

Erratum to A LINEAR ANTENNA ARRAY FAILURE CORRECTION USING FIREFLY ALGORITHM

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A LINEAR ANTENNA ARRAY FAILURE CORRECTION USING FIREFLY ALGORITHM

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Abstract—The element failure of antenna arrays increases the sidelobe power level. In this paper, the problem of antenna array failure has been addressed using Firefly Algorithm (FA) by controlling only the amplitude excitation of array elements. A fitness function has been formulated to obtain the error between pre-failed (original) sidelobe pattern and measured sidelobe pattern and this function has been minimized using FA. Numerical example of large number of element failure correction is presented to show the capability of this flexible approach.

1. INTRODUCTION

For wireless communication system, the antenna array is one of the most important components to improve the system capacity and spectral efficiency. The active antenna array is widely used in many applications like satellite communication, sonar, mobile communication etc. for signal acquisition purpose. Generally the antenna array consists of large number of radiating elements or sub-arrays. Due to large number of elements presented in an array, there is always a possibility of failure of one or more elements in the antenna array system. The failures of elements in the array destroy the symmetry and may cause sharp variation in field intensity across the array, distort the pattern in the form of increased sidelobe level. In some situation like space platform the replacement of the defective element of the array is not possible. It is possible in case of active

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antennas to restore the radiation pattern with minimal loss of quality without replacing the defective element by controlling the excitations of the normal antenna elements of the array. Many conventional techniques are proposed to solve this problem by improving the array pattern in presence of defective elements like a numerical technique based algorithm [1] to regain the directional pattern of linear antenna array with single element failure conditions, the accumulated averaging scheme combined with the conjugate gradient algorithm [2] for partial compensate the degraded pattern of hexagonal array, shore's sidelobe sector nulling method [3], an orthogonal method [4], conjugate gradient based method [5].

Generally analytical approaches unable to handle failed element problem, where antenna array considered as nonuniformly spaced array. This problem is also a challenging problem for numerical approaches due to arbitrariness of the geometrical layout of the remaining non defective array elements and of the desired beam shape. Population-based, stochastic methods can provide an effective solution for such problems, as they tend to explore multiple solutions simultaneously, relying only on zero order information. Many stochastic methods have been proposed to solve the problem of antenna array failure using Genetic Algorithm (GA) [6, 7], use of combination of GA and Fast Fourier Transform(FFT) [8], adaptive neuronal system [9], Simulated Annealing (SA) [10, 11].

In this paper, an effective method based on the Firefly Algorithm (FA) is proposed for array failure correction of arbitrary linear antenna arrays. The FA algorithm is a new swarm intelligence based algorithm [12–14] which can deal with continuous variables in multi-dimensional spaces more naturally and efficiently. The FA has been shown to outperform Artificial Bees Colony Algorithm (ABC) in terms of convergence and cost minimization in a statistically meaningful way [15]. The performance of FA has been found more superior than Particle Swarm Optimization (PSO) in terms of finding optimum solutions for the desired beam patterns of ring antenna array [16].

For a uniformly spaced linear array, the array-failure correction is a much more complex problem than simple sidelobe reduction in antenna design. In this paper, FA has been successfully applied first time for linear antenna array failure problem and the antenna pattern has been corrected using amplitude only control. The amplitude only control is preferred as it is simple to implement than amplitude and phase control because it does not need accurate adjustment of phase shifters and only attenuators have to be adjusted in amplitude only control [17]. A large failure rate (31.25%) has been considered to demonstrate the effectiveness of this algorithm.

The problem formulation has been discussed and modeled the fitness function in the second section. Third section of the paper gives a brief introduction of FA algorithm. Simulation results and discussion has been presented in Section 4 and the work has been concluded in the last section.

2. PROBLEM FORMULATION

The linear array of M identical dipoles is shown in Figure 1 having a uniform spacing of half a wavelength between elements. The array factor (AF) of an arbitrary antenna array can be generally written as

$$AF = W^C S(\theta, \theta_p) \tag{1}$$

where,

$$W^C = \{w_1, w_2, w_3, \dots, w_M\}^T, \quad w_n \in C^{NC}, \quad n = 1, 2, \dots, M \tag{2}$$

is the weighting vector; θ_p and θ are the main beam direction and the direction variable respectively; S is the steering vector; C^{NC} is a subset or the set of the all of the all real number, indicating the weights of antenna elements of the linear array.

