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Synthesis of Linear Array of Parallel Dipole Antennas with Minimum Standing Wave Ratio Using Simulated Annealing and Particle Swarm Optimization approach

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Abstract – **In this paper, we propose a technique based on two evolutionary algorithms simulated annealing and particle swarm optimization to design a linear array of half wavelength long parallel dipole antennas that will generate a pencil beam in the horizontal plane with minimum standing wave ratio (SWR) and fixed side lobe level (SLL). Dynamic range ratio of current amplitude distribution is kept at a fixed value. Two different methods have been proposed with different inter-element spacing but with same current amplitude distribution. First one uses a fixed geometry and optimizes the excitation distribution on it. In the second case further reduction of SWR is done via optimization of inter-element spacing while keeping the amplitude distribution same as before. Coupling effect between the elements is analyzed using induced EMF method and minimized in terms of SWR. Numerical results obtained from SA are validated by comparing with results obtained using PSO.**

***Keywords:* Dipole antennas, Simulated Annealing (SA), Particle Swarm Optimization (PSO), Mutual coupling, Standing wave ratio (SWR)**

I. INTRODUCTION:

The synthesis problem of an antenna array is related with the calculation of the excitation and geometry that produce a desired pattern. Many methods have been adopted for achieving specified radiation pattern [1-6]. One of them was the method of Dolph that suggested a Chebyshev excitation amplitude distribution on the array element [1,2]. Later Bucci et al. developed a synthesis method to generate an asymmetrical pencil beam pattern using common amplitude and varying phase distributions [3]. Design of super-directive array generating shaped beam with or without reducing side lobe is proposed by Hansen [4]. Meanwhile Elliott[5] described an improved design procedure that retained all the important features of the earlier approach in it and included the effect of external mutual coupling. Coupling can be minimized by reducing the dynamic range of the excitation distribution with a little compromise on the design specifications [6]. However it is not always possible to ensure that the excitation distributions have small dynamic range [5,6].

In this paper, simulated annealing algorithm and particle swarm optimization [7,8] are used to synthesize two antenna arrays, one with known inter-element spacing but unknown excitation and other with unknown inter-element spacing but known excitation. This known excitation distribution is same as the previous one.

At first we consider a linear array with fixed geometry (half-wave dipoles and half wave length spacing) and optimize current distribution on it to obtain a power pattern with desired value of SLL. Using induced EMF method impedance matrix is calculated and thus SWR is minimized to reduce mutual coupling effect.

Next, for further reduction of coupling, in terms of SWR, spacing between array elements (half-wave dipoles) are suitably varied using SA. Induced EMF method is used to calculate impedance matrix and impedance matching condition is achieved by varying the inter-element spacing while keeping the excitation of the array elements same as obtained in the previous case. For both the cases we use a common current distribution but different inter-element spacing.

Synthesis process is again simulated using PSO [8] algorithm following the same two stage procedure as described above and results obtained are compared with that of previous one to justify the effectiveness of SA.

Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA) [6-10] has become standard procedures for designing such kind of optimized antennas. Most works consider the minimization of the sidelobe level at a fixed main beam-width and treat the design problem as a single objective minimization problem. There are few works in this area that include mutual coupling effect [10]. In this work we tried to minimize coupling effect by minimizing standing wave ratio along with fixed dynamic ranges of excitation amplitude. Impedance matrix is derived using induced EMF method [11] as the dipoles used in our experiment are very thin and a sinusoidal current distribution is assumed.

II. PROBLEM FORMULATION

Consider a linear array of $2N$ half-wavelength long center-fed very thin dipole antennas laid down symmetrically along x-axis with inter-element spacing d

as shown in Fig. 1. Here N elements are placed on each side of the origin. Excitation and geometry both are assumed symmetric with respect to the center of the array in order to generate symmetric broadside pencil beam patterns in azimuth (x-y) plane.

