Array Antenna Pattern Synthesis using Improved Particle Swarm Optimization (IPSO) Algorithm

Rajesh Bera[1†], **Sabiha Cheruvu**[2], **Krishanu Kundu**[3], **Prashant Upadhyay**[4], and **Durbadal Mandal**[5], Non-members

ABSTRACT

Antenna arrays are used in many different systems, including radar, military systems, and wireless communications. The design of the antenna array has a significant impact on how well the communication system performs. The large number of pieces and the large sidelobe levels provide the biggest design hurdles for such arrays. The antenna arrays have recently been heavily thinned using optimization approaches that take advantage of evolutionary algorithms in order to lower power consumption and enhance the radiation pattern by lowering sidelobe levels. A global optimum for this kind of algorithm is not guaranteed, though, because of the stochastic nature of the resolution techniques. This work characterizes the optimal pattern synthesis of a linear array antenna using the Improved Particle Swarm Optimization (IPSO) algorithm. The main aim is to obtain a low Side Lobe Level (SLL) that avoids interference and a narrow beam width for acquiring high directivity to obtain the optimal solution established on the action of the swarm that adopts the fitness function. To achieve these targets, we analyze the optimization of the excitation amplitude and inter-element spacing of the array. In this article, we have presented the optimal power pattern obtained by two different types of excitation amplitude distributions for both uniformly spaced linear arrays and non-uniformly spaced linear arrays. In the first case of amplitude distribution, namely, non-uniform distribution of excitation amplitude, synthesis of the array pattern for three different values of inter-element spacing as well as optimized spacing are presented for different array sizes. In the second case, optimal thinning of a uniformly spaced array as well as a non-uniformly spaced (optimized) array has been presented. The IPSO algorithm provides a radiation pattern that is used to determine the set of antenna array parameters. The design of an antenna array using the IPSO algorithm gives significant enhancements when compared with a uniformly excited and uniformly spaced array. The flexibility as well as ease of implementation of the IPSO algorithm are evident from this analysis, showing the algorithm's usefulness in electromagnetic optimization problems.

Keywords: First Null Beamwidth (FNBW), Improved Particle Swarm Optimization (IPSO), Linear Array Antenna, Non-uniform Excitation, Side Lobe Level (SLL), Thinning

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1. INTRODUCTION

Antenna arrays are most often used in phased array applications such as satellite, radar, wireless communication, military, and other areas [1]. The antenna array consists of various parameters such as narrow beam width, side lobe level, directivity, noise sensitivity, and the dynamic range of the elements [2]. These antenna arrays enlarge system coverage, enhance the quality of the signal, and increase the efficiency of the spectrum for generating steerable beams by improving the directivity [3]. Even though single radiation features of antennas affect the overall array's radiation pattern. Further, the performance of the array is determined by the array factor, which is dependent on antenna radiation [4]. An antenna array follows the analytic approach. This approach guides to many other closed-form solutions, such as the use of regularity in the array configuration and uniform element spacing [5]. An antenna array consists of different identical radiating elements in an electrical or geometrical configuration [6]. There are different control parameters that are used to configure the pattern of elements such as linear, elliptical, circular, rectangular, and spherical with respect to the excitation amplitude and phase of the individual elements of the overall array. The main aim of an antenna array is to define the physical design and produce a radiation pattern that is similar to the desired radiation pattern. A linear array gives good directivity with a narrow gain width, but radiation is obtained in all directions. Here we are reducing the relative Side Lobe Level (SLL) and First Null Beam Width with respect to the main beam

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for a linear antenna array. It can be performed by providing the interspacing between each element with a non-uniform excitation of an array [7]. An array antenna has increasing gain and directivity in order to differentiate the single radiating element. In a linear array, all the elements are placed in a straight line with uniform spacing between them [6]. Each single element of excitation amplitude is known as a "weight factor." One can change the pattern by changing the values for different array elements. The weight factor is designed to direct an array factor, thus reducing the SLL value [4]. All the elements are said to be in the "on" state in a fully populated array, known as the "excited state. The antenna elements are said to be open-circuited or terminated when all the elements are said to be in an "off" state. To produce low SLL (side lobe level) and FNBW (first null beam width), we need to switch off some of the elements, which is known as thinning [8]. The cost and number of antenna elements can be reduced by using thinning [3]. While designing an antenna, we consider the length of the element, element spacing, and excitation amplitude. By choosing the above parameters, one can attain the results by using different optimization methods such as genetic algorithms (GA), particle swarm optimization (PSO), the grey wolf optimization algorithm, the artificial bee colony algorithm, and the ant colony algorithm [3].

2. ARRAY ANTENNA

Antennas perform a key role in electromagnetic fields, which are used to transmit or receive energy in wireless networks. In the absence of an antenna, the energy will be localized, and there will be no interaction between unconnected points. It is a transducer that converts one form of energy into another form in terms of current or voltage. The radiation pattern of each element is said to be constant at a given frequency. The application of array antennas is to improve directivity and monitor the side lobe structure [9]. The synthesis of antenna arrays is classified into two types, such as deterministic and stochastic. The deterministic model follows analytical and semi-analytical methods. It is time-consuming, as well, because the number of elements in an array increases. whereas stochastic methods are usual in electromagnetics and have numerous advantages when compared to deterministic methods. It includes neural networks (NN) and evolutionary algorithms such as the Genetic Algorithm (GA), Particle Swam Algorithm (PSO), Grey Wolf Algorithm [GWA], Differential Evolution (DE), and Tabu Search (TS) [10]. The signal transmission and reception systems such as radar, sonar, AM/FM and satellite radio, cellular phones, GPS, and wireless LANs There are various diversity methods to improve the quality of the signal (QoS) and lessen interference in terms of time, frequency, code, and space. Antenna arrays are generally used in wireless, satellite, mobile, and radar communications systems. They are used to improve the performance of the system by strengthening directivity, improving signal quality, extending system coverage, and increasing spectrum efficiency. Systems with a narrow first null beam width (FNBW) are necessary for high directivity. The systems need to have a low SLL compared to other systems operating in a similar frequency band. The above-mentioned requirements for SLL and FNBW are compared to the narrow beam width of an array, which generally doesn't produce low SLL. Therefore, the performance of each element can't be improved without degrading the others [3]. A desired pattern is designed based on the need for radiation. The simulated results show the calculated pattern that reaches the desired pattern with low SLL. This type of optimization improves the antenna's efficiency [1]. There are many numerical ways that become more familiar in the synthesis of antenna arrays, such as Powell's method, Differential Optimization (DE), Biogeography-Based Optimization (BBO), Particle Swarm Optimization (PSO), Genetic Algorithm (GA) [11], Social Spider Algorithm [12], Political Optimizer [13], Flower Pollination Algorithm [14], and Invasive Weeds Optimization [15]. The characteristics of antenna arrays have various applications, like beam forming and null positioning. Null positioning removes the unwanted signals that cause interference. In order to ignore interference with other radiating sources by producing directive in a particle direction by keeping SLL value small [16].

