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Synthesis of Linear Array for Sidelobe Reduction using Particle Swarm Optimization

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Abstract : In radiation patterns of any antenna or array, it is often difficult to control sidelobe level using conventional technique. In view of this an attempt is made to synthesize linear arrays to yield low sidelobes using the particle swarm optimization (PSO) algorithm. The array design is first formulated as an optimization problem with the goal of sidelobe level (SLL) suppression, and the optimum current excitations are determined by using PSO algorithm. The patterns are numerically computed for small and large arrays and the results obtained are compared with those of conventional methods in the present paper. These low side lobe patterns are useful to overcome EMI problems in radar system.

Keywords : Linear array, Taylor Method, Particle Swarm Optimization, Sidelobe level.

1. INTRODUCTION

Design of antennas with high directive characteristics is often necessary in many of the radar and wireless systems which may not be possible with a single antenna. So the above requirement has necessitated the need for antenna arrays which can improve gain, directivity and radiation characteristics of the field pattern. The synthesis of antenna arrays that generate a desired radiation pattern is a highly nonlinear optimization problem. Many analytical methods such as Taylor method, Chebyshev have been proposed in the literature which has their own advantages and disadvantages [1 – 4].

Reduction of sidelobes with prescribed beamwidth is achieved with proper current distribution to resemble the Chebyshev pattern was solved by Dolph [5]. Synthesis of narrow beam with low sidelobe is proposed for linear arrays with continuous line source aperture by Taylor [6]. The resultant patterns consist of monotonically decreasing sidelobes. To extend the same objective for discrete arrays using Taylor's distribution, a method has been proposed to determine the element excitations by Villeneuve [7]. However Olen and Compton [8] have proposed a technique to minimize the difference between the desired pattern and the obtained pattern using an iterative process.

An alternative to the traditional methods, computational techniques like genetic algorithms (GA) and simulated annealing (SA) are proposed and proved to have the capability in handling multi-objective problems in array synthesis [9 – 11] with enhanced solution space for better optimization. With the application of popular Genetic Algorithms (GA) for linear array synthesis in its binary form, more variety of problems related to array synthesis [12 – 14] were reported in the literature by several authors. This technique is effectively implemented on linear arrays and as well as circular arrays [15].

Tabu Search is another such stochastic technique which is verified for its application in array synthesis for sidelobe reduction for fixed beam width [16]. Therefore, a systematic approach leading to an efficient search over the entire space with iterative process is required. Compared to GA and SA, particle swarm optimization (PSO)

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algorithm is much easier to implement as it requires minimum mathematical preprocessing [17] and is chosen in this paper to achieve required goal. Application of PSO to linear array antenna design was proposed by Rahmat Samii [18].

However, synthesis of radiation patterns using PSO for small and large arrays with reduced sidelobes has not been reported so far. Therefore, in this paper an attempt is made to use PSO for the synthesis of the amplitude excitation coefficients to yield a desired radiation pattern of a linear antenna array with reduced sidelobes.

The paper is organized as follows. In Section 2, the array synthesis using Taylor method is discussed. Section 3 deals with concept of particle swarm optimization algorithm. In section 4, Array Synthesis using particle swarm optimization and formulation of fitness function is explained. The synthesized radiation patterns with reduced sidelobes are presented in section 5. Finally, conclusions are drawn in section 6.

2. ARRAY SYNTHESIS USING TAYLOR'S METHOD

Taylor synthesis is an analytical technique used for the reduction of sidelobe of array beam pattern. But the disadvantage of this approach is that sidelobe levels are maintained as of constant value in case of some of the sidelobes only. In general in antenna design, it is often desired to achieve the narrowest beam widths, besides low side lobe level. Considering the linear array of N elements, the Taylor amplitude excitation coefficients are given by [19]

$$a_i = \frac{\lambda}{\mathrm{N}d}\left\{1 + 2\sum_{n=1}^{\bar{n}-1} f(n, \mathrm{A}, \bar{n}) \cos\left(\frac{2\pi n x_i}{\mathrm{N}+1}\right)\right\} \tag{1}$$

