Multiobjective Optimization Using Modified Binary PSO for Reduction of Sidelobe Level of the Thinned Array Antenna

A. Gayatri[1]; M. Surendra Kumar[2]; A.M. Prasad[3]

[1]Department of ECE, GITAM, India.
[1]gayatriallu@gmail.com
[2]Department of ECE, KLR College of Engineering &Technology, India.
[2]principal.klrt@klr.ac.in
[3]Department of ECE, University College of Engineering JNTUK, India.
[3]a_malli65@yahoo.com

Abstract

To design an efficient communication system, controlling the energy present in the side lobes of the far-field pattern is essential with a considered antenna array. This paper discussed one method for synthesizing a thin antenna array for optimizing three objectives simultaneously. They are several active elements, peak SLL and FNBW. All these objectives are in contrast in nature. This multi-objective technique furnishes appreciable flexibility for any specified application. A planar array antenna of 20X10 and 10X10 is synthesized using modified BPSO and in the position updating equation, a modified sigmoid function is used, including spread distance. Numerical results state that MBPSO performs well, and the array antenna of 20X10 with 54% filled aperture (108 elements) produces maximum PSLL and FNBW of -19.28dB and 28^0 in the remaining $\emptyset$ plane, respectively. The pattern representation in the far-field at three cutting planes with low PSLL's of -20dB.Whereas 10X10 planar array antenna with 52% thinning percentage produces the best PSLL of -22.04 dB and -23.44 dB in $\emptyset = 0^0$ & 90^0 principal planes, respectively. The FNBW has observed in two planes is around 31^0. And also achieved a compromised solution of PSLL and FNBW of -19.28 dB and 27^0, respectively.

Key-words: Planar Array, Antenna Array, Thinning, PSO, Sidelobe Level.

Abbreviations: MO-MBPSO, modified binary PSO, FNBW, Peak Side Lobe Level.

1. Introduction

A finite power grant is provided to the engineers to transfer the data or information to the receiver end on the ground in satellite communication. There should be a control on the amount of

radiation in sidelobe when broadcast channels are unsecured, and at operating frequencies, interference due to adjacent regions must be prohibited. Therefore, power should be radiated in the direction in which the receivers are placed. By implementing the introduced approach, antenna performance can be controlled by adaptively switching on or switching off each element of the antenna array [1]. Hence, this procedure radiates the power transmitted to a defined area without using attenuators or high-priced amplifiers. The individual radiating elements can be either switched on or switched off [2]. In thinned arrays, active elements or elements switched on are given uniform amplitude, while inactive or matched loads terminate the switched-off elements. Less cost, weight reduction, less power consumption, and feed network complexity are the advantages of Thinned arrays [3]. Therefore, synthesizing thin arrays can be done to obtain the low Peak SLL and FNBW (first null beam width). The most challenging thing is to synthesize the aperiodic array antennas, and in the last five decades, many thinning techniques have been proposed [4][5]. From the vast number of possible solutions available, finding the optimal thin area for extensive array synthesis is a complex process that cannot be solved using analytical methods.

Several alternative thinning methods were introduced to limit the count of elements used to radiate, which results in the same radiation characteristics as that of the original structure [6,7]. In past years, the usage of global optimization schemes has given noteworthy advancements in the fabrication of thinned antenna arrays. These techniques, like genetic algorithm (GA) [8], simulated annealing [9], ACO - ant colony optimization [10], PSO - particle swarm optimization [11], and Boolean differential evolution (DE) [12], were used earlier in the fabrication of thinned arrays for many applications.

Randy L. Haupt, in 1994[8], worked on the thinned array synthesis on 200 element linear and planar arrays and is optimized using GA. Linear array with a 77% filling rate produces a maximum SLL of -22.09 dB. And

40 x 40 planar array of isotropic point sources with 81% filled square lattice creates a maximum SLL of -17.2 dB.

FNBW and PSLL's pareto front was found out in the past few years by applying various multi-objective optimization schemes to synthesize aperiodic arrays [13-14]. And this optimization procedure denominated NSGA-II[15-17], which is proposed for computing the MSLL, null control, and scanning range to give a perspective on all design choices for linear array antenna with 65degrees, 75degrees with a maximum level of 22 dB.