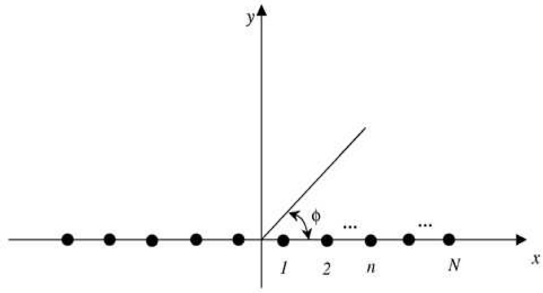

***Fig. 1**: 2N-element antenna array geometry having symmetrical distribution along x-axis.*

3. LINEAR ARRAY ANTENNA

A linear array consists of a set of similar elements arranged in a particular dimension in a given desired direction. Linear arrays have equidistant or non-equidistant element spacing, which is used in the analysis of the directional properties of arrays in antenna theory [17, 18].

The array factor is probably the most significant function in the entire array theory. Basically, AF is a function of the elemental positions with respect to the array and the weights related to the amplitude as well as the phase of the excitation current. Array performance could be properly optimized by proper alteration of the above parameters, achieving coveted characteristics. As per the norms of pattern multiplication, we can attain the total array field (comprising identical as well as similar elements) by multiplying the field relative to a single array element placed at the origin with the array factor (AF).

Let us consider a 2N-element antenna array having symmetrical distribution along the x-axis (Fig. 1). Here array factor can be formulated as

$$AF(\phi) = 2\sum_{n=1}^{N} I_n \ \cos\left[kx_n \ cos(\phi) + \psi_n \ \right] \quad (1)$$

where k represents wave number, and I_n, ψ_n and x_n are used for denoting excitation amplitude, phase, as well as location of the nth array element, receptively.

Array thinning is nothing but the elimination of radiating elements from a uniformly spaced or periodic array to obtain a desired radiation pattern. The goal of thinning is to reduce the cost, weight, design complexity, and power consumption [19]. While performing thinning of an array, some of the elements in a uniformly spaced or period array are turned off to produce a low side lobe level. In this, it has two states: "on" or "off", where the position of the elements is said to be fixed. Here, the elements are said to be terminated or open circuited when they are in the "off" state. The advantage of thinning an array to obtain a low side-lobe level when compared to the non-uniform spacing of the elements [20] Various thinning techniques are adopted to reduce the number of antenna elements without changing the radiation properties of the antenna.

4. IMPROVED PARTICLE SWARM OPTIMIZATION (IPSO) TECHNIQUE

The PSO algorithm was proposed by Kennedy and Eberhart in 1995. It is an optimization technique inspired by the social behavior of organisms such as bird flocking or fish schooling. It is also used for representing the sociocognition of human and artificial agents [21]. It is an evolutionary algorithm able to resolve multidimensional optimization problems in different domains. It depends on the social interaction between independent particles during their search for the optimal solution [22]. Swarm adapts its search patterns from its own experience and from other members' experiences. A member of the swarm is known as a "particle", which represents a "solution" from the search space. The global optimum is defined as the location of food. Based on the best experiences of the swarm for the search of the global optimum, it considers each particle's fitness value and a velocity in its flying direction.

A flow chart for PSO optimization is shown in Fig. 2. The PSO algorithm is programmed and simulated using MATLAB. 1. First of all, we initialize each particle with its random velocity and random position. 2. Then we calculate the cost for each of the particles. If the current cost is lower than the best value so far, then it is considered to be the best value. 3. Further, we choose the particle with the lowest cost of all; we call it gBest. 4.

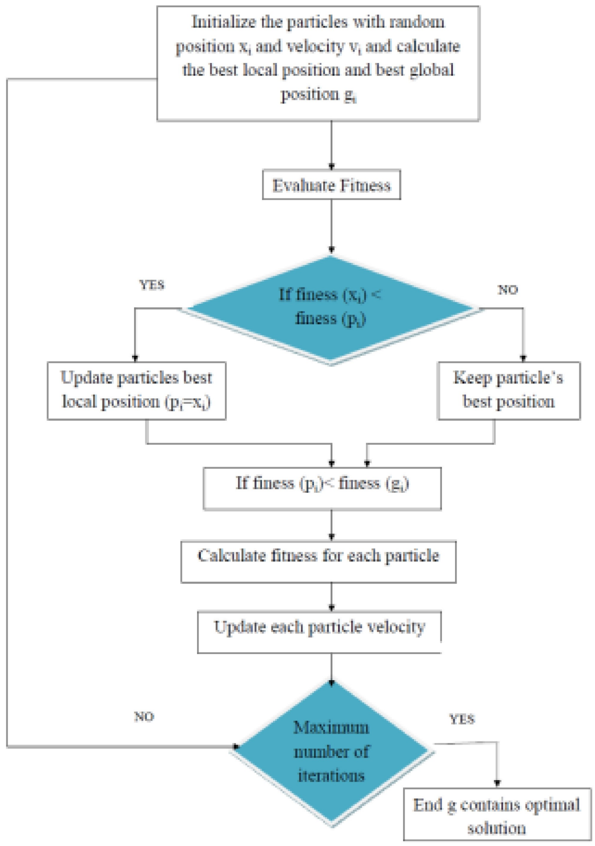

Fig. 2: *Flow chart for PSO algorithm.*

By using the given equation, we calculate a new velocity and position for each particle. 5. Repeat steps 2-4 until maximum iteration or minimum error criteria are not attained. After finding the two best values, the particle updates its velocity and positions. In the equation, (a) and (b) are the velocities of the particle at the kth iteration [8].