Here, $\bar{n}$ is the number used to decide the number of close in sidelobe to be set with a constant level which is considered as 6 in this paper. The other parts of the equation (1) are given by

$$x_i = i - \left(\frac{\mathrm{N}-1}{2}\right) \tag{2}$$

The coefficients $f(n, \mathrm{A}, \bar{n})$ are the samples of Taylor line source pattern and is given by

$$f(n, \mathrm{A}, \bar{n}) = \frac{\left[(\bar{n}-1)!\right]^2}{(\bar{n}-1+n)!(\bar{n}-1-n)!}\prod_{m=1}^{(\bar{n}-1)}\left[1-\left(\frac{n}{u_m}\right)^2\right] \quad |n| < \bar{n}$$

$$= 0 \qquad |n| \geq \bar{n} \tag{3}$$

$$u_m = \left\{\pm a\sqrt{A^2 + \left(m - \frac{1}{2}\right)^2}\right\} \quad 1 < m < \bar{n}$$

$$= \pm m \qquad \bar{n} < m < \infty \tag{4}$$

The scaling factor a is determined by making the zero location, and is given by

$$a = \frac{\bar{n}}{\sqrt{\mathrm{A}^2 + \left(\bar{n} - 0.5\right)^2}} \tag{5}$$

Here, the parameter A is related to the maximum desired side lobe level R by

$$\mathrm{A} = \frac{1}{\pi}\cosh^{-1}\mathrm{R} \tag{6}$$

$$\mathrm{R} = 10^{\mathrm{sll}/20} \tag{7}$$

Using equation (1), the Taylor amplitude excitation coefficients are computed for number of array elements N = 10 to 90 in steps of 20.

3. PARTICLE SWARM OPTIMIZATION

Kennedy and Eberhart proposed particle swarm optimization (PSO) based on the social behavior of flock of birds in 1995 [20]. Every bird is a particle in hyper-dimensional search space. Also every particle has some socio-psychological nature by which it tries to enhance its scope of other particles. In PSO the swarm is a collection of particles in motion. And every particle concerns a potential solution. The solution approaches the desired value as the particle moves with its knowledge of personal experience as well as global. To accomplish for this it has 2 parameters *i.e.* position and velocity of the particle.

$$x_i(t) = i^{th} \text{ particle position at time slot ‘}t\text{’}. \tag{8}$$

$$v_i(t) = i^{th} \text{ particle velocity at time slot ‘}t\text{’}. \tag{9}$$

In a particular iteration the position is updated as

$$x_i(t + 1) = x_i(t) + v_i(t + 1) \tag{10}$$

It can be understood from above expression that the velocity updates the position with the knowledge of globally exchanged information. Updating velocity, there are many methods for adopting PSO, Individual Best PSO, Global best PSO and Local Best PSO. However, in the present work, global best PSO is considered as it is supposed to have good convergence criterion. In Global Best PSO, the velocity is updated with including the knowledge of the best particle's position in the flock.

$$v_i(t + 1) = v_i(t) + \rho_1(x_{i(\text{pbest})} - x_i(t)) + \rho_2(x_{\text{gbest}} - x_i(t)) \tag{11}$$

For above all the three cases the personal best is updated in iteration as follows

if $\quad \text{Fitness}\,(x_i(t)) < \text{pbest}(x_i)$

then $\quad x_{i(\text{pbest})} = x_i(t)$

else $x_{i(\text{pbest})}$ remains with its value

Also in Global Best method the x_{gbest} is updated as

if $\quad \text{Fitness}\,(x_i(t)) < \text{gbest}$

then $\quad x_{\text{gbest}} = x_i(t)$

else x_{gbest} will retain its value

A. PSO with Inertial factor

Eberhart and Shi [21]proposed a method of multiplying a random number (called inertial weight) with previous velocity. This is method is called as PSO with Inertia. The concept of inertia is to allow the particle to move in the same direction as it was in the previous iteration. The modified position for this method is given as

$$x_i(t + 1) = x_i(t) + \omega(t)\mathrm{V}_i(t) + \rho_1\left(x_{i(pbest)} - x_i(t)\right) + \rho_2\left(x_{gbest} - x_i(t)\right) \tag{12}$$

the $w(t)$ is varying with iteration (time slots) and should be decreasing as it progresses with it. Typically $w(t)$ starts with 0.9 and ends with 0.4.

