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A Linear Antenna Array Failure Correction with Null Steering using Firefly Algorithm

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ABSRTACT

The element failure of digital beam forming array antenna systems used in defence equipment increases the side lobe power level which distorts the beam pattern of the antenna array. The problem of array failure correction becomes more complex when null steering conditions are required to be added. In this paper, the problem of linear antenna array failure has been addressed with multiple wide band null steering using firefly algorithm (FA) by controlling the amplitude and phase excitation of array elements. A fitness function in the form of template has been formulated to obtain the error between original (pre-failed) side lobe pattern and measured side lobe pattern and this error function has been minimized using FA. Numerical example of element failure correction of element failure of array along with multiple nulls is presented to show the capability of this flexible approach.

Keywords: Digital beamforming array antenna system, linear antenna array, side lobe level, element failure, null steering, optimization, firefly algorithm

1. INTRODUCTION

The digital beamforming antenna array is one of the most important components in wireless communication systems used in defence applications to improve the system capacity and spectral efficiency. The pattern synthesis of active antenna array is required in many defence applications like radar, satellite communication, sonar, mobile communication etc., where interference signals are considered to be a main problem. It is necessary to produce nulls in specified direction to reduce the effect of interfering signals during antenna beamforming. The desired patterns of linear antenna array with suppressed sectors in the interference directions can be easily achieved with well known analytical techniques, if all array elements radiate properly. In literature, the different conventional[1-3] and evolutionary techniques[4-11] have been applied for producing nulls in antenna pattern. In general, the antenna array used in different applications consists of large number of radiating elements or sub-arrays. Due to ageing or excessive temperature, there is always a possibility of failure of one or more elements in the antenna array system. The failures of elements in the antenna array destroy the symmetry of the array and may cause sharp variation in field intensity across the array and distort the pattern in the form of increased side lobe level and mainbeam width. The replacement or repair of the defective element of the antenna array is not possible in systems which used for critical situation like war field, space platform etc.

It is possible to re-synthesize the radiation pattern of array with minimal loss of quality and suppressed sectors in the interference directions. It can be realized by controlling the excitation of the normal antenna element of the array without replacing the defective element. Many conventional techniques have been proposed to solve only the problem of element failure of antenna array by improving the array pattern in presence of defective elements like a numerical technique based algorithm[12] to re-obtain the directional pattern of linear antenna array with single element failure conditions, partial compensated the degraded pattern of planar array using combination of accumulated averaging scheme and conjugate gradient algorithm[13], shore's side lobe sector nulling method[14], an orthogonal method[15] and conjugate gradient based method[16].

Generally analytical approaches are unable to handle the antenna array failure problem, when a non uniformly spaced array is considered. This problem is also a hard problem for numerical approaches due to randomness of the geometrical layout of the remaining non defective array elements and of the desired beam shape. Population-based, stochastic search approaches can provide an effective solution for such complex problems, as they tend to explore multiple solutions simultaneously, relying only on zero order information. Many stochastic search methods have been proposed to solve the problem of antenna array failure using genetic algorithm (GA)[17-18], particle swarm optimization (PSO)[19], adaptive neural system[20], simulated annealing (SA)[21], firefly algorithm (FA)[22] and hybrid methods[23]. Some stochastic approaches have been also proposed to solve the problem of antenna array along

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with null steering problem using simulated annealing (SA)[24], particle swarm optimization (PSO)[25] and hybrid method[26].

In this paper, an effective method based on the firefly algorithm (FA) is proposed for array failure correction of arbitrary linear antenna arrays along with null steering problem. The FA algorithm is a swarm intelligence based algorithm[27-29] which can solve problems with continuous variables in multi-dimensional spaces more naturally and efficiently. The FA has been demonstrated to outperform artificial bees colony algorithm (ABC) in terms of convergence and cost minimization in a statistically meaningful way[30]. The performance of the firefly algorithm 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[31]. The array-failure correction along with null steering is a much more complex problem than simple side lobe reduction in antenna design for a uniformly spaced linear array. In this paper, FA has been successfully applied for linear antenna array failure problem and the antenna pattern has been corrected along with multiple wideband null steering in the desired directions using amplitude and phase control.

