Synthesis of Aperiodic Antenna Array with Minimum Sidelobe Levels Using Modified Differential Evolution

Prasad Rao Rayavarapu, Dharma Raj Cheruku, Srinu Budumuru

Abstract*: *The Antenna array is an essential part in the wireless communication systems. Design of a low sidelobe level antenna arrays crucial in design of the efficient antenna array system. In this paper, the synthesis of an aperiodic antenna array synthesis for minimal sidelobe levels has been discussed. A novel modified differential evolution (MDE) is proposed for controlling the sidelobe energy by optimizing the antenna element positions. Different mutation schemes have been adopted in developing the MDE algorithm. The steps involved in the development of MDE and problem formulation for the minimizing sidelobe levels is discussed clearly. Various popular synthesis examples have been considered and synthesized. Both small and larger arrays have considered in this paper. The obtained proposed MDE array designs are compared with the traditional differential evolutions (DE) and particle swarm optimization methods (PSO). Numerical results demonstrated that the proposed MDE method outperforms the traditional PSO and DE in terms of producing low PSLL and convergence rate.

Index Terms*: *Antenna array, Sidelobe level, Differential Evolution, Particle swarm optimization, PSLL, Convergence rate.

I. INTRODUCTION

Antenna is a vital part of the wireless communication systems. Now a days the demand of the performance of the communication system has grown rapidly. But the performance of the single antenna is limited to produce high directive electronic steerable beams. Electronically steerable beams will achieve through the concept of the array geometry. Antenna array [1] is an assembly of several radiating antenna elements in a proper electrical and geometrical configuration. It has capable of achieving high directive, narrow beams, electronically steerable beams, cancelling the interference from undesired directions etc. Because of these advantages, antennas have been widely used in radar, mobile, satellite and ground communications. But, the main source of problem in communication systems with antenna arrays are the pattern sidelobes. In transmission mode, these excessive sidelobes wastes energy in undesired directions, whereas permits unwanted energy through undesired directions to the own system in receiving mode. It may cause interference to other and as well as own communication systems. It is required to design an antenna array system with low pattern sidelobes. Also, in some applications, the far field radiation patter possesses nulls in some desired directions. So, controlling the sidelobe energy is essential in order to design an efficient communication system The radiation pattern of antenna array(suppressing the strength of peak sidelobe level (PSLL) and placing the nulls in unwanted directions) for far field highly influenced by altering the amplitude, excitation of phase and position of individual elements. Altering the amplitude and phase excitations leads to feeding complexity. Another way of achieving the desired radiation characteristics is through the optimization of the element positions (Aperiodic antenna array synthesis). The researchers have been considered the aperiodic antenna array synthesis as an optimization problem. Several traditional methods and evolutionary methods have been applied successfully to the aperiodic antenna synthesis problems to suppress the PSLL while maintaining proper beam width (BW). Several evolutionary algorithms such as genetic algorithm (GA) [2-8], particle swarm optimization (PSO) [9-12], differential evolution (DE) [13-16] and cat swarm optimization (CSO) [17], ant colony optimization [18] and invasive weed optimization [19-20] etc. have been successfully applied to aperiodic antenna array synthesis problems. GA, DE and PSO have been widely employed for aperiodic array synthesis problems. But DE has its own disadvantages. It has shown low convergence properties and low solution accuracy while solving complex antenna array synthesis problems.In this paper, we have proposed the modified differential evolution (MDE) to the aperiodic antenna array synthesis problems. The mutation operation DE/rand-to-best/2 [21-22] is considered. Also in order to enhance the exploration and local search capabilities, we have adopted two mechanisms in the proposed MDE. The same has been discussed in Section II. The brief organization of the paper is as follows. The detail description of the MDE algorithm is discussed in Section II. In Section III, the topology of the linear antenna array is briefly discussed. The problem formulation for minimizingthe PSLL is discussed in Section IV.Design synthesis examples have been illustrated in Section V. Finally the conclusions are discussed in Section VI.

