Performance of Beamwidth Constrained Linear Array Synthesis Techniques Using Novel Evolutionary Computing Tools

Chowdary S.R. Paladuga [1], Chakravarthy V.S.S.S. Vedula [1], Jaume Anguera [2,3], Rabindra K. Mishra [4], and Aurora Andújar [2,3]

[1] Department of Electronics & Communication Engineering
Raghu Institute of Technology, Visakhapatnam, India
satishchowdary@ieee.org, sameervedula@ieee.org

[2] Department of Electronics and Telecommunications
University Ramon Llull, Barcelona, Spain

[3] Fractus Antennas, Barcelona, Spain
jaume.anguera@fractusantennas.com, aurora.andujar@fractusantennas.com

[4] Department of Electronics, Berhampur University
Berhampur, Odisha, India
r.k.mishra.ieee@gmail.com

Abstract **─** Antenna array synthesis for desired radiation characteristics is a challenging field of research in electromagnetics. When an array synthesis problem is visualized as an optimization problem several design parameters involved in synthesis process are considered as degrees of freedom. Every combination of design parameters forms a synthesis technique. In this paper, certain emphasis is given to analyse the techniques of linear array (LA) design using evolutionary computing tools. Novel computing tools like Flower Pollination Algorithm is used for LA synthesis using different degrees of freedom and compared with a conventional Tchebycheff method. Accelerated Particle Swarm Optimization (APSO) is also employed to study the consistency of the technique with the employed computing tool. Radiation patterns are generated with optimized SLL and Tchebycheff beamwidth constraint.

Index Terms **─** Antenna optimization, array synthesis, flower pollination algorithm, particle swarm optimization.

I. INTRODUCTION

Radiating elements for modern wireless communications needs to possess certain features like high directivity, good control on sidelobe level (SLL), control on beam width (BW) and beam steering (BS) capabilities [1]. Single element antenna fail to achieve the above, as they exhibit poor directivity and no control on SLL and BW. Impetus to highly directive communication systems is made possible with the advent of the antenna arrays are capable of controlling radiation pattern for desired main BW, half power BW and SLL with proper modifications of geometrical and electrical properties of the array [2]. Among different array geometries, linear array is the simplest form of the array in which all the elements are arranged on a straight line. Many conventional numerical techniques which are derivative based are proposed for such array synthesis. These conventional techniques are time consuming with complex numerical steps and always tend to stick in the local minima. Also, they fail to handle multimodal or multi objective problems. In the recent past, several meta-heuristic algorithms are proposed to overcome the computational complexity and its drawback. These algorithm are versatile and also robust. They are capable of handling multimodal problems with ease. Many algorithm like genetic algorithm (GA) [3], particle swarm optimization (PSO) [4], simulated annealing (SA) [5], fire fly (FF) [6], and Teaching Learning Based Optimization [7] and have already been successfully applied for antenna design. An antenna array synthesis problem involves in determining weights for the geometrical properties like spacing (d) between elements or electrical properties like current excitation and phase excitation that produces desired radiation pattern. The evolutionary computing tools are efficient and robust to synthesize antenna array of any geometry like linear, circular and conformal [8]. Also, capable of producing wide variety of radiation patterns for several applications like beamforming, mono-pulse radar etc. [9].

An array synthesis problem can be addressed as an optimization problem which involves in determining the

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optimal weights for one or more array parameters in order to produce the desired radiation pattern. Amplitude only technique is one of the simple strategy to obtain the design criteria which involves in obtaining the amplitudes of coefficients of current excitation at each element in the array [10]. However, including spacing as additional parameter for synthesis of array is another intelligent way to achieve the convergence quickly. In this paper, such an attempt is made to investigate the advantage in adding additional parameter to the synthesis process and compare the results with the process involving only one parameter. In this regard, amplitude and spacing between the elements are considered in a two-parameter method while amplitude only is used in a one-parameter method. It is concluded from the literature that incorporating newly proposed heuristic approaches which are widely accepted in other disciplines for antenna array synthesis is a predominant part of research in electromagnetics. This consistently helped antenna engineers to take on the challenges of pattern synthesis for wireless applications. Accordingly, in this paper, two new algorithms namely APSO and Flower Pollination Algorithm (FPA) have been chosen. Further a comparative study is performed to analyze the performance of these algorithms over existing popular numerical technique called Tchebycheff technique. Several objectives are considered for synthesis of linear arrays in this work. Obtaining a very low SLL of -50dB with narrowest possible BW that is equal to the TBW for the same SLL is one of the major objective of investigation. The other objectives is to study the synthesis process using both amplitude only and amplitude-space techniques. Symmetrical linear arrays is considered in all the cases mentioned in this work.

