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Failure Correction of Linear Antenna Array by Changing Length and Spacing of Failed Elements

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Abstract—This paper presents a new approach for linear antenna array failure correction using geometry optimization of the failed antenna elements. It is done by changing the length and spacing of failed elements while the spacing and length of remaining elements are fixed. The flower pollination algorithm based on the characteristic of flowering plants has been used to correct the radiation pattern of linear antenna array with desired side lobe level and minimum return loss. Simulations are performed using Matlab. Two examples are given to show the effectiveness of the proposed method. In addition, the obtained results from simulation on Matlab are also validated by the results obtained from FEKO analysis.

1. INTRODUCTION

Linear antenna array [1, 2] is used to generate highly directive radiation pattern, which is very useful in many applications, such as telecommunications and radar. When the equally spaced antenna array is excited uniformly, it will produce high directive radiation pattern but will also generate relatively higher side lobe level. The side lobe level will worsen, in case of failure of even two or three elements in an antenna array, and specifically in analog beam forming; it will lead to the replacement of the elements, which results in time consumption. The scenario will be different in digital beamforming, because the failed elements are not required to be changed. Instead, the beamforming weights of the remaining unaffected elements can be modified in such a way that the resulting radiation pattern closely matches with the expected pattern. Till date, literature survey reveals that different techniques have shown their own merits and demerits over others in array failure correction.

Techniques for failure correction of an antenna array to restore the original pattern by changing the excitation amplitude of the antenna elements are detailed in [3–8]. Antenna array failure correction by genetic algorithm has been detailed in [3, 4]. A method for array failure correction with digitally beamforming using linear symmetrical array has been described in [5]. Antenna array failure correction using firefly, differential search and improved bat algorithm is discussed in [6–8]. A comprehensive study of the mutual coupling that exists in antenna arrays has been discussed by various researchers [9–11]. Methods for array failure correction of linear array antenna in presence of mutual coupling effect are detailed in [12, 13]. However, techniques to generate the original pattern by changing the excitation amplitudes are not cost effective and also provide complexity in their feeding network. Techniques for synthesis of non-uniformly spaced antenna arrays have been discussed by various researchers in [14–17]. Synthesis of circular antenna arrays with sparseness characteristics, sparse concentric rings array for LEO satellites and circular antenna arrays for reduction of side lobe level are detailed in [14–16]. Ref. [17] reports a method to correct the damaged pattern in the presence of faulty elements by changing the element position of the antenna elements for linear antenna array. In this paper, we provide an alternative method to generate the original pattern for failure correction in linear antenna array: only

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by changing the length of failed element and spacing of failed element. Currents across the failed and non-defective array elements are calculated using the induced EMF method which considers mutual coupling between the elements of an array. Matlab software has been used for simulation and to evaluate the performance of the antenna array failure correction using optimization process generated by flower pollination algorithm [18–21].

Here, we use FPA algorithm because it provides better results than other algorithms in many antenna design problems [19–21]. FPA provides better results in synthesis of non-uniformly spaced antenna array than other algorithms to obtain low side lobe level with placement of deep nulls [19, 20] and to achieve low side lobe level under both no beam scanning and beam scanning conditions [21].

In addition, this paper also presents a validation of obtained results from simulation using FEKO Software. FEKO [22] is a comprehensive electromagnetic software tool. The software is based on the Method of Moments (MoM).

2. MAJOR CONTRIBUTION OF THE PROPOSED WORK

In the introduced work, linear antenna array failure correction is done using length and spacing of failed elements. The proposed technique is different from [3–8, 12, 13] in the sense that the authors here considered only the length and spacing of failed elements as design variables to obtain the corrected radiation pattern with desired requirements. Moreover, this technique is different from [3–8, 17] in the sense that authors here considered real antennas including mutual coupling effect. In addition, coupling effect is also compensated by minimizing the return loss of the antenna elements with corrected pattern. Here, the obtained results from simulation are also validated using FEKO Software.