II. MODIFIED DIFFERENTIAL EVALUATION (MDE)

MDE also works with mutation, crossover and selection. We have used DE/rand-to-best/2 mutation operator in the mutation process. The same has been explained briefly as follows.

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A. *Initialization*

In initialization, finite number of solutions, called number of population (NP) is created randomly from the solution space. Each one represents one possible solution of the problem.

B. *Mutation*

The next process in the algorithm is the mutation in which a mutant vector is created for each solution vector in the population. Thus the size of the mutant matrix will be same as the population matrix. The procedure for creating mutant vector may be of mainly four types. Differential algorithm can be represented in different variants. A user defined factor called the weight factor or scale factor (SF) is to be given which is used in the evaluation of the mutant vector.
Many varieties of mutation operators exist in the literature. In this paper, the mutation variant DE/rand-to-best/2 has been considered.

$$M_i = x_{r_1} + SF * (x_{best} - x_{r_1}) + SF * (x_{r_2} - x_{r_3}) + SF * (x_{r_4} - x_{r_5}) \quad (1)$$

Where x is a set of the NP number of parent solutions of that generation. The $x_{r_1}, x_{r_2}, x_{r_3}, x_{r_4}$ and x_{r_5} are random numbers generated solution vectors from the parent set of solutions$x$. At the starting of DE evolutionary process, minimum crossover ratio (CR) and maximum SF are good to explore more in the search space, whereas maximum CR and minimum SF are good for local search in the final evolutionary process. The equations for SF and CR are given below.

$$SF(g) = SF_{max}\exp(c.g), c = \frac{ln\left(\frac{SF_{min}}{SF_{max}}\right)}{Maxgen} \quad (2)$$

$$CR(g) = CR_{min} + (CR_{max} - CR_{min}) * \frac{g}{MaxGen} \quad (3)$$

Where $g$the current generation of the evolutionary process is, $MaxGen$ is the number of generations in the evolutionary process. $CR_{min} and CR_{max}$ are the minimum and maximum adjusting rate of CR, $SF_{min} and SF_{max}$ are the minimum and maximum adjusting rate of SF.

C. *Crossover*

The cross over operation produces vectors called trial vectors. These vectors are produced by combination of the target vectors or the initial solution vectors and the mutated vectors. For this operation, a user defined parameter called Crossover Ratio (CR) is defined. The value of the cross over ratio should be set to a value as given in equation 3. The first target vector and the first mutated vector are considered for operation If the random number is greater than the CR the value of the variable is to be copied from the target vector for creating a trial vector. If the random number is less than or equal to the CR value then the variable is to be copied from the mutated vector. Thus the trail vector is formed as,

$$U_i = \begin{cases} M_i & if\ random\ number(j) <= CR \\ X_i & if\ random\ number(j) > CR \end{cases} \quad \begin{matrix} \text{for i = 1,2,3 ....NP} \\ and \text{ j = 1,2.....Nvar} \end{matrix} \quad (4)$$

After this operation we will get NP number of trial vectors. Then all the target vectors and the trial vectors will undergo selection process.

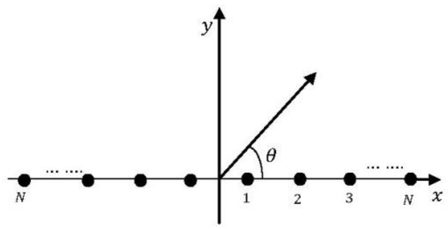
D. *Selection*

In this process a selection between the parent solution $x$and the trail vector $(U_i)$is done to get the population for new generation. For each value of i = 1, 2, 3...NP the objective function values for x_i and U_i are compared. The vector having the index best is the solution having the best value of objective function. If the problem is a maximization problem then the solution having the highest value of objective function is to be chosen. If it is a minimization problem then the solution having the minimum value for the objective function is chosen as the best one. The better or minimum valued vector will go to the next generation. Thus we are getting better solutions in the next generation.

The steps from 'b' to 'd'are repeated in each generation. After certain generations all the solutions will have the best solution. The generation loop is stopped on reaching predefined tolerance. The flow chart of the MDE is given Figure 1.

