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Thinning of Antenna Arrays for Direct Broadcast Satellite System

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ABSTRACT— ***In antenna array thinning some antenna elements are made 'ON' and some antenna elements are made 'OFF" strategically. Keeping some of the antenna elements 'OFF' and reducing use of digital beamformer, desired characteristics of the array can be achieved in direct broadcast satellite (DBS) communication, to achieve higher gain and saving power utilization. In this paper, array thinning is done using differential evolution (DE) algorithm, an optimization technique. DE optimized results are compared with corresponding fully populated arrays. Lower side lobe levels (SLL) are achieved using DE optimized thinned arrays compared to fully populated arrays. Both linear array and planar are considered for array thinning.***

Keywords—Thinned array, differential evolution algorithm, side lobe level, linear array, planar array

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1. INTRODUCTION

Thinned array antenna involves switching 'OFF' some antenna elements from an antenna array to achieve high gain with reduced power consumption. In direct broadcast satellite system (DBS) subscribers receive signal directly from a geostationary satellite [1]. Primary requirement for a DBS system is high gain antenna with high effective isotropic radiated power (EIRP) by using large antenna array. To achieve desired antenna parameters, the use of digital beam former which is attached with each antenna elements in a direct broadcast satellite system (DBS), is reduced by switching off some antenna elements in a thinned array system. Thinned arrays have been of interest for large antenna systems. In array thinning keeping antennas 'ON' and 'OFF' strategically [2, 3] same radiation pattern like a fully populated array can be achieved. Thinned array and fully populated array are shown in Fig. 1.

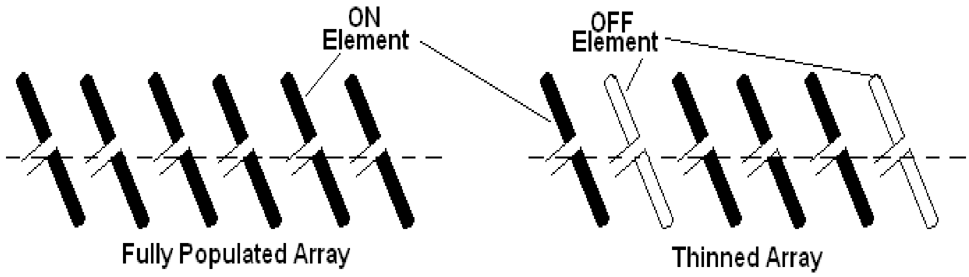


Figure 1: Fully Populated Array and Thinned Array

In a fully populated array all the elements are switched 'on'. By thinning of an array overall cost and weight of the antenna system can be reduced in addition to low power consumption. Another important advantage of a thinned array is that side lobe level can be reduced by array thinning. Various thinning methods are available to reduce SLL, such as, thinning based on empirical or analytical formula [4], space or density tapering [5], statistically thinned arrays [6] etc. But optimization technique is the most popular technique for array thinning and used for various types of arrays including linear array, circular array, elliptical array [3,7-10].

In this paper, optimization technique differential evolution (DE) is used for array thinning. MATLAB is used to simulate thinned array. Linear antenna arrays of 12 elements and 20 elements are considered for array thinning. Almost same radiation characteristics of fully populated array are achieved thinned array with reduced side lobe level. The application of DE optimization method is also extended to optimization of planar thinned array. Better result is obtained using DE optimization than fully populated array.