3. THEORY

We have considered two different examples of linear array of parallel dipole antennas. Dipoles are parallel to Z-axis and placed along the X-axis, as shown in Fig. 1. Here, original pattern as well as

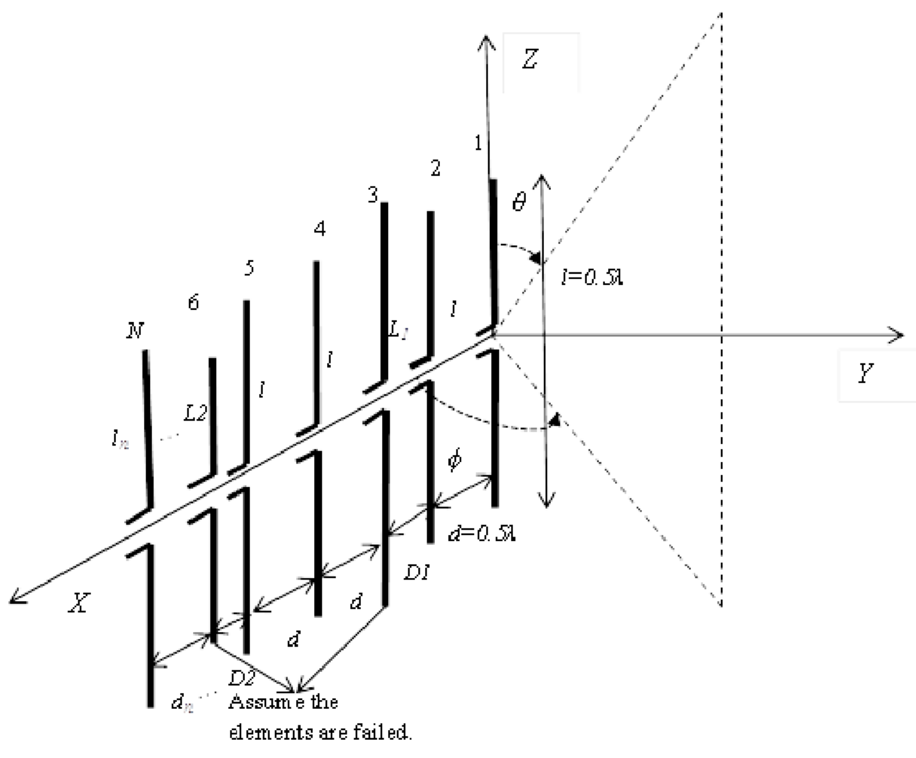

Figure 1. Geometry of a linear array with failed and non-defective element.

other parameters in the presence of failed elements is restored by changing the length and spacing of failed elements. The length and spacing of the remaining elements are fixed. In fact, changing the spacing and length of failed elements modifies the position of failed and non-defective elements and length of failed elements, and as a result, currents across both failed and non-defective elements are modified owing to the mutual coupling effect. Failure of a dipole antenna implies that the voltage excitation across it is zero, but the current flowing through it is not zero because of induced current due to mutual coupling, and it behaves as a parasitic radiator. Far-field pattern computed in X-Y plane requires evaluation of the current amplitudes. It is calculated by the matrix equation [10]:

$$[I] = [Z]^{-1}[V] \tag{1}$$

where $[V]$ is the vector of voltages applied to the antenna elements. V is known in the case of corrected pattern. Voltages are kept zero for failed elements, and the remaining elements are excited by unit voltage. $[I]$ is the vector of complex current excitations of both the failed and non-defective elements, and $[Z]$ is the mutual impedance matrix. The self and mutual impedances are calculated by induced Electro-Motive Force method, assuming a sinusoidal current distribution on each dipole. The integration is solved using 16-Point Gauss-Legendre quadrature integration formula. The expression for the far-field pattern $\mathrm{FFP}(\theta, \phi)$ of linear array design incorporating the coupling effects is given by:

$$\mathrm{FFP}(\theta, \phi) = \left[\sum_{n=1}^{N} I_n \exp^{jkd_n \sin(\theta)\cos(\phi)}\right] \cdot \mathrm{ELP}(\theta) \tag{2}$$

where I_n is the complex current of the nth dipole placed along X-axis. N is the total number of antenna elements, $k = 2\pi/\lambda =$ wave number, $\lambda =$ wavelength. θ measured from Z-axis is the polar angle, and φ is the azimuth angle of the far-field measured from X-axis (0° to 180°), $d_n =$ distance from origin to centre of n-th dipole. $\mathrm{ELP}(\theta)$ is the element pattern of each Z-directed vertical dipole antenna. The element pattern is given below considering $\theta = 90^\circ$ for horizontal plane:

$$\mathrm{ELP}(\theta) = \frac{\cos\left(\dfrac{kl_n \cos(\theta)}{2}\right) - \cos\left(\dfrac{kl_n}{2}\right)}{\sin(\theta)} \tag{3}$$

where l_n is the length of n-th dipole antenna. This section also presents additional desired features, namely the minimization of return loss of the n-th dipole elements, when the corrected radiation pattern is generated. The active impedances [10] of the array elements, Z_n^A, are given by:

$$Z_n^A = |V_n/I_n| \tag{4}$$

where V_n and I_n are the voltage and current across the dipole n. Consider that the characteristic impedance (Z_o) of the network involved in feeding is 50 ohms; the return loss (RL) at the input of the n-th dipole element [12] is given in dB by:

$$\mathrm{RL}_n = -20\log_{10}\left[\frac{|Z_n^A| - Z_o}{|Z_n^A| + Z_o}\right] \tag{5}$$

In the end, the minimum return loss ($\mathrm{RL}_{\min}$) among all elements is derived. The objective is now to find the set of length and spacing of failed elements using FPA that will minimize the following fitness function.

$$\mathrm{fitness} = \sum_{i=1}^{2} wet_i \times F_i^2 \tag{6}$$

where

$$F_1 = \begin{cases} \mathrm{SLL}_{ob} - \mathrm{SLL}_{de}, & \text{if } \to \mathrm{SLL}_{ob} > \mathrm{SLL}_{de} \\ 0, & \text{if } \to \mathrm{SLL}_{ob} \leq \mathrm{SLL}_{de} \end{cases} \tag{7}$$

$$F_2 = \begin{cases} \mathrm{RL}_{ob}^{\min} - \mathrm{RL}_{de}^{\min}, & \text{if } \to \mathrm{RL}_{ob}^{\min} > \mathrm{RL}_{de}^{\min} \\ 0, & \text{if } \to \mathrm{RL}_{ob}^{\min} \leq \mathrm{RL}_{de}^{\min} \end{cases} \tag{8}$$

The coefficients wet_1 and wet_2 are the weights applied to each term in Eq. (6). SLL and RL are the values of side lobe level and return loss, respectively. Suffixes *ob* and *de* refer to obtained and desired values.

4. FLOWER POLLINATION OPTIMIZATION ALGORITHM

FPA [18–21] is evolved by X.-S. Yang using the property of flower pollination. Its property described by four rules is given below:

1. We can consider biotic and cross-pollination procedure for global pollination procedure, and the motion of pollen is similar to Levy flight motion.
2. Abiotic and self-pollination are applied to local pollination procedure.
3. Insects can evolve the flower constancy, a type of pollinators. It is similar to breeding probability comparable to the equality of two flowers involved.
4. We can control the interaction between local pollination and global pollination through a switch probability $p \in [0, 1]$.