2. PROBLEM FORMULATION

For linear array beamforming, one of the three approaches i.e. amplitude-only, phase-only or the amplitude-phase can be employed[32]. It is difficult to compensate the degradation of a damaged array pattern with amplitude-only approach, as the failed elements introduce an asymmetrical aperture distribution. The phase-only approach with constant amplitude requires a large number of array elements to produce low side lobes pattern[33]. Consequently, amplitude-phase approach is used for redistribution of weights of the antenna array to correct the damaged pattern.

The linear antenna array of P identical radiators with a uniform spacing of half a wavelength between different elements is shown in Fig. 1. The array factor (AF) of an arbitrary antenna array can be generally written as,

$$\mathrm{AF} = \mathrm{W}\,\mathrm{S}\left(\phi, \phi_m\right) \tag{1}$$

where

$$W = \{w_1, w_2, w_3 ....w_P\}^T, \quad w_p \in C^{CN}, \quad p = 1,2,...P \tag{2}$$

is the weighting vector, ϕ and ϕ_m are the direction variable and the main beam direction respectively and S is the steering vector. C^{CN} is a subset or the set of the all complex numbers, indicating the weights of elements of linear antenna array.

The steering vector S of linear array of P identical radiators is given as

$$S = \exp\left\{ jkd\left(p - \frac{P-1}{2}\right).(\cos\phi - \cos\phi_m)\right\} \quad p = 1,2,...P \tag{3}$$

where k is the wave vector and d is the spacing between array elements. The p^{th} radiator or element failure of array is done by setting the weight w_p equal to zero in Eqn. (1). The element or radiator failure of antenna array causes the distortion in side lobe level (SLL) and main beam pattern, which is corrected as per original antenna pattern and multiple nulls are generated in desired interference directions by recalculating the amplitude and phase of the non failure elements or radiators using the firefly algorithm.

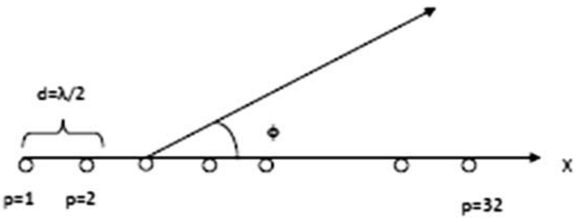

Figure 1. Linear array of identical radiators with a uniform spacing of half a wavelength.

The objective of the work is to restore the SLL of the original pattern and optimize the directivity of the antenna array along with multiple wideband null steering in the desired interference directions. To achieve the objective, a template has been constructed on the basis of the specified SLL, the required shape of the main lobe and the desired multiple suppressed sectors in interference directions as shown in Fig. 2. The designed template is then cast over the antenna array pattern generated by individual solution provided by Firefly Algorithm to evaluate their cumulative difference. The determined cumulative difference is taken as a fitness value of the solution.

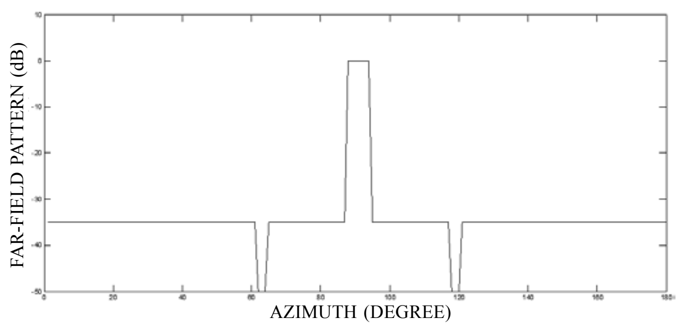

Figure 2. The template to evaluate the fitness value.