Jin and Rahmat-Samii [11] in 2007 have utilized PSO[18-19] for performing synthesis on optimization problems with single objective binary values. Single accurate Particle Swarm

Optimisation algorithms such as RPSO and BPSO are proposed to optimize antenna arrays(aperiodic) with the lowest peak SLL of -19.6 dB, with 132 number of elements gets turned on.

Later a hybrid approach[20] was introduced to the synthesizing thinned array of square type. The solution gives a good compromise in terms of both peak SLL and element filling percentages.

The fundamental commitment of this paper is to utilize an modified BPSO to synthesize thinned arrays to obtain low SLL and minimum FNBW. Explanation of MBPSO along with sigmoid limiting transformation S was given in section II. Section III explains Planar array concepts. Objective functions are mentioned in section IV. Solutions related to the objectives are described in section V.

2. Modified Binary PSO (MBPSO)

The MBPSO differs in position updated equation by introducing the new sigmoid function in the position updating equation. The remaining process is similar to the traditional binary PSO. The method of conventional BPSO is available in the literature [11]. The BPSO algorithm is widely used in several engineering problems. But it lacks the local search capabilities with good solution accuracy.

The velocity equation can be written as

$$V_{i,j}^{g+1} = \omega.V_{i,j}^{g} + C.r.(p_{gbest} - X_{i,j}^{g}) \tag{1}$$

Where i, j, g represents particle index in the swarm, particle position index, generation number. Where i^{th} particle velocity represented with $V_{i,j}^{g}$. C defines acceleration coefficient, inertia weight represented with ω, finally random number $r \in [0, 1]$.

The updated velocity of jth bit in i^{th} particle defines the possible position of a particle, which is in the range of 0 to 1. This value can be implemented based on an intermediate variable denoted with sigmoid limiting transformation S.

The sigmoid limiting transfer function for traditional BPSO is modeled as

$$S(V_{i,j}^{g+1}) = \begin{cases} \frac{1}{1+e^{Vmax}} \to 0, & V_{i,j}^{g+1} = -V_{max} \to \infty \\ \frac{1}{2}, & V_{i,j}^{g+1} = 0 \\ \frac{1}{1+e^{-Vmax}} \to 1, & V_{i,j}^{g+1} = V_{max} \to \infty \end{cases} \tag{2}$$

But this function leads to a low convergence rate, as mentioned in the literature. And also, it has been said that BPSO lacks local search capabilities. To enhance those capabilities, we have introduced the standard Gaussian spread number in the sigmoid function. It allows lower changes around the mean position of the parent particle.

$$S\left(V_{i,j}^{g+1}\right) = \begin{cases} \dfrac{1}{1+e^{Vmax+D_i^k}} \to 0, & V_{i,j}^{g+1} = -V_{max} \to \infty \\ \dfrac{1}{2}, & V_{i,j}^{g+1} = 0 \\ \dfrac{1}{1+e^{-Vmax-D_i^k}} \to 1, & V_{i,j}^{g+1} = V_{max} \to \infty \end{cases} \qquad (3)$$

The sigmoid limiting transformation with the domain of $[-V_{max}, V_{max}]$ having the span of $\left[1/1 + e^{Vmax+D_i^k}, 1/1 + e^{-Vmax-D_i^k}\right]$, subset of $[0, 1]$. Spread distance generated by the standard Gaussian spread number $G(0,\sigma^2)$ is represented by $D_i^k \Sigma$ is the standard deviation.