B. PSO with Constriction Factor

Clerc [22] in 2000 mimicked PSO and suggested PSO with constriction factor. In some cases the particles converge as there is no more change is observed in velocity over iteration in time. In such cases the constriction factor prevents this collapse if the right social conditions are in place.

$$x_i(t + 1) = x_i(t) + \chi\left[v_i(t) c_1 \rho_1\left(x_{pbest} - x_i(t)\right) + c_2\rho_2\left(x_i(t)\right)\right] \tag{13}$$

where

$$\chi = \frac{2k}{\left|2 - \phi - \sqrt{\phi^2 - 4\phi}\right|} \tag{14}$$

and

$$\phi = c_1 + c_2 \text{ and } > 4 \tag{15}$$

2. Array synthesis using pso

The simplest configuration of a linear array is the array of isotropic radiators equally spaced along a line. An N element broadside linear array is shown in Fig. 1.

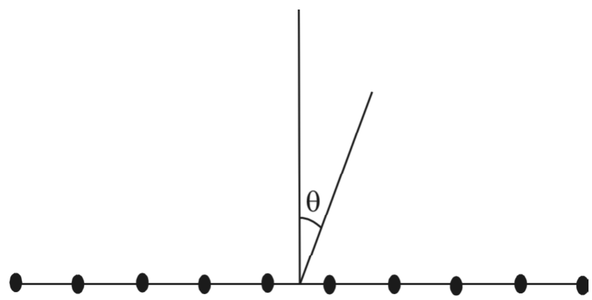

Fig. 1. Linear Array Geometry.

The elements are excited around the center of the linear array. For even numbered linear array the array factor with the above consideration can be written as

$$E(\theta) = 2\sum_{n=1}^{N} A_n \cos\,[\pi(n-0.5)\sin\theta] \tag{16}$$

Here, q = angle between the line of observer and broadside

A_n = excitation of current for the nth element on either side of the array.

N = Number of Elements

Normalized far field can be expressed in dB as

$$E(\theta) = 20\log_{10}\frac{|E(\theta)|}{|E(\theta)|_{max}} \tag{17}$$

For the linear array optimization for sidelobe reduction, the objective function must quantify the entire array radiation pattern. The fitness function to be minimized with particle swarm optimization is expressed as

$$\text{Fitness Function} = \max(E(q)) \text{ for } q \neq 0 \tag{18}$$

As the optimization problem here is minimization one, an inertial weight strategy in PSO anticipating for an accelerated process is used. The population (swarm size) is initialized with certain number of birds where each bird refers to an array of excitation coefficients. Each bird represents the amplitude excitation coefficients of an N element linear array.

The gbest and the pbest are selected based on the problem, from the current generation and the memorized data from the previous generations. The inertial weight parameter '*w*' is initialized with optimum value as proposed in most of the literature. The velocity (*v*) and the array weights (*x*) are updated accordingly with the expressions mentioned in equations (11) & (13). The number of generations and the target side lobe level are initialized according to the problem and the execution terminates on either for a specified sidelobe level is achieved or the completion of number of iterations.

4. RESULTS

In the present work, Particle Swam Optimization is applied to determine the amplitude excitation coefficients to obtain the optimized radiation patterns with a maximum sidelobe level less than -50dB. Here, an equally placed linear array with one-half-wavelength-spaced isotropic elements is considered. For number of array elements equal to 10 to 90 insteps of 20, the amplitude excitation coefficients are determined using PSO. Applying these coefficients for the array elements, the respective radiation patterns are numerically computed. The optimized Amplitude distributions computed using PSO and their respective radiation patterns are presented in Figures 2 – 11.

