

Unequally Spaced Linear Antenna Array Synthesis with Minimum Side Lobe Levels Using Modified Differential Evolution Algorithm

S. Venkata Rama Rao , A. Mallikarjuna Prasad , Ch. Santhi Rani

Abstract: Antenna arrays are popularly used in various applications which include satellite, radar, wireless and cellular mobile communications etc. The present day communication systems performance greatly depends on the efficient design of antenna array systems. To meet the demands of noise free communications, it is required to design the antenna arrays with low side lobe levels (SSL). In this paper, a modified version of differential evolution (DE) algorithm is proposed to synthesize the linear antenna arrays with minimum side lobe levels. The mutation part of the traditional DE has been modified by adopting the normal mutation parameter. The various linear antenna arrays (10, 20 and 28 element) have been considered for the synthesis. The proposed modified DE (MDE) along with traditional DE algorithm and particle swarm optimization (PSO) algorithms have been applied. All the algorithms are applied to optimize the position between the elements. The numerical illustrations illustrate that the proposed method is out performed the traditional DE and PSO in terms of low side lobe level and convergence rate. From these results it is demonstrating that MDE is best suitable candidate for the optimization problems.

Index Terms: Convergence rate, differential evolution, linear antenna array, MDE, PSO, side lobe levels.

I. INTRODUCTION

The main objective of array antenna pattern synthesis is to approximate the desired radiation pattern by controlling the antenna array elements positions and by varying excitation currents amplitudes and phases to each antenna element. The optimization algorithms used for antenna arrays synthesis are either stochastic or deterministic. In antenna array synthesis problem stochastic optimization algorithms widely used because these algorithms can easily escape from local minima [1], [2].

Antenna array synthesis can be achieved by both deterministic and stochastic optimization algorithms. The deterministic optimization algorithm performs calculations over regions of the solution space, whereas the optimization algorithm performs calculations on single points. Most of the case stochastic optimization algorithms for example, genetic algorithm (GA) [3], DE algorithm [4], PSO algorithm [5], [6], bees algorithm [7], tabu search algorithm [8], ant colony

optimized (ACO) algorithm [9], cat swam optimization algorithm [10] and so on out performs deterministic optimization algorithms in antenna array synthesis problems. In recent years unequally spaced or aperiodic array antennas are wide spread in radar communication and satellite communication (SATCOM). If the periodicity in antenna array is changed, the aperiodic antenna array suppresses the sidelobe levels to minimum level. Different methods of synthesis of antenna arrays are presented to reduce the SLL to minimum level [11]. In unequally spaced arrays main beam can be steered over a larger frequency bandwidth compared with an equally spaced array. The unequally spaced antenna arrays can be classified into thinned and nonuniform arrays depending on whether the number of array elements is fixed or not [12]. The number of elements in the thinned arrays is not fixed. But in unequally-spaced arrays the number of array elements is fixed and the positions of elements are optimized with a real vector. In this paper a modified DE algorithm is proposed for synthesis of nonuniform arrays.

II. PATTERN SYNTHESIS OF LINEAR ANTENNA ARRAY

We assume linear array geometry as shown in Fig. 1 with symmetrically placed $2N$ isotropic antenna elements along x axis.

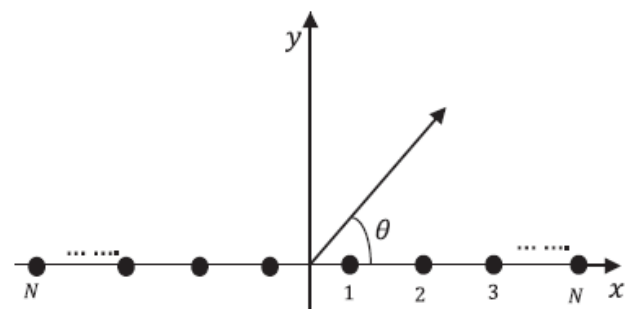


Fig.1. Symmetric linear array geometry

A. Array Factor of linear array

Antenna arrays can be realized by simply looking into its radiation pattern and can be obtained from its array factor (AF).