2. DIFFERENTIAL EVOLUTION ALGORITHM

Differential evolution (DE) is an adaptive method for global optimization. Remarkable performance in optimization problems can be achieved using DE [11, 12]. The optimization problem begins by designing an objective function that can model the problems of the objectives under constraints. In differential evolution, an initial population size of target vectors is defined and each target vector consists of various parameters of the design problem. For each parameter, a lower bound and an upper bound are defined ($X_i^L < X_{i,j}(0) < X_i^U$). Then random selection of initial parameter are done within the interval (X_i^L, X_i^U). Other parameter vectors are selected randomly for each target vector. Difference of weight of any two parameters, are added to the third vector which forms a donor vector.

$$V_{k,n}(t+1) = X_{m,n}(t) + F*(X_{i,n}(t) - X_{j,n}(t)) \quad (1)$$

The difference between two vectors, are scaled by scaling factor F which is added to the third one, and it ranges from 0 to 2. Components of the donor vector enter into the trial vector with probability CR

$$T_{k,n}(t+1) = V_{k,n}(t+1) \text{ if rand(0,1)} < \text{CR}$$
$$= X_{k,n}(t) \text{ otherwise} \quad (2)$$

Then for better fitness, the trial vector is compared with the target vector, and passed to the next generation. For computation, following fitness function is used

F= ∑| Reflection coefficient at frequency i| *(3)*

Where, over the frequency range of interest, the above summation is performed.

3. DESIGN OF THINNED ARRAY USING DIFFERENTIAL EVOLUTION ALGORITHM

Consider a 'N' element linear array (Fig. 2) consist of isotropic antennas without any mutual interference between them, are placed in fixed inter element spacing 'd'.

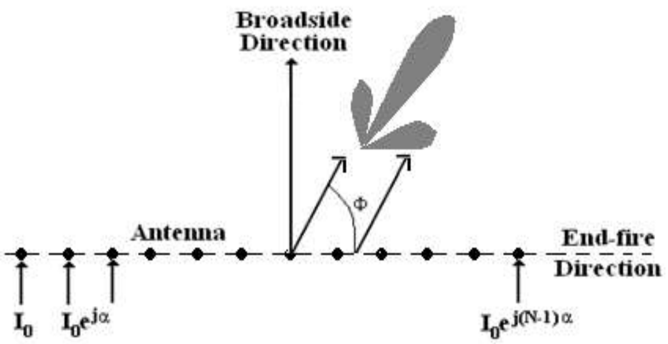


Figure 2: Linear Antenna Array

The array factor (AF) for a linear array of N antennas at scanning angle Ø is [13],

$$AF = \sum_{n=1}^{N} In.e^{j(n-1)\beta d(\cos\theta - \cos\phi)} \quad (4)$$

Where, β= 2π/λ, λ= wavelength, α = progressive phase shift between elements. Array factor governs the radiation pattern generated by the phased array, contains main beam as well as all sidelobes. The objective function, minimizing the maximum side lobe level, can be determined from array factor by excluding main beam then normalize it. Hence the cost function to be optimize is,

$$SLL_{\max} = \max \left| \frac{AF(\theta)}{\max(AF)} \right| \theta = \theta_{SLM} \quad (5)$$

Where, $\theta_{SLM} = 0^{\circ} \leq \theta \leq (\phi - LN) \cup (\phi + RN) \geq \theta \geq 180^{\circ}$

LN = first left null point to main beam at scanning angle Ø.

RN = first right null point to main beam at scanning angle Ø. Normalized array factor is

$$AF_{norm} = \frac{\mathrm{AF}}{\mathrm{AFmax}} \quad (6)$$

Design consideration of thinned array utilizes only two fixed values of exciting current amplitude weight, for ‘ON’ state current amplitude is ‘1’ and ‘OFF’ state current amplitude is ‘0’. This status of elements is similar to discrete or binary values. Therefore, such type of array design requires a kind of optimization algorithm which can support binary values. Among various optimization techniques, DE is applied for optimization. The cost function is used in optimization of 12 and 20 elements antenna arrays with inter-element spacing of d= 0.5λ. MATLAB is used to determine the cost function, the optimal plot for the different population and variables. For 12 element thinned array design using DE, population size of 48, 60, 72, 84, 96, 108, 120 are considered. Number of Generations=200. The optimal plot of normalized array factor is shown in Fig. 3.

