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Firefly Algorithm for Failure Correction of Linear Array of Dipole Antennas in Presence of Ground Plane with Mutual Coupling Effects

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***Abstract* ─** In this paper, firefly algorithm is utilized for the correction of radiation pattern of a linear antenna array of parallel half-wavelength dipole antennas spaced uniformly when defected completely with more than one dipole element. Mutual coupling between the antennas along has been considered along with the effect of distance between the antenna array and the ground plane on the radiation pattern. Adjustments are done in the values of the excitation voltage of the remaining non-defective elements through evolutionary algorithm such that the parameters, namely, side lobe level and maximum reflection coefficient (S_{11}) in dB of the corrected pattern are calculated and efforts are taken to make it closer to the original pattern values. This certainly avoids replacing of defective elements. The element pattern of individual elements in the array has been assumed omnidirectional in the plane considered. Examples are shown to produce the response of the proposed approach using evolutionary algorithm for three element failures out of twenty elements in the array with the effect on various distances between the antenna array and ground plane. Even though, the method is utilized here for a linear dipole antenna array, it can be applied for other antenna array configurations also.

***Index Terms* ─** Antenna array, failure correction, mutual coupling, reflection coefficient, side lobe level.

I. INTRODUCTION

High directivity is one of the major advantages of equally spaced linear antenna array [1,7] over individual elements, when it is excited uniformly. But, this will well result in production of relatively higher side lobe level (SLL), which in a radiation pattern refers to the ratio of the amplitude of the peak of main lobe to that of peak of the side lobe in decibels. The level of 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 resulting in time consumption. The scenario will be different in digital beam forming, as there is no need to replace the defective elements. Instead, the current or voltage excitations of the remaining unaffected elements can be modified in such a way that the resulting radiation pattern closely matches with the expected pattern. Literature survey has revealed that this alternative of replacement proved quite applicable in various field of operations like radar, satellite and in military applications. There is no single method or a combination of methods that has been evolved as the best one, which can produce a radiation pattern that exactly matches with the desired one.

Literature survey reports many array failure correction techniques in the past [2-6]. Array failure correction using genetic algorithm has been described in the article [2,3]. Array failure correction with a digitally beamformed array is discussed in [4]. Failure correction method of array in general is presented in [5]. Simulated annealing technique [6] is applied to optimize the performance of arrays with failed elements.

An exhaustive study of the mutual coupling that exists in antenna arrays has been discussed by researchers dealing with various applications of antenna arrays [7-11]. In this paper, firefly algorithm [12,13] is used in recovering the damaged pattern with expected side lobe level and reflection coefficient (S_{11}) in dB respectively.

Instead of using isotropic antennas for testing, here, the real antennas with mutual coupling has been considered for various distances between the ground plane and the array. The reason for optimizing reflection coefficient (S_{11}) in dB is to have a better match between antenna and its feeding network. When the antenna is considered a faulty one, the voltage across it is assumed

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as zero, but the current flowing through it is not zero because of induced current due to mutual coupling or in other words, it will act as a parasitic radiator.

II. THEORY

The free space far-field pattern $FAR(\phi)$ in azimuth plane (x-y plane) for a linear array [1] of parallel half-wavelength dipole antennas equally spaced at a distance d apart along the x-axis shown in Fig. 1, is given by Equation (1):

$$FAR(\phi) = \left[\sum_{n=1}^{N} I_n e^{j(n-1)kd\cos\phi} \right] \times EP(\phi), \quad (1)$$

where n=element number, N=total number of element, j=imaginary quantity, d=inter element spacing, k=2π/λ=wave number, λ=wavelength, ϕ=azimuth angle of the far-field point measured from x-axis (0 to 180 degree), I_n=complex excitation current of n-th element, obtained from $[I]_{N\times 1}=[Z]^{-1}_{N\times N}\,[V]_{N\times 1}$, being $[Z]$ the impedance matrix (size NxN) and $[V]$ the voltage matrix (size Nx1) of the elements (obviously V_n=0 for faulty element).

The expressions related to self-impedances Z_{nn} and mutual impedances Z_{nm} in the impedance matrix Z are taken from [7] and applied assuming the dipoles to be very thin and sinusoidal current distribution in every dipole, the former being calculated specifically with Tai's formula [7].

All the elements are fed with constant excitation phase of zero degree. The element pattern of each and every dipole element in the array has been assumed omnidirectional in the plane considered, i.e., $EP(\phi)$=1.

A sum pattern is generated in the broadside direction for the currents I_n that are calculated from the input voltage excitations and the mutual coupling impedance matrix.

If the active impedance is real, every dipole will be radiating effectively, but since,

$$V_n = Z_{nn} I_n + \sum_{m\neq n} Z_{nm} I_m, \quad (2)$$

where Z_{nn} is the self-impedance of dipole n and Z_{nm} is the mutual impedance between dipoles n and m, the active impedance ($Z_n^A=V_n/I_n$) becomes:

$$Z_n^A = Z_{nn} + \sum_{m\neq n} Z_{nm}(I_m / I_n). \quad (3)$$

When a ground plane is placed at a distance h behind the array, and parallel to x-z plane, the image principles [7] are applied to calculate the self and mutual impedances of the elements and to calculate the new impedance matrix of the antenna array.