3. FIREFLY ALGORITHM

The firefly algorithm (FA) is a nature-inspired algorithm based on the social behavior of firefly swarm. The fireflies show flashing behaviors with different flashing pattern for communication with each other, to find mates and search for pray. The Firefly Algorithm was proposed by Yang[29], in which three idealized rules have been used:

a) All fireflies are unisex and each firefly can be attracted by other firefly irrespective of their sex;
b) Attractiveness of each firefly is proportional to its brightness. For any two flashing fireflies, the firefly with less brightness will move towards the firefly with high brightness. Attractiveness between the two fireflies is proportional to their individual brightness or attractiveness and distance between them;
c) The cost function of the problem is determined by the brightness of a firefly and it can simply be proportional to the brightness for optimization problem.

The pseudo-code for FA is shown in Figure 3 and the steps involved in FA are summarized as under:

Step 1 (Initialization): Initialize the location of *N* fireflies[30] in *Z* dimension space within the space boundary and is given as

$$x_{nz}(0) = rand_{nz}(0,1)(x_{nz}^{U} - x_{nz}^{L}) + x_{nz}^{L}$$
$$n=1,2,3,\ldots N;\ z=1,2,3,\ldots Z \quad (4)$$

where x_{nz}^{U} and x_{nz}^{L} represents the upper and lower limits of the z^{th} variable in the population respectively, $rand_{nZ}(0,1)$ is a uniformly distributed random value within the limit *0* to *1*.

Step 2 (Computation of light intensity of fireflies): In this step, the brightness of each firefly is computed in terms of its cost function at the present location of respective firefly in current generation of FA. For a maximization problem, the light intensity or brightness of firefly is directly proportional and for a minimization problem it is inversely proportional to its cost function.

Step 3 (Updatation of the location of the fireflies): In this step, each firefly moves toward the other firefly with more brightness or light intensity in the population and update its location for the next iteration of the algorithm. The location of each moving firefly in the population is updated based on the attractiveness between the moving firefly and firefly with more light intensity.

The variation of light intensity and formulation of the attractiveness are the two important issues used in the Firefly Algorithm. For simplicity, light intensity is used to calculate the attractiveness of a firefly, which is further used to determine the cost function of the problem. The attractiveness β is a relative term which is judged by the other fireflies and it is change with the distance r_{lm} between firefly *l* and firefly m. In addition, 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 vary with the degree of absorption. In the simplest form, the light intensity *I(r)* changes according to the inverse square law $I(r) = I_s/r^2$ where I_s is the light intensity or brightness at the source. The light intensity *I* varies with the distance *r* i.e. $I = I_0 e^{-\gamma r}$, where I_0 is the original light intensity for a given medium with a constant light absorption coefficient. The combined effect of both the absorption and inverse square law is used to avoid the singularity condition at $r = 0$ in the expression I_s/r^2 and it can be approximated using the Gaussian form $I(r) = I_0 e^{-\gamma r^2}$ as discussed in[29].

We can now define the attractiveness β of a firefly by $\beta(r) = \beta_0 e^{-\gamma r^2}$, where β_0 is the attractiveness at r = 0, because the attractiveness of the firefly is proportional to the light intensity seen by adjacent fireflies. The attractiveness between the two fireflies in Z- dimensional search space is determined as[29,31]:

$$x_l = x_l + \beta_0 e^{-\gamma r_{lm}^2}(x_l - x_m) + \alpha\varepsilon_s \quad (5)$$

where γ is the light absorption coefficient which is fixed for the given medium and its value can varies from 0.01 to 100 depending upon the characteristics of the medium; α is a randomization parameter used to generate randomness in Eqn. (5) and its value vary from 0 to 1; ε_s is a vector of random numbers drawn from a Gaussian distribution or an uniform distribution[31]; the attractiveness between the two fireflies *l* and *m* is represented by the product of β_0 and $e^{-\gamma r_{lm}^2}$ terms. The attractiveness of firefly is given by β_0 *at* Cartesian distance $r = 0$. For simplicity, the value of β_0 is taken unity in most cases of our implementation. The Cartesian distance r_{lm} between any two fireflies *l* and m at x_l and x_m respectively is determined as[29,31]:

$$r_{lm} = \|x_l - x_m\| = \sqrt{\sum_{t=1}^{T}(x_{l,t} - x_{m,t})^2} \quad (6)$$

As per Firefly algorithm, the firefly with highest light intensity is not allowed to move in any direction, while the rest of fireflies change their position according to Eqn. (5) at current generation. In this way, the algorithm gradually updates the global best (g_B) solution in the successive iteration.