$$V_i^{(k+1)} = w * V_i^k + C_1 * rand_1 * \left(pbest_i^k - S_i^k\right) + C_2{}^* rand_2{}^* \left(gbest^k - S_i^k\right) \quad (2)$$

$$S_i^{(k+1)} = S_i^k + V_i^{(k+1)} \quad (3)$$

where $V_i^{(k)}$ is the velocity of i^{th} particle at k^{th} iteration, w is the weighting function, C_1, C_2 are the positive weighting factors, $rand_1$ and $rand_2$ are the random numbers between 0 and 1, $S_i^{(k)}$ is the current position of i^{th} particle at k^{th} iteration, $pbest^{(k)}$ is the personal best of i_{th} particle at k_{th} iteration, and $gbest^{(k)}$is the personal best of i_{th} particle at k_{th} iteration.

The global search ability of the above basic PSO is very much enhanced with the help of the following modifications. This modified PSO is termed as IPSO [23]. The two random parameters $rand_1$ and $rand_2$ of Eq. (2) are independent. If both are large, both the personal and social experiences are over used and the particle is driven too far away from the local optimum. If both are small, both the personal and social experiences are not used fully and the convergence speed of the technique is reduced. So, instead of taking independent $rand_1$ and $rand_2$, one single random number r_1 is chosen so that when r_1 is large, $(1 - r_1)$ is small and vice versa. Moreover, to control the balance of global and local searches, another random parameter r_2 is introduced.

Finally, with all modifications, the modified velocity of the i^{th} particle vector at the $(k+1)^{th}$ iteration, replacing Eq. (2), is expressed as follows:

$$\begin{aligned} V_i^{(k+1)} &= r_2 * sig\left(r_3\right) * V_i^k \\ &+ \left(1-r_2\right) * C_1 * r_1 * \left\{pbest_i^k - S_i^k\right\} \\ &+ \left(1-r_2\right) * C_2 * \left(1-r_1\right) * \left\{gbest^k - S_i^k\right\} \\ &+ (1-r_2) * c_1 * r_1 \left(S_i^k - pworst_i^k\right) \end{aligned} \quad (4)$$

where $sig\left(r_3\right)$ is a function defined as:

$$\begin{aligned} sig\left(r_3\right) &= -1 \ when \ r_3 \leq 0.05 \\ &= +1 \ when \ r_3 > 0.05 \end{aligned}$$

where V_i^k is the velocity of the i_{th} particle at the $(k+1)^{th}$ iteration; r_1, r_2, and r_3 are the random numbers between 0 and 1; S_i^k is the current position of the i_{th} particle at the iteration; $pbest^k$ and $pworst_i^k$ are the personal best and the personal worst of the i_{th} particle, respectively; $gbest^k$ is the group best among all $pbests$ for the group. The searching point in the solution space is modified by Eq. (3) as usual.

After defining the array factor and selecting a suitable algorithm, the next step in the design process is to formulate the objective function that is to be minimized. The objective function, or "Cost Function" (CF) may be written as Eq. (5).

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

W_{F1} ($unitless$) and $W_{F2}(radian^{-1})$ are the weighting factors. θ_{msl1} is the angle where the maximum side lobe $\left(AF\left(\theta_{msl1}, I_{mi}\right)\right)$ is attained in the lower band and θ_{msl2} is the angle where the maximum side lobe $\left(AF\left(\theta_{msl2}, I_{mi}\right)\right)$ is attained in the upper band. $FNBW_{computed}$ and $FNBW\left(I_{mi}=1\right)$ refer to the computed first null beam widths in radian for the non-uniform excitation case and the uniform excitation case, respectively. The minimization of CF indicates the maximum reduction of SLL both in the lower and upper sidebands. The evolutionary optimization techniques employed individually for optimizing the current excitation weights result in minimizations of CF and hence reductions in both SLL and FNBW. All the elements have the same excitation phase of zero degrees.

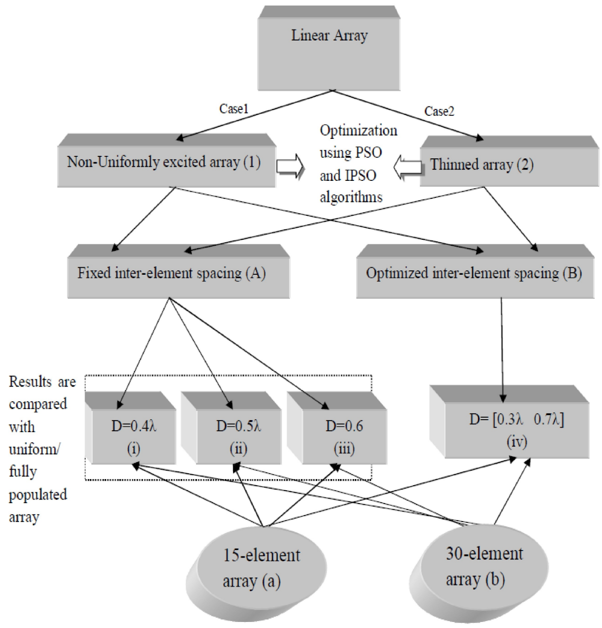

***Fig. 3**: Work flow diagram which summarizes the work flow of this paper conveniently.*

5. RESULTS AND DISCUSSION

Here we consider linear arrays for the optimal pattern synthesis of 15-element and 30-element LA. Two cases are considered based on the excitation amplitude distribution pattern for the synthesis of 15-element and 30-element LA. In the first case, a non-uniform distribution of excitation amplitude has been considered for the array pattern synthesis. In this case, normalized power patterns have been obtained for the three different values of inter-element spacing (0.4λ, 0.5λ, and 0.6λ). In the second case, array pattern synthesis for the thinned array (ON-OFF array) is presented for the three different values of inter-element spacing, e.g., 0.4λ, 0.5λ, and 0.6λ. The optimal power pattern is obtained for the array with optimized inter-element spacing and compared to the fixed inter-element spaced array for both cases. A normalized power pattern is also obtained for the fully populated array (the uniformly excited array) for all the cases. The IPSO algorithm provides a radiation pattern that is used to determine the set of antenna array parameters, and finally the results are compared to those using the conventional PSO technique. The entire work is presented by the flow diagram in Fig. 3, and every block is marked by either a number or alphabet to represent and summarize the work flow conveniently and effectively.