Where 'X' updated for the jth bit in the ith particle as

$$X_{i,j}^{g+1} = \begin{cases} One \ if \ r < S(V_{i,j}^{g+1}) \\ 0 \ \ if \ r \geq S(V_{i,j}^{g+1}) \end{cases} \qquad (4)$$

3. Planar Array

The azimuth plane considers the uniform planar array of 2N X 2M elements, as shown in figure1. The array factor (AF) of the symmetric array is given by

$$AF(I,\theta) = 2 \sum_{n=1}^{N} I_n \cos[\pi.(n-0.5).\cos(\theta)] \qquad (5)$$

Where I_n is n^{th} element excitation amplitude, θ is azimuth angle and $I = I_n$, n=1, 2, …N. Element spacing can consider to be 0.5λ. In thinned array, active element status ON considered as I_n=1, OFF element status considered as $I_n = 0$. Figure 3 shows the $2N \times 2M$ elements of the planar array and array factor given by

$$AF(I,\theta,\phi) = 4 * \sum_{n=1}^{N} \sum_{m=1}^{M} I_{nm} . \cos[\pi.(n-0.5).U] . \cos[\pi.(m-0.5).V] \qquad (6)$$

Here $U \ is \ \sin(\theta)\cos(\phi), V \ is \ \sin(\theta)\ sin(\phi)$,

$I_{nm} = (n,m)^{th}$ element amplitude excitation.

If $(m, n)^{th}$ element of the thinned array is ON condition, then $I_{mn} = 1$ otherwise element to be OFF if $I_{mn} = 0$.
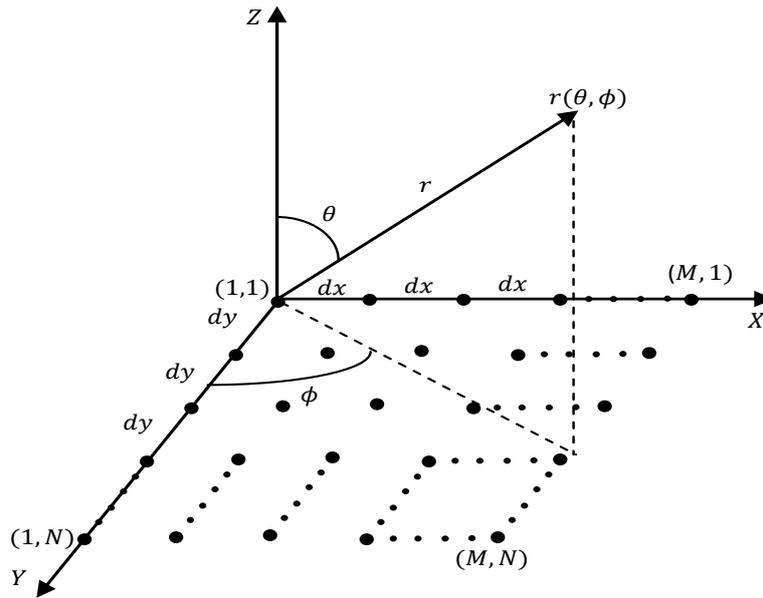
4. Problem Statement

The array factor of a planar array, where the elements are isotropic as, is given by

The planar array with isoropic elements depicted in Fig.1 and the array factor can be given as

$$AF(\theta,\phi) = \sum_{n=1}^{N} \sum_{m=1}^{M} I_{mn} e^{j(m-1)(kd_x \sin\theta \cos\phi + \beta_x)} \ e^{j(n-1)(kd_y \sin\theta \sin\phi + \beta_y)} \qquad (7)$$

Fig. 1 - Uniformly Spaced Planar Array

$$\beta_x = -kd_x \sin\theta_s * \cos\phi_s \ \ and \ \ \beta_y = -kd_y \sin\theta_s * \sin\phi_s$$

where β_x & β_y - Element to element Progressive phase shifts

k - wave number

θ_s & ϕ_s - elevated scan angles and

d_x and d_y - adjacent elements spacing

I_{mn} - (m, n) element amplitude excitation.

If (m, n)th element of the thinned array is ON condition, then $I_{mn} = 1$ otherwise $I_{mn} = 0$.

The essential content of this paper is to plan an ideal planar array antenna with simultaneous minimization of the peak SLL and FNBW. This was defined with two objective functions as follows,

   i.   Reduction in the normalized peak SLL in the entire $\emptyset$ plane of 0^0 to 90^0

$$f_1 = \max\left(\left|\frac{\text{AF}(\theta,\emptyset)}{\text{AF}_{\max}}\right|\right) \tag{8}$$

where $\text{AF}_{\max}$ - peak magnitude of primary beam and

       f_1 - fitness over the region of θ and $\emptyset$ excludes the major beam.

  ii. ii. Reduction in FNBW

$$f_2 = \max(2\theta_{fn}) \tag{9}$$

where θ_{fn} represents the first null position.