Step 4 : Ranking of fireflies and computation of current global best- All the fireflies are ranked based on their light intensity or brightness in the current generation and position of the brightest firefly in the population is taken as current global best (g_B). The brightest firefly has a best fitness value among all the fireflies at the current generation.

Step 5: Repeat the Step 2 to Step 4 until end condition is met by the algorithm as shown in Fig. 3**.** The terminating condition of the algorithm is a condition under which either the total numbers of iterations are completed or desired value of cost function is achieved**.** The location of the best firefly (g_B) provides the best solution and the corresponding brightness of the firefly provide the best fitness value of the objective function using Firefly algorithm.

Initialize the position of *N* fireflies

$$x_{nz}(0) \leftarrow \{x_{1Z}(0), x_{2Z}(0) \ldots x_{NZ}(0)\}$$

Define light absorption coefficient γ

$$g \leftarrow 0$$

while the terminating condition is false **do**

Compute light intensity *I* by

$$\{f(x_{1Z}(g)), f(x_{2Z}(g)) \ldots f(x_{NZ}(g))\}$$

for *l = 1 to N* **do**

for *m = 1 to N* **do**

if ($I_m > I_l$), move firefly *l* toward firefly *m*

end if

Compute the Cartesian distance, $r_{lm} = \|x_l - x_m\|$

Compute attractiveness, $\beta = \beta_0 e^{-\gamma r_{lm}^2}$

Update the position of firefly, $x_l = x_l + \beta(x_l - x_m) + \alpha\varepsilon_s$

end for *m*

end for *l*

Rank the fireflies and computation of current global best

$g \leftarrow g+1$ **end while**

Figure 3. A firefly algorithm.

4. SIMULATION RESULTS AND DISCUSSION

A classic Dolph – Chebyshev 32 elements linear array has been considered with a side lobe level (SLL) of -35 dB. The steering vector S of the linear array is given by Eqn. (3). The above considered linear array having 4 element failure condition with the defective elements are located at 1st, 2nd, 31th and 32th positions has been simulated. Figure 4(a) depicts the original array pattern of linear array system without element failure condition with main beam and a side lobe level of -35 dB. When the elements of the array at the above mentioned locations become defective, the SLL increase to a maximum unacceptable value of -25.08 dB at 82.9° and 97.1° as shown in Fig. 4(b).