III. BASICS OF LINEAR ANTENNA ARRAY

The symmetrically placed 2N element linear antenna array is considered for the synthesis and illustrated in Figure 2.



Figure

1.Illustration of 2N-element linear antenna array [1].

The array factor of the linear antenna array [1] is

$$AF(\theta) = \sum_{n=1}^{2N} I_n \cos[kx_n \cos(\theta) + \varphi_n] \quad (5)$$

Where$k = 2\pi/\lambda, I_n, \varphi_n, and\ x_n$respectively.

For the uniform amplitude and phases,

$$AF(\theta) = \sum_{n=1}^{2N} \cos[kx_n \cos(\theta)] (6)$$

$$AF(\theta) = \sum_{n=1}^{2N} \cos[kx_n \cos(\theta)]$$

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IV. PROBLEM FORMULATION: MINIMIZATION OF PSLL

The main objective of this paper is to minimizing the PSLL in angular region of the sidelobe region by optimizing the positions between the antenna elements i.e., by varyingx_n. To achieve this, the fitness function is mathematically formulated as

$$Fitness = max\left(\frac{AF(\theta)}{AF_{max}}\right) \quad (7)$$

Where $AF_{max}$is the peak of the main beam and the fitness is valid in the side lobe region of θ.

Numerical illustrations:

In this paper, we have synthesizedsmaller and larger array problems to show the exploration and convergence capabilities of the proposed MDE. A 32 element and 64 element linear antenna arrays have been considered.For these two examples, the proposed MDE has been employed to minimizing the sidelobe levels by optimizing the position between the antenna elements along with the traditional DE and PSO. The initial parameters for the aforementioned algorithms are given in Table 1. These are algorithms are governed by the stochastic principles, so it is necessary to obtain the mean performance of these algorithms. To obtain the average performance, the algorithms are performed for 50 trails. The angular region in array factor is sampled at 0.2^0 during the synthesizing process. The average results has been noted. All the simulations are performed using MATLAB. However, to avoid the mutual coupling effects, the minimum inter element spacing is maintained in the optimizing process as 0.5λ.

a. 32-element linear array:

The first example illustrates the 32 element array synthesis problem for minimum PSLL. The PSLL and BW of the uniformly illuminated 32-element periodic array is 13.23 dB and 7.2^0 respectively. MDE, PSO and DE algorithms have been applied to minimize the PSLL by optimizing the positions between the elements. Table 2 shows the optimized element positions obtained by using MDE, PSO and DE algorithms in suppressing PSLL. The radiation pattern of the optimized MDE, PSO and DE algorithms radiation patterns is shown in Figure 3. For clear understanding, the zoomed view of the Figure 3 is showin Figure 4. The corresponding array performance of these arrays is listed in Table 3. It can be seen from Figure 3 and Table 3 that, the proposed MDE approach produced better PSLL compared to traditional PSO and DE. MDE produced PSLL of -22.65 dB, whereas PSO and DE produces -20.52 dB and -19.41 dB respectively. MDE approached array produces-2.13 dB and 3.24 dB low PSLL compared PSO and DE respectively. The average PSLL obtained using MDE, PSO and DE are -22.38 dB, -20.21 dB and -19.35 dB respectively. Apart from the PSLL values, the convergence properties is another parameter to evaluate the performance of the algorithms. The convergence properties of MDE algorithm while synthesizing 32 element array along with PSO and DE algorithms is shown in Figure 5. It can be seen from Figure 5 that, the MDE outperforms in terms of fast convergence rate and acquiring low fitness values compared to traditional algorithms.

Table 2. Optimized positions of a 32 element linear array using MDE, PSO and DE.