5. Numerical Illustrations

A 10X10 isotropic planar antenna array equispaced at $0.5\lambda_0$ is designed and synthesized by using the proposed MO-MBPSO by the trading of PSLL and FNBW parameters. Two principal planes $\emptyset = 0^0$ & 90^0 have been considered Planar array with 100 element population evaluated for 500 generations in the optimization. The array antenna radiation pattern is computed at azimuth region of -90^0 to 90^0 in two principal planes of $\emptyset = 0^0$ & 90^0 plane of 0^0 to 90^0 . The Pareto front by the trading of PSLL and FNBW is shown in figure 2. We have obtained several optimal compromised results. The MO-MBPSO produces a Pareto optimal set of 28 Pareto optimal arrays.

b. Case 1: Low PSLL design/solution from the Pareto front

We have considered the solution with low PSLL from the Pareto front. The PSLL value represents in the Pareto front is -22.04 dB. The respective thinned antenna design for that solution is given in table 1. Where '1' represents turned ON, and '0' represents turned 'OFF.' Because of the symmetry of the planar array, we have shown the quarter geometry of the planar array. Total 52 elements are turned off in a 10X10 planar array. Forty-eight elements are turned ON. The thinning percentage is 52%. The produced best PSLL is -22.04 dB and -23.44 dB in $\emptyset = 0^0$ & 90^0 principal planes, respectively. The FNBW has observed in two planes is around 31^0. Figure 3 represents the radiation pattern of the design.

Table 1 - Thinned Geometry of the MO-BPSO with Low PSLL

1	1	0	0	1
1	1	1	0	0
1	0	1	1	0
0	0	1	0	0
1	1	0	0	0

b. Case 2: Compromised Design/Solution from the Pareto Front

We have considered the compromised solution of PSLL and FNBW as shown in the Pareto front. The PSLL is observed as -19.28 dB with an FNBW of approximately 27^0. The respective thinned antenna design for that solution is given in table 2. Because of the symmetry of the planar array, we have shown the quarter geometry of the planar array. The percentage of thinning is 44%. Total 56

elements are turned on. The obtained PSLL is -22.04 dB and -23.44 dB in $\emptyset = 0^0$ & 90^0 principal planes, respectively, its radiation pattern shown in figure 4.

Fig. 2 - Pareto Front by Trading off PSLL and FNBW Using MO-MBPSO at $\emptyset = 0^0$ & 90^0 Planes of 10X10 Planar Antenna Array
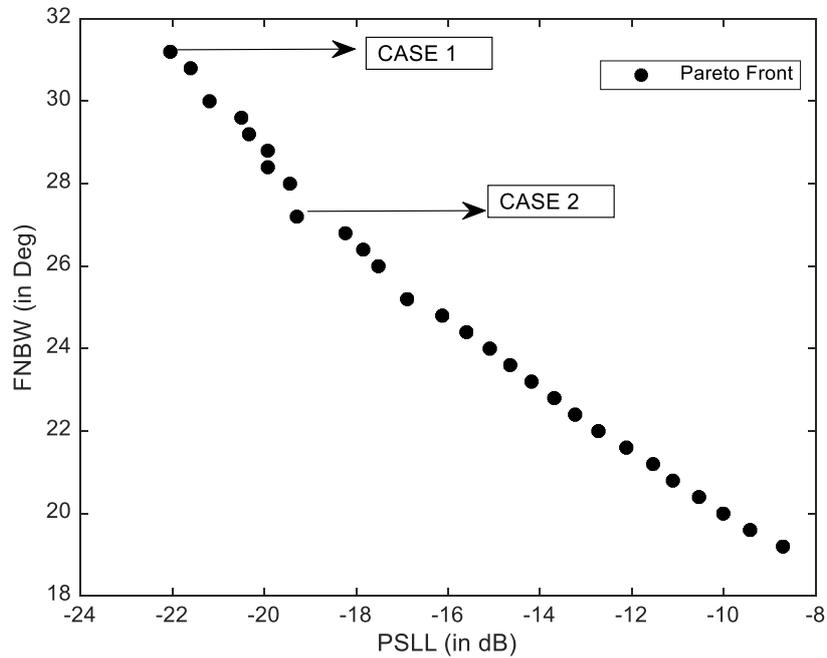