For execution approach in algorithm, a set of upgrading formulae are required for updating equations by changing the rules. In the global pollination step, flower pollen gametes are transferred by insects which can travel up to long distance. Accordingly mathematical representation of flower consistency is described as:

$$Y_i^{t+1} = Y_i^t + \delta H(Y_i^t - Y_*), \tag{9}$$

where, Y_i^{t+1} is the vector of solution Y_i at generation t, Y_* the present optimum solution, and δ is a scaling factor and controls the step size. H is the power of pollination, which refers the step size. Insects can travel a long distance with different distance steps, so we can use a Levy flight to imitate this specialty efficiently. Therefore, Levy distribution is considered from $H > 0$.

$$H \sim \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{S^{1+\lambda}} \quad S \gg S_0 > 0 \tag{10}$$

$\Gamma(\lambda)$ is the gamma function in Eq. (10). It is valid for large steps $S > 0$. Rule 2 and 3 can be described as:

$$Y_i^{t+1} = Y_i^t + \varepsilon(Y_j^t - Y_k^t) \tag{11}$$

Equation (11) is utilized to model the local pollination, where Y_j^t and Y_k^t are pollen from different flowers of the same plant species. This is essential to mimicking the flower consistency in a limited

- *Initialize a population of* n *flowers/gametes with random solutions, switch probability and maxgeneration*
- *Find the best solution* Y_* *in initial population*
- **While** ($t <$ *maxgeneration*)

    for $i = 1$:n

    if rand < *switch probability*

    Draw a step vector H that obeys Levy distribution using equation

    $$Y_i^{t+1} = Y_i^t + \delta H(Y_i^t - Y_*),$$

    else

    Draw ϵ *from a uniform distribution in* [0, 1].

    Randomly choose j and k among solution and undergo local pollination using

    $$Y_i^{t+1} = Y_i^t + \varepsilon(Y_j^t - Y_k^t)$$

    end if

    Evaluate new solutions

    Update them if they are better

    end for

    Find Y_*

    end while

Figure 2. Summary of flower pollination algorithm.

neighborhood. Mathematically, if Y_j^t and Y_k^t are selected from the same population, then it is identical to a local random walk if we draw ε from a uniform distribution in [0, 1]. Pollination occurs better in a flower from the neighboring flower than by the faraway flowers. For this, a switch probability $p = 0.555$ is employed for switching between global pollination and local pollination (rule 4). The following algorithm [18] summarizes the complete FPA algorithm.

All the steps used in flower pollination algorithm are given in Fig. 2.

5. NUMERICAL EXAMPLES

5.1. Simulation

In examples, 15- and 25-element linear arrays placed along X-axis are considered. The original pattern for both the examples without any failed element is generated by changing the excitation amplitude of the antenna elements, as done in previous papers [3–8, 12, 13]. For original pattern, length and spacing of antenna elements are 0.5λ. Radius of the dipoles is 0.003λ.

We arbitrarily choose the third element ($V3 = 0$), eighth element ($V8 = 0$) and thirteenth ($V13 = 0$) element to be faulty for example1 (15 elements linear array) and similarly second element ($V2 = 0$), fifth element ($V5 = 0$), fifteenth element ($V15 = 0$), and twenty-second ($V22 = 0$) element to be faulty for example2 (25 elements linear array). The far-field pattern of the defected array is made by setting the voltage excitation of failed elements to zero in the voltage excitations of the original pattern.

Now the corrected patterns for both the examples are obtained only by changing the length (L) and spacing (D) of failed elements (the design variables) using FPA. In our case, FPA is run for 400 iterations for example1 and 600 iterations for example2 with a population size of 60. Length and spacing of non-defective elements are fixed, and they are given by spacing (d) = 0.5λ and length (l) = 0.5λ as shown in Fig. 1. Non-defective elements are excited by unit voltage.

5.2. FEKO Assessment

The basic flow of performing a FEKO analysis:

1. Build the antenna array geometry and surrounding geometry in CADFEKO.
2. Meshing of designed antenna array and the surrounding geometries.
3. Request for types of solution and setting solution parameters, run the FEKO solver, read in and illustrate the results using PostFEKO.

All the steps are detailed in FEKO tutorial [22]. Now, the far-field pattern is generated in PostFEKO. Fig. 3 shows the constructing geometry of antenna array on CADFEKO.