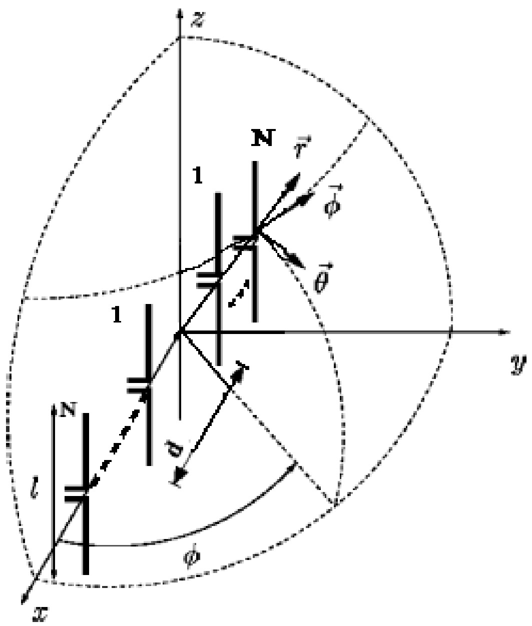

Fig 1. Geometry of uniformly spaced linear array of parallel dipoles along x-axis.

The far-field pattern $F(\phi)$ in the horizontal xy plane in the absence of any ground plane is given by (1)[11]. Element pattern has been assumed omnidirectional in the horizontal plane in absence of ground plane.

$$F(\phi) = \sum_{n=1}^{N} 2I_n \cos[(n-0.5)kd\cos\phi] \tag{1}$$

Normalized power pattern in dB can be expressed as follows

$$P(\phi) = 10\log_{10}\left[\frac{|F(\phi)|}{|F(\phi)|_{\max}}\right]^2 = 20\log_{10}\left[\frac{|F(\phi)|}{|F(\phi)|_{\max}}\right] \tag{2}$$

where n is the element number, $k = 2\pi/\lambda =$ free-space wave number, $\lambda =$ wavelength at the design frequency, j the imaginary unit , d is the inter-element spacing, ϕ is the azimuth angle of the far-field point measured from x-axis, $[I]$ the current matrix of size $N\times 1$, $[Z]$ the mutual impedance matrix of size $N\times N$ that can be stated as follows

$$Z = \begin{bmatrix} Z_{00} & Z_{01} & Z_{02} & \cdots & Z_{0N} \\ Z_{10} & Z_{11} & Z_{12} & \ldots & Z_{1N} \\ Z_{20} & Z_{21} & Z_{22} & \ldots & Z_{2N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ Z_{N0} & Z_{N1} & Z_{N2} & \ldots & Z_{NN} \end{bmatrix} \tag{3}$$

Here $Z_{n,m}$ is the mutual impedance between dipoles n and m [11]. Value of $Z_{n,m}$ depends on the geometry of the dipoles and their mutual geometric relations. Simulated annealing algorithm is used to optimize antenna arrays shown in Fig.1. The radiation patterns (pencil beam) produced by these arrays are required to satisfy the condition of low SLL, impedance-matching condition and optimum dynamic range ratio. In order to optimize the antenna arrays according to the above three conditions, a cost function J is formed as a weighted sum of three respective terms, as given by the following equation:

$$J = w_1 * (SLL - SLL_d)^2 + w_2 * SWR_{\max} + w_3 * (DRR - DRR_d)^2 \tag{4}$$

Where SWR_{max} is the maximum SWR value (SWR is different for different element). SLL, SLL_d, DRR, DRR_d are obtained and desired values of corresponding terms. DRR stands for dynamic range ratio that is computed from the given expression.

$$DRR = \frac{\max(I_n)}{\min(I_n)} \tag{5}$$

Impedance matching condition stated above is achieved by minimizing SWR. According to the transmission line theory [11] input impedance $Z_{n,n}$ of each (n-th) element is defined as $Z_{n,n} = V_n / I_n$, where V_n = complex excitation voltage of n-th element, obtained from the expression $[V]_{N\times 1} = [Z]_{N\times N}[I]_{N\times 1}$. Thus $Z_{n,n}$ generates an array of 20 elements that has to be as close as possible to the characteristic impedance Z_0 (50Ω) of the transmission line that feeds the element for efficient radiation. Reflection coefficient at the input of the n-th element is derived by the expression

$$R_n = \frac{Z_{n,n} - Z_0}{Z_{n,n} + Z_0} \tag{6}$$

Using R_n value we calculate SWR at the input of the n-th element using the expression

$$SWR = \frac{1 + |R_n|}{1 - |R_n|} \tag{7}$$

Impedance matching is obtained if $Z_{n,n} = Z_0$ i.e when SWR=1. For practical purpose maximum tolerable value of SWR is 2. The coefficients w_1, w_2 and w_3 are weight factors and they describe the importance of the corresponding terms that compose the cost function. SA and PSO both attempts to minimize the cost function to meet the desired pattern specification.