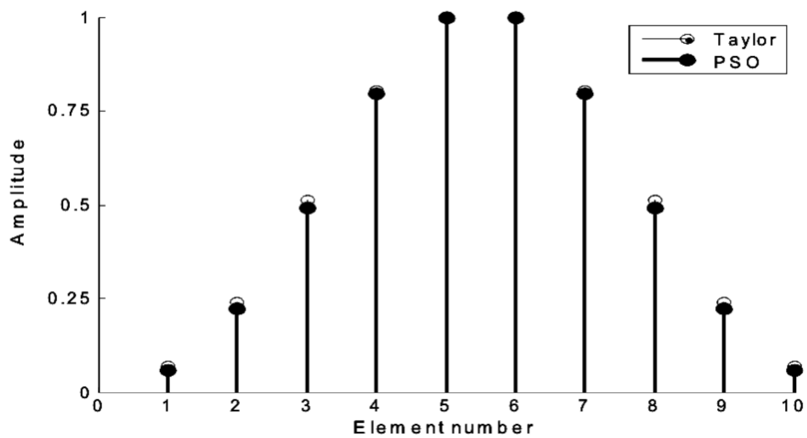

Fig. 2. Normalized Amplitude Excitations for an array of N= 10 Elements using Taylor Amplitude Distribution and PSO

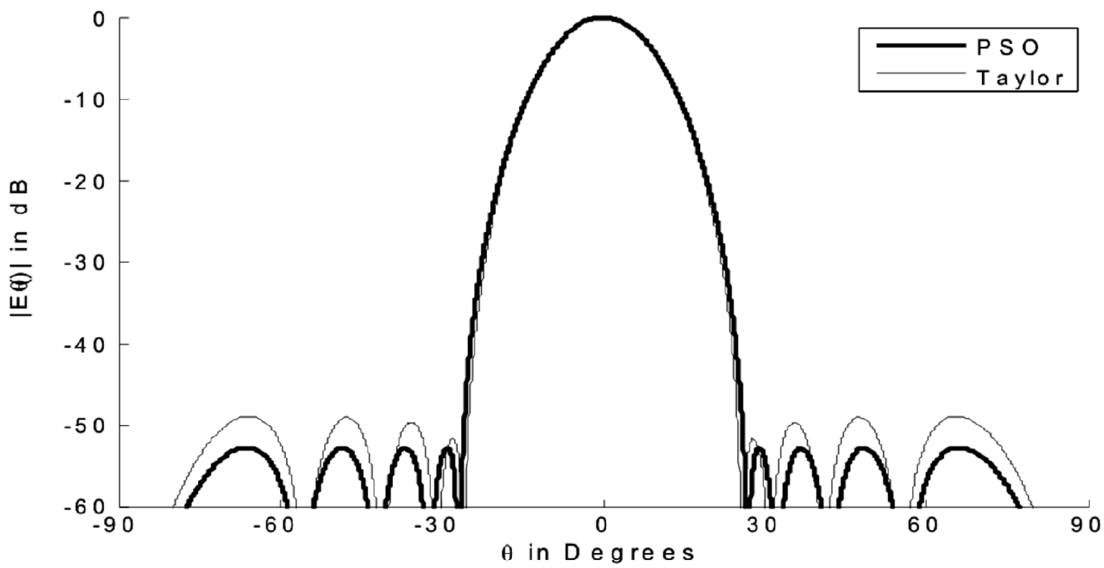

Fig. 3. Radiation Patterns for Number of Elements N = 10 using Taylor Amplitude Distribution for nbar = 7, SLL =- 50 dB and with a reduced SLL of -52.82 dB using Particle Swarm Optimization