The steering vector S of linear array of M identical elements is given as

$$S = \exp \left\{ jkd_x \left(n - \frac{M-1}{2} \right) \cdot (\cos \theta - \cos \theta_p) \right\} \quad n = 1, 2, \dots, M \tag{3}$$

where d_x is the spacing between elements of array. The K th element failure is done by setting the weight w_k equal to zero in Equation (1). The element failure of antenna array causes the disturbance in main

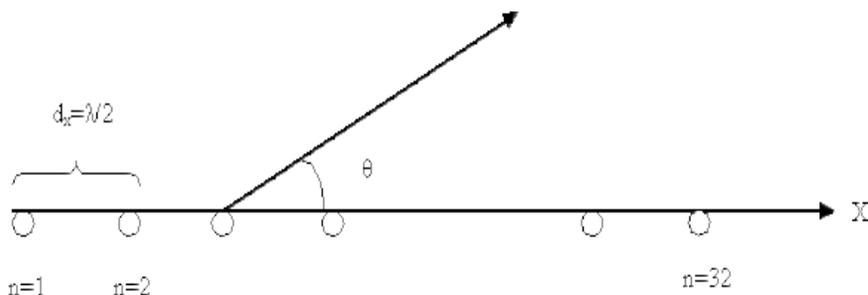


Figure 1. Linear array of identical dipoles with a uniform spacing of half a wavelength.

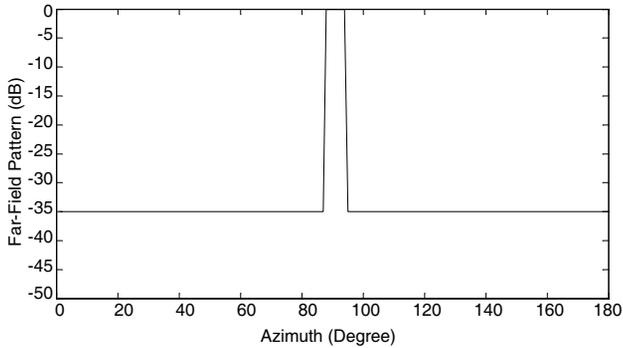


Figure 2. A template to evaluate the fitness.

beam and Side Lobe Level (SLL) pattern, which is corrected by recalculating the amplitude of the non failure elements using the Firefly Algorithm.

The objective is to re-obtain or restore the SLL of the original pattern and optimize the directivity of the antenna array. For this purpose, a template has been constructed on the basis of the specified SLL and the required shape of the main lobe as shown in Figure 2. This template is cast over the array pattern generated by each solution provided by Firefly Algorithm to determine their cumulative difference. The determined cumulate difference is taken as a fitness measure of the solution.

3. FIREFLY ALGORITHM

The Firefly Algorithm imitates the social behavior of firefly flying in the summer sky of the tropical and temperate regions. The fireflies use bioluminescence with different flashing pattern for communication with each other, search for pray and to find mates. To develop a firefly-inspired algorithm, some of the characteristics of fireflies have been idealized [18]. For simplicity, only three idealized rules have been used: 1) All fireflies are unisex so that one firefly will be attracted toward the other fireflies without considering their sex; 2) Attractiveness is proportional to brightness of the firefly. For any two flashing fireflies, the firefly with less brightness will move towards the brighter one. Attractiveness is proportional to the brightness of the two fireflies, which decreases with increasing distance between them. If there are no brighter fireflies than a particular firefly, then this individual firefly will move randomly in the space; 3) The brightness of a firefly is determined by the cost function of the problem. For an optimization problem,

brightness can simply be proportional to the value of the cost function. The pseudo-code for FA is shown in Figure 3. The steps involved in FA are summarized as under:

Step 1 (Initialization): The first step of Firefly algorithm is to initialize the location of S fireflies [15, 16] in T dimensional search space within the search boundary is given as

$$x_{st}(0) = rand_{st}(0, 1) (x_{st}^U - x_{st}^L) + x_{st}^L$$

$$s = 1, 2, 3, \dots S; \quad t = 1, 2, 3, \dots T \tag{4}$$

where x_{st}^U and x_{st}^L indicates the upper and lower limits of the t th variable in the population respectively, $rand_{st}(0, 1)$ is a uniformly distributed random value within $[0, 1]$.