In this paper, we follow a two-stage procedure. In the first stage, under the assumption that all the radiating elements are identical and uniformly spaced 0.5λ apart, excitation distribution is optimized to reduce SLL and SWR value.

In the second stage, inter-element spacing is varied to reduce SWR further for the same array. For both the cases a common current distribution is used and obtained from the first case. To generate desired pencil beam, all excitation current phases are kept fixed at 0 degree and excitation current amplitudes are varied in the range 0 to 1. For the first case spacing is prefixed at 0.5 wavelengths. For second case, spacing is varied in the range 0.4 to 0.8 wavelength uniformly. Excitation current and geometry both are assumed symmetric about the center of the array.

III. A. OVERVIEW OF SIMULATED ANNEALING

Simulated annealing (SA) [12-15], a heuristic search method based on ideas drawn from statistical physics, has been found to be very effective in solving many combinatorial optimization problems. It works by emulating the physical process whereby a solid is slowly cooled so that when eventually its structure is “frozen” this happens at a minimum energy configuration. The algorithm can be summarized as follows

1. Let S be a finite set.
2. A real valued cost function J is defined on S. Again $S^* \subset S$ be the set of global minima of the function J, assumed to be a proper subset of S.
3. For each $i \in S$, a set $S(i) \subset S - \{i\}$, called the set of neighbor of i.
4. For every i, a collection of positive coefficient q_{ij}, $j \in S(i)$, such that $\sum_{j \in S(i)} q_{ij} = 1$. It is assumed that $j \in S(i)$ if and only if $i \in S(j)$.
5. A decreasing function defined by $T : N \to (0, \infty)$, called the cooling schedule .Here N is the set of positive integer, and $T(t)$ is called temperature at time t. It is referred to as temperature, since it plays a similar role as the temperature in the physical annealing process.
6. Initial state $x(0) \in S$. If the current state $x(t)$ is equal to i, chose a neighbor j of i at random. The probability that any particular $j \in S(i)$ is selected is equal to q_{ij}. Once j is chosen the next state $x(t+1)$ is determined as follows.

If $J(j) \le J(i)$, then $x(t+1) = j$.

If $J(j) > J(i)$, then

$x(t+1) = j$ with probability $\exp[-(J(j) - J(i))/T(t)]$

$x(t+1) = i$ otherwise.

Formally

$$P[x(t+1) = j | x(t) = i] = q_{ij} \exp\left[-\frac{1}{T(t)} \max\{0, J(j) - J(i)\}\right]$$

If $\quad j \ne i, j \in S(i)$

If $j \ne i$, $j \notin S(i)$, then $P[x(t+1) = j | x(t) = i] = 0$

7. The calculation of this probability relies on the temperature parameter T. To avoid getting trapped at a local minimum point, the rate of reduction should be slow. In our problem the following method to reduce the temperature has been used:

   $$T(t+1) = (T(t) - T_f)(1 - nf/nf_{\max}) + T_f$$

   Where T_f = final temperature and $nf_{\max}$ = maximum number of iteration.
8. Thus, at the start of SA most worsening moves may be accepted, but at the end only improving ones are likely to be allowed. This can help the procedure jump out of a local minimum. The algorithm may be terminated when maximum number of iterations is satisfied or after a pre-specified run time. State i corresponding to the minimum cost function $J(i)$ is taken as the answer.

III. B. OVERVIEW OF PARTICLE SWARM OPTIMIZATION:

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Eberhart and Kennedy in 1995 [16], inspired by social behavior patterns of organisms that live and interact within large groups. In particular, it incorporates swarming behaviors observed in flocks of birds, schools of fish, or swarms of bees, and even human social behavior. The idea of PSO algorithm is that particles move through the search space with velocities which are dynamically adjusted according to their historical behaviors. Therefore, the particles have the tendency to move towards the better and better search area over the course of search process. PSO algorithm starts with a group of random (or not) particles (solutions) and then searches for optima by updating each generation. Each particle is treated as a volume-less particle (a point) in the n-dimensional search space. The i-th particle is represented as $X_i = (x_{i1}, x_{i2} \cdots, x_{in})$. At each generation, each particle is updated by following two best values:

i) The first one is the best solution (fitness) it has achieved so far (the fitness value is also stored). This value is called c-best.

ii) Another best value that is tracked by the particle swarm optimizer is the best value obtained so far by any particle in the population. This best value is a global best and called g-best. When a particle takes part in the population as its topological neighbors, the best value is a local best and is called l-best.