Array Type	Algorithm	Optimized Positions (Because of the symmetry of the array, half of the positions have provided)
32 Element	Periodic Array	±0.2500 ±0.7500 ±1.2500±1.7500 ±2.2500 ±2.7500 ±3.2500 ±3.7500 ±4.2500 ±4.7500 ±5.2500 ±5.7500 ±6.2500 ±6.7500 ±7.2500 ±7.7500
	MDE	±0.2500 ±0.7500 ±1.2500 ±1.7500 ±2.2500 ±2.7500 ±3.3005 ±3.8006 ±4.5287 ±5.0909 ±5.6856 ±6.4971 ±7.3127 ±8.2421 ±9.2796 ±10.0315
	PSO	±0.2500 ±0.7500 ±1.2500 ±1.7672 ±2.2993 ±2.8573 ±3.4734 ±4.0792 ±4.7182 ±5.3062 ±5.9386 ±6.8800 ±7.5930 ±8.7124 ±9.4989 ±10.2500
	DE	±0.2500 ±0.7500 ±1.2500 ±1.7500 ±2.2500 ±2.7500 ±3.2500 ±3.7500 ±4.2500 ±4.7500 ±5.2500 ±5.7681 ±6.4658 ±7.3064 ±9.0662 ±9.8025

Table 1. Initial parameters for MDE, DE and PSO algorithms

MDE		DE		PSO	
Parameter	Value	Parameter	Value	Parameter	Values
Population	50	Population	50	Number of particles	50
Number of generations	500	Number of generations	500	Number of generations	500
SFmin	0.6	SF	0.9	c_1	2
SFmax	0.5	CR	0.5	c_2	2
CRmax	0.9	-	-	ω	0.9
CRmin	0.1	-	-	-	-

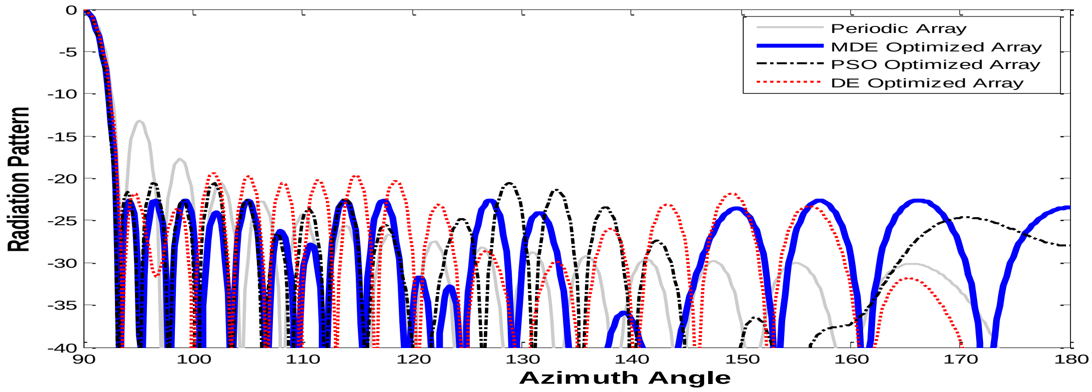

Figure 2. Radiation pattern of a 32 element linear array using MDE, PSO and DE along with uniformly illuminated periodic 32 element linear array.*(Due to symmetry of the array, half of the radiation pattern is provided)*