Step 2 (Computation of light intensity of fireflies): In this step, the light intensity or brightness of each firefly is determined at current generation by the cost function at their present location. The light intensity or brightness is directly proportional to the cost function of individual firefly for maximization problem and is inversely proportional to cost function of individual firefly for minimization problem.

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Initialize the location of  $S$  fireflies  $x_{st}(0) \leftarrow \{x_{1T}(0), x_{2T}(0) \dots x_{ST}(0)\}$ 
    Define light absorption coefficient  $\gamma$ 
         $g \leftarrow 0$ 
    while the terminating condition is not true do
        Compute light intensity  $I$  by  $\{f(x_{1T}(g)), f(x_{2T}(g)) \dots f(x_{ST}(g))\}$ 
            for  $s = 1$  to  $S$  do
                for  $k = 1$  to  $S$  do
                    if ( $I_k > I_s$ ), move firefly  $s$  toward firefly  $k$ 
                    end if
                Compute the Cartesian distance,  $r_{sk} = \|x_s - x_k\|$ 
                Compute attractiveness,  $\beta = \beta_0 e^{-\gamma r_{sk}^2}$ 
                Update the location of firefly,  $x_s = x_s + \beta(x_s - x_k) + \alpha \varepsilon_s$ 
            end for k
            end for s
        Rank the fireflies and computation of current global best
         $g \leftarrow g + 1$  end while
    