II. DESIGN FORMULATION

Array design formulation and the corresponding fitness formulation for the desired objectives are presented in this Section as follows.

A. Array factor formulation

Linear array design problem involves in generating optimal set of design parameters like amplitudes or inter-element spacing or both that yields radiation pattern with optimum SLL with predefined BW. The geometry of the array is as shown in Fig. 1.

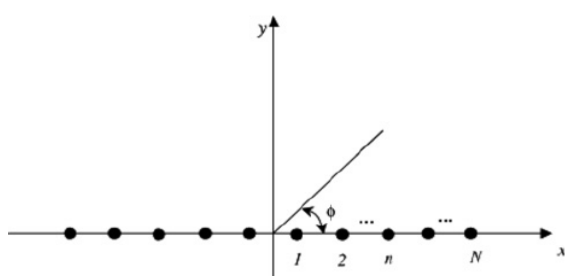

Fig. 1. Geometry of linear array antenna.

The LA geometry specified in the Fig. 1 has the centre of the array length as the reference and the elements are symmetrical arranged around the reference point. The array factor of such a linear symmetric array is given as (1) [11]:

$$AF(\theta)=2\sum_{n=1}^{N} A_n \cos[\mathrm{kd}_n \cos\theta+\beta_n], \tag{1}$$

where
n refers to n^{th} element and n=1,2…..N,
N is the total number of elements in the array,
k is wave number given as 2Π/λ,
θ is observation angle,
A_n refers to the amplitude of excitation of n^{th} element,
d_n refers to the spacing between the nth element and the reference point.

B. Fitness formulation

The formulation of fitness function incorporates the objective of SLL reduction and BW control. The radiation pattern is the distribution computed array factor (AF) values for every interval of azimuthal angle (θ) over a range of -90^0 to 90^0. Hence, the fitness is formulated as a function of AF values in order to obtain the desired patterns:

$$SLL_{diff} = SLL_{des} - \max[\,|\,\mathrm{AF}(\theta)\,|_{-90}^{\theta_0-\frac{BW_{obt}}{2}}\,], \tag{2}$$

$$\mathrm{BW}_{diff} = |\,\mathrm{BW}_{Cheb} - \mathrm{BW}_{obt}\,|, \tag{3}$$

$$\begin{aligned} \mathrm{f}_1 &= SLL_{diff} && if\ SLL_{diff} > 0 \\ &= 0 && otherwise \end{aligned}, \tag{4}$$

$$\begin{aligned} \mathrm{f}_2 &= SLL_{diff} && if\ SLL_{diff} > 0 \\ &= 0 && otherwise \end{aligned}, \tag{5}$$

$$f = c_1 \mathrm{f}_1 + c_2 \mathrm{f}_2, \tag{6}$$

where, SLL_{diff} is the difference between the desired SLL (SLL_{des}) and the obtained SLL (SLL_{obt}). BW_{diff} is the difference between the desired TBW (BW_{Cheb}) and the obtained beamwidth (BW_{obt}). In this case f_1 is responsible for SLL reduction and f_2 controls the BW of the array. The final fitness *f* value calculated as summation of f_1 and f_2, where c_1 and c_2 are two constant biasing weighting factors such that:

$$c_1 + c_2 = 1. \tag{7}$$

However, in the current work no biasing is applied and the objectives are provided with equal weight, such that $c_1=c_2$.