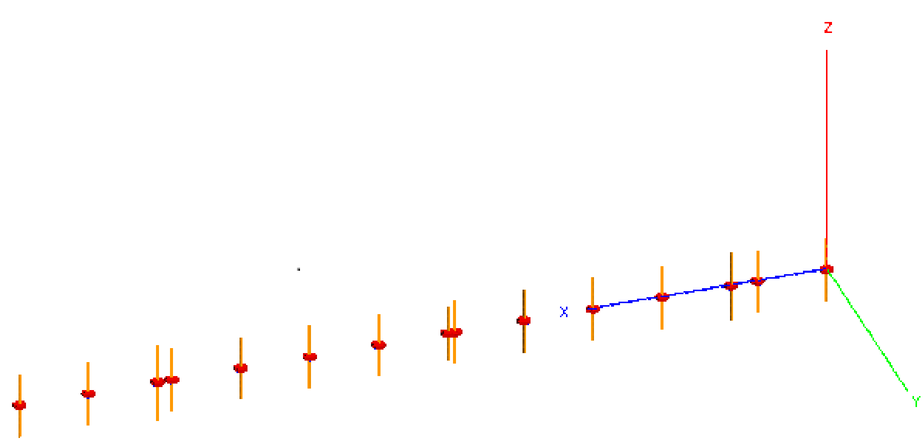

Figure 3. Constructing geometry of linear antenna array along x-axis on CADFEKO.

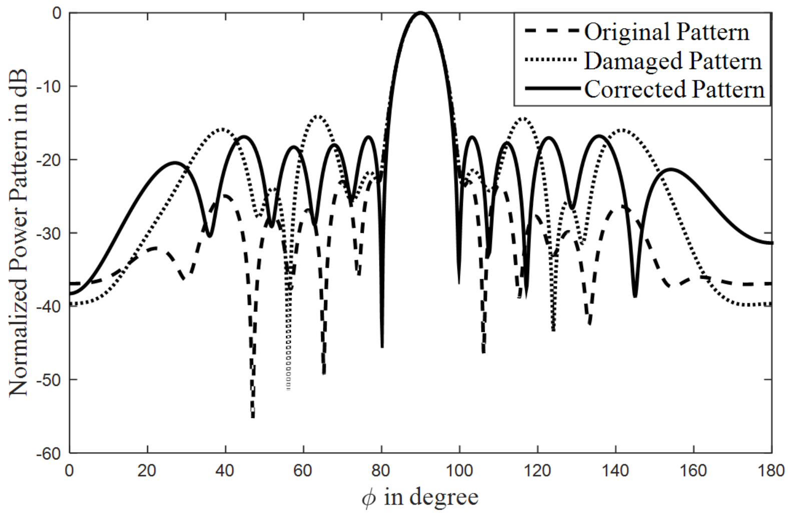

Figure 4. Normalized power pattern in dB for example1.

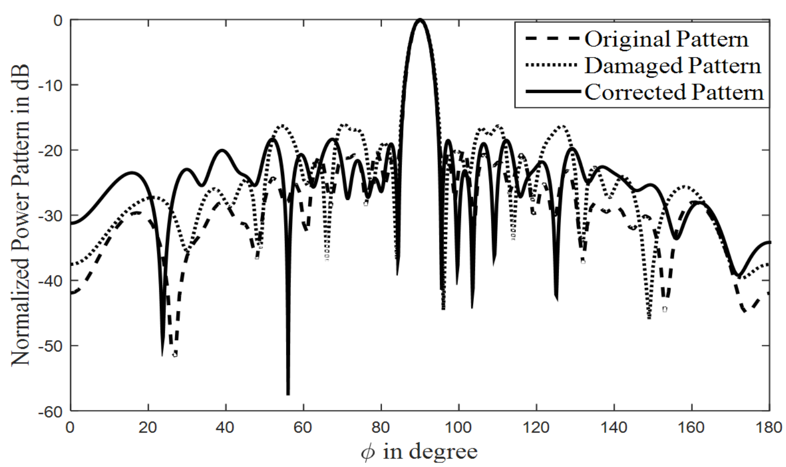

Figure 5. Normalized power pattern in dB for example2.