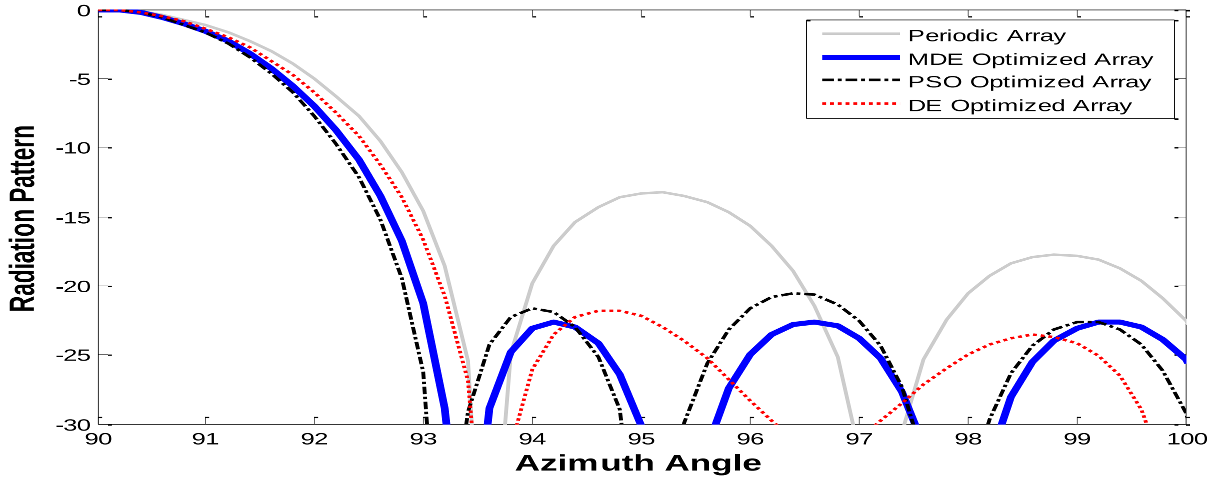

Figure 3. Zoomed view of the angular region 90^0 to 100^0 in Figure1.

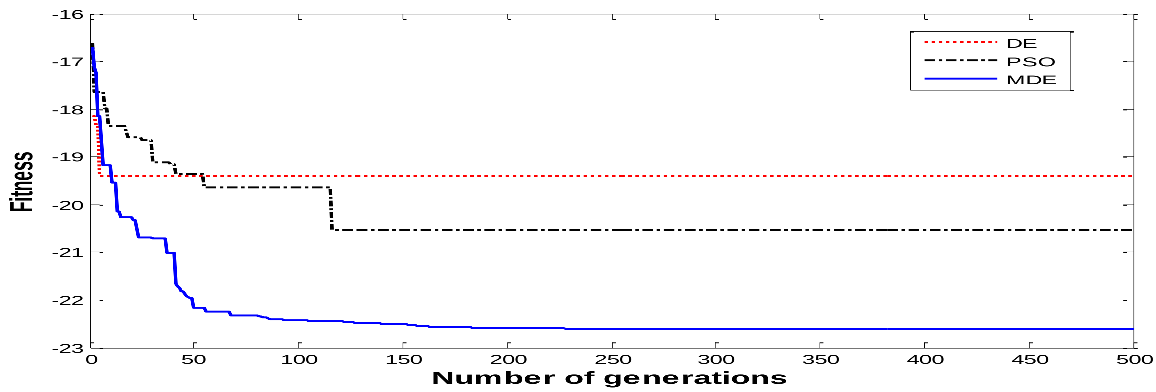

Figure 4. The evolution of PSLL over the generations in synthesizing 32 element linear array using MDE, PDO and DE.

b. 64-element linear array

The second example illustrates the 64-element array synthesis problem for minimum PSLL. The PSLL and BW of the uniformly illuminated 64-element periodic array is 13.23 dB and 3.6^0 respectively. The obtained element positions using MDE, PSO and DE are listed in Table 4. The obtained MDE, PSO and DE array patterns are shown in Figure6. The magnified version of the Figure 5 is shown in Figure 7. The array performance in terms of PSLL and FNBW is given in Table 5. It is seen from Figure 6 and Table 5 that, MDE produces lower PSLL compared to PSO and DE. MDE achieved PSLL of -22.87 dB, PSO achieved PSLL of -19.18 dB and DE achieved PSLL of -19.13 dB.MDE produces 3.69 dB and 3.74 dB low PSLL compared to PSO and DE respectively.