III. ARRAY DESIGN USING FLOWER POLLINATION ALGORITHM

The FPA mimics the flower pollination phenomenon [12] through biotic and abiotic processes which is essential for reproduction in floral plants. Pollination is the process by which pollens migrate and meet the pollen of another flower of same plant or other plant of same species resulting in successful fertilization. Pollination can be local or global. Self pollination can be treated as local pollination in which the pollen of a flower is shared by same flower or another flower of the same plant. Biotic cross pollination, which takes place over long distances is known as global pollination. Reproduction and evolution of the plant species is greatly affected by several aspects like fertilization, floral constancy and mutualism. Mutualism limits the memory and energy consumption of the pollinators and often leads to successful fertilization. Each individual member of the population refers to an array. After initialization radiation pattern is computed for each individual using the array factor formulation for linear arrays. Using the fitness function, the cost is evaluated for each individual. Best individual with minimum cost is chosen and its characteristics for convergence is obtained to validate the optimum solution. If the convergence is achieved then the process is terminated and the best individual's weights are considered for the objective. If the convergence is not achieved the weights of each individual are modified according to the FPA structure as given in next section. Demonstration of the FPA implementation for LA synthesis is as shown in Fig. 2. Like every population based algorithm the starting point of FPA is population initialization. *M* individuals are used as population. Each individual has its own solution in the *N*-dimensional solution space. *N* also refers to number of design variables. Hence, each solution is a set of *N*-dimensional vector which is given as:

Initial population:

$$pop=[x_1(k),x_2(k)\,....],\tag{8}$$

where k is the iteration number,

$$\begin{bmatrix} x_1 \\ x_2 \\ . \\ x_M \end{bmatrix} = \begin{bmatrix} I_1^1, I_1^2, ..., I_1^N \\ I_2^1, I_2^2, ..., I_2^N \\ .... \\ I_M^1, I_M^2, ..., I_M^N \end{bmatrix}.\tag{9}$$

Equation (9) is used to represent the initial population for amplitude only technique in which I is current excitation coefficient and d is inter-element spacing.

When both current excitation and inter element spacing are used the (9) is modified to (10) in such a way that x is vector of dimension 2N. The first N values are used as current excitations and the remaining N are used as inter element spacing for the corresponding element. Implementation of the algorithm for array synthesis involves in considering each individual that corresponds to an array of *N* elements.

The algorithm was implemented using MATLAB® software. Numerical value representing the element is the current excitation coefficient of that element:

$$\begin{bmatrix} x_1 \\ x_2 \\ . \\ x_M \end{bmatrix} = \begin{bmatrix} I_1^1, I_1^2, ..., I_1^N, d_1^1, d_1^2, ...d_1^N \\ I_2^1, I_2^2, ..., I_2^N, d_2^1, d_2^2, ...d_2^N \\ .... \\ I_M^1, I_M^2, ..., I_M^N, d_M^1, d_M^2, ...d_M^N \end{bmatrix}.\tag{10}$$

Finally the fitness is evaluated for each individual and the best among them is supposed to be the individual with minimum fitness. This is given as [11,12]:

$$x^*(\mathrm{k})=\arg\min_{m=1,....M} f(\mathrm{x}_m(\mathrm{k})).\tag{11}$$

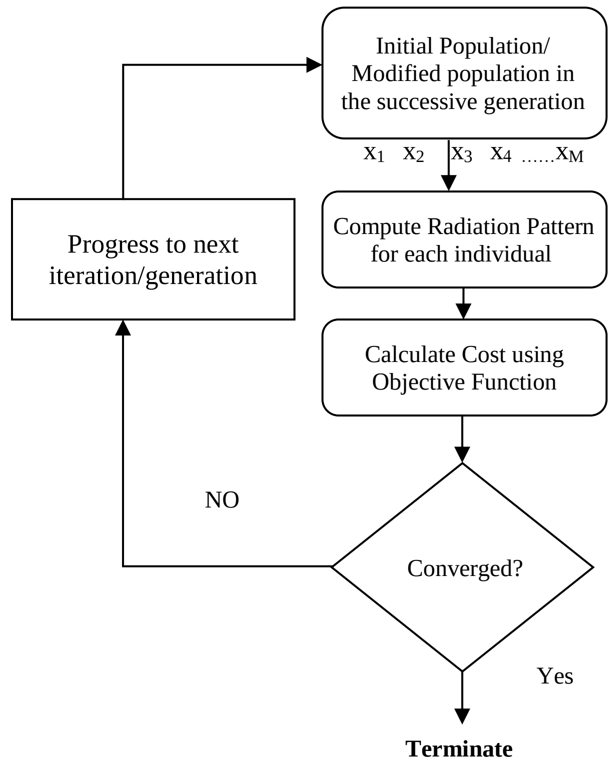

Fig. 2. Flowchart demonstrating the implementation of FPA for linear array synthesis.