Here we consider the following parameters for the PSO and IPSO algorithms: population size = 50; generations $w_c = 10000$; weight factor w, where $w_{max} = 0.9$ and $w_{min} = 0.4$; acceleration constants c11 = 1.0 and c22 = 1.0. All the results are tabulated in corresponding tables, and all the table captions are summarized in one table (Table 1), which also reflects the corresponding 'work flow number' with the reference of Fig 3.

Table 1*: Table of all table captions with corresponding flow number in the 'work flow diagram' in Fig. 3.*

Table 2:	Performances of optimized 15-element LA for different inter-element spacing using evolutionary algorithms. 1-(A&B)-a
Table 3:	Performances of thinned 15-element LA for different inter-element spacing using evolutionary algorithms. 2-(A&B)-a
Table 4:	Excitation amplitude distribution of optimized 15-element LA of uniform and optimized spacing using evolutionary algorithms. 1-(A&B)-a
Table 5:	Excitation amplitude distribution of 15-element thinned LA of uniform and optimized spacing using evolutionary algorithms. 2-(A&B)-a
Table 6:	Performances of thinned 30-element LA for different inter-element spacing using evolutionary algorithms. 1-(A&B)-b
Table 7:	Performances of optimized 30-element LA for different inter-element spacing using evolutionary algorithms. 2-(A&B)-b
Table 8:	Excitation amplitude distribution of optimized 30-element LA of uniform and optimized spacing using evolutionary algorithms. 1-(A&B)-b
Table 9:	Excitation amplitude distribution of 30-element thinned LA of uniform and optimized spacing using evolutionary algorithms. 2-(A&B)-b

In the first case, the performance of optimized 15-element LA for different inter-element spacing is presented in Table 2. Here, in case of $d = 0.4\lambda$, for uniform excitation where we obtained SLL = -13.1dB and FNBW = 19.4, using PSO we obtained SLL = -14.6dB and FNBW = 21.40, and using IPSO we obtained SLL = -15.05dB and FNBW = 21.20. In case of $d = 0.5\lambda$, for uniform excitation where we got SLL = -13.1dB and FNBW = 15.60, using PSO we obtained SLL = -13.7dB and FNBW = 16.20, using IPSO we obtained SLL = -14.8dB and FNBW = 16.80, In the case of $d = 0.6\lambda$, for uniform excitation where we got SLL = -13.1dB and FNBW = 13, using PSO we obtained SLL = -12.7dB and FNBW = 13.40, using IPSO we obtained SLL = -13.3dB and FNBW = 13.60. For optimized inter-element spacing 'd' using PSO, we obtained SLL = -13.5dB, FNBW = 15.80, and using IPSO, SLL = -15.4dB, FNBW = 16.60.

Figs. (4-7) show normalized power patterns of 15-element non-uniformly excited linear array.

From Table 3, thinned 15 -element for linear array we have consider four different 'd' and optimized values for Uniform excitation, PSO and IPSO. In the case of $d = 0.4\lambda$, for uniform excitation where we got SLL = -13.1 and FNBW = 19.4, PSO we obtained SLL = -12.03 and FNBW = 19.40, and for IPSO SLL = -11.4 and FNBW = 19.40.

In the case of $d = 0.5\lambda$, for uniform excitation where we got SLL = -13.1and FNBW = 15.60, PSO we obtained SLL = -14.3 and FNBW = 18.60, for IPSO SLL = -15.5 and FNBW = 19.40.

In the case of $d = 0.6\lambda$, for uniform excitation where we got SLL = -13.1 and FNBW = 13, PSO we obtained

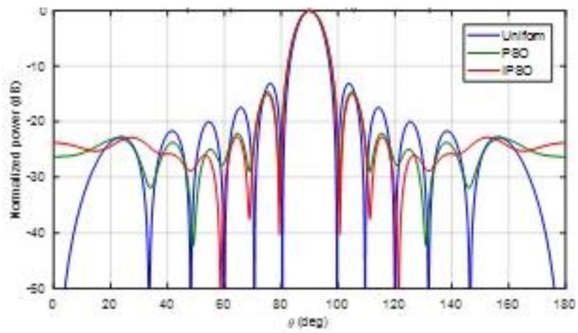

Fig. 4*: Normalized power pattern of* 0.4λ *spaced 15-element non-uniformly excited linear array.*

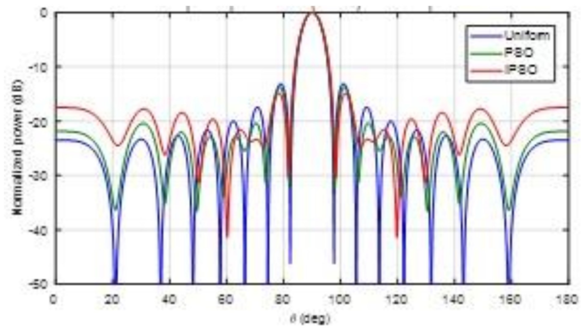

Fig. 5*: Normalized power pattern of* 0.5λ *spaced 15-element non-uniformly excited linear array.*

