimension	40	Search space dimension	40
Choice of initial population	random	Choice of initial population	random
Termination condition	A maximum iteration of 1000	Termination condition	A maximum iteration of 1000

Table 2. Desired and obtained results for the first case (pencil/pencil beam pair) computed using FA and PSO.

Design parameters		FA		PSO	
		Pencil beam 1	**Pencil beam 2**	**Pencil beam 1**	**Pencil beam 2**
SLL (dB)	*Desired*	-24.0000	-28.0000	-24.000	-28.0000
	Obtained	-22.7574	-24.4177	-21.7951	-23.5566
HPBW (degree)	*Desired*	5.0000	7.0000	5.0000	7.0000
	Obtained	6.0000	6.2000	5.8000	6.0000
FNBW (degree)	*Desired*	12.0000	16.0000	12.0000	16.0000
	Obtained	14.8000	16.4000	14.4000	15.6000

Table 3. Desired and obtained results for the second case (pencil/flat-top beam pair) computed using FA and PSO.

Design parameters		FA		PSO	
		Pencil beam	**Flat - top beam**	**Pencil beam**	**Flat-top beam**
SLL (dB)	*Desired*	-22.0000	-20.0000	-22.0000	-20.0000
	Obtained	-20.5647	-17.0880	-17.8248	-15.3343
HPBW (degree)	*Desired*	9.0000	26.0000	9.0000	26.0000
	Obtained	6.0000	29.2000	5.0000	30.2000
FNBW (degree)	*Desired*	18.0000	50.0000	18.0000	50.0000
	Obtained	13.8000	46.6000	11.0000	45
Ripple (dB) ($-12^o \leq \theta \leq 12^o$)	*Desired*	----	0.1000	----	0.1000
	Obtained	----	1.0419	----	0.8190

4. SIMULATION RESULTS

The fitness functions for both the cases are minimized individually using FA and PSO based on the proposed method for the optimal synthesis of the dual radiation pattern of pencil/pencil and pencil/flat-top beam pairs. The results presented in this section are the best set of results (in terms of lower fitness value) obtained from 20 different run of each of the algorithm for each individual case. All patterns are obtained in $\varphi = 0°$ plane.

The design specifications of the reconfigurable array of first case and its corresponding obtained results using FA and PSO are shown in Table 2. Similarly for the second case, the design specifications and its corresponding results obtained using FA and PSO are shown in Table 3.

From Table 2, it can be seen that the obtained values of SLL for pencil beam 1 and pencil beam 2 for the pencil/pencil beam pair,

Table 4. Optimum discrete radial amplitudes, discrete radial phases and the two combinations of the state of the switches computed using FA for generating dual radiation pattern of pencil/pencil beam-pair (case I).

Ring Number	Optimum normalized amplitude (4-bit)	Optimum Phase (5-bit) (degree)	Switches state for pencil beam1 $\begin{bmatrix} 1 \rightarrow "on" \\ 0 \rightarrow "off" \end{bmatrix}$	Switches state for pencil beam2 $\begin{bmatrix} 1 \rightarrow "on" \\ 0 \rightarrow "off" \end{bmatrix}$
1	0.5625	45.0000	1	1
2	0.5625	56.2500	1	1
3	0.7500	45.0000	1	1
4	0.6875	22.5000	1	1
5	0.8125	45.0000	1	1
6	0.5625	45.0000	0	1
7	0.6875	33.7500	1	0
8	0.5000	33.7500	1	1
9	0.4375	90.0000	0	0
10	0.2500	45.0000	1	1

Table 5. Optimum discrete radial amplitudes, discrete radial phases and the two combinations of the state of the switches computed using PSO for generating dual radiation pattern of pencil/pencil beam-pair (case I).