Fig. 3 - MO-MBPSO based Radiation Pattern for Synthesized Antenna Array with low PSLL at $\emptyset = 0^0$ & 90^0 Planes of 10X10 Planar Antenna Array
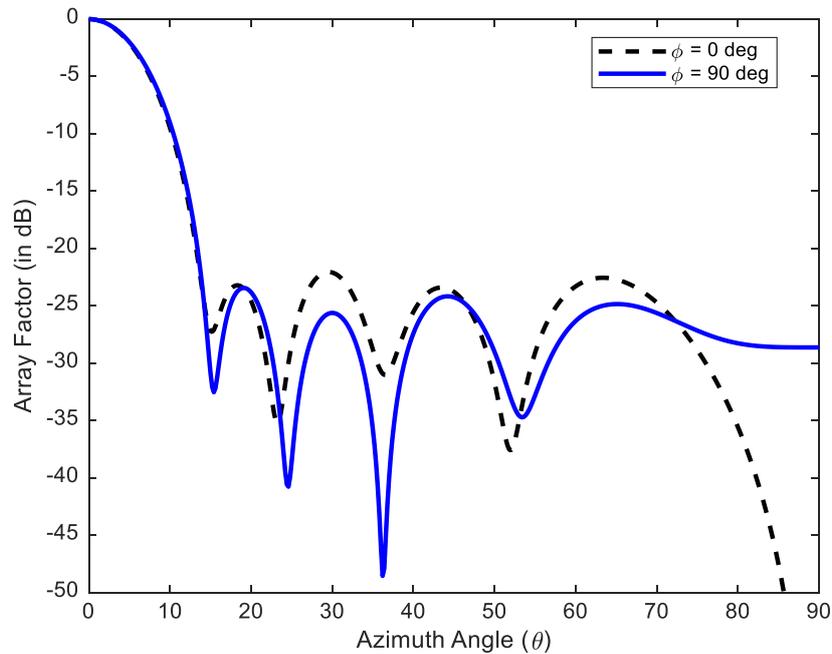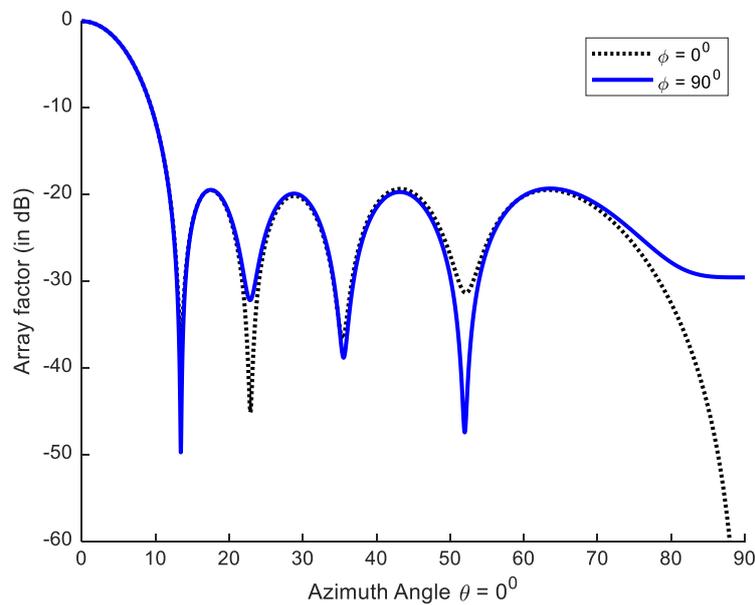
Table 2 - Thinned Geometry of the MO-BPSO with the Compromised Solution of PSLL and FNBW