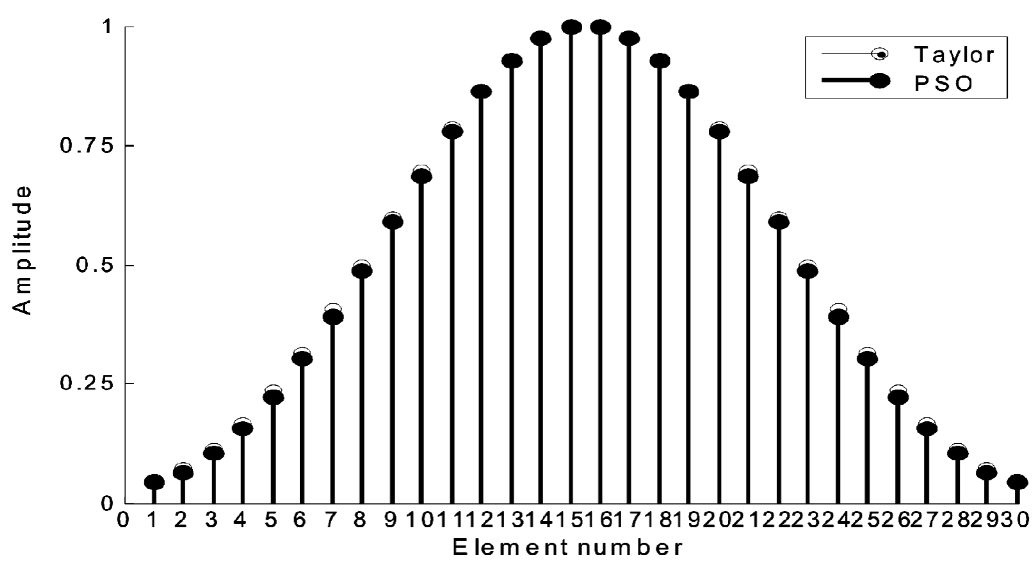

Fig. 4. Normalized Amplitude Excitations for an array of N= 30 Elements using Taylor Amplitude Distribution and PSO

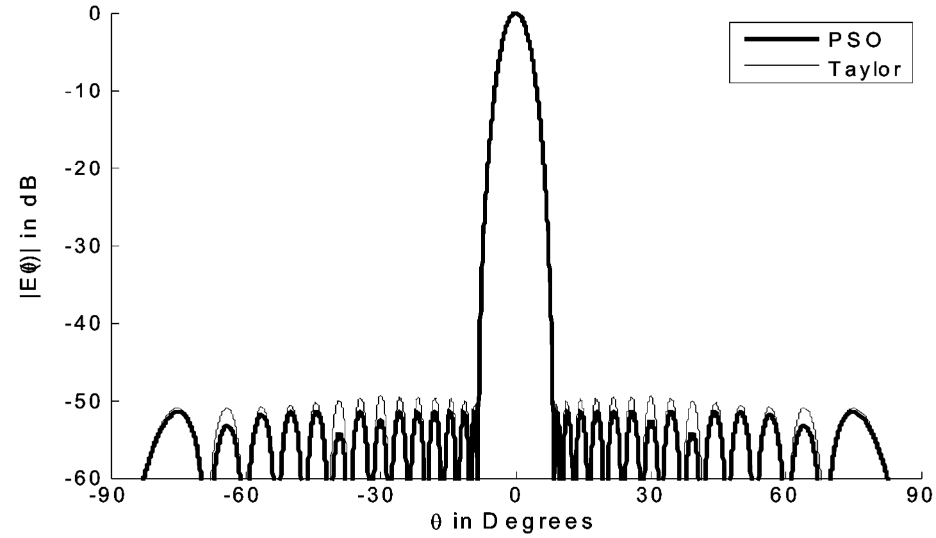

Fig. 5. Radiation Patterns for Number of Elements N = 30 using Taylor Amplitude Distribution for nbar = 7, SLL = -50 dB and with a reduced SLL of -51.46 dB **using Particle Swarm Optimization**