```

Figure 3. A firefly algorithm.

Step 3 (Update of the location of the fireflies): In this step, each firefly in the population move toward the adjacent firefly with more light intensity and update its position for the next iteration of the algorithm. The location of the moving firefly is updated based on the attractiveness between the moving firefly and firefly with more light intensity. In the firefly algorithm, there are two important issues: the variation of light intensity or brightness and formulation of the attractiveness. For simplicity, we can always consider that the attractiveness of a firefly is calculated by its brightness or light intensity which in turn is associated with the encoded cost function. In the simplest case, for maximum and minimum optimization problems, the brightness I of a firefly at a particular location x can be taken as $I(x) \propto f(x)$ and $I(x) \propto 1/f(x)$ respectively. However, the term attractiveness β is relative which is judged by the other fireflies. Thus, it will vary with the distance r_{sk} between firefly s and firefly k . In addition, light intensity or brightness of the firefly decreases with the distance from its source, and light is also absorbed in the medium, so we should allow the attractiveness to change with the degree of absorption. In the simplest form, the brightness or light intensity $I(r)$ varies according to the inverse square law $I(r) = I_s/r^2$ where I_s is the intensity at the source. For a given medium with a constant light absorption coefficient, the brightness or light intensity I varies with the distance r , i.e., $I = I_0e^{-\gamma r}$, where I_0 is the original light intensity or brightness. In order to avoid the singularity condition at $r = 0$ in the expression I_s/r^2 , the combined effect of both the absorption and inverse square law and can be approximated using the Gaussian form as $I(r) = I_0e^{-\gamma r^2}$ as discussed in [14].

As a firefly's attractiveness is proportional to the light intensity seen by adjacent fireflies, we can now define the attractiveness β of a firefly by $\beta(r) = \beta_0e^{-\gamma r^2}$, where β_0 is the attractiveness at $r = 0$.

The attractiveness between the two fireflies in T -dimensional search space is determined as [14, 16]:

$$x_s = x_s + \beta_0e^{-\gamma r_{sk}^2} (x_s - x_k) + \alpha \varepsilon_s \quad (5)$$

where γ is the light absorption coefficient which varies from 0.01 to 100 depending upon the characteristics of the medium and is fixed in the given medium, α a randomization parameter to introduce randomness in Equation (5) whose value vary from 0 to 1, ε_s a vector of random numbers drawn from uniform distribution or a Gaussian distribution [16], and the attractiveness between the two fireflies s and k is represented by the product of β_0 and $e^{-\gamma r_{sk}^2}$ terms. The attractiveness is given by β_0 at Cartesian distance $r = 0$. For most cases in our implementation, the value of β_0 is taken unity. The