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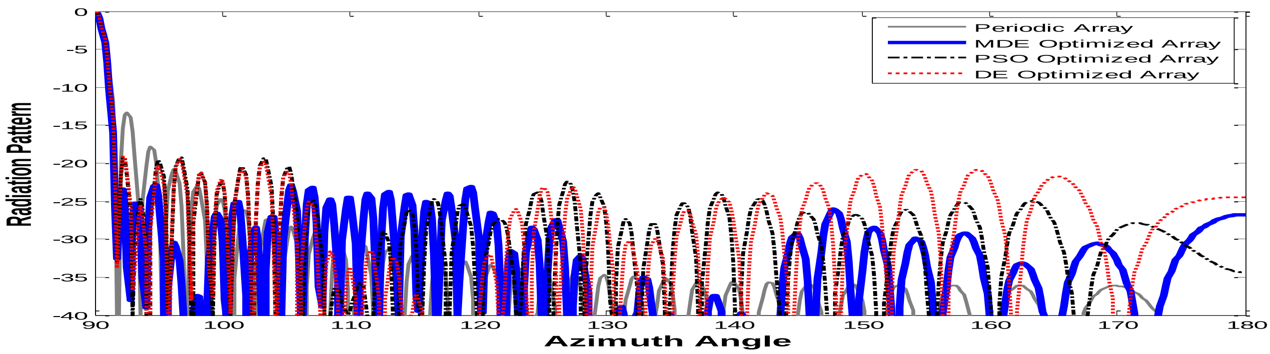

Figure 5. Radiation pattern of a 64 element linear array using MDE, PSO and DE along with uniformly illuminated periodic 64 element linear array. *(Due to symmetry of the array, half of the radiation pattern is provided* The convergence plots using MDE, PSO and DE is shown in Figure 8. It can be seen from Figure 8 that, MDE outperforms traditional PSO and DE in terms of convergence rate. Finally, it can be seen from 32 and 64 element synthesis results that, the proposed MDE algorithm outperforms the traditional algorithms in terms of solution accuracy (low PSLL). Also, MDE requires less number of generations to reaching the optimal solutions compared to traditional algorithms.

Table 4. Optimized positions of a 64 element linear array using MDE, PSO and DE.

Array Type	Algorithm	Optimized Positions (Since linear antenna array is symmetric, so half of the positions are given below)
64 Element	Periodic Array	±0.2500 ±0.7500 ±1.2500±1.7500 ±2.2500 ±2.7500 ±3.2500 ±3.7500±4.2500 ±4.7500 ±5.2500 ±5.7500 ±6.2500 ±6.7500 ±7.2500 ±7.7500 ±8.25 ±8.75 ±9.25 ±9.75 ±10.25 ±10.75 ±11.25 ±11.75 ±12.25 ±12.75±13.25 ±13.75 ±14.25 ±14.75±15.25±15.75
	MDE	±0.2500 ±0.7500 ±1.2500 ±1.7500 ±2.2500 ±2.7500 ±3.2500 ±3.7500 ±4.2500 ±4.7500 ±5.2500 ±5.7500 ±6.2500 ±6.7500 ±7.3167 ±7.8747 ±8.4455 ±8.9742 ±9.5959 ±10.1209 ±10.7265 ±11.5542 ±12.4124 ±13.3317±14.1433 ±14.9624 ±15.7860 ±16.5308 ±17.3415 ±18.2207 ±20.2112 ±20.7500
	PSO	±0.2500 ±0.7500 ±1.2500 ±1.7500 ±2.2500 ±2.7500 ±3.2500 ±3.7500 ±4.2500 ±4.7500 ±5.2500 ±5.7500 ±6.2500 ±6.7500 ±7.2500 ±7.7500 ±8.2500 ±8.7500 ±9.2500 ±9.7500 ±10.2500 ±11.0408 ±11.7403 ±12.7130 ±13.2484 ±13.7498 ±15.2613 ±16.2500 ±16.7500 ±17.2500 ±17.7500 ±18.2500
	DE	±0.2500 ±0.7500 ±1.2500 ±1.7500 ±2.2500 ±2.7500 ±3.2500 ±3.7500 ±4.2500 ±4.7500 ±5.2500±5.7500 ±6.2500 ±6.7500 ±7.2500 ±7.7500 ±8.2500 ±8.7500 ±9.2500 ±9.7500 ±10.2500 ±10.9802 ±11.6761 ±12.5367 ±13.0557 ±13.8349 ±14.9274 ±16.2500 ±16.7500 ±17.2500 ±17.7500 ±18.2500

Table 5. PSLL and FNBW of a synthesized 64 element optimized arrays.