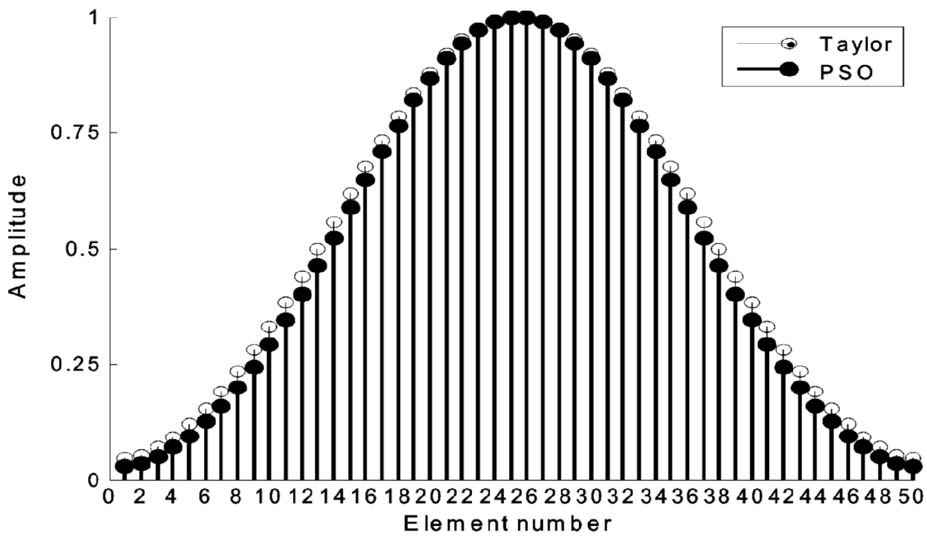

Fig. 6. Normalized Amplitude Excitations for an array of N= 50 Elements using Taylor Amplitude Distribution and PSO

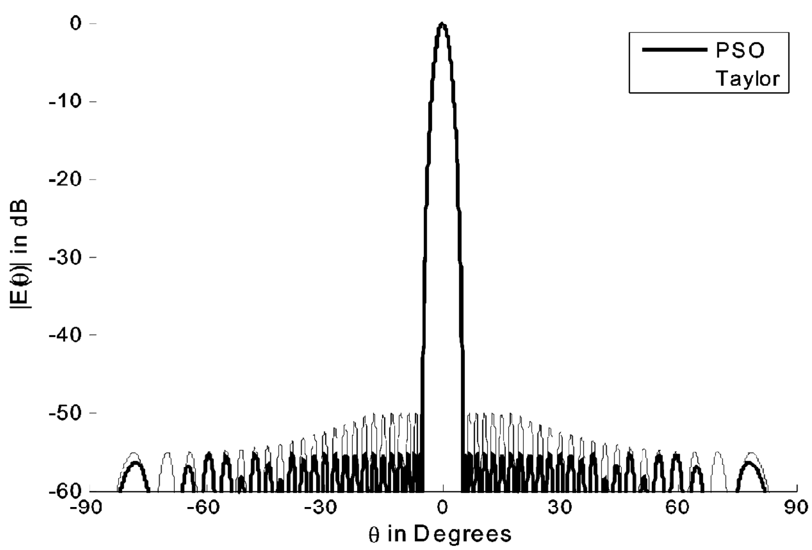

Fig. 7. Radiation Patterns for Number of Elements N=50 using Taylor Amplitude Distribution for nbar = 7, SLL = -50 dB and with a reduced SLL of -55.36 dB using Particle Swarm Optimization