Cartesian distance r_{sk} between any two fireflies s and k at x_s and x_k respectively is determined as [14, 16]:

$$r_{sk} = \|x_s - x_k\| = \sqrt{\sum_{t=1}^T (x_{s,t} - x_{k,t})^2} \quad (6)$$

As per Firefly algorithm, the brightest firefly is not allowed to move in any direction, while the rest of fireflies change their location according to Equation (5) at current generation. In this way, the global best (g_{BEST}) solution is updated gradually by the algorithm in the successive iteration.

Step 4 (Ranking of fireflies and computation of current global best): The fireflies are ranked based on their brightness in the current generation and location of the brightest firefly in the population is taken as current global best (g_{BEST}). The brightest firefly has a best fitness value at the current generation.

Step 5: Repeat from steps 2 to 4 until terminating condition is achieved as shown in Figure 3. The terminating condition is a condition when either the total numbers of iterations are completed or desired value of cost function is achieved. The location of the best firefly (g_{BEST}) gives the optimum solution and the corresponding brightness of the firefly provide the optimum fitness value of the objective function using Firefly algorithm.

4. SIMULATION RESULTS AND DISCUSSION

The Firefly algorithm discussed above has been implemented in MatLab. The four FA parameters, i.e., the population size U , the light absorption coefficient γ , the randomization parameter α and the attractiveness β are set to values 50, 1, 0.25 and 0.2 respectively.

4.1. The Classic Dolph-Chebyshev 32 Elements Linear Array Design

Let us consider 32 elements Classic Dolph-Chebyshev (CDC) linear array design with an SLL of -35 dB. The steering vector S of the array design is given by Equation (3).

The above selected linear array design having 10 element failure condition with the defective elements are located at 1st, 2nd, 3rd, 5th, 6th, 27th, 28th, 30th, 31th and 32th positions has been simulated. Figure 4(a) shows the original array pattern of CDC linear array design without element failure condition with main beam and an SLL of -35 dB. When the elements of the array at the above

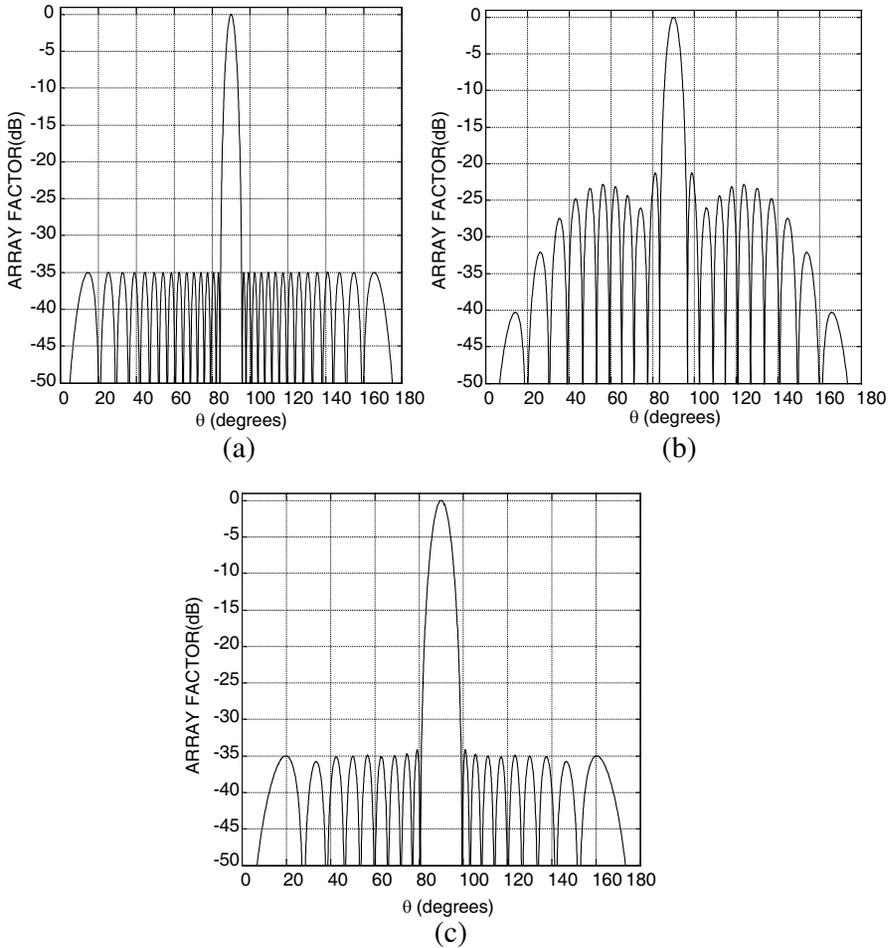


Figure 4. Far field array pattern of 32 elements CDC linear array design with main beam at broadside. (a) Original. (b) Damaged. (c) Corrected.