Obtained original, damaged and corrected power patterns for example1 at $\theta = 90$ degree are depicted in Fig. 4. It is assumed that $\text{wet}_1 = \text{wet}_2 = 1$ (equal importance is given to both SLL and RL) for original pattern in both examples and corrected pattern for example1. For corrected pattern of example2, these values are $\text{wet}_1 = 3$ and $\text{wet}_2 = 1$.

Obtained original, damaged and corrected power patterns for example2 at $\theta = 90$ degrees are shown in Fig. 5. The spacing of failed elements is allowed to vary between 0.05λ and 1λ for example1, and 0.04λ and 1λ for example2, and the length of failed elements is allowed to vary between 0.4λ and 0.7λ for both examples. Table 1 shows the desired and obtained values for original, damaged and corrected patterns.

Program is written and executed in MATLAB. The computational time iss measured with a PC with Intel(R) Core(TM) i5-4690 processor of clock frequency 3.50 GHz and 4 GB of RAM. Measured computational time for corrected pattern (example1 and example2) is 6239.80 seconds and 24781.55 seconds. Fig. 6 and Fig. 7 show the value of voltage excitations for original pattern. Table 2 and Table 3 show the length and spacing of antenna elements (in λ) for corrected pattern. Length and spacing of failed elements are highlighted with bold text. Length and spacing of antenna elements obtained from Table 2 and Table 3 are used to create the geometry of antenna array on CADFEKO.

Table 1. Desired and obtained results.

Design parameters	Desired values	original pattern		damaged pattern		corrected pattern	
		Example1	Example2	Example1	Example2	Example1	Example2
Side Lobe Level (dB)	−20	−22.7837	−20.0545	−14.1177	−16.0612	−16.8002	−18.3400
Minimum Return Loss (dB)	15	17.6962	15.1705	14.7817	12.6066	14.8181	13.7856

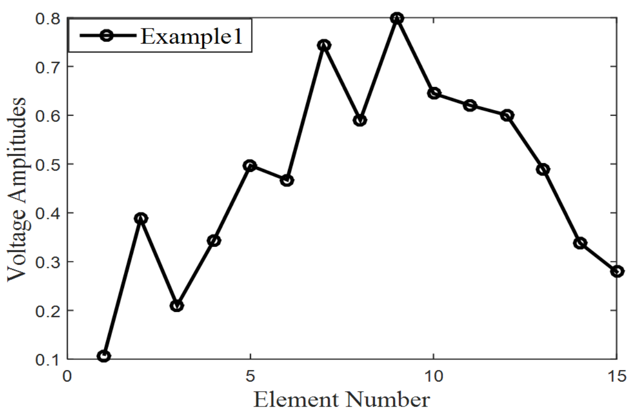

Figure 6. Voltage amplitudes for original pattern.

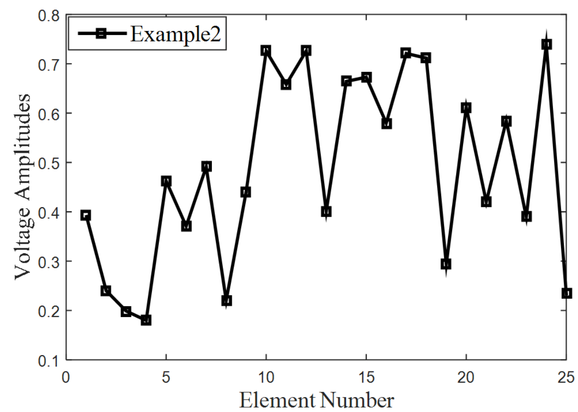

Figure 7. Voltage amplitudes for original pattern.