IV. RESULTS AND DISCUSSIONS

Results pertaining to the TBW constrained SLL reduction using FPA and APSO are presented in this section using both amplitude only (Amp-only) and amplitude-spacing (Amp-Sp) techniques. Case 1 presents the radiation patterns obtained using the three synthesis methods using amplitude only, while Case 2 refers to similar but using Amp-Sp technique. In both the cases the number of elements in the LA are considered to be 8 and 32. The proposed simulation based experimental frame work is useful in evaluating the performance of the technique using both the algorithms. However, the performance of both the algorithms assumed to be at par with each other, while the inference is the adaptability of the evolutionary tools in incorporating any technique of synthesis. For the simulation study, both the algorithms are tuned for array synthesis problem. Parameters like initial population, termination criterion and other algorithm specific parameters play a vital role in finding solution to the problem. These parameters and their values are listed in Table 1 and Table 2.

Table 1: Algorithm specific parameters used in APSO for the simulation study

Parameter	Value
Initial Population (number of birds)	60
Convergence speed determinants α, β, and γ	0.2, 0.5, 0.95
Termination Criterion	Min cost (0) or max number of generations (1000)

Table 2: Algorithm specific parameters used in FPA for the simulation study

Parameter	Value
Initial Population	25
Probability of switching	0.8
Termination Criterion	Minimum cost (0) or maximum number of generations (1000)

The initial population in APSO is larger than the FPA because of the fact that, the APSO uses only the global search while FPA employs both global and local search techniques using switching parameter. Hence, for better convergence choice of large population is always useful.

A. Case-1

The radiation pattern plots for the linear array with N=8 and 32 and their corresponding convergence plots are presented in Fig. 3, Fig. 4, Fig. 5 and Fig. 6. The SLL obtained using APSO and FPA are well maintained at the same level as that of Tchebycheff with the constraint of the Tchebycheff beam width (BW). It can be inferred from both the converegence plots that APSO and FPA have similar converegence characteristics. However, the FPA consumed relevantly less number of iterations with respect to APSO because of the search capability. Inspite of this, the convergence time of APSO is better than FPA as the APSO employs only the global search technique.

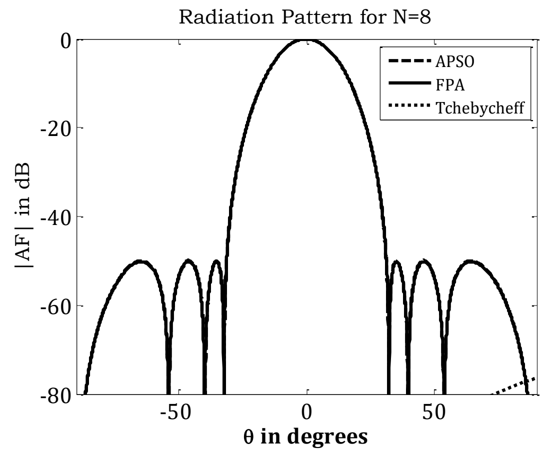

Fig. 3. Comparison of radiation pattern of 8 element LA with non-uniform amplitude distribution.

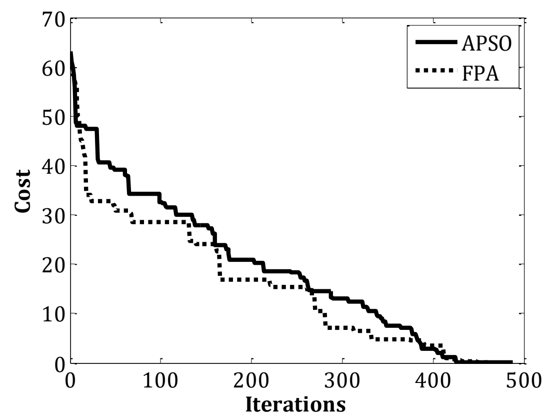

Fig. 4. Comparison of convergence characteristics for 8 element LA.

B. Case-2

In this case, the amplitude-spacing technique is employed to synthesize linear array of 8 and 32 element size. The simulated radiation pattern plots using APSO, FPA and Tchebycheff methods along with the convergence plots are presented in Fig. 7, Fig. 8, Fig. 9 and Fig. 10. The convergence trend is similar to the previous case. The FPA is consumed less number of iterations than APSO while the computation time is better in the case of APSO. The non-uniform amplitude distribution for Amp-Only technique and the corresponding non-uniform amplitude and non-uniform spacing in Amp-Sp technique are presented in Table 3 and Table 4.