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In general AF is depends on number of elements in the array, separation distance between adjustment elements and the weights used for relative excitation of the current magnitudes and phases. The array factor for the 2N-element linear antenna array the array factor at an arbitrary angle θ can be expressed as [2]

$$AF(I, X, \phi, \theta) = \sum_{n=-N}^N I_n e^{j(kx_n \sin \theta + \phi_n)} \quad (1)$$

Where I represent amplitude excitation vector, X is the array element positions vector and ϕ is the vector of excitation phases, I_n and ϕ_n represents the current excitation and element phase, which is positioned at x_n . And the wave vector of incident wave with wavelength λ is $k = 2\pi/\lambda$

B. Peak Side Lobe Level (PSLL)

In array radiation pattern the side lobe levels cause the wastage of energy and are usually unwanted. In most applications of antenna arrays, these side lobe levels needs to be suppressed without changing the main beam the gain. The peak side lobe level can be expressed as [1]

$$PSLL(I, X, \varphi) = \max_{\forall \theta \in S} \left| \frac{AF(I, X, \varphi, \theta)}{AF(I, X, \varphi, \theta_0)} \right| \quad (2)$$

Where S is the space spanned by the angle θ not including main lobe with the center at θ_0 . Compared to amplitude and phase excitation techniques, amplitude excitation minimizes cost of the system [1], [2]. For the uniform excitation of amplitude, the excitation current of all elements I_n is assumed to be 1.0 and for uniform phase excitation $\phi_n = 0$. Hence, AF in equation (1) can be modified as

$$AF(X, \theta) = \sum_{n=-N}^N e^{j(kx_n \sin \theta)} \quad (3)$$

Consequently, equation (2) becomes

$$PSLL(X) = \max_{\forall \theta \in S} \left| \frac{AF(X, \theta)}{AF(X, \theta_0)} \right| \quad (4)$$

Where, θ_0 is considered to be 0° .

III. DIFFERENTIAL EVOLUTION (DE)

The Differential Evolution like genetic algorithm is the population based metaheuristic algorithm. In 1995 the DE algorithm is invented by Storn and Price uses the fundamental operations mutation, crossover and finally selection similar to GA algorithm. Unlike GA algorithm DE uses only the mutation as the primary search operation.

A. Classic Differential Evolution

Classic Differential Evolution (CDE) algorithm starts with a population of N_p individuals. It optimizes an objective function by initialization and evolution processes. First the initial population P^0 is generated by initialization process. Then the evolution process of population is carried out from the generation P^n to P^{n+1} generation until final conditions are

attained. In the evolution process from generations P^n to P^{n+1} the mutation, crossover and selection operations are performed one by one.

(a) **Differential Mutation:** In DE algorithm after initialization process a mutant vector or donor vector is produced with differential mutation operator. Then in each generation this donor vector is combined with parent vector to produce trial vector. Differential mutation creates a mutant vector $X^{n+1,v,i}$ given as [1]

$$X^{n+1,v,i} = X^{n,b,i} + \sum_{y \geq 1} F_y (X^{n,p_{1y}} - X^{n,p_{2y}}) \quad (5)$$

$$1 \leq i \neq p_{1y} \neq p_{2y} \leq N_p$$

Where, the mutation intensity F_y is a positive real number in [0, 1]. The optimization parameters vector for the mutation base $b^{n,i}$ is $X^{n,b,i}$. And p_{1y} and p_{2y} are integer numbers.

(b) **Crossover:** Next the child vector $C^{n+1,i}$ is generated through crossover operator. The variants of DE algorithm commonly use two basic crossover methods such as explicitly exponential crossover and binomial (or uniform) crossover. In uniform crossover the child vector $C^{n+1,i}$ is generated according to the following formula [1]:

$$x_j^{n+1,c,i} = \begin{cases} x_j^{n+1,v,i} & \beta_j^{n+1,i} \leq c_r \\ x_j^{n,i} & otherwise \end{cases} \quad (6)$$

Where and C_r is the control parameter of DE algorithm is constant in the range [0, 1] and $\beta_j^{n+1,i}$ is random number.

(c) **Selection:** The DE algorithm uses selection process to determine surviving of the target vector to subsequent generation. In the selection process the value of the objective function for every trial vector $f(X^{n+1,c,i})$ is compared with its related target vector $f(X^{n,i})$ and the vector corresponding to better fitness value will continue to the next generation. The selection operation mathematically expressed as [1]

$$p^{n+1,i} = \begin{cases} c^{n+1,i} & f(X^{n+1,c,i}) < f(X^{n,i}) \\ p^{n,i} & f(X^{n+1,c,i}) \geq f(X^{n,i}) \end{cases} \quad (7)$$

B. Dynamic Differential Evolution

Submit For each evolution loop in classic differential evolution the population is not changed up to a new population replaces it. This static nature of classic DE algorithm results in slower convergence. Dynamic differential evolution (DDE) updates the population dynamically for responding to variation of status of population. In DDE trial and target individuals are compared if trial one is better than target one then without delay target individual is replaced by trial individual in the same generation itself.