1	0	0	0	1
1	1	1	1	0
1	0	1	1	1
0	0	1	0	1
1	1	0	0	0

Fig. 4 - MO-MBPSO based Radiation Pattern for Synthesized Antenna Array with a Compromised Solution of PSLL and FNBW at $\emptyset = 0^0$ & 90^0 Planes of 10X10 Planar Antenna Array

Planar array antenna of 20X10 isotropic elements with spacing $0.5\lambda_0$ considered. The optimization was done for 100 planar arrays for 500 generations with crossover probability 0.9 and mutation probability 0.1. Here analysis done for 0.9 crossover and 0.1 mutation probability. The radiation plot is figured out at 1801 angles from -90^0 to 90^0 in the azimuth region in the entire $\emptyset$ plane of 0^0 to 90^0 .The MO-MBPSO brings out an optimal Pareto set for 80 arrays, and its Pareto front is shown in Fig.5.

From Fig.5, one of the best solutions was scrutinized for the review, and the results are analyzed with the literature [8]. The arrangement of this planar array and its radiation plot in the far-field are shown in Fig.6 and Fig.7, respectively. The 54% filled elements (108 elements) generate maximum Peak SLL and FNBW of -19.28dB and 28^0 in the entire $\emptyset$ plane, respectively. Fig.8 describes radiation in the far-field region with low peak SLL's of -20dB at three cutting planes. Using single objective optimization of GA [8], a related planar array of 20 x 10 were designed previously and obtained the peak SLL as -15.16dB and FNBW of 47^0 in the entire $\emptyset$ plane. The results obtained in the proposed method in this paper are better than the previously proposed method.

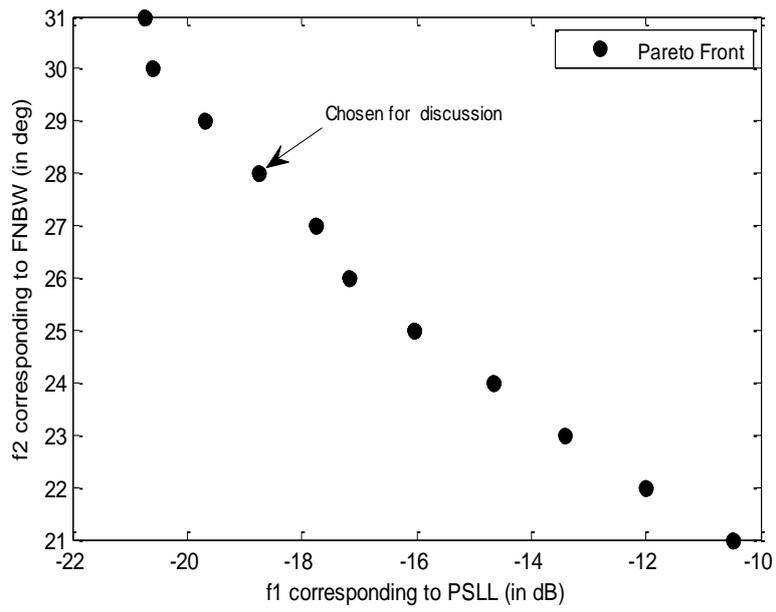Fig. 5 - Pareto Front for Trading-off PSLL and FNBW MO-MBPSO

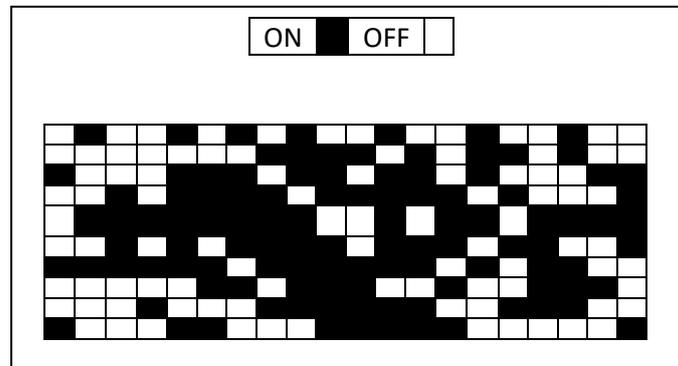Fig. 6 - MO-MBPSO based 20 × 10 Planar Thinned Array Geometry