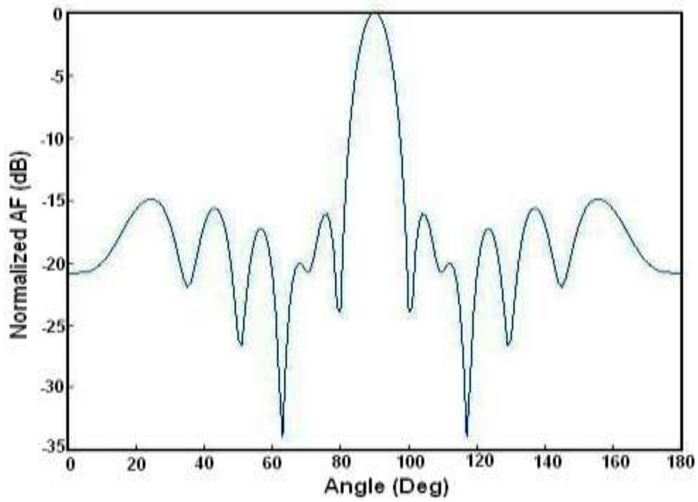


Figure3: Optimal Radiation Pattern for 12-Elements Thinned Array

Variation of cost function with population size of 48 is plotted in Fig. 4.

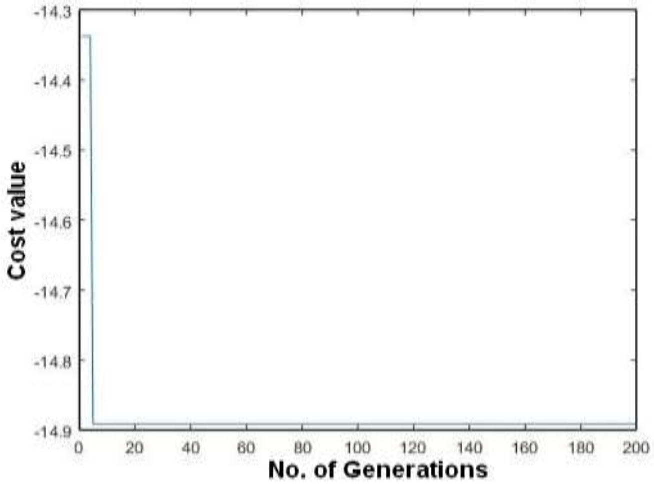


Figure 4: Cost Value for N=12, Population Size 48

Maximum side lobe level of about -15 dB is achieved for 12 element linear array. The ‘ON’ and ‘OFF’ positions of the array is 111111111101. The first null beamwidth (FNBW) is 20 degree. For fully populated array, FNBW is calculated from the formula [13] FNBW=2λ/Nd, Where λ=wavelength, N=number of elements, d=inter element spacing=0.5λ. Calculated value of FNBW for fully populated array is 19.1 degree and computed value of maximum side lobe level is -13.1 dB. Therefore, by thinning using DE, side lobe level is reduced by 1.8 dB. The results are shown in Table 1.

Table 1: Performance of thinned array antenna for 12 element linear array

Population size	**"ON" and "OFF" positions**	**SLL_{max} (dB)**	**FNBW(Deg)**
48	111111111101	-14.9	20
60	111111111101	-14.9	20
72	111111111101	-14.9	20
84	111111111101	-14.9	20
96	111111111101	-14.9	20
108	111111111101	-14.9	20
120	111111111101	-14.9	20

In Table 1, investigation for a 12 elements array is done by varying population size. There is no change in SLL, FNBW or 'ON' and 'OFF' positions of the array with variation of population size. For 20 element linear array with 200 generations, the result for normalized array factor is shown in Fig. 5.