In most cases DDE algorithm outperforms the classic DE algorithm.

C. Differential Mutation

The differential mutation best value expressed mathematically as [1]

$$X^{n+1,v,i} = X^{n,p_b} + \sum_{y \geq 1} F_y (X^{n,p_{1y}} - X^{n,p_{2y}}) \quad (8)$$

$$1 \leq i \neq p_{1y} \neq p_{2y} \neq p_b \leq N_p$$

Where X^{n,p_b} is the optimization parameters vector of individual p^{n,p_b} and is randomly chosen from p^n by satisfying the condition,

$$f(X^{n,p_b}) \leq \min_{\forall y} [f(X^{n,p_{1y}}), f(X^{n,p_{2y}})] \quad (9)$$

IV. MODIFIED DIFFERENTIAL EVOLUTION ALGORITHM

In MDE, we have replaced the traditional position updating equation by adopting the normal mutation mechanism. Normal mutation permits equal likelihood of movement in the positive and negative ways around the parent position. The modified DE updates the positions of the parent population using normal distribution. It is the major difference compared to the traditional DE. This step permits the DE to have a smaller (Large probability) and as well as larger mutations (Low probability) in the neighbourhood of parent position in a more systematic way.

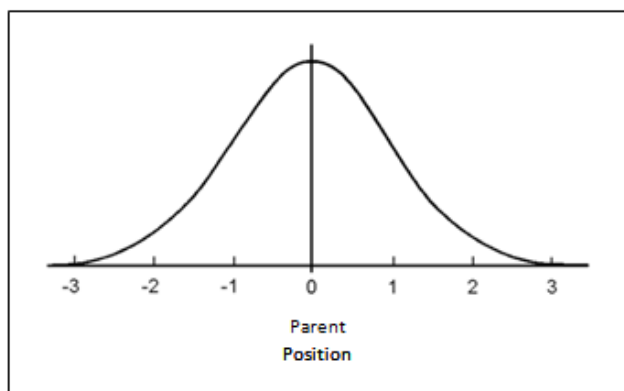


Fig. 2. Normal Distribution Curve

Fig.2 shows the normal distribution curve. In this normal mutation approach smaller mutations are good turned over larger ones. The normal distribution density function mathematically expressed as

$$f_{normal}(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (10)$$

Where, μ is mean and σ standard deviation. The normal random number (N) following the above normal law is given

as

$$NM(\mu, \sigma^2) = \mu + \sigma NM(0,1) \quad (11)$$

For the normally distributed random number $NM(0,1)$, mean is zero and standard deviation is 1. By using the aforementioned equations, the updated position is defined by using the normal mutation random number. Therefore, for every dimension the position of i^{th} population is updated as

$$X_{n+1,v,i} = X^{n,b,i} + [SF * X^{n,b,i} * N(0,1)] \quad (12)$$

Where $X^{n,b,i}$ the previous position of the population, σ is standard deviation and SF is the scaling factor.

V. SIMULATION RESULTS

In this paper MDE algorithm is proposed to synthesize the linear array antennas for obtaining lowest side lobe levels. This design requirement is achieved with MDE algorithm by optimizing the array element positions. Various linear array configurations with uniform amplitude and phase excitations are considered for analysis. The final results obtained with MDE algorithm are compared with non-optimized conventional array, PSO and DE optimized antenna array configurations. The parameter values assumed for both DE and MDE algorithms are number of population $NP=50$, crossover rate (CR) is 0.5 and scaling factor (SF) is 0.9. For PSO algorithm both C_1 and C_2 are taken as 2, population size of 50 and $r \in [0, 1]$. Each of these two algorithms is executed 10 times. For each run 300 generations are considered and the radiation pattern is obtained with 1200 angles. And the azimuth angular region is considered between the angles 0° to 180° . The element position optimised with PSO, DE and MDE algorithms are shown in table 1 and the optimized array parameters in terms of PSL and FNWB are shown in table 2. All the calculations are carried out using MATLAB R2015a on a system at operating 1.7 GHz with 4GB RAM.