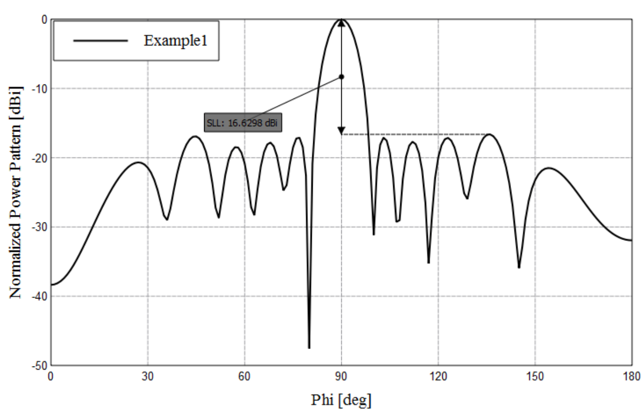

Figure 8. Normalized power pattern in dB obtained from FEKO.

For validation of the results, unit voltage for non-defective elements and zero voltage for failed elements are considered as voltage excitations during FEKO analysis. Fig. 8 and Fig. 9 show the corrected pattern obtained from FEKO. Minimum return loss among all the antenna elements obtained from FEKO (example1 and example2) is 11.10 dB and 9.8 dB.

From the obtained pattern using simulation (Fig. 4 and Fig. 5) and FEKO (Fig. 8 and Fig. 9), it is observed that the objective to generate the corrected pattern with desired side lobe level has been achieved, and the error is less in obtained pattern from simulation and FEKO analysis. A better match

Table 2. Antenna height and spacing for the array (example1).

Element Number	Length of Antenna (in λ)	Spacing (in λ)	Element Number	Length of Antenna (in λ)	Spacing (in λ)
1	0.5000	0.0000	9	0.5000	0.5000
2	0.5000	0.5000	10	0.5000	0.5000
3	***L1*** **0.5375**	***D1*** **0.1910**	11	0.5000	0.5000
4	0.5000	0.5000	12	0.5000	0.5000
5	0.5000	0.5000	**13**	***L3*** **0.6045**	***D3*** **0.1016**
6	0.5000	0.5000	14	0.5000	0.5000
7	0.5000	0.5000	15	0.5000	0.5000
8	***L2*** **0.4289**	***D2*** **0.0500**			

Table 3. Antenna height and spacing for the array (example2).

Element Number	Length of Antenna (in λ)	Spacing (in λ)	Element Number	Length of Antenna (in λ)	Spacing (in λ)
1	0.5000	0.0000	14	0.5000	0.5000
2	***L1*** **0.4713**	***D1*** **0.6150**	**15**	***L3*** **0.6280**	***D3*** **0.0430**
3	0.5000	0.5000	16	0.5000	0.5000
4	0.5000	0.5000	17	0.5000	0.5000
5	***L2*** **0.4695**	***D2*** **0.3523**	18	0.5000	0.5000
6	0.5000	0.5000	19	0.5000	0.5000
7	0.5000	0.5000	20	0.5000	0.5000
8	0.5000	0.5000	21	0.5000	0.5000
9	0.5000	0.5000	**22**	***L4*** **0.5017**	***D4*** **0.5050**
10	0.5000	0.5000	23	0.5000	0.5000
11	0.5000	0.5000	24	0.5000	0.5000
12	0.5000	0.5000	25	0.5000	0.5000
13	0.5000	0.5000			