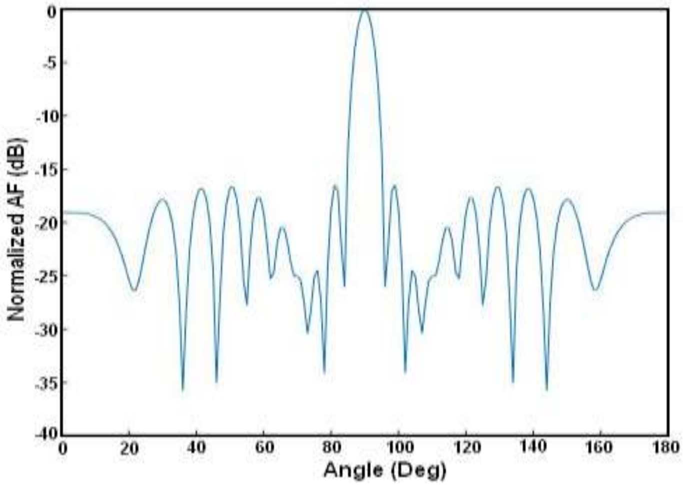
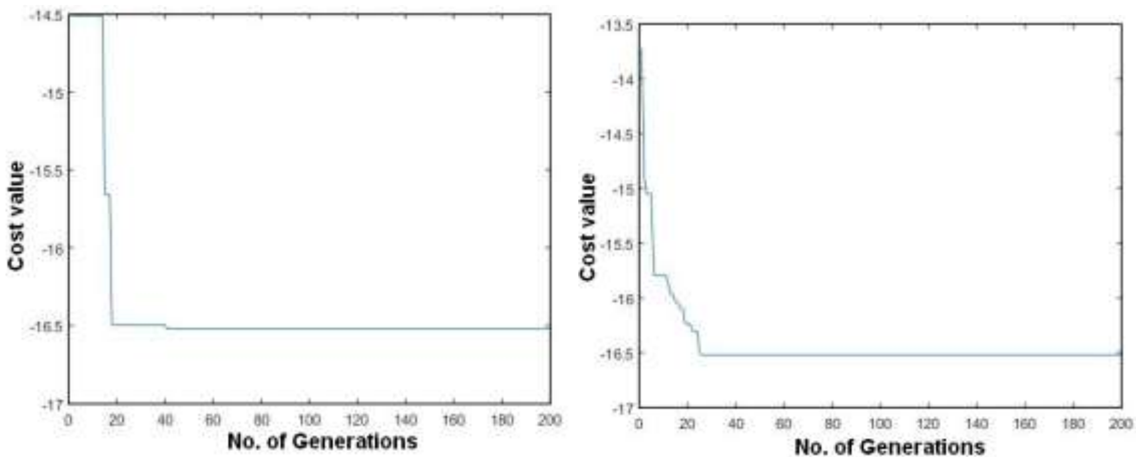


Figure 5: Optimal Radiation Pattern for 20-elements Thinned Array

Variations of cost function with number of generations for 20 element linear thinned array are shown in Fig. 6(a) and Fig. 6(b) for different population sizes.



(a) (b)

Figure 6: Cost Value for (a) N=20, Population Size 80, (b) N=20, Population Size 120

Maximum side lobe level of about -16.5 dB is achieved for 20 element linear array. The first null beamwidth (FNBW) is 12 degree. Calculated value of FNBW for fully populated array is 11.45 degree and computed value of maximum side lobe level is -13.25 dB. Therefore, by thinning using DE, side lobe level is reduced by 3.25 dB. The 'ON' and 'OFF' positions of the array differ with population size and the results are tabulated in Table 2.

Table 2: Performance of thinned array antenna for 20 element linear array

Population size	"ON" and "OFF" positions	SLL_{max} (dB)	FNBW(Deg)
80	10111111111111111011	-16.5	12
100	10111111111111111011	-16.5	12
120	11011111111111111101	-16.5	12
140	10111111111111111011	-16.5	12
160	11011111111111111101	-16.5	12
180	11011111111111111101	-16.5	12
200	11011111111111111101	-16.5	12

In Table 2, investigation for a 20 elements array is done by varying population size. Due to variation of population size SLL, FNBW do change, but 'ON' and 'OFF' positions of the array change with population size.