5.1 Design examples for optimizing lowest SLL

In antenna arrays the side lobes represent unwanted radiation in unwanted directions. These side lobe levels of linear antenna array are to be optimized to the lowest levels by choosing optimum position in the antenna array.

The fitness function consider for this analysis minimizes maximum peak side lobe level and is achieved by [6]:

$$Fitness = Min \left[Max \left(20 \log \frac{|AF(\theta)|}{Max |AF(\theta)|} \right) \right] \quad (13)$$

Where, the azimuth angle θ is along the side lobes region.



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Table 1. Optimized antenna element position by using MDE, DE and PSO algorithms

S.No	Array Type	Algorithm	Optimized Array Positions
1	10-Element linear Array	Modified DE	0.2500,0.7500,1.2500,1.8889,2.6067
		DE [1]	0.2500,0.7500,1.2500,1.8587,2.5217
		PSO [5]	0.2974,0.8863,1.5466,2.3596,3.0030
2	20-Element linear Array	Modified DE	0.2500,0.7500,1.2500,1.7500,2.2500,2.7500,3.3182,4.1237,4.8595,5.6824
		DE [1]	0.2500,0.7500,1.2500,1.7500,2.2500,2.7500,3.2500,3.9637,4.7073,5.3869
		PSO [5]	0.2863,0.8362,1.3634,1.8687,2.5372,3.2030,3.7401,4.4824,5.2260,5.7939
3	28-Element linear Array	Modified DE	0.2500,0.7500,1.2500,1.7500,2.2500,2.7500,3.2500,3.7500,4.2500,4.9085,5.7413,6.4912,7.4817,8.2500
		DE [1]	0.2500,0.7500,1.2500,1.7500,2.2500,2.7500,3.2500,3.7500,4.2500,4.750,5.2500,5.9870, 6.6458, 9.2500
		PSO [5]	0.2500,0.7500,1.2500,1.8244,2.3577,2.8760,3.3915,4.0165,4.5889,5.1634, 5.7821, 6.5805, 7.3183,8.2500

Table 2. Optimized antenna parameters in terms of PSL and FNBW by using DE and MDE algorithms

S.No	Array Type	Algorithm	PSLL (dB)		FNBW (Degrees)	
			Original PSLL	Optimized PSLL	Original FNBW	Optimized FNBW
1	10-Element linear Array	Modified DE	-12.9681	-17.8364	23.6	22.4
		DE [1]		-16.4753		22.8
		PSO [5]		-15.0665		18.4
2	20-Element linear Array	Modified DE	-13.1894	-19.6731	12	11.6
		DE [1]		-18.4251		11.6
		PSO [5]		-16.0132		10.4
3	28-Element linear Array	Modified DE	-13.2353	-20.6105	8.4	8.4
		DE [1]		-18.5168		8.8
		PSO [5]		-17.4733		8.0

array pattern.

Example 1

A linear array of 10 elements is considered for obtaining SLL with minimum value in the angular region of $\theta = [0^\circ, 79^\circ]$ and $\theta = [101^\circ, 180^\circ]$. Then array pattern synthesised with MDE algorithm is compared with conventional and DE, PSO optimised array patterns. From Fig.3 it is observed that the reduction in the SLL with MDE algorithm is improved than conventional DE and PSO optimized array patterns. The SSL with proposed MDE algorithm is reduced by about 4.87dB from -12.96 dB to -17.83dB as compared with conventional array pattern. From table 2 it is also observed that the PSLL is reduced by about 3.51dB, 2.10dB with DE and PSO optimized patterns as compared with conventional



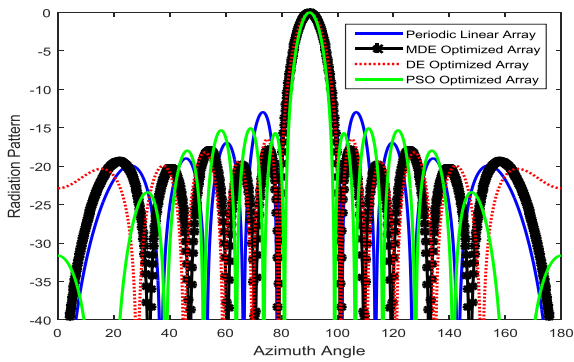


Fig.3. Normalized array factor of linear antenna array with 10 elements.