Ring Number	Optimum normalized amplitude (4-bit)	Optimum Phase (5-bit) (degree)	Switches state for pencil beam1 $\begin{bmatrix} 1\rightarrow \text{"}on\text{"} \\ 0\rightarrow \text{"}off\text{"} \end{bmatrix}$	Switches state for pencil beam2 $\begin{bmatrix} 1\rightarrow \text{"}on\text{"} \\ 0\rightarrow \text{"}off\text{"} \end{bmatrix}$
1	0.3125	45.0000	0	0
2	0.5625	-22.5000	1	1
3	0.5625	-22.5000	1	1
4	0.5000	-56.2500	1	1
5	0.5625	-33.7500	1	1
6	0.3750	-45.0000	0	1
7	0.4375	-33.7500	1	0
8	0.4375	-33.7500	1	1
9	0.3125	33.7500	0	0
10	0.1875	-33.7500	1	1

computed using FA are much better than those computed using PSO. The other obtained parameters, computed using FA and PSO for the first case are quite comparable.

The two optimum combinations of the state of the switches along with optimum discrete radial amplitude and optimum discrete radial phase distributions of the array elements for generating dual radiation pattern of pencil/pencil beam pair (case I) using FA and PSO are shown in Table 4 and Table 5, respectively.

The normalized power patterns for the first case, computed individually using FA and PSO are shown in Figure 2 and Figure 3, respectively.

The convergence characteristics of the FA and PSO for the first case (pencil/pencil beam pair) is shown in Figure 4 in terms of best fitness value versus generations for the best run of each algorithm (best out of 20 different runs). From the magnifying portion of the graph, it can be seen that the performance of FA over PSO is much better for the minimization of the fitness function of 'case I'.

From Table 3 it can be seen that the obtained value of ripple (absolute value) for the flat-top beam of 'case II' , computed using FA, in the region $-12^\circ \leq \theta \leq 12^\circ$ is 1.0419 dB, whereas ripple computed using PSO for the flat-top beam of 'case II' in the same region is 0.8190 dB . The other specified parameters of the pencil/flat-top beam pair (case II) computed using FA is significantly better than those computed using PSO.

The optimum combinations of state of the switches and optimum discrete radial amplitude and radial phase of the array elements for generating dual radiation pattern of pencil/flat-top beam pair (case II) using FA and PSO are shown in Table 6 and Table 7, respectively.

The normalized power patterns for the second case, computed individually using FA and PSO are shown in Figure 5 and Figure 6, respectively.

The convergence characteristic of FA and PSO for the second case (pencil/flat-top beam pair) is shown in Figure 7 in terms of best fitness value versus generations for the best run of each algorithm (best out of 20 different runs). The zooming portion of Figure 7 clearly indicates

Table 6. Optimum discrete radial amplitudes, discrete radial phases and the two combinations of the state of the switches computed using FA for generating dual radiation pattern of pencil/flat-top beam-pair (case II).

Ring Number	Optimum normalized amplitude (4-bit)	Optimum Phase (5-bit) (degree)	Switches state for pencil beam $\begin{bmatrix} 1 \rightarrow \text{"on"} \\ 0 \rightarrow \text{"off"} \end{bmatrix}$	Switches state for flat-top beam $\begin{bmatrix} 1 \rightarrow \text{"on"} \\ 0 \rightarrow \text{"off"} \end{bmatrix}$
1	1.0000	-33.7500	1	1
2	0.5000	-11.2500	1	1
3	0.1250	-11.2500	0	1
4	1.0000	11.2500	1	0
5	0.1250	146.2500	0	1
6	0.4375	-45.0000	1	0
7	0.3750	11.2500	1	0
8	0.4375	-11.2500	1	0
9	0.2500	22.5000	1	0
10	0.2500	112.5000	0	0

Table 7. Optimum discrete radial amplitudes, discrete radial phases and the two combinations of the state of the switches computed using PSO for generating dual radiation pattern of pencil/flat-top beam-pair (case II).

Ring Number	Optimum normalized amplitude (4-bit)	Optimum Phase (5-bit) (degree)	Switches state for pencil beam $\begin{bmatrix} 1 \rightarrow "on" \\ 0 \rightarrow "off" \end{bmatrix}$	Switches state for flat-top beam $\begin{bmatrix} 1 \rightarrow "on" \\ 0 \rightarrow "off" \end{bmatrix}$
1	0.8750	11.2500	1	1
2	0.3125	-22.5000	1	1
3	0.1250	-33.7500	0	1
4	0.8125	101.2500	0	0
5	0.1250	-146.2500	0	1
6	0.6250	11.2500	1	0
7	0.3750	101.2500	0	0
8	0.2500	-22.5000	1	0
9	0.2500	56.2500	1	0
10	0.3750	-45.0000	1	0

Table 8. Comparative performance of the FA and PSO.