In a planar array, antennas are arranged in two dimensions, along x-axis and along y-axis. DE is also applied for the thinning of a 4X4 planar antenna array. For a planar array, the cost function is the array factor for planar array. The diagram of planar array is shown in Fig. 7.

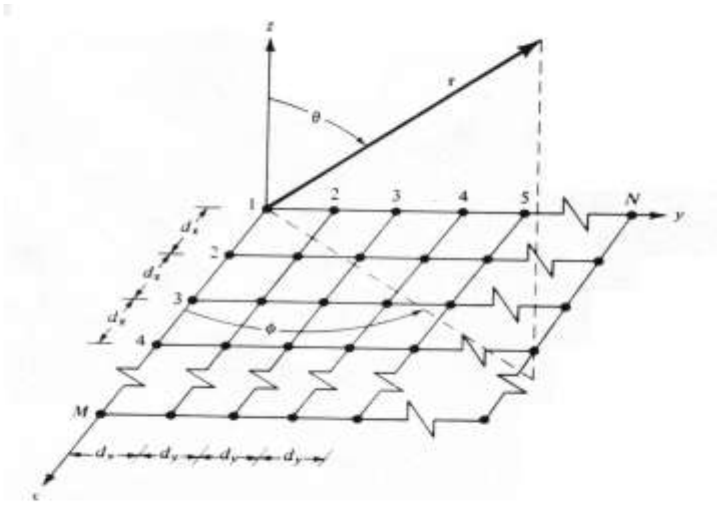


Figure 7: Planar Array Antenna

Here, M antennas are in the x-axis and N antennas in the y-axis with inter-element spacing d_x and d_y respectively. Here, inter-element spacing is d_x=d_y=d=0.5λ. Progressive phase shift along x-axis and y-axis are β_x and β_y respectively. It is assumed that the normalized current distribution in each axis is same but absolute values correspond to a factor $I_{1n}(n=1,\ldots..,N)$.

The array factor (AF) of the entire array for planar array is given by [14, 15]

$$AF=\sum_{n=1}^{N} I_{1n}\left[\sum_{m=1}^{M} I_{m1} e^{j(m-1)(kd_x \sin\theta.\cos\phi+\beta_x)}\right] e^{j(n-1)(kd_y \sin\theta.\cos\phi+\beta_y)} \tag{7}$$

or

$$AF=S_{x_M}.S_{y_N}$$

Where,

$$S_{x_M}=AF_{x1}=\sum_{m=1}^{M} I_{m1} e^{j(m-1)(kd_x \sin\theta.\cos\phi+\beta_x)} \tag{8}$$

$$S_{y_N}=AF_{1y}=\sum_{n=1}^{N} I_{1n} e^{j(n-1)(kd_y \sin\theta.\sin\phi+\beta_y)} \tag{9}$$

In the array factors above:

$$\sin\theta.\cos\phi=\hat{x}.\hat{r}=\cos\gamma_x \tag{10}$$

$$\sin\theta.\sin\phi=\hat{y}.\hat{r}=\cos\gamma_y \tag{11}$$

The AF of a rectangular array is the product of the array factors of the linear arrays in the *x* and *y* directions. For a uniform planar (rectangular) array $I_{m1} = I_{1n} = I_0$, for all *m* and *n*.

$$AF = I_0 \sum_{m=1}^{M} e^{j(m-1)(kd_x \sin\theta.\cos\phi+\beta_x)} \sum_{n=1}^{N} e^{j(n-1)(kd_y \sin\theta.\sin\phi+\beta_y)} \quad (12)$$

The normalized array factor can be obtained as,

$$AF_n(\theta,\phi) = \left\{ \frac{1}{M} \frac{\sin\left(M\frac{\psi_x}{2}\right)}{\sin\left(\frac{\psi_x}{2}\right)} \right\} \left\{ \frac{1}{N} \frac{\sin\left(N\frac{\psi_y}{2}\right)}{\sin\left(\frac{\psi_y}{2}\right)} \right\} \quad (13)$$

Where, $\psi_x = kd_x \sin\theta.\cos\phi + \beta_x$ *(14)*

$$\psi_y = kd_y \sin\theta.\sin\phi + \beta_y \quad (15)$$

For fully populated array, the plot of normalized array factor is shown in Fig. 8.