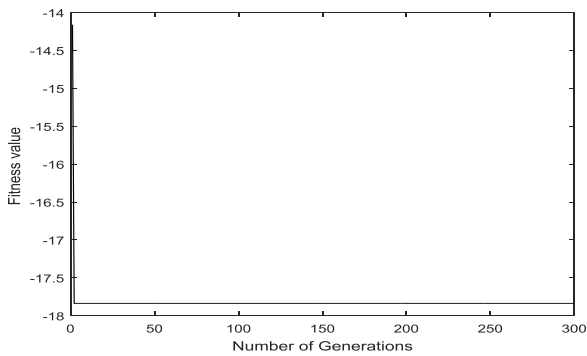


Fig.4. Convergence plot of fitness function of 10-element linear array using MDE Algorithm

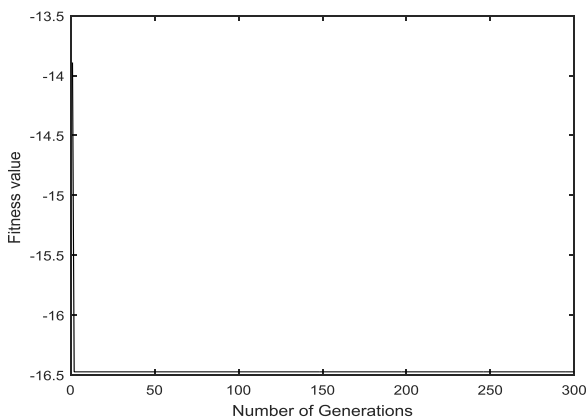


Fig.5. Convergence plot of fitness function of 10-element linear array using DE Algorithm

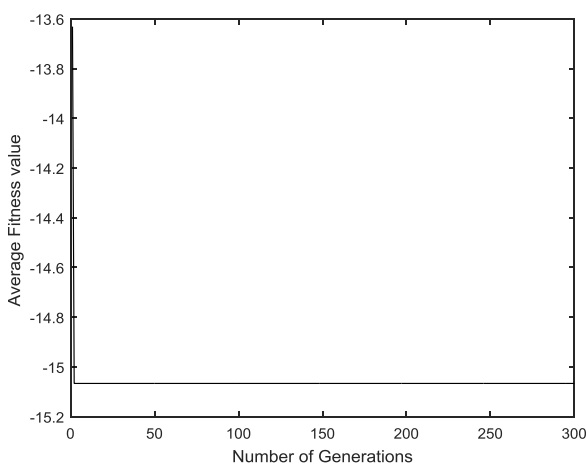


Fig.6. Convergence plot of fitness function of 10-element linear array using PSO Algorithm

The convergence properties linear array with 10 elements by using MDE, DE and PSO are shown in the figures 4, 5 & 6 respectively.

Example 2

In this example MDE algorithm is applied to 20 element uniform linear array with element spacing of 0.5λ . As compared to conventional array pattern the SLL of MDE pattern is reduced by 5.86 dB from -13.23 dB to -19.09 dB in the angular region of $\theta = [0^\circ, 84.4^\circ]$ and $\theta = [95.6^\circ, 180^\circ]$. And as compared to DE pattern the SLL is reduced by 1.3 dB from -17.8 dB to -19.09 dB as shown in Fig.7.

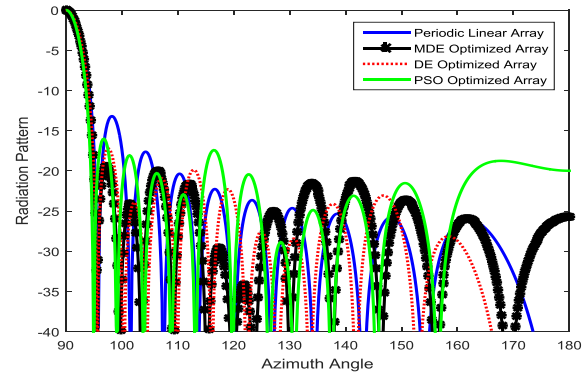


Fig.7. Normalized array factor of linear antenna array with 20 elements.