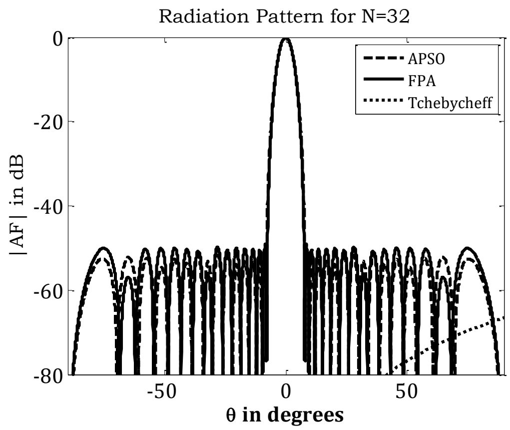

Fig. 5. Comparison of radiation pattern of 32 element LA with non-uniform amplitude distribution.

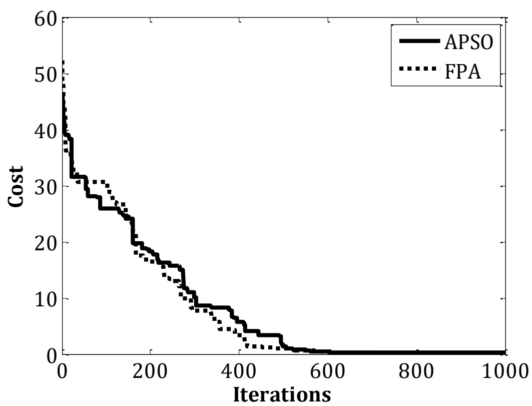

Fig. 6. Comparison of convergence characteristics for 32 element LA.

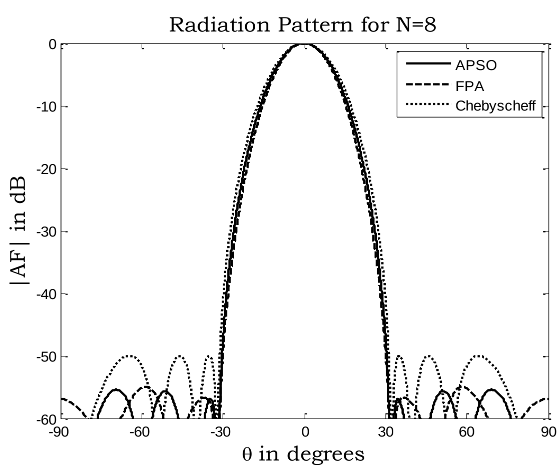

Fig. 7. Comparison of radiation pattern of 8 element LA with non-uniform amplitude and space distribution.

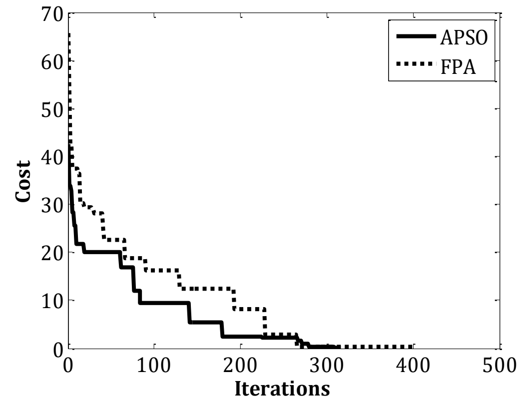

Fig. 8. Convergence plot for 8 element linear array synthesized using amplitude-spacing technique.

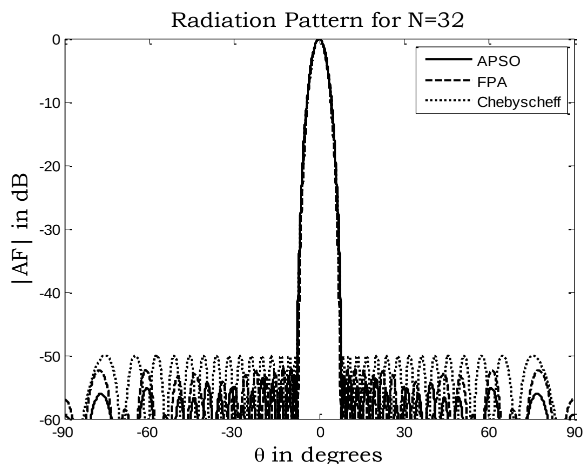

Fig. 9. Comparison of radiation rattern of 32 element LA with non-uniform amplitude and space distribution.