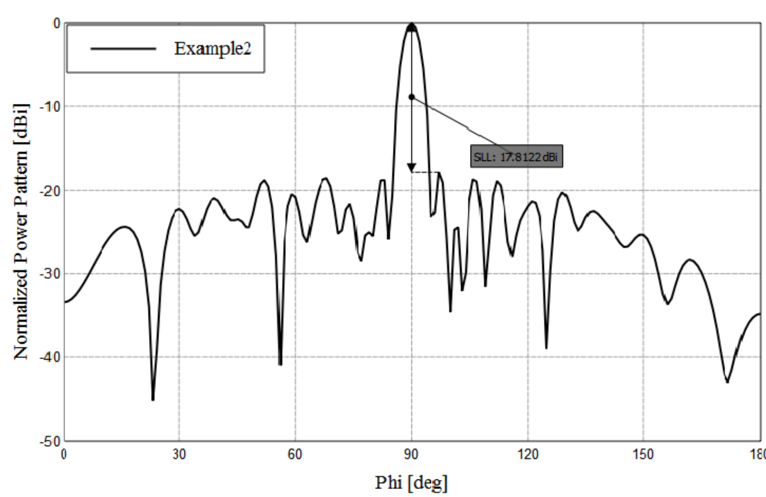

Figure 9. Normalized power pattern in dB obtained from FEKO.

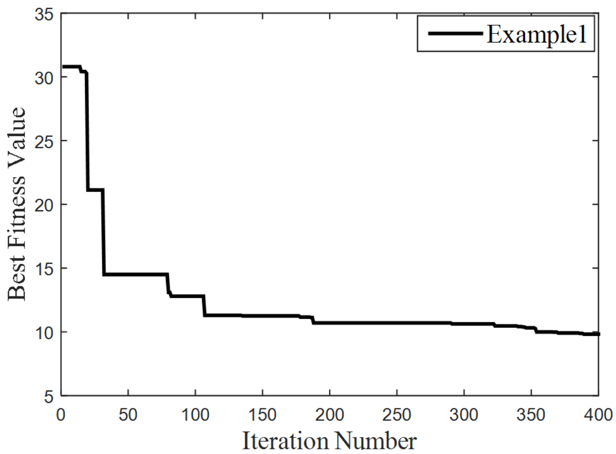

Figure 10. Best fitness value versus iterations for corrected pattern.

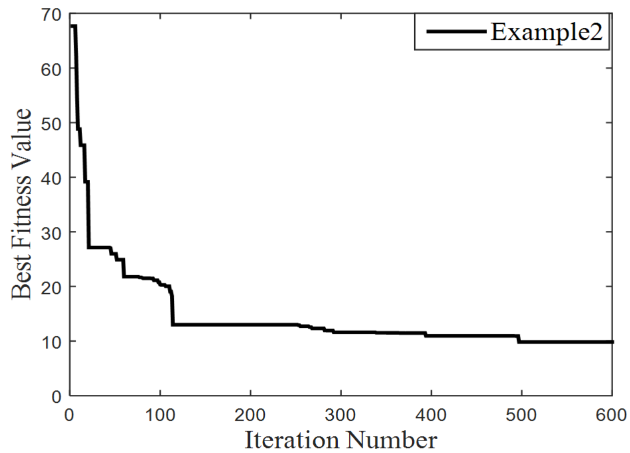

Figure 11. Best fitness value versus iterations for corrected pattern.

between antenna and feed network is provided by minimizing the return loss of the antenna elements. Obtained values of return loss from simulation and FEKO analysis show that matching is well under control for all the antenna elements of an array. Figs. 10 and 11 show the global best fitness value versus iteration number obtained using FPA for both examples.

6. CONCLUSIONS

This paper presents a new technique for linear antenna array failure correction using geometry optimization of the failed antenna elements including mutual coupling effect. This technique is better than the previous techniques where excitation amplitudes are required for failure correction of antenna array. The introduced technique is a cost effective method because it does not require additional attenuators or phase shifters. In addition, this technique reduces the computational complexity in large antenna array problem where failure correction of some elements require modification of all unfailed elements excitation. Two examples have been shown to illustrate the results obtained by this approach. Obtained results show the effectiveness of the proposed approach. For validating the obtained results, FEKO is successfully utilized here to generate the corrected power pattern. Results obtained from simulation and FEKO analysis nearly match each other. This method works well for different antenna elements. This technique can be extended to other antenna array configurations including the ground plane effect.

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