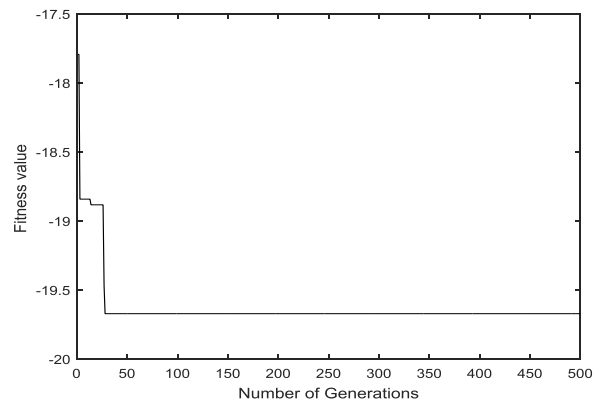


Fig.8. Convergence plot of fitness function of the 20-element linear array using MDE Algorithm

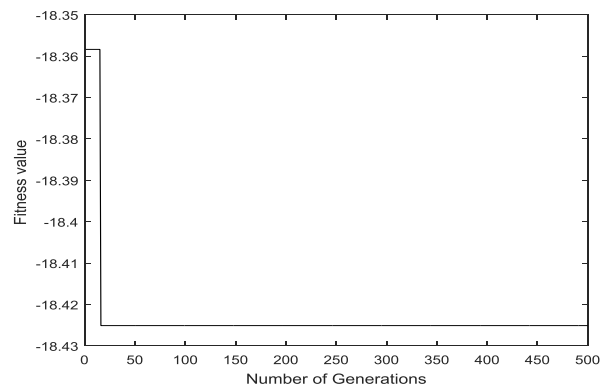


Fig.9. Convergence plot of fitness function of 20-element linear array using DE Algorithm



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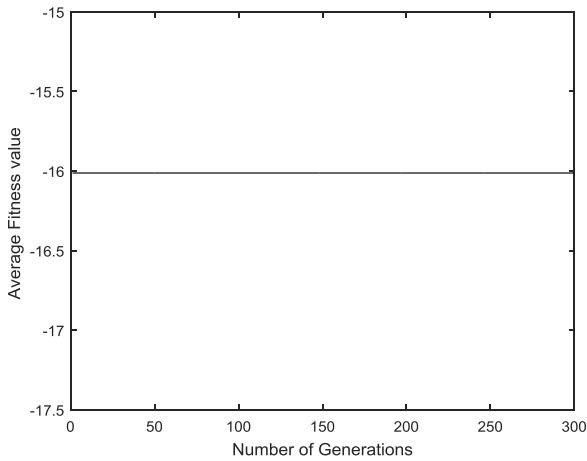


Fig.10. Convergence plot of fitness function of 20-element linear array using PSO Algorithm

The convergence properties of linear array with 20 elements by using MDE, DE and PSO are shown in the figures 8, 9 & 10 respectively.

Example 3

In the third example the 28 elements linear array is consider for minimum SLL value in angular region of $\theta = [0^0, 86^0]$ and $\theta = [94^0, 180^0]$. It seen from Fig.11, that the SSL obtained with proposed MDE algorithm is decreased by about 7.37dB, 2.09dB and 3.14 dB when compared with conventional, DE and PSO optimized array patterns respectively. The convergence properties of 28 element linear array by using MDE, DE and PSO are shown in the Figs. 12, 13 & 14 respectively.

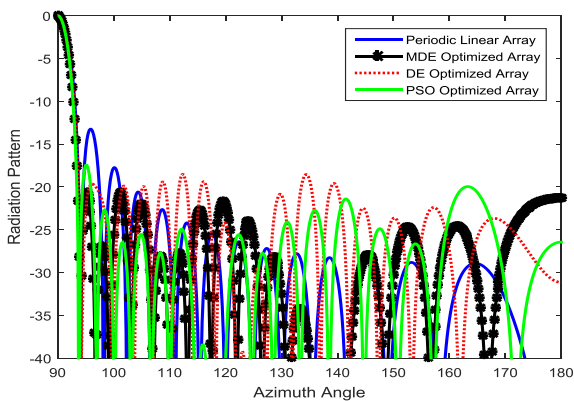


Fig 11. Normalized array factor of 28 element linear antenna array.