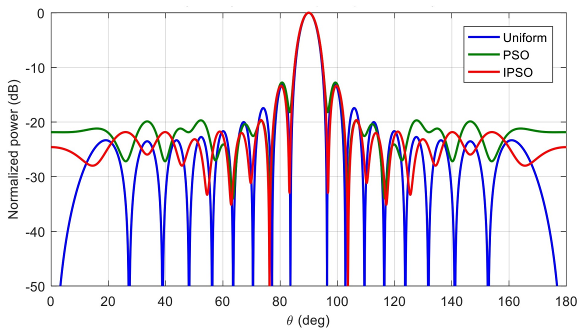

Fig. 6*: Normalized power pattern of* 0.6λ *spaced 15-element non-uniformly excited linear array.*

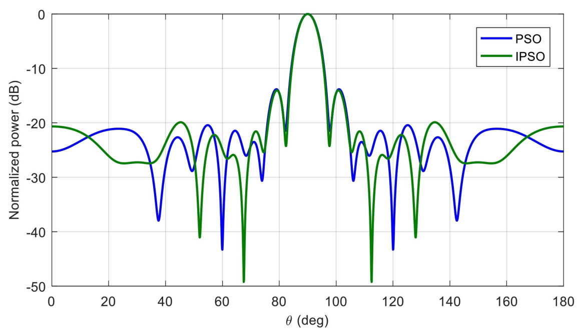

Fig. 7*: Normalized power pattern of 15-element non-uniformly excited and non-uniformly spaced linear array.*

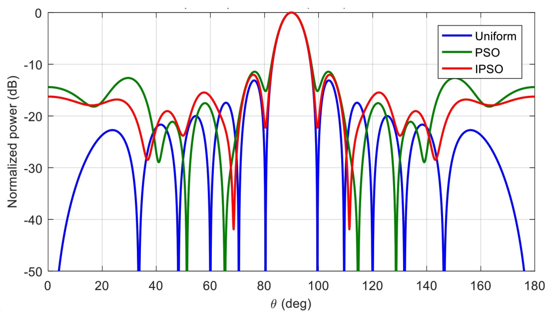

Fig. 8: *Normalized power pattern of* 0.4*λ* *spaced 15-element thinned linear array.*

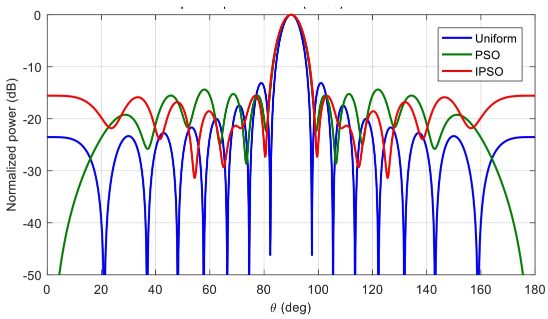

Fig. 9: *Normalized power pattern of* 0.5*λ* *spaced 15-element thinned linear array.*

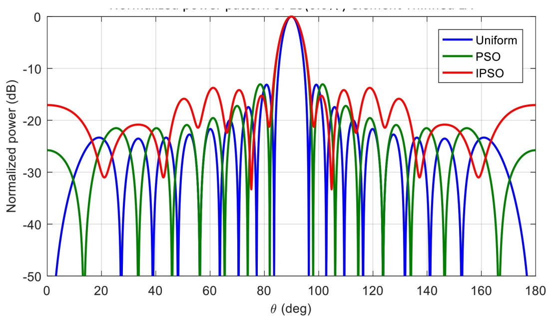

Fig. 10: *Normalized power pattern of* 0.6*λ* *spaced 15-element thinned linear array.*

SLL = -13.05 and FNBW = 16.20, for IPSO SLL = -13.7 and FNBW = 16.60.

For optimized PSO, SLL = -13.8, FNBW = 15.80, optimized IPSO SLL = -14.03, FNBW = 15.60. Figs. (8-11) show normalized power patterns of 15-element thinned array. Excitation amplitude distribution of optimized 15-element LA of uniform and optimized spacing using evolutionary algorithms tabulated in Table 4. Excitation amplitude distribution (thinning) of optimized 15-element LA of uniform and optimized spacing using evolutionary algorithms tabulated in Table 5.

The below graphs shows that Normalized power pattern of 0.4λ, 0.5λ, and 0.6λ spaced 15-element thinned linear array elements with different values for reducing side lobe level and first null beam width using PSO algorithm.

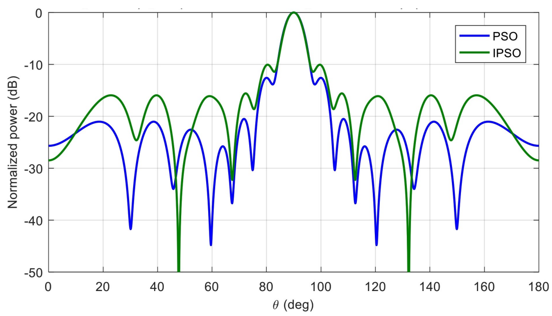

Fig. 11: *Normalized power pattern of 15-element non-uniformly spaced thinned linear array.*

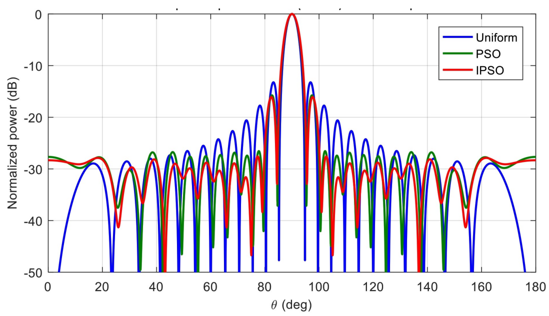

Fig. 12: *Normalized power pattern of* 0.4*λ* *spaced 30-element non-uniformly excited linear array.*

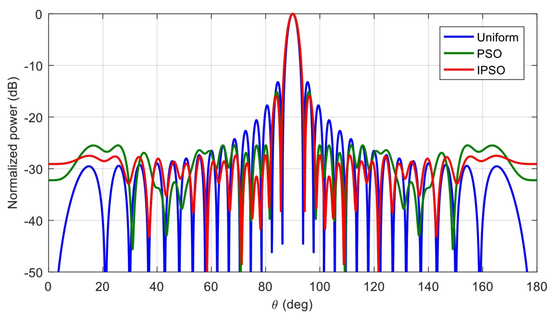

Fig. 13: *Normalized power pattern of* 0.5*λ* *spaced 30-element non-uniformly excited linear array.*