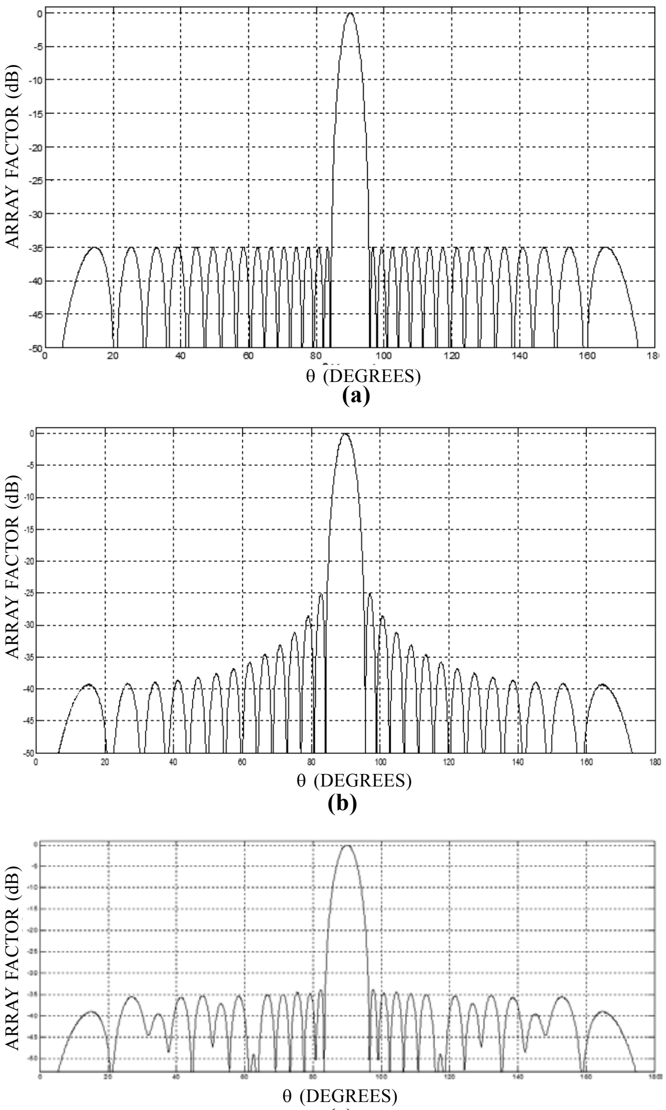

Figure 4. Far field array pattern of 32 elements linear array with main beam at broadside (a) Original, (b) Damaged, and (c) Corrected along with nulls at 62° and 118°.

The firefly algorithm has been implemented in MatLab as per above description. The four FA parameters, i.e., the population size *U,* the light absorption coefficient γ, the attractiveness β and the randomization parameter α are set to values 50, 1, 0.2, and 0.25 respectively. The FA has been run to correct the failed pattern and produce the nulls at the desired direction as per the objective function described in section 2. The Fig. 4(c) depicts the corrected far field array pattern obtained using FA with main beam and nulls, which corrected the SLL value from -25.08 dB to -35 dB and produced nulls at 62° and 118°. The program has been run 15 times for 500 iterations and best result registered. The convergence characteristics shown in Fig. 5 indicate that the FA algorithm converges in around 230 generations.

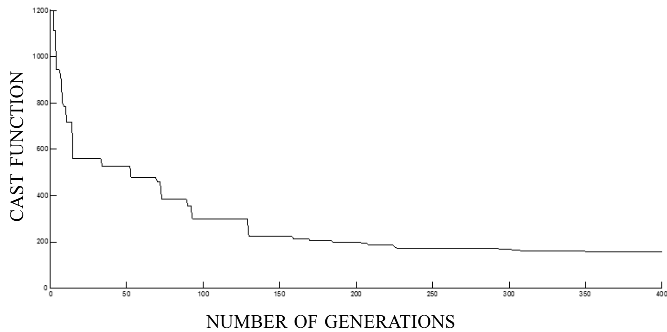

Figure 5. Cost function progress curve.

The beamwidth of original, damaged and corrected patterns have been observed 4.2°, 4.6°, and 4.8°, respectively. The directivity of an antenna array is a figure of merit which determines the power density of the antenna system radiates in the direction of its strongest emission. 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 Fig. 6(a), which is distorted by the failed elements of the array design to 13.88 dB and -11.2 dB of main lobe and side lobes respectively as shown in Fig. 6(b). Figure 6(c) shows the recovery of directivity to 13.6 dB of main lobe and -20.13 dB of side lobe along with two null steered at 62° and 118° by FA.

Similarly, the original, damaged array pattern of linear array with main beam shifted at 49° and 131° is shown in Figs. 7(a) - 7(d). The corrected pattern of linear array with main beam shifted at angle 49° along with nulls steered at angle 22° and 77° is shown in Fig. 7(e). Figure 7(f) depicts corrected