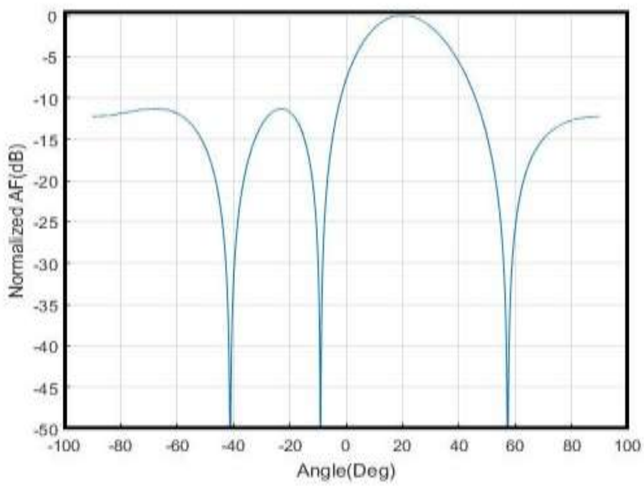


Figure 8: Normalized Array Factor of Fully Populated 4x4 Planar Array

Here, the main beam tilted at 20^0, SLL_{max}=-11.3 dB, FNBW= 58.16^0. Now, for 4x4 Planar array antenna, optimization is done by using differential evolution (DE) algorithm considering population size of 32,48,64,80 and 96 for 50 generations. The DE optimized radiation pattern for 4x4 planar array antenna, with 50 generations for population size of 32 and 64 are shown in Fig. 9 and Fig. 10 respectively.

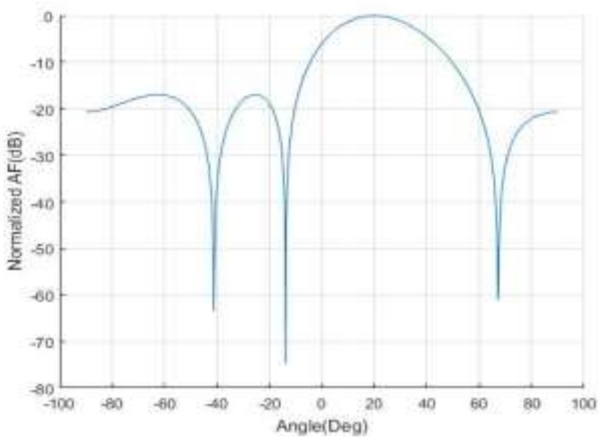


Figure 9: Normalized Array Factor for 4X4 Planar Array with Population Size of 32