mentioned positions become defective, the side lobe level increase to the unacceptable value of -21.29 dB as shown in Figure 4(b).

The FA has been run to correct the failed pattern as per the objective function described in Section 2. The Figure 4(c) shows the corrected far field array pattern with main beam, which corrected the SLL value from -21.29 dB to -35 dB. The program has been run 20 times and best result noted. Figure 5 shows the convergence characteristics which indicates that the FA algorithm converges in

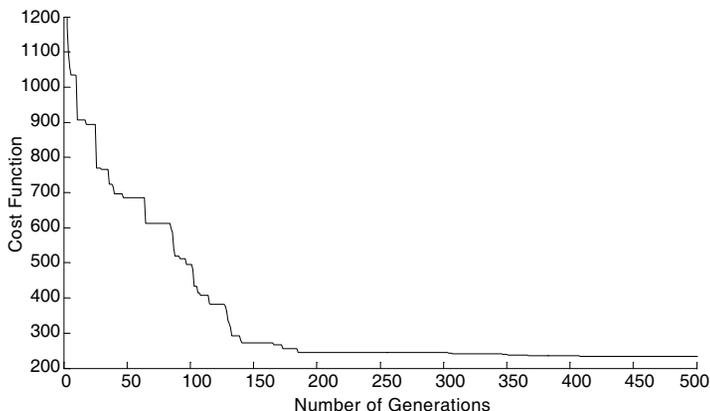


Figure 5. Fitness progress curve.

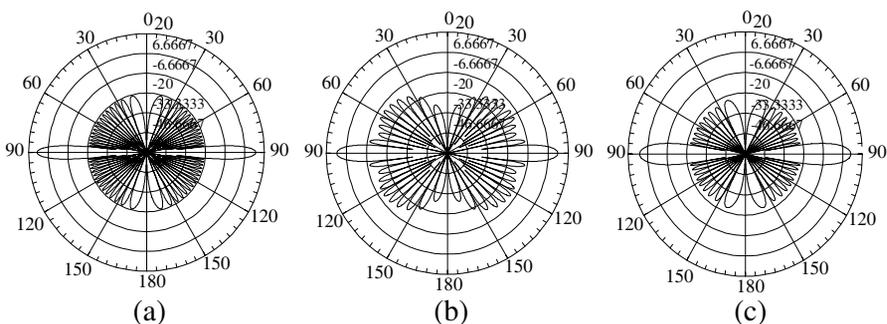


Figure 6. Directivity pattern with main beam. (a) Original. (b) Damaged. (c) Corrected.

around 190 generations.

The beamwidth of original, damaged and corrected patterns have been observed 4.2° , 5.2° and 6.6° respectively. The directivity of the original array design have been observed 14.21 dB of main lobe and -20.8 dB of side lobes as shown in Figure 6(a), which is distorted by the failed elements of the array design to 13.1 dB and -8.189 dB of main lobe and side lobes respectively as shown in Figure 6(b). Figure 6(c) shows the recovery of directivity to 12.16 dB of main lobe and -22.01 dB of side lobe by FA.

Likewise, the corrected pattern of CDC linear array design with main beam shifted at 49° and 131° is shown in Figure 7. The normalized excitation coefficients of original antenna array, antenna array with 10 element failure condition without optimization and

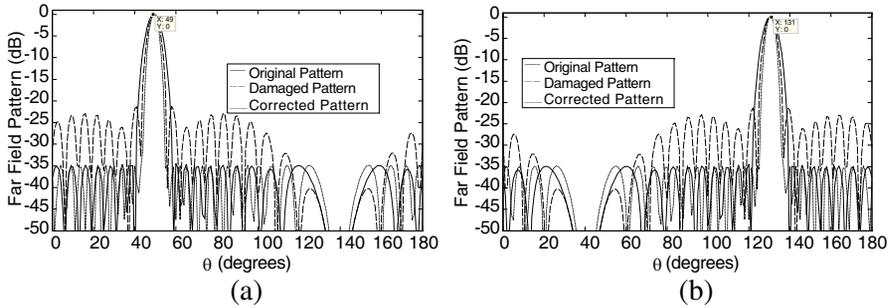


Figure 7. Corrected pattern with main beam pointing at (a) 49° . (b) 131° .

Table 1. Normalized excitation coefficient for corrected radiation pattern of 32 elements CDC linear array design by FA.

Element Location	Original Dolph Chebyshev Weights	Damaged Weights	Corrected Weights	Element Location	Original Dolph Chebyshev Weights	Damaged Weights	Corrected Weights
1.	0.2503	0	0	17.	1.0000	1.0000	1.000
2.	0.1774	0	0	18.	0.9863	0.9863	0.9674
3.	0.2341	0	0	19.	0.9594	0.9594	0.8967
4.	0.2976	0.2976	0.0201	20.	0.9202	0.9202	0.8068
5.	0.3669	0	0	21.	0.8700	0.8700	0.6888
6.	0.4406	0	0	22.	0.8103	0.8103	0.5729
7.	0.5170	0.5170	0.1882	23.	0.7431	0.7431	0.4409
8.	0.5943	0.5943	0.2219	24.	0.6703	0.6703	0.3411
9.	0.6703	0.6703	0.3411	25.	0.5943	0.5943	0.2219
10.	0.7431	0.7431	0.4409	26.	0.5170	0.5170	0.1882
11.	0.8103	0.8103	0.5729	27.	0.4406	0	0
12.	0.8700	0.8700	0.6888	28.	0.3669	0	0
13.	0.9202	0.9202	0.8068	29.	0.2976	0.2976	0.0201
14.	0.9594	0.9594	0.8967	30.	0.2341	0	0
15.	0.9863	0.9863	0.9674	31.	0.1774	0	0
16.	1.0000	1.0000	1.000	32.	0.2503	0	0

antenna array with 10 element failure condition with optimization are listed in Table 1. It has to be noted that the failed condition of antenna array element is represented by 0 depicted in different columns of Table 1.