Array Type	Algorithm	PSLL (dB)	Beam Width (in Deg.)
64 Element	Periodic Array	-13.23	3.6
	MDE	**-22.87**	3.6
	PSO	-19.18	3.6
	DE	-19.13	3.6

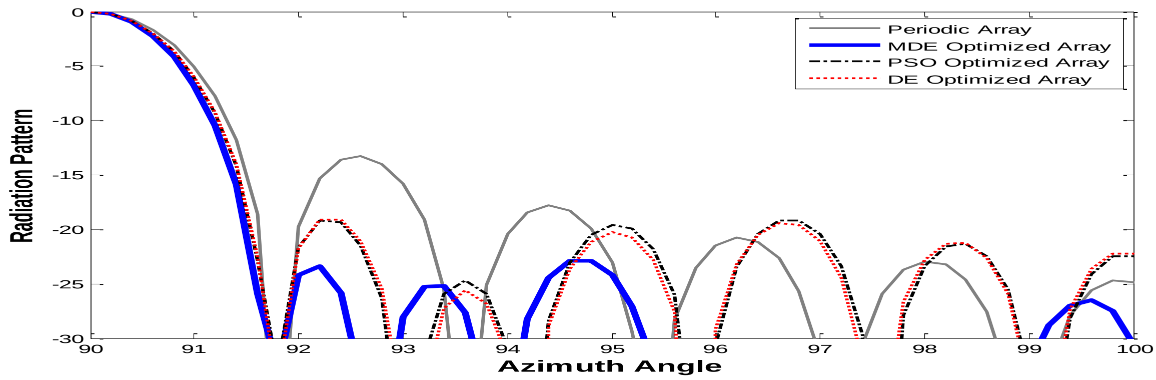

Figure 6. Zoomed view of the angular region 90^0 to 100^0 in Figure 3

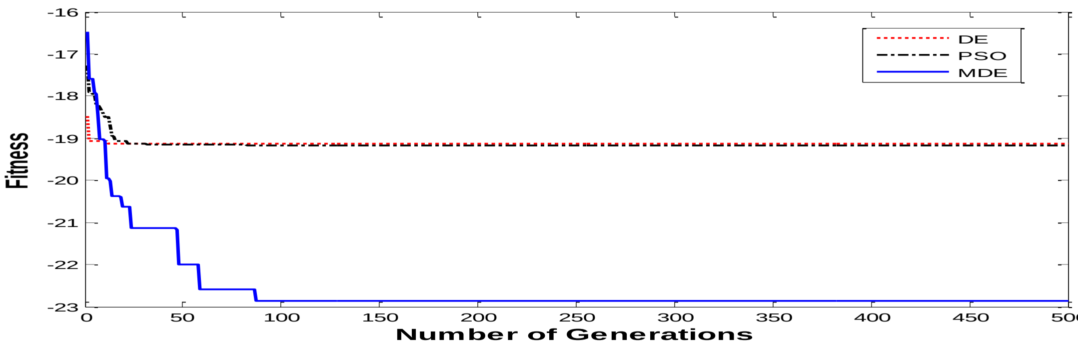

Figure . The evolution of PSLL over the generations in synthesizing 64 element linear array using MDE, PDO and DE.

V. CONCLUSION

In this paper, a novel MDE is proposed for the aperiodic antenna array synthesis. MDE is employed to optimize the element positions for minimizing the sidelobe levels along with traditional PSO and DE. The obtained array designs have been compared with periodic antenna array, traditional PSO and DE methods. The proposed MDE method significantly produces lower PSLL while maintain narrow BW. It outperforms interms of low PSLL for both PSO and DE. Also, MDE performs faster speed of evolution while achieving the good solution accuracy. It outperforms PSO and DE in terms of convergence speed. Thus the performance of the communication systems is greatly improved by adopting these array designs.

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