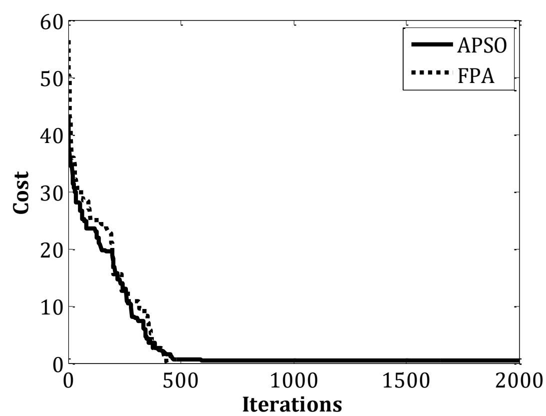

Fig. 10. Convergence plot for 32 element linear array synthesized using amplitude-spacing technique.

Table 3: Non-uniform amplitude distribution and amplitude-spacing distribution for Fig. 3 and Fig. 5 radiation patterns

Element Number	Fig. 3			Fig. 5	
	Amp			Amp (Sp in λ)	
	APSO	FPA	Tcheb	APSO	FPA
1 & 1’	0.932	0.954	1.00	0.92 (0.48)	0.83 (0.61)
2 & 2’	0.670	0.684	0.71	0.72 (0.50)	0.55 (0.61)
3 & 3’	0.326	0.332	0.34	0.37 (0.53)	0.22 (0.62)
4 & 4’	0.088	0.089	0.09	0.09 (0.56)	0.04 (0.63)

Table 4: Non-uniform amplitude distribution and amplitude-spacing distribution for Fig. 4 and Fig. 6 radiation patterns

Element Number	Fig. 4			Fig. 6	
	Amp			Amp (Sp in λ)	
	APSO	FPA	Tcheb	APSO	FPA
1 & 1’	0.944	0.926	1.000	0.98 (0.45)	0.69 (0.55)
2 & 2’	0.925	0.910	0.979	0.95 (0.46)	0.74 (0.59)
3 & 3’	0.884	0.871	0.939	0.82 (0.41)	0.71 (0.63)
4 & 4’	0.827	0.818	0.882	0.99 (0.46)	0.62 (0.62)
5 & 5’	0.757	0.749	0.811	0.54 (0.41)	0.44 (0.56)
6 & 6’	0.676	0.677	0.728	0.98 (0.41)	0.35 (0.41)
7 & 7’	0.588	0.590	0.639	0.94 (0.64)	0.42 (0.51)
8 & 8’	0.496	0.505	0.546	0.63 (0.61)	0.35 (0.59)
9 & 9’	0.409	0.418	0.455	0.46 (0.48)	0.22 (0.52)
10 & 10’	0.325	0.340	0.367	0.36 (0.47)	0.20 (0.45)
11 & 11’	0.250	0.263	0.287	0.33 (0.46)	0.18 (0.58)
12 & 12’	0.184	0.195	0.215	0.29 (0.59)	0.10 (0.55)
13 & 13’	0.127	0.142	0.154	0.16 (0.61)	0.08 (0.44)
14 & 14’	0.084	0.095	0.105	0.08 (0.44)	0.07 (0.64)
15 & 15’	0.051	0.060	0.066	0.08 (0.52)	0.03 (0.60)
16 & 16’	0.036	0.043	0.050	0.04 (0.66)	0.01 (0.45)

The corresponding SLL obtained with the BW constraint using amplitude only technique and the amplitude spacing technique were presented in Table 5.

Table 5: SLL using amplitude only and Amp-Sp techniques

S.No	No. of Elements	SLL (dB) Using FPA		SLL (dB) Using APSO	
		Amp Only	Amp-Sp	Amp Only	Amp-Sp
1	8	-50.0	-56.7	-51.4	-57
2	32	-50.0	-52.3	-51.4	-53.2

From the radiation pattern plots and the corresponding SLL using both the techniques it is clear that there’s respectable amount of SLL suppression in Amp-Sp which is better than Amp-Only technique. The response is consistent even when the adopted algorithm is changed from FPA to APSO.

V. CONCLUSION

The study involved in using two improved evolutionary computing tools for effective design of linear arrays which has not been attempted earlier. In the investigation, both conventional and evolutionary computing techniques have been presented for distinct cases. It may be mentioned that inclusion of additional parameter of antenna in conventional design makes the task more complicated. However, it is determined that the use of new evolutionary computing tools made it possible to include inter element spacing in the design which has yield improved performance.

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