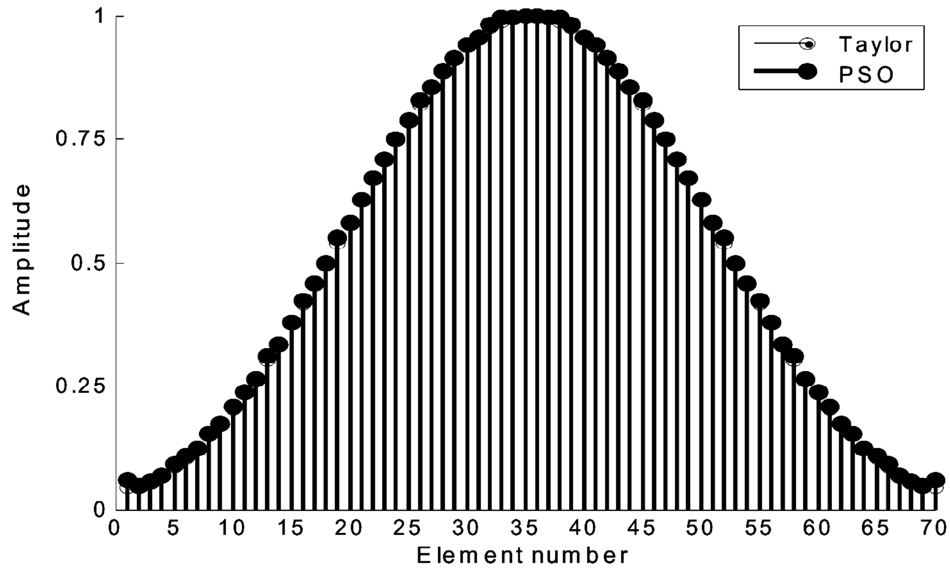

Fig. 8. Normalized Amplitude Excitations for an array of N=70 Elements using Taylor Amplitude Distribution and PSO

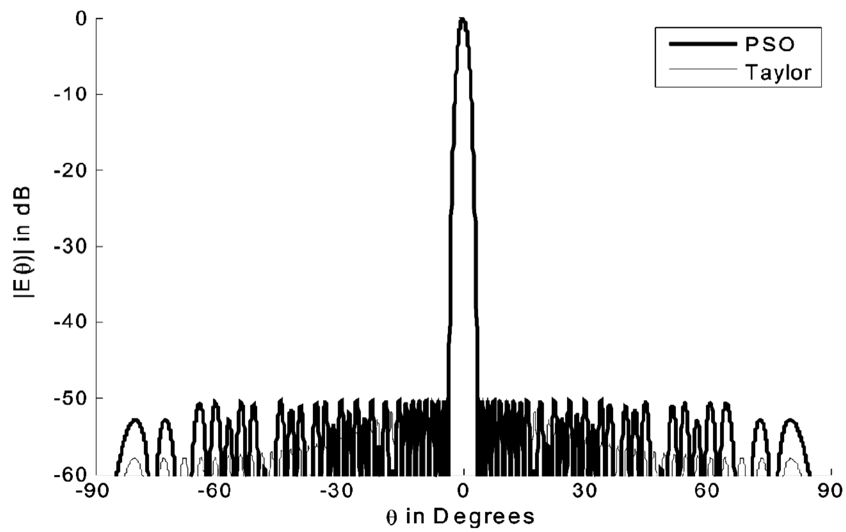

Fig. 9. Radiation Patterns for Number of Elements N=70 using Taylor Amplitude Distribution for nbar = 7,SLL =-50 dB and with a reduced SLL of -51.51 dB using Particle Swarm Optimization