In every iteration, theses two best values are combined to adjust the velocity along each dimension and that velocity is then used to compute a new move for the particle. The portion of the adjustment to the velocity influenced by the individual's previous best position (c-best) is considered the cognition component, and the portion influenced by the best in the neighborhood (l-best or g-best) is the social component.

With the addition of the inertia factor ω, by Shi and and Eberhart [17] (for balancing the global and the local search), these equations are:

$$v_{i+1} = \omega * v_i + c_1 * random(0,1) * \left(cbest_i - x_i\right) + c_2 random(0,1) * (gbest - x_i) \quad (9)$$

$$x_{i+1} = x_i + v_i \quad (10)$$

where random(0, 1) is a random number independently generated within the range of [0,1] and *c1* and *c2* are two learning factors which control the influence of the social and cognitive components (Usually, *c1 = c2 = 2*). In equation 9 if the sum on the right side exceeds a constant value, then the velocity on that dimension is assigned to $\pm V_{i\max}$. Thus, particle's velocities are clamped to the range of $\left[-V_{i\max}, +V_{i\max}\right]$ which serves as a constraint to control the global exploration ability of PSO algorithm. This also reduces the likelihood of particles for leaving the search space. Note that this does not restrict the values of x_i to the range $\left[-V_{i\max}, +V_{i\max}\right]$; it only limits the maximum distance that a particle moves during iteration.

The steps involved in standard PSO are given below:

Step 1: Initialize positions and associated velocity of all particles (potential solutions) in the population randomly in the n-dimension space.

Step 2: Evaluate the cost value of all particles.

Step 3: Compare the personal best (pbest) of every particle with its current cost value. If the current cost value is better, then assign the current cost value to pbest and assign the current coordinates to pbest coordinates.

Step 4: Determine the current best cost value in the whole population and its coordinates. If the current best cost value is better than global best (gbest), then assign the current best cost value to gbest and assign the current coordinates to gbest coordinates.

Step 5: Update velocity (V_i) and position (X_i) of the n-th dimension of the i-th particle.

Step 6: Repeat steps 2–5 until a stop criterion is satisfied or a prespecified number of iteration is completed, usually when there is no further update of best cost value.

IV RESULTS AND DISCUSSIONS

We consider two linear arrays of 20 dipole antennas of length 0.5λ and radius 0.005λ. First array elements are uniformly placed 0.5λ apart along x-axis. To generate a pencil beam, all excitation current phases are kept fixed at 0 degree and excitation current amplitudes are varied in the range 0 to 1. For the second case array elements are positioned uniformly along the same. Here inter-element spacing is varied in the range 0.4 to 0.8 wavelengths uniformly to achieve the desired goal. Desired DRR value of amplitude distribution is prefixed at 7.0.

Because of symmetry, only ten amplitudes and ten phases are to be optimized. For the first case, SA is designed to generate a vector of 10 real values between zero and one. In the second case, SA is designed to generate a vector of one real value i.e. inter-element spacing between 0.4 and 0.8.

In our method we find a common excitation distribution for both the cases. For the first case spacing is kept fixed at 0.5λ where in the second case it is suitably varied within the specified range.

For design specifications as given in Table-1 and 2, SA simulates the whole annealing procedure in 2000 iterations from 100 to 0 degrees. Later we reanneal it from 10 to 0 degrees. Entire process takes 909.797000 seconds. In every run, SA generates a new set of solution, neighbor of current one and compares with the best solution found so far. If new cost function value is less than that of current one, it accepts the new solution otherwise retains the current value. The probabilities are chosen so that the system ultimately moves to states of lower value. The steps are repeated until the system reaches a state that is good enough for the application. For the second case to optimize inter element spacing time requirement remains almost same.