4.2. The Classic Dolph-Chebyshev 42 Elements Linear Array Design

Now consider 42 elements CDC linear array design with an SLL of -35 dB. The aim of this example is to demonstrate the effectiveness of this method in solving array failure problem in the more complex array design problem. The simulation has been performed on the selected linear array design having six element failure condition with the defective elements are located at 2nd, 4th, 6th, 37th, 39th and 41th positions. The array pattern of the selected CDC linear array design in its original form without any element failure is shown in Figure 8(a) and its distorted form due to presence of defective elements are shown in Figure 8(b). The presence of the defective elements at the above mentioned location increases the side lobe level to an unacceptable value which is maximum of -21.93 dB at 13.5° and 166.5° .

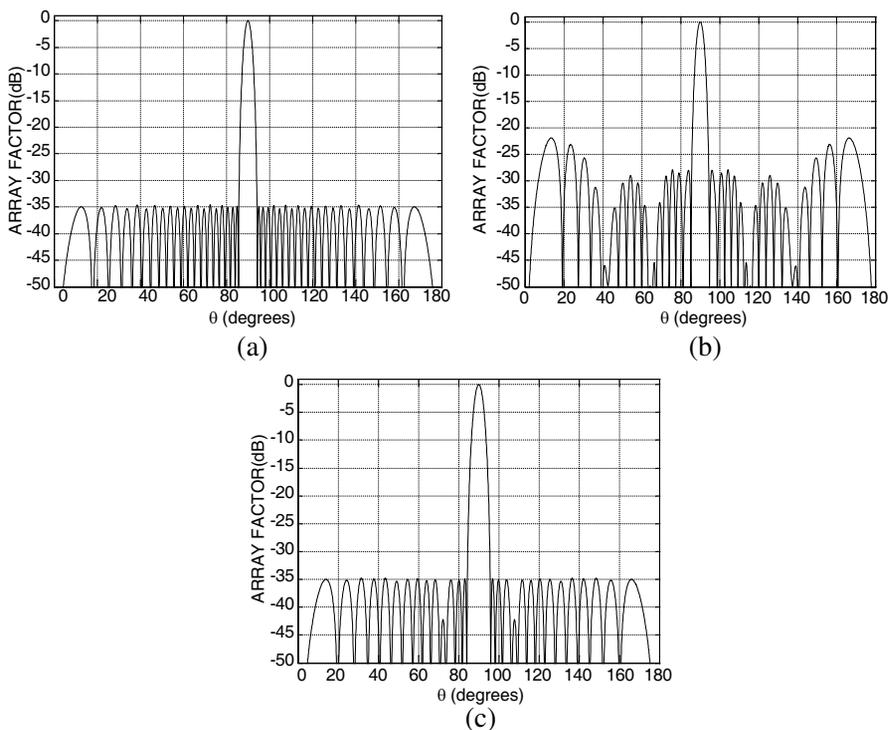


Figure 8. Far field array pattern of 42 elements CDC linear array design with main beam at broadside. (a) Original. (b) Damaged. (c) Corrected.

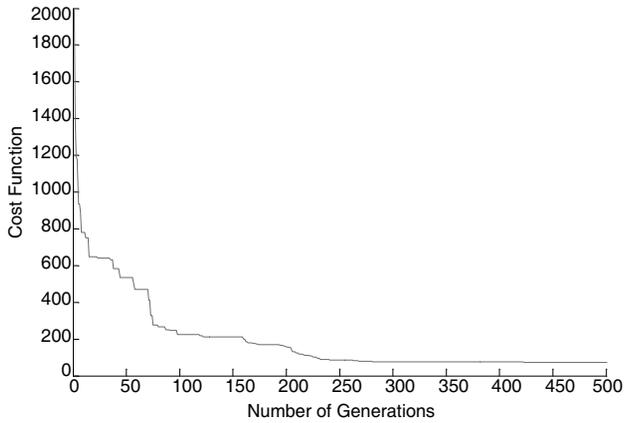


Figure 9. Fitness progress curve of 42 elements CDC linear array design.

The FA has been run to correct the failed pattern as per the objective function described in Section 2. The Figure 8(c) shows the corrected far field array pattern with main beam, which corrected the SLL value from -21.93 dB to the desired value of -35 dB. The convergence characteristics are shown in Figure 9. It can be seen that FA converges in around 240 generation for this case. The algorithm take more time to recalculate the optimum excitations of the selected linear array than the previous selected 32 element linear array due to increased complexity of the design.

5. CONCLUSION

The field pattern of a high performance antenna array design can be seriously degraded with the malfunctioning of large antenna elements. In this paper, the Firefly algorithm is proposed for solving a practical problem of linear antenna array design by re-optimizes only the amplitude excitations of the remaining elements to recover the original pattern of the antenna array. The proposed method proved its effectiveness to suppress the sidelobe level of linear array in presence of large number of antenna element failures. Moreover, this method is simple to implement as amplitude only control require only adjustment of attenuators and not any phase shifters as required in amplitude and phase control method. This method can be extended to planar or conformal antenna arrays.

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