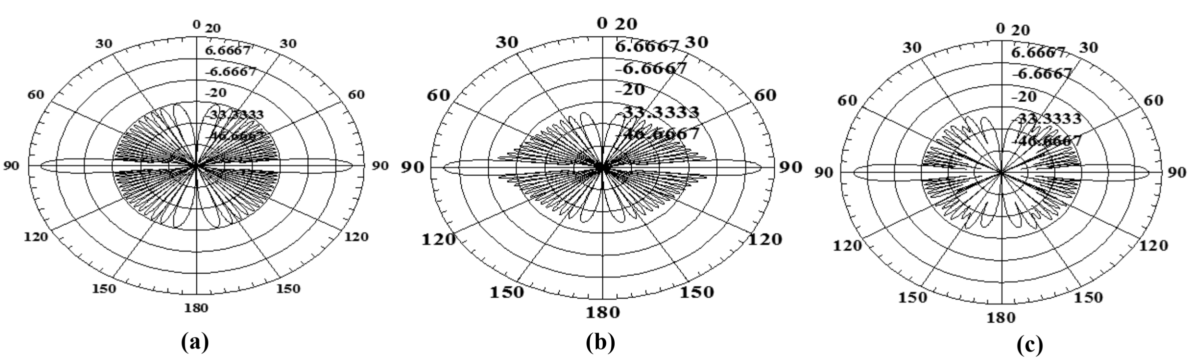

Figure 6. Directivity pattern with main beam (a) Original, (b) Damaged, and (c) Corrected along with nulls at 62° and 118°.

linear array pattern with main beam shifted at 131° with nulls produced at 103° and 158°. The normalized excitation coefficients of original linear antenna array, antenna array with 4 element failure conditions without optimization and antenna array with 4 element failure condition with optimization using FA are listed in Table 1. It has to be noted that the damaged condition of antenna array element is represented by 0 in different columns of Table 1.

It is not necessary to have null steering symmetric to the main beam. In this work, the code is written in such a way that null steering remains symmetric around main lobe. Asymmetric null steering can be done by changing the logic of the program.

5. CONCLUSIONS

The field pattern of high performance digital beamforming array antenna systems can be seriously degraded with the malfunctioning of antenna elements. In such condition, it is a big challenge to steered nulls in the desired direction along with restoration of the original pattern of antenna array. In this paper, the Firefly algorithm is proposed for solving a practical problem of linear antenna array system by re-optimizes the amplitude and phase excitations of the remaining elements to recover the original pattern of the antenna array and produced nulls in the desired direction. The proposed method proved its effectiveness to suppress the side lobe level and introduction of nulls in the field pattern of antenna array in presence of antenna element failures. The work can be extended to locate the faulty elements and determine its position in the array. Also the mutual coupling of the elements can be added in the analysis process. This method can be extended to planar or conformal antenna arrays.