Table 1
Desired and obtained results for 0.5λ spacing using SA

Design Parameters	Pencil Beam	
	Desired	Obtained
Side Lobe Level (dB)	30	30.1127
Standing wave ratio (SWR)	NA	1.2946
Optimized DRR =7.9998		

Table 2
Desired and obtained result for 0.58274λ spacing using SA

Design Parameters	Pencil Beam	
	Desired	Obtained
Side Lobe Level (dB)	30	30.1127
Standing wave ratio (SWR)	NA	1.2417
Optimized DRR =7.9998		

Table-1 and Table-2 respectively show the desired and obtained results for both the cases in absence of ground plane. Input parameters obtained from the process are shown in Table-3 and Table-4. A common current amplitude distribution is used for both the cases for network simplification and phase is prefixed at zero. In the second case, inter element spacing is controlled for further mitigation of coupling effect. Because of symmetry, remaining ten elements are also be excited with the same parameters. There is a good agreement between the desired and synthesized results for both the cases. SWR values for individual elements are shown in the table. Maximum SWR value is minimized in each step and for the first case it is found 1.2946 where it reduces to the value 1.2417 when inter-element spacing is optimized. For both the cases SLL value meets the desired specification of SLL (30 dB). Desired dynamic range ratio of excitation distribution is fixed at 8.

Table 3
Amplitude distributions, spacing and SWR value of the array using SA

n	Uniformly spaced array		
	Current amplitude I_n	Spacing	SWR_n
1	0.82738	0.5	1.2946
2	0.89702	0.5	1.0806
3	0.73826	0.5	1.0576
4	0.7194	0.5	1.1124
5	0.57736	0.5	1.0485
6	0.51718	0.5	1.1134
7	0.37372	0.5	1.0619
8	0.27461	0.5	1.0478
9	0.23541	0.5	1.1491
10	0.11213	0.5	1.0707
Phase is fixed at 0 degree in both the cases			

Table 4
Amplitude distributions, spacing and SWR value for the array using SA

Optimally spaced array		
Current amplitude I_n	Spacing	SWR_n
0.82738	0.58274	1.2417
0.89702	0.58274	1.1211
0.73826	0.58274	1.0082
0.7194	0.58274	1.0025
0.57736	0.58274	1.1016
0.51718	0.58274	1.0714
0.37372	0.58274	1.1922
0.27461	0.58274	1.0779
0.23541	0.58274	1.104
0.11213	0.58274	1.1334
Phase is fixed at 0 degree in both the cases		

The optimized result shows excellent matching with desired specification. To compensate mutual coupling, second array alignment is proved better than that of first one. Using the proposed technique we can further lower the SLL value along with a very good SWR

Radiation patterns using the optimized data are plotted bellow. Figure2 and Figure3 shows the normalized absolute power patterns (pencil-beam) in dB for uniformly spaced array elements at 0.5λ and 0.58274λ apart (optimized spacing) respectively. Patterns are shown in phi space ranging from 0 degree to 180 degree

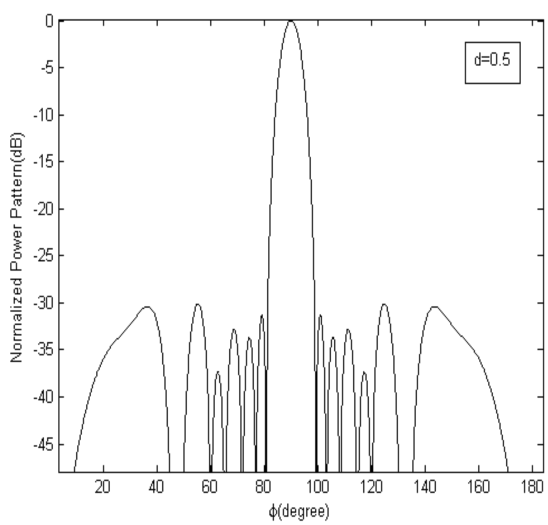

Fig. 2. Normalized absolute power patterns in dB for pencil-beam array with 0.5λ spacing using SA