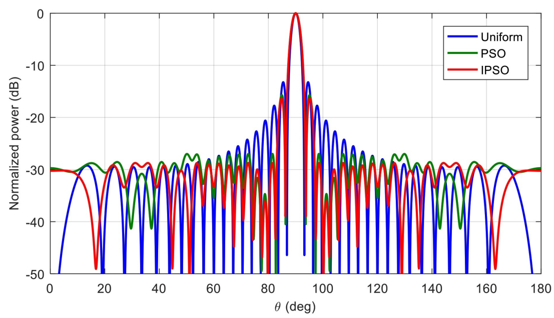

Fig. 14: *Normalized power pattern of* 0.6*λ* *spaced 30-element non-uniformly excited linear array.*

From Table 6, 30-element for non-uniformly excited linear array we have consider four different 'd' and optimized values for Uniform excitation, PSO and IPSO.

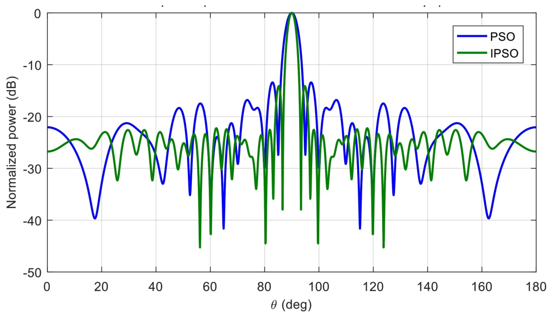

Fig. 15: *Normalized power pattern of 30-element non-uniformly excited and non-uniformly spaced linear array..*

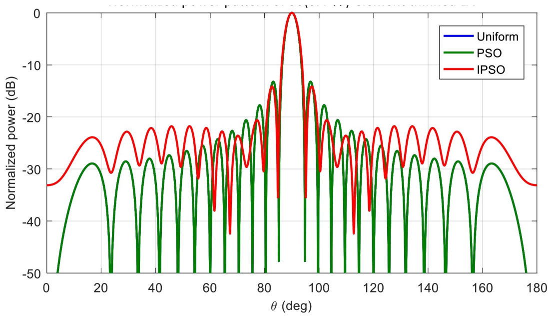

Fig. 16: *Normalized power pattern of* 0.4λ *spaced 30-element thinned linear array.*

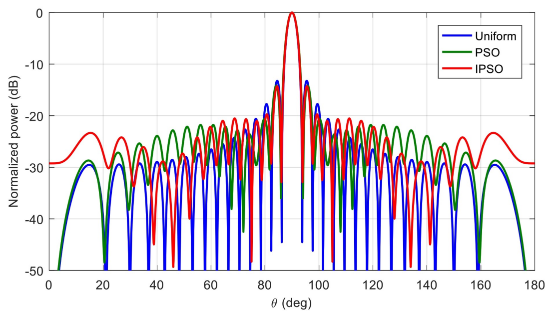

Fig. 17: *Normalized power pattern of* 0.5λ *spaced 30-element thinned linear array.*

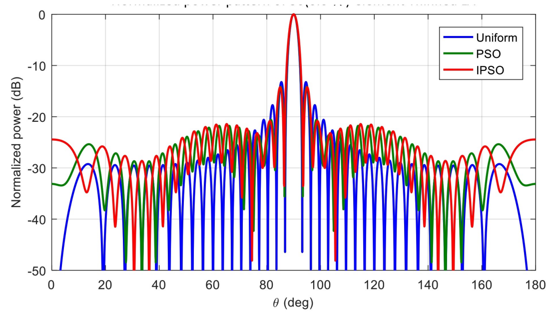

Fig. 18: *Normalized power pattern of* 0.6λ *spaced 30-element thinned linear array.*

In the case of $d = 0.4\lambda$, for uniform excitation where we got SLL = -13.2 and FNBW = 9.80, PSO we obtained SLL = -15.7 and FNBW = 10.80 and for IPSO SLL = -16.08

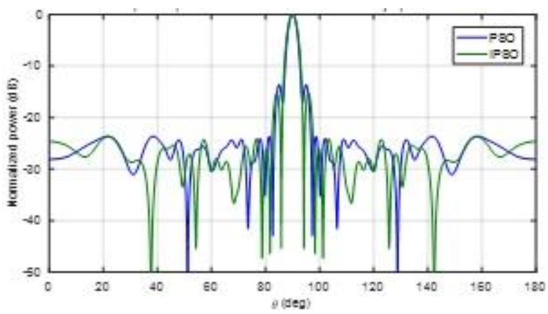

Fig. 19: *Normalized power pattern of 30-element non-uniformly spaced thinned linear array.*

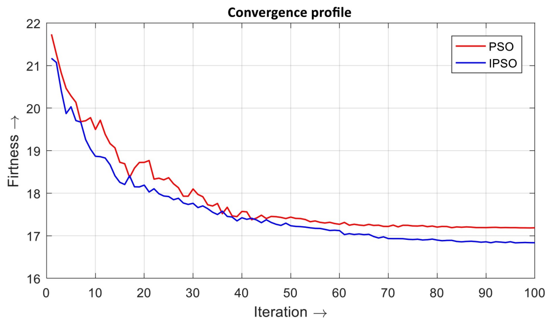

Fig. 20: *Convergence profiles using PSO and IPSO for the optimization of 30 elements thinned LA (Corresponding to Fig. 17).*

and FNBW = 11.20. In the case of $d = 0.5\lambda$, for uniform excitation where we got SLL = -13.2 and FNBW = 7.80, PSO we obtained SLL = -15.1 and FNBW = 8.80, for IPSO SLL = -15.9 and FNBW = 9. In the case of $d = 0.6\lambda$, for uniform excitation where we got SLL = -13.2 and FNBW = 6.60, PSO we obtained SLL = -15.7 and FNBW = 7.60, for IPSO SLL = -16.3and FNBW = 7.8.