Fig. 7 - MO-MBPSO based Farfield Region Radiation Pattern in Ø Region
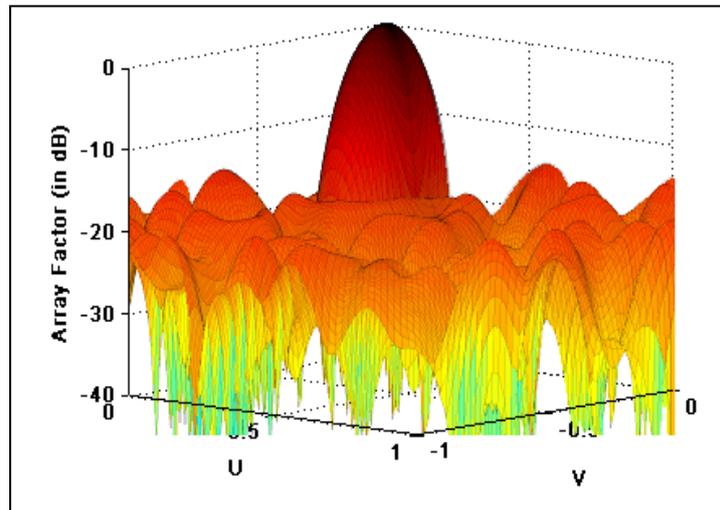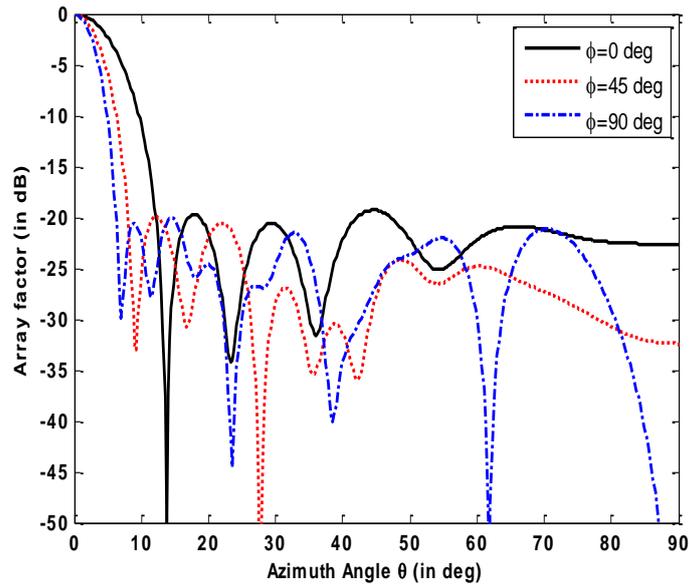
Fig. 8 - Three Cutting Planes Radiation Pattern for far fild Region

6. Conclusion

In this report, the MBPSO was successfully applied in the synthesis of thinned antenna array pattern. The use of Sigmoid limiting transformation along with standard gaussian spread distance has improved the accuracy and the convergence rate in the array design. As per the results, the synthesis of 20X10 planar array with 54% filled aperture there is a notable decrement observed in the peak SLL and FNBW of -19.28dB and 28^0 in the entire $\emptyset$ plane, respectively. PSLL of -20dB was also observed at three cutting planes of the radiation plot in the far-field region. And another planar array 10X10 with 52% thinning percentage produces the best PSLL of -22.04 dB and -23.44 dB in $\emptyset = 0^0$ & 90^0 principal planes, respectively. The FNBW has observed in two planes is around 31^0. And also achieved a compromised solution of PSLL and FNBW of -19.28 dB and 27^0, respectively. As per the observation, sidelobe levels are greatly minimized with larger beam widths. This type of design will enhance the accuracy of the satellite communication reducing the interference.

References

Yong-Qing Zou, Hong-Tao Zhang, Wei Wang, and Mou-Ping Jin, *"Dual Circularly Polarized Waveguide Antenna Array for Satellite Communications in the X Band,"*.