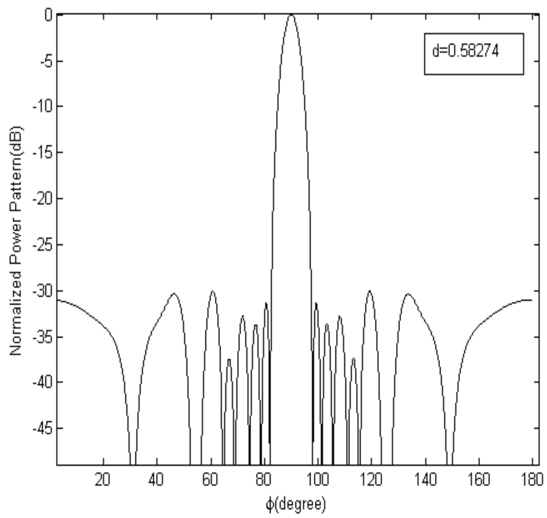

Fig. 3. Normalized absolute power patterns in dB for pencil-beam array with 0.58274λ spacing using SA

SA makes the design procedure simple and its results meet the desired specifications. To validate the proposed technique, performance of SA is compared with that of PSO. Clerc's Constricted PSO of Type 1 is used to optimize the same synthesis problem stated above. To obtain the design specification presented in Table-5 and Table-6, algorithm is run for 200 iterations and the results are compared. In the numerical experiments, the parameters used by the PSO algorithm are: acceleration constant $c_1 = c_2 = 2$; Initial and final inertia weight 0.9 and 0.4; maximum particle velocity 0.5; matrix of ranges for each input variable is set [0 1] like before to limit the maximum distance that a particle will move during one iteration.; population size 24; minimum global error gradient 1e-5.

The algorithm is run for 25 repetitions to set the values of different parameters those have significant impact on the efficiency and reliability of the PSO. It is seen that maximum particle velocity is related to V_{imax}. The performance of optimization improves as V_i shrinks. Obviously, there must be a lower limit to this reduction, as V_i is the step size of the swarm, the maximum distance a particle can travel in an iteration. Reducing it by too much impedes the ability of the swarm to search.

It is also noticed that, as the population size increases the number of iterations required to solve the functions reduces. It is expected that, more particles would search more space, and a solution would then be found sooner. However, as the population increases, iterations represent a greater cost, as more particles call upon the evaluation function. A population size of 24 appears to be a good choice for our purpose

Table 5
Desired and obtained result for the array with 0.5λ spacing

Design Parameters	Pencil Beam	
	Desired	Obtained
Side Lobe Level (dB)	30	30.7782
Standing wave ratio (SWR)	NA	1.3108
Optimized DRR = 6.3132		

Table 6
Desired and obtained result for the array with 0.58274λ spacing

Design Parameters	Pencil Beam	
	Desired	Obtained
Side Lobe Level (dB)	30	30.7782
Standing wave ratio (SWR)	NA	1.3108
Optimized DRR = 6.3132		

Table-5and Table-6 respectively show the desired and obtained results using PSO for both the cases in absence of ground plane. Input parameters obtained from the process are shown in Table-7 Table 8. A common current amplitude distribution is used for both the cases for network simplification and phase is prefixed at zero like before. In the second case, inter element spacing is controlled for further mitigation of coupling effect.

Table-7
Amplitude distributions, spacing and SWR value of the array using PSO

n	Uniformly spaced array		
	Current amplitude I_n	Spacing	SWR_n
1	0.9200	0.5	1.3108
2	0.9622	0.5	1.0707
3	0.78614	0.5	1.0772
4	0.7393	0.5	1.0776
5	0.67555	0.5	1.1009
6	0.54882	0.5	1.0822
7	0.40991	0.5	1.0547
8	0.33102	0.5	1.1199
9	0.20922	0.5	1.0023
10	0.15241	0.5	1.2600

Table-8
Amplitude distributions, spacing and SWR value of the array using PSO

n	Optimally spaced array		
	Current amplitude I_n	Spacing	SWR_n
1	0.9200	0.6254	1.2614
2	0.9622	0.6254	1.1677
3	0.78614	0.6254	1.0416
4	0.7393	0.6254	1.0020
5	0.67555	0.6254	1.1373
6	0.54882	0.6254	1.0330
7	0.40991	0.6254	1.1517
8	0.33102	0.6254	1.0065
9	0.20922	0.6254	1.1321
10	0.15241	0.6254	1.1129

Radiation patterns using the optimized data are plotted bellow. Figure 4 shows the normalized absolute power patterns (pencil-beam) in dB for uniformly spaced array elements at 0.5λ. Patterns are shown in phi space ranging from 0 degree to 180 degree.