For optimized PSO, SLL = -13.4, FNBW = 10.20, optimized IPSO SLL = -14.1 FNBW = 7. Figs. 12-15 show normalized power patterns of 30-element non-uniformly excited linear array.

From Table 7, thinned 30-element for linear array we have consider four different 'd' and optimized values for Uniform excitation, PSO and IPSO. In the case of $d = 0.4\lambda$, for uniform excitation where we got SLL = -13.2 and FNBW = 9.80, PSO we obtained SLL = -13.2 and FNBW = 9.80, and for IPSO SLL = -14.1 and FNBW = 10.40. In the case of $d = 0.5\lambda$, for uniform excitation where we got SLL = -13.2 and FNBW = 7.80, PSO we obtained SLL = -14.1 and FNBW = 8.40, for IPSO SLL = -14.2 and FNBW = 8.80. In the case of $d = 0.6\lambda$, for uniform excitation where we got SLL = -13.2 and FNBW = 6.60, PSO we obtained SLL = -14.1 and FNBW = 7, for IPSO SLL = -14.2 and FNBW = 7.20. For optimized PSO, SLL = -13.6, FNBW = 7.60, optimized IPSO SLL = -15.2, FNBW = 8.60. Excitation amplitude distribution of optimized 30-element LA of uniform and optimized spacing using evolutionary algorithms tabulated in Table 8.

Table 2: *Performances of optimized 15-element LA for different inter-element spacing using evolutionary algorithms.*

	d= 0.4		d =0.5		d=0.6		d=optimized	
	SLL (dB)	FNBW (Degree)	SLL(dB)	FNBW (Degree)	SLL(dB)	FNBW (Degree)	SLL(dB)	FNBW (Degree)
Uniform	-13.1310	19.4000	-13.1310	15.6000	-13.1328	13	-	-
PSO	-14.6531	21.4000	-13.7682	16.2000	-12.7690	13.4000	-13.5989	15.8000
IPSO	-15.0592	21.2000	-14.8779	16.8000	-13.3569	13.6000	-15.4388	16.6000

Table 3: *Performances of thinned 15-element LA for different inter-element spacing using evolutionary algorithms.*

	d= 0.4		d =0.5		d=0.6		d=optimized	
	SLL (dB)	FNBW (Degree)	SLL(dB)	FNBW (Degree)	SLL(dB)	FNBW (Degree)	SLL(dB)	FNBW (Degree)
Uniform	-13.1310	19.4000	-13.1310	15.6000	-13.1328	13	-	-
PSO	-12.0375	19.4000	-14.3815	18.6000	-13.0572	16.2000	-13.8298	15.8000
IPSO	-11.4415	19.4000	-15.5630	19.4000	-13.7424	16.6000	-14.0385	15.6000

Table 4: *Excitation amplitude distribution of optimized 15-element LA of uniform and optimized spacing using evolutionary algorithms.*

	d= 0.4	d =0.5	d=0.6	d=optimized
Uniform	1	1	1	-
PSO	0.5446 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.3682 0.7755	0.8534 0.0100 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000	0.4854 0.5477 0.5990 0.5556 0.4606 0.6780 0.4797 0.3515 0.4888 0.2291 0.4893 0.3990 0.3764 0.2558 0.3179	Amplitude: 0.4651 0.8310 0.7410 0.9721 1.0000 0.7081 0.7697 0.5591 0.8242 0.4537 0.6445 0.5041 0.5395 0.3820 0.1621 Spacing: 0.5534 0.5603 0.4696 0.5398 0.4651 0.4346 0.5594 0.5594 0.5566 0.4465 0.3849 0.3783 0.5318 0.5603
IPSO	1.0000 0.4626 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.6236 0.3911	1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.8710 1.0000 1.0000 1.0000 1.0000 0.4895 0.7541	0.2866 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.8986 0.8479 1.0000 1.0000 1.0000 0.6478 1.0000	Amplitude: 0.4450 0.5785 0.9618 1.0000 1.0000 1.0000 0.8834 0.9267 1.0000 0.9250 0.8063 0.9473 0.6224 0.5702 0.1599 Spacing: 0.5777 0.3890 0.5458 0.3937 0.5669 0.4518 0.4058 0.5239 0.4973 0.4123 0.5171 0.5806 0.5806 0.5577

Table 5: *Excitation amplitude distribution of 15-element thinned LA of uniform and optimized spacing using evolutionary algorithms.*

	d= 0.4	d =0.5	d=0.6	d=optimized
Uniform	1	1	1	-
PSO	1 0 1 1 1 1 0 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1 0 1 1 0 0	0 1 1 1 1 1 1 1 1 1 1 1 1 0 0	Amplitude: 0 1 1 1 1 1 1 1 1 1 1 1 1 0 1 Spacing: 0.5295 0.6018 0.5126 0.4757 0.4165 0.4115 0.5354 0.4093 0.5119 0.6024 0.4387 0.4070 0.6026 0.5452
IPSO	1 0 1 1 1 1 1 0 1 0 1 0 1 0 1	0 0 1 1 1 1 1 1 1 1 1 1 1 0 1	1 1 1 1 1 1 1 1 1 0 1 1 0 0 0	Amplitude: 0 0 1 1 1 1 1 1 1 1 1 1 1 1 0 Spacing: 0.4295 0.4961 0.4918 0.5609 0.5116 0.4331 0.5238 0.4849 0.4840 0.4653 0.4373 0.5540 0.5496 0.5781

Table 6: *Performances of thinned 30-element LA for different inter-element spacing using evolutionary algorithms.*

	d= 0.4		d =0.5		d=0.6		d=optimized	
	SLL (dB)	FNBW (Degree)	SLL(dB)	FNBW (Degree)	SLL(dB)	FNBW (Degree)	SLL(dB)	FNBW (Degree)
Uniform	-13.2332	9.8000	-13.2310	7.8000	-13.2359	6.6000	-	-
PSO	-13.2332	9.8000	-14.1665	8.4000	-14.1740	7	-13.6551	7.6000
IPSO	-14.1654	10.4000	-14.2842	8.8000	-14.2389	7.2000	-15.2671	8.6000