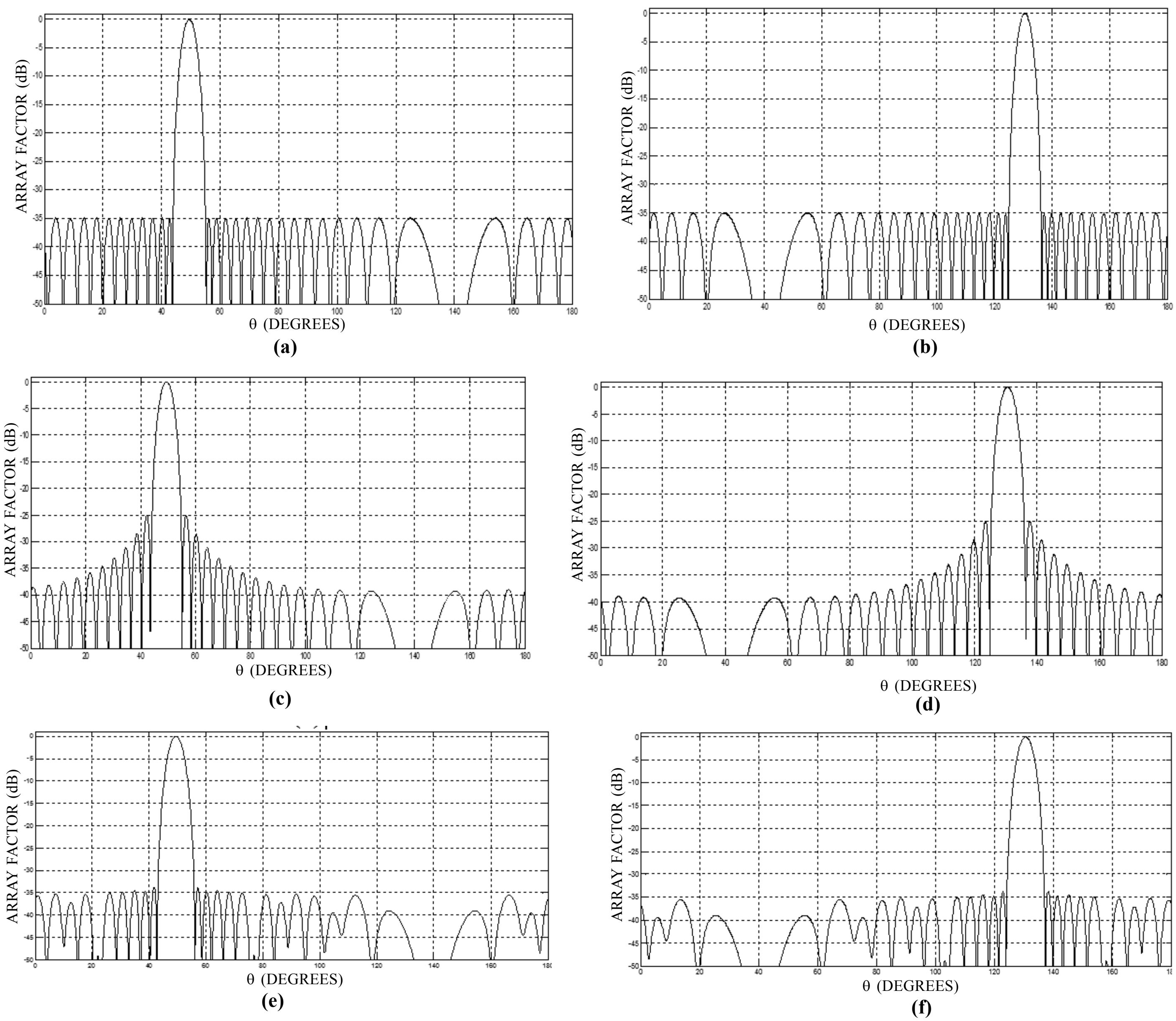

Fig. 7: Far field pattern linear array with main beam pointing at an angle (a) Original at 49°, (b) Original at131°, (c) Damaged at 49°, (d) Damaged at 131°, (e) Corrected at 49° with nulls at 22° and 77°, (f) Corrected at 131° with nulls at 103°and 158°.

Table 1. Normalized excitation coefficient for corrected radiation pattern of 32 elements linear array with null steering 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	0.7801-j*0.0092
2	0.1774	0	0	18	0.9863	0.9863	0.7787-j*0.0001
3	0.2341	0.2341	0.1530-j*0.0041	19	0.9594	0.9594	0.7677-j*0.0171
4	0.2976	0.2976	0.1506-J*0.0091	20	0.9202	0.9202	0.6926+j*0.0010
5	0.3669	0.3669	0.2042-j*0.0027	21	0.8700	0.8700	0.6549+j*0.0
6	0.4406	0.4406	0.2715+j*0.0086	22	0.8103	0.8103	0.5976-j*0.0016
7	0.5170	0.5170	0.3168-j*0.0116	23	0.7431	0.7431	0.5428-j*0.0017
8	0.5943	0.5943	0.3786+j*0.0023	24	0.6703	0.6703	0.4681-j* 0.005
9	0.6703	0.6703	0.4681-j* 0.005	25	0.5943	0.5943	0.3786+j*0.0023
10	0.7431	0.7431	0.5428-j*0.0017	26	0.5170	0.5170	0.3168-j*0.0116
11	0.8103	0.8103	0.5976-j*0.0016	27	0.4406	0.4406	0.2715+j*0.0086
12	0.8700	0.8700	0.6549+j*0.0	28	0.3669	0.3669	0.2042-j*0.0027
13	0.9202	0.9202	0.6926+j*0.0010	29	0.2976	0.2976	0.1506-J*0.0091
14	0.9594	0.9594	0.7677-j*0.0171	30	0.2341	0.2341	0.1530-j*0.0041
15	0.9863	0.9863	0.7787-j*0.0001	31	0.1774	0	0
16	1.0000	1.0000	0.7801-j*0.0092	32	0.2503	0	0

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