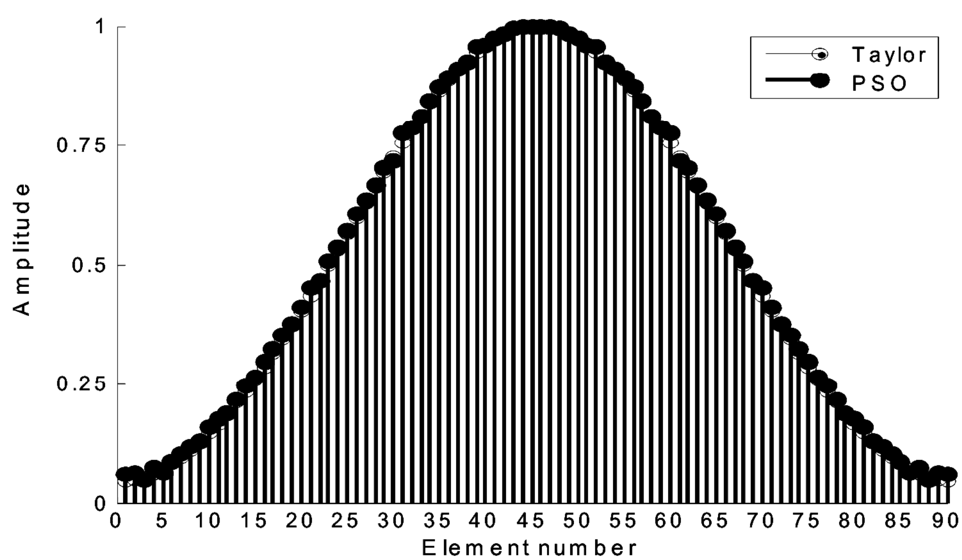

Fig. 10. Normalized Amplitude Excitations for an array of N = 90 Elements using Taylor Amplitude Distribution and PSO

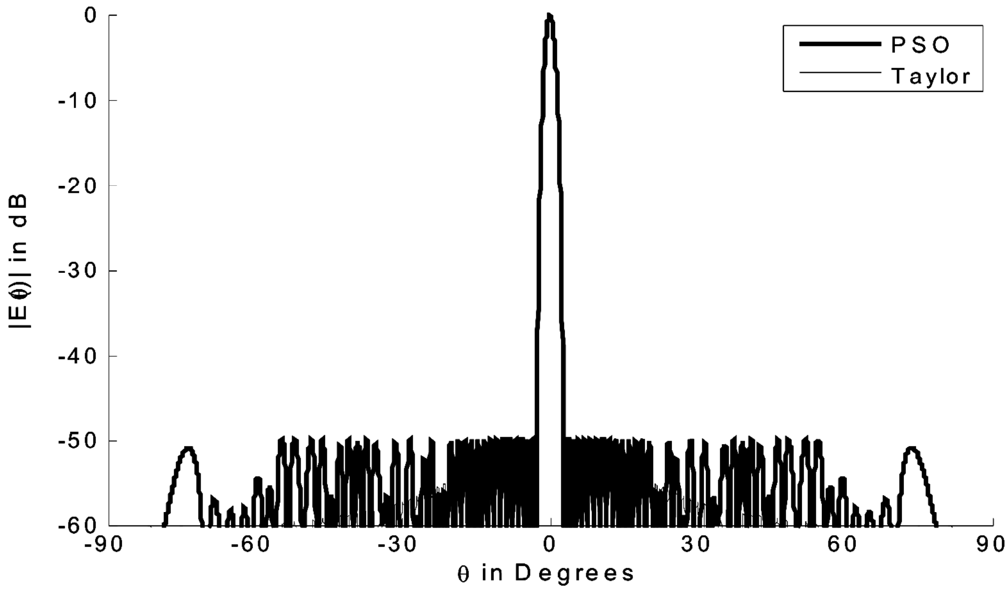

Fig. 11. Radiation Patterns for Number of Elements N = 90 using Taylor Amplitude Distribution for nbar = 7, SLL= - 50 dB and with a reduced SLL of -51.08 dB using Particle Swarm Optimization

5. CONCLUSION

The synthesis of excitation distribution for a specified far-field sidelobe envelope has been presented using particle swarm optimization algorithm. The algorithm for linear arrays is applied to obtain the lowest possible relative side lobe level. The merit of the algorithm is that it can optimize a large number of discrete parameters. The PSO searches effectively for the best current amplitude excitations that produce the low sidelobes. The results reveal that the design of non-uniform excited linear antenna array with optimized amplitude weights offers a considerable sidelobe level reduction without deteriorating the beam width. The method can be extended to other geometries and constraints.

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