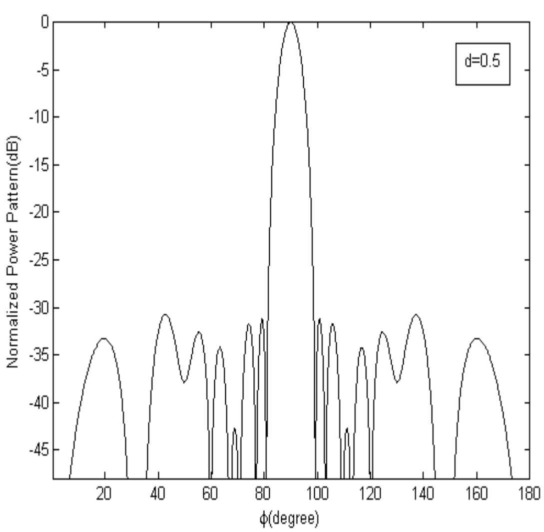

Fig. 4. Normalized absolute power patterns in dB for pencil-beam array with 0.5λ spacing using PSO

Figure 5 shows the normalized absolute power patterns (pencil-beam) in dB for uniformly spaced array elements at 0.6254λ apart (optimized spacing). Patterns are shown in phi space ranging from 0 degree to 180 degree

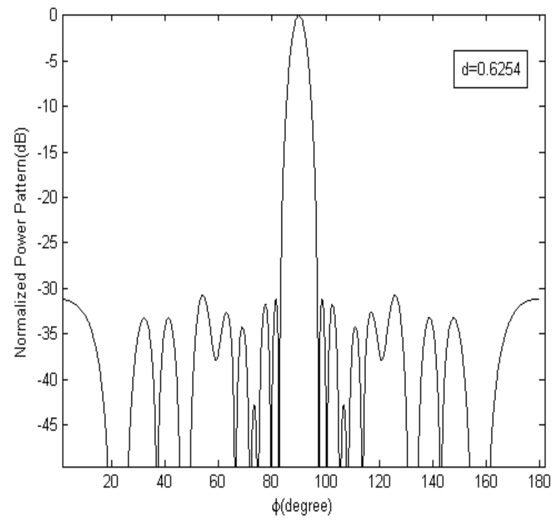

Fig. 5. Normalized absolute power patterns in dB for pencil-beam array with 0.6254λ spacing using PSO

Entire process using PSO takes 1515.125 seconds, though PSO needs less number of iterations to attain the minimum value. In second case also PSO takes almost same time to optimize the inter element spacing.

It is seen that smaller number of function evaluations are required to reach the minimum in the successful runs, when a suitable initial particle position i.e PSO seed value is used. This peculiarity makes PSO very useful for hybrid algorithms that combines the advantages of different optimization techniques, as PSO can reach the optimum after few iteration when it receives a good starting solution from the other algorithms [18].

Results show the computation time taken in case of SA is less than that of PSO. Both the techniques offer accurate results. The only drawback of PSO algorithm is that it becomes easily trapped into local optimization [18]. SA has a strong ability to avoid the problem using probability searching. It accepts all the changes that lead to improvements in the fitness of a solution and allow the probabilistic acceptance of changes, which lead to worse solutions. This causes slower convergences than PSO.

V CONCLUSION

The use of simulated annealing and particle swarm optimization in the synthesis of uniformly spaced linear array of half wave parallel dipoles is presented here. In this paper two examples have been presented. In the first case, excitation current amplitude is optimized whereas in the second case inter-element spacing is only varied in order to obtain a low value of SLL and SWR. In both the cases a common excitation distribution is used and phase is prefixed at zero degree. Result shows spacing has minimal effect on SLL level but plays a significant role in SWR minimization. The excitation and geometry both are symmetric in nature that greatly simplifies the feed network. Mutual impedance matrix is calculated using induced EMF method. In the proposed method, driving point impedance of each element is varied suitably by optimizing array geometry. Thus active impedances become matched with feed network and mutual coupling effect is compensated. Fixing the dynamic range ratio of excitation current amplitude to a lower value with little compromise on the design specifications further reduces effect of coupling. There is a very good agreement between desired and obtained results using both the techniques. However PSO offers outstanding performance in speed of convergence and precision of the solution for global optimization. We can extend this work further by using method of moments for getting more accurate results. The technique is capable of optimizing more complex geometries and therefore is suitable for many applications in communications area.

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