***Table 7**: Performances of optimized 30-element LA for different inter-element spacing using evolutionary algorithms.*

	d= 0.4		d =0.5		d=0.6		d=optimized	
	SLL (dB)	**FNBW (Degree)**	**SLL(dB)**	**FNBW (Degree)**	**SLL(dB)**	**FNBW (Degree)**	**SLL(dB)**	**FNBW (Degree)**
Uniform	-13.2332	9.8000	-13.2310	7.8000	-13.2359	6.6000	-	-
PSO	-15.7516	10.8000	-15.1283	8.8000	-15.7118	7.6000	-13.4146	10.2000
IPSO	-16.0811	11.2000	-15.9024	9	-16.3239	7.8000	-14.1180	7

***Table 8**: Excitation amplitude distribution of 30-element thinned LA of uniform and optimized spacing using evolutionary algorithms.*

	d= 0.4	**d =0.5**	**d=0.6**	**d=optimized**
Uniform	1	1	1	-
PSO	0.4998 0.2686 0.7128 0.5134 0.8828 0.5542 0.9996 0.7936 1.0000 1.0000 1.0000 1.0000 0.8419 0.9879 0.9981 0.9067 1.0000 1.0000 0.9966 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.9296 0.6243 0.5994 0.2380 0.8204	0.4918 0.4017 0.9990 0.6019 1.0000 0.8311 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.9928 1.0000 0.7212 1.0000 0.8924 1.0000 1.0000 1.0000 1.0000 0.8293 0.9838 0.8959 0.4643 0.3960 0.7388 0.6944	0.4761 0.6334 0.5320 0.4703 0.8302 1.0000 1.0000 0.8975 0.9808 1.0000 1.0000 0.9595 1.0000 1.0000 0.9005 1.0000 0.9946 0.9833 0.9847 0.9998 0.9999 1.0000 1.0000 1.0000 1.0000 0.5543 1.0000 0.3528 0.4385 0.5498	Amplitude: 0.0100 0.8102 1.0000 1.0000 0.3945 1.0000 0.8780 0.7948 0.3790 1.0000 1.0000 1.0000 1.0000 1.0000 0.8042 0.9395 0.0154 1.0000 0.0799 0.9886 1.0000 1.0000 0.5768 0.9811 1.0000 0.0100 1.0000 0.3288 1.0000 0.0100 Spacing: 0.5846 0.4144 0.4144 0.6185 0.4144 0.4144 0.4617 0.6185 0.4677 0.4144 0.4985 0.5011 0.6185 0.6185 0.6185 0.4283 0.6167 0.6160 0.4123 0.6185 0.4144 0.4144 0.4154 0.4944 0.6185 0.4133 0.5308 0.4144 0.4144
IPSO	0.6714 0.5113 0.5959 0.6368 0.9999 0.8297 1.0000 1.0000 1.0000 0.9988 1.0000 1.0000 1.0000 1.0000 1.0000 0.9092 1.0000 0.8836 0.9855 1.0000 1.0000 1.0000 1.0000 1.0000 0.7084 0.9692 0.3643 0.9464 0.1801 1.0000	0.4738 0.8136 0.5131 0.8348 0.5256 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.8284 1.0000 0.8908 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.9397 1.0000 0.7696 1.0000 0.4803 0.6779 0.8331	0.4718 0.4978 0.5059 0.6480 0.6897 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.9664 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.6077 1.0000 0.4995 0.4577 0.4717 0.4543	Amplitude: 1.0000 1.0000 0.5622 0.4789 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.7155 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 0.0120 1.0000 Spacing: 0.3985 0.3985 0.5947 0.3985 0.3985 0.5947 0.5947 0.5947 0.3985 0.5947 0.3987 0.5947 0.3985 0.5947 0.5947 0.5947 0.3985 0.5947 0.3992 0.5947 0.5947 0.5947 0.3985 0.3985 0.3985 0.3983 0.5947 0.3985 0.5947

***Table 9**: Excitation amplitude distribution of 30-element thinned LA of uniform and optimized spacing using evolutionary algorithms.*

	d= 0.4	**d =0.5**	**d=0.6**	**d=optimized**
Uniform	1	1	1	-
PSO	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1	0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1	Amplitude: 1 1 0 1 1 1 1 0 1 1 1 1 0 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 Spacing: 0.4336 0.4791 0.4679 0.3951 0.4422 0.5837 0.4200 0.5614 0.5582 0.5663 0.4186 0.4651 0.5267 0.5472 0.5837 0.5742 0.4550 0.4899 0.4545 0.5581 0.4573 0.5359 0.5211 0.4858 0.5839 0.4813 0.4701 0.4003 0.5839
IPSO	1 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	1 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	Amplitude: 0 0 0 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 0 0 0 Spacing: 0.5196 0.4961 0.4064 0.5323 0.5165 0.5969 0.5343 0.5165 0.4382 0.4367 0.6048 0.4874 0.4997 0.4641 0.4610 0.5216 0.5445 0.5489 0.5299 0.5186 0.5036 0.5222 0.4228 0.4881 0.4057 0.5036 0.5173 0.4490 0.5137

Figs. 16–19 show normalized power patterns of a 30-element non-uniformly excited linear array. The excitation amplitude distribution of a 30-element thinned LA with uniform and optimized spacing using evolutionary algorithms is tabulated in Table 9. Convergence profiles using PSO and IPSO for the optimization of 30 elements thinned LA (corresponding to Fig. 17) are shown in Fig. 20.

6. CONCLUSION

In this paper, the performance of an array antenna has been optimized using the IPSO technique, and all the results are compared with the conventional swarm optimization technique. An antenna array contains a large number of elements in order to reduce the element count, cost, weight, and power consumption. Here, thinning is performed by removing some elements from an array by setting on and off some elements. The array factor of the antenna is used to evaluate its features such as half power beam width (HPBW) and side lobe level (SLL). The performance of the array has been optimized using the design variables, namely: a) inter-element spacing; b) excitation amplitude.

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