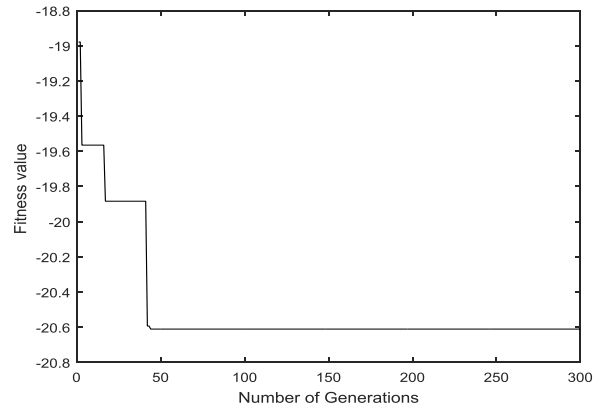


Fig.12. Convergence plot of fitness function of 28-element linear array using MDE Algorithm

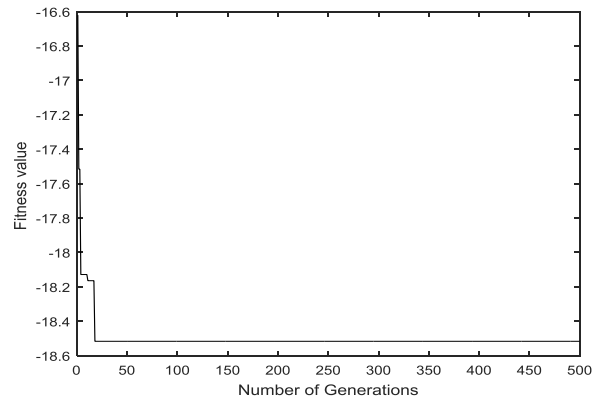


Fig.13. Convergence plot of fitness function of 28-element linear array using DE Algorithm

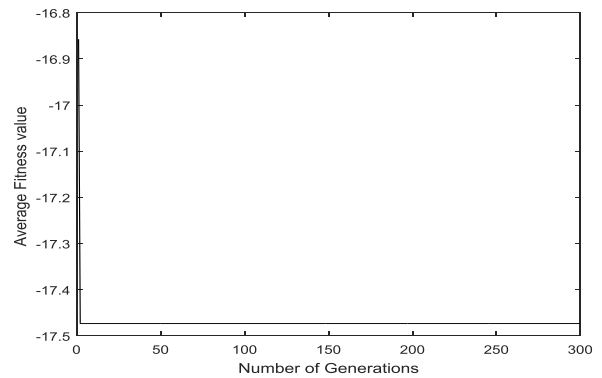


Fig.14. Convergence plot of fitness function of the 28-element linear array using PSO Algorithm

5.2. Convergence property of MDE Algorithm

It can be observed that from all the convergence plots the proposed MDE convergence rate is faster than the DE and PSO in achieving the lower PSLL levels.

VI. CONCLUSION

In this work, the modified differential evolution algorithm is proposed for linear antenna array synthesis problems. A 10, 20 and 28 element linear antenna arrays has been synthesized.

The algorithms DE, PSO and proposed MDE are applied to linear antenna array synthesis by optimizing array element positions. Numerical illustrations demonstrated that the MDE outperformed traditional DE and PSO. It can be seen that -17.83dB PSLL has been obtained by using MDE algorithm whereas -16.47dB and -15.06dB obtained by using traditional DE and PSO optimization algorithms for linear antenna array of 10 elements. There is a significant reduction of SLL of -1.36dB and -2.77dB when compared to DE and PSO optimised algorithms. For the 20 element linear array by using MDE algorithm, there is a significant reduction of -1.25dB and -3.66dB compared to the traditional DE and PSO. The PSLL of -19.67dB is obtained by using MDE algorithm whereas -18.42dB and -16.01dB are the PSLLs obtained by using traditional DE and PSO algorithms for the linear antenna array of 20 elements. It can also be noted that a PSLL of -20.61dB has been obtained by using MDE algorithms whereas -18.51dB and -17.47dB has been obtained by using traditional DE and PSO algorithms for linear array of 28 elements. There is a significant reduction of -2.1dB and -3.14dB when compared to traditional DE and PSO algorithms. It can be seen from all the convergence graphs for all the linear antenna arrays, MDE out performed DE and PSO in terms of convergence rate. Finally we can conclude that the MDE out performed traditional DE and PSO algorithms with reference to solution accuracy SLL and convergence rate. The proposed MDE antenna array designs can be greatly useful in wireless communication systems for noise free communication.

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