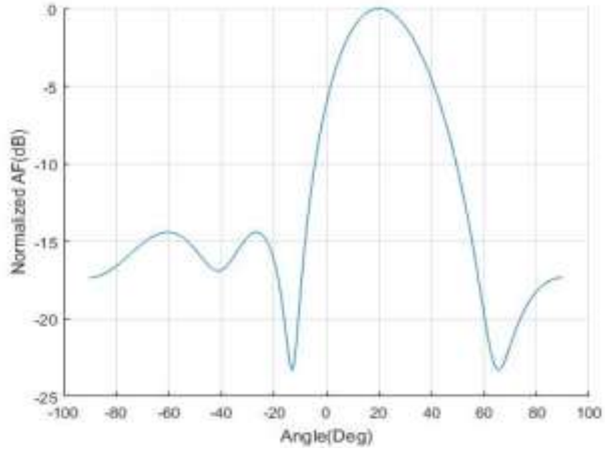
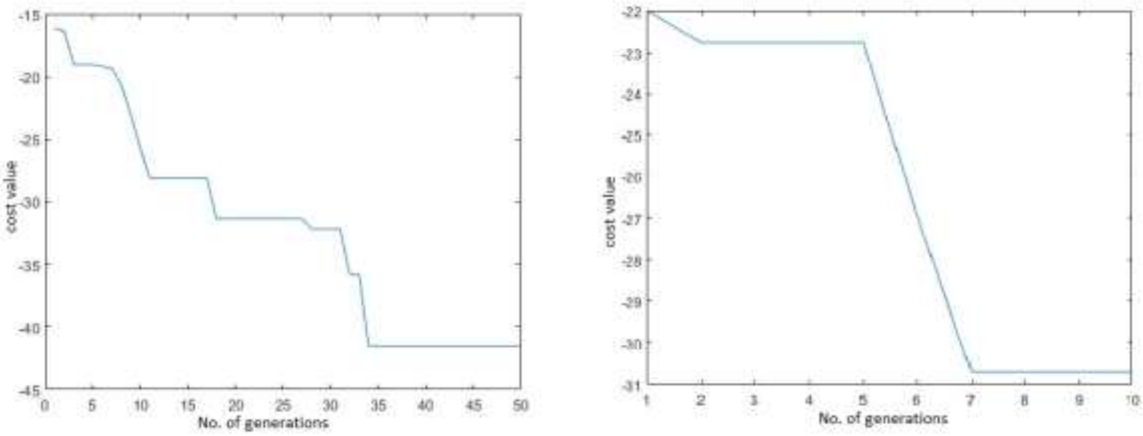


Figure 10: Normalized Array Factor for 4X4 Planar Array with Population Size of 64

The cost values with 50 generations for population size of 32 and 64 are shown in Fig. 11(a) and in Fig. 11(b).



(a) (b)

Figure 11: Cost Value for 50 Generations with (a) Population Size of 32 (b) Population Size of 64

The performance of DE optimization for 4X4 planar thinned array antenna for 50 generations with d=0.5λ is tabulated in Table 3.

Table 3: Performance of 4X4 planar thinned array antenna for 50 generations and d=0.5λ

Population size	"ON" and "OFF" positions	SLL_{max}(dB)	FNBW(Deg)
32	0011110001111110	-16.9	67.5
48	1100011010110000	-14.4	66
64	0110000110010110	-14.4	66
80	1111011011101110	-15.5	74
96	1111101011110110	-13.8	65.2

In Table 3 side lobe levels are reduced compared to fully populated array by 5.6 dB, 3.1 dB, 3.1dB, 4.2dB, 2.5dB while varying the population size 32,48,64,80 and 96 respectively.

4. CONCLUSION

Optimization technique, differential evolution algorithm is used to optimize the side lobe levels of the thinned array antennas with keeping almost same radiation patterns. In direct broadcast satellite system, large number of antennas are used in an array which produces high side lobe levels with appearance of grating lobes in different scan angles. Here, both for linear and planar arrays, array spacing is considered to be 0.5λ to minimize the appearance of grating lobes. Using array thinning, side lobe levels are reduced without any major change in the characteristics of the main beam. For 12-elements array side lobe level is reduced by about 1.8 dB than fully populated array (Table 1). In case of 12-element array, for different population sizes, 'ON' and 'OFF' positions of the array remain same (Table 1). For 20 element linear array, side lobe level reduction of more than 3 dB is achieved (Table 2). But as antenna elements increases, for 20-element array, it is different for different population sizes (Table 2). For 4X4 planar array, maximum reduction of SLL of 5.6 dB is achieved compared to fully populated array (Table 3). Antenna array with almost same radiation pattern, like, fully populated array having less energy consumption and reduced SLL can be designed using DE optimization method for a DBS satellite system.

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