Different Cases	Algorithms	Best performance in terms of fitness value (out of 20 fitness values)	Mean fitness value	Standard Deviation of the fitness values
Case I	FA	23.3771	**23.6427**	**0.1473**
	PSO	31.1654	**32.1574**	**0.4576**
Case II	FA	31.4815	**31.9932**	**0.1663**
	PSO	53.7415	**54.3325**	**0.4211**

the superiority of FA over PSO for minimizing the fitness function of 'case II'.

Table 8 shows the comparative performance of the two algorithms. The lower mean fitness values of FA with respect to PSO over all the cases prove FA as the best performing algorithm for the proposed problem.

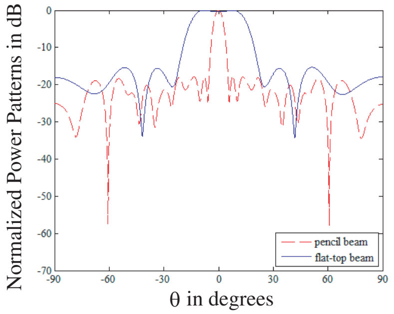

Figure 6. Dual radiation pattern of pencil/flat-top beam pair (case II) computed using PSO (shown in $\varphi = 0^\circ$ plane).

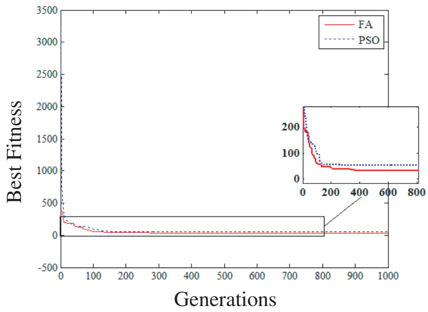

Figure 7. Convergences of FA and PSO for the minimization of the fitness function of case II.

Table 9. *P*-value obtained using Wilcoxon's two-sided rank sum test for the comparison pairs.

Different Cases	**Comparison pair**	***P*-value**
Case I	FA/PSO	6.7956e-008
Case II	FA/PSO	6.7860e-008

Table 9 shows the *P*-values obtained through Wilcoxon's rank sum test [30–32] between the FA and PSO for two different cases of design considerations. All the *P*-values are less than 0.05 (5% significant level) which is a strong proof against null hypothesis indicating that better final fitness value obtained by the best algorithm is statistically significant and has not occurred by chance.

5. CONCLUSIONS

A new method of generating dual radiation pattern from a concentric ring array by modifying the state of the switches, which are assumed to be connected with the rings of the array is presented. The optimum amplitudes and phases of the array elements are strictly dependent on the state of the switches. Two different types of beam pairs: a pencil/pencil beam pair and a pencil/flat-top beam pair are generated in the vertical plane based on the proposed method. The method is much simpler than the phase only synthesis of dual radiation pattern, because it doesn't required to compute two different set of phase distribution of the array elements, modifying which will produce the two different patterns. The number of switches considered in this method is significantly less and the array is excited in terms of a 4-bit radial amplitude distribution and 5-bit radial phase distribution among the elements. This leads to simple feed network design and less computational complexity.

Based on the proposed method, two fitness functions are formulated for generating dual radiation pattern of pencil/pencil and pencil/flat-top beam pairs. The two fitness functions are minimized individually using FA and PSO for optimal synthesis of the two beam pairs. The comparative performance of FA and PSO clearly shows the superiority of FA over PSO in terms of finding optimum solutions for the desired beam patterns. The quality of the solutions produced individually using FA and PSO for the two different cases of design considerations are analyzed statistically and the superiority of FA is proven over PSO for the proposed problem.

The design method can be used directly in practice to synthesize reconfigurable concentric ring isotropic antenna arrays with discrete amplitudes, discrete phases and the control over beams by the modification of the state of the switches. It can also be used for synthesizing other array configurations.

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