King D.D., Packard R.F., Thomas R.K. Unequally-spaced broadband antenna arrays', *IRE Trans. Antennas Propag.,* 1960, 8(7), 380– 384.

Ishimaru A., Chen Y.S. Thinning and broadbanding antenna arrays by unequal spacings. *IEEE Trans. Antennas Propag.,* 1965, 13(1), 34– 42.

Leeper D.G., *Thinned periodic antenna arrays with improved peak sidelobe level control.* U.S. patent 4071848, January 1978.

Ill P.M.N. Keizer, "Large Planar Array Thinning Using Iterative FFT Techniques," *IEEE Transactions on Antennas and Propagation, 5*7(10), 2009.

Oliveri, G., M. Donelli, and A. Massa, "Linear array thinning exploiting almost difference sets," *IEEE Transactions on Antennas and Propagation, 5*7, 3800–3812, 2009.

Oliveri, G., L. Manica, and A. Massa, "ADS-based guidelines for thinned planar arrays," IEEE Transactions on Antennas and Propagation, Vol. 58, 1935–1948, 2010.

R.L. Haupt, "Thinned arrays using genetic algorithms," *IEEE Trans. Antennas Propag*., vol. 42, no. 7, pp. 993–999, Jul. 1994.

Vittorio Murino, Andrea Trucco, and Carlo S. Regazzoni, "Synthesis of Unequally Spaced Arrays by Simulated Annealing," *IEEE Transactions on Signal Processing, 4*4(1), 1996.

O. Quevedo-Teruel and E. Rajo-Iglesias, "Ant Colony Optimization in Thinned Array Synthesis with Minimum Sidelobe Level," *IEEE Antennas and Wireless Propag. Lett*., vol.5, pp. 349-352, May 2006.

N. Jin and Y. Rahmat-Samii, "Advances in Particle Swarm Optimization for Antenna Designs: Real-Number, Binary, Single-Objective and Multiobjective Implementations," *IEEE Trans. Antennas Propag*., 55(3), 556-567, 2007.

L. Zhang, Y.C. Jiao, Z.B. Weng and F.S. Zhang, "Design of planar thinned arrays using a Boolean differential evolution algorithm," *IET Microwaves, Antennas &Propag.*, 4, 2172-2178, 2010.

Joshua S. Petko and Douglas H. Werner, "Pareto Optimization of Thinned Planar Arrays with Elliptical Mainbeams and Low Sidelobe Levels," *IEEE Transactions on Antennas and Propagation, 5*9(5), 2011.

Meijer C.A, "Simulated annealing in the design of thinned arrays having low sidelobe levels," in *Proc. Symposium on communications and signal processing,* 1998, 361-366.

Tokan F and Gunes F, "Pareto Optimal Synthesis of the Linear Array Geometry for minimum Sidelobe Level and Null Control During Beam Scanning," *International Journal of RF and Microwave Computer- aided Engineering*, 20, 557-566, 2010.

Kalyanmoy Deb, Amrit Pratap, Sammer Agarwal and T. Meyarivan, "A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II," *IEEE Transactions on Evolutionary Computation, 6*(2), 2002.

M.A. Panduro, D.H. Covarrubias, C.A. Brizuela and F.R. Marante, "A Multiobjective Approach in the Linear Antenna Array Design," *AEU-Int. Journal of Elec. and Communications*, 59(4), 205 – 212, 2005.

Aseel abdul-karim qasim, Adheed hassan sallomi, "Optimisation of Adaptive Antenna Array Performance Using Particle Swarm Algorithm," *2019 First International Conference of Computer and Applied Sciences (CAS),* 978-1-7281-4048-3.

W.B. Wang, Q.Y. Feng and D. Liu, "Synthesis of Thinned Linear and Planar Antenna Arrays using Binary PSO Algorithm," *PIER, 127,* 371-387, 2012.

Massimo Donelli, Anna Martini and Andrea Massa, "A hybrid approach based on PSO and Hadamard difference sets for the synthesis of square thinned arrays," *IEEE Antennas and Wireless Propag. Lett*., 57(8), 2491-2495, 2009.