In the impedance matrix, self-impedance Z_{nn} is replaced by (Z_{nn}–Z_{nn}^{*}) and mutual impedance Z_{nm} is replaced by (Z_{nm}–Z_{nm}^{*}), where Z_{nn}^{*} is the mutual impedance between the nth dipole and its image, and Z_{nm}^{*} is the mutual impedance between the nth dipole and the image of the mth dipole.

The expression for the element factor is also obtained from [7].

The far-field pattern (in ϕ-domain) in the horizontal plane in the above case is given by equation (4):

$$FAR(\phi) = \sum_{n=1}^{N} \left[\sin(kh\sin\phi)\right] I_n e^{j(n-1)kd\cos\phi}, \quad (4)$$

where h is distance between ground plane and array and the bracketed term in above equation is the element factor.

Considering that the characteristic impedance Z_0 of the feeding network is 50 Ω, the reflection coefficient (S_{11}) in dB at the input of n-th dipole antenna [1] is given by:

$$S_{11}^{n} = 20\log_{10}\left[\frac{\left|Z_n^A\right| - Z_0}{\left|Z_n^A\right| + Z_0}\right]. \quad (5)$$

Finally, the maximum reflection coefficient (S_{11}^{m}) among all elements is derived. A low value of S_{11}^{m} ensures that the impedance matching condition holds good for all the elements of the array. The active impedance of failed element is assumed zero.

The problem is now to find the set of new excitation voltage amplitude of the elements excluding the failed elements using firefly algorithm that will minimize the chosen fitness function and at the same time correct the damaged pattern.

For obtaining the optimized (original) radiation pattern without any failures, the following cost function $F1$ is used:

$$F1 = k1(SLL_o - SLL_d)^2 H(T1). \quad (6)$$

For obtaining the failure corrected pattern,

$$F2 = k1(SLL_o - SLL_d)^2 H(T1) + k2(S_{11}^{mo} - S_{11}^{md}) H(T2), \quad (7)$$

is used, where $T1=(SLL_o - SLL_d)$ and $T2=(S_{11}^{mo} - S_{11}^{md})$. $H(T1)$ and $H(T2)$ denotes the Heaviside step functions, which can be can be expressed as follows:

$$H(Ti) = \begin{cases} 0, & if\ Ti < 0 \\ 1, & if\ Ti \geq 0 \end{cases}, \quad (8)$$

for i=1 and 2.

In Equations (6) and (7), SLL_o is the obtained side lobe level and SLL_d is the desired side lobe level in dB, S_{11}^{mo} denotes the maximum obtained reflection coefficient in dB and S_{11}^{md} denotes the desired maximum reflection coefficient in dB, $k1$ and $k2$ are weighting coefficients to control each of the terms of Equations (6) and (7). The desired side lobe level is set to -20 dB and maximum reflection coefficient (S_{11}) is set to be -15 dB. In this correction process, the values of the controlling weights are made equal to unity.

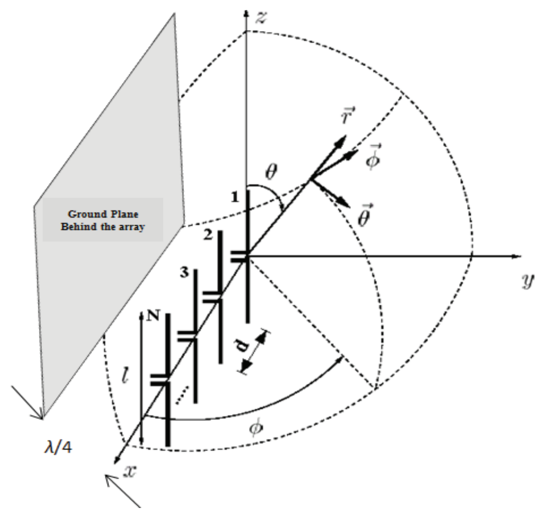

Fig. 1. A uniformly spaced linear array of parallel dipole antennas with ground plane placed at a distance $\lambda/4$ behind the array.

III. FIREFLY ALGORITHM

The firefly algorithm was developed by the author Yang and it was based on the unique flash characteristic features of fireflies [12,13], which uses flash as the signal to attract other fireflies. The algorithm is described as follows.

A. Initial positions

The fireflies are initially positioned in the w-dimensional space as described below:

$$v_m = (v_{m1}, v_{m2}, \ldots\ldots, v_{mw}), \quad (9)$$

for m=1, 2……,.

B. Brightness of fireflies

For a minimization problem with function $f(v_m)$, the value of the brightness (I_m) of each firefly at any generation is calculated and is:

$$I_m \alpha 1 / f(v_m). \quad (10)$$

C. Global best

The fireflies are positioned in a hierarchy depending on the value of their intensity or brightness at that particular generation. For a given population, the position of the firefly with a value of maximum brightness is treated to be current global best *(gbest)* and its brightness is treated as best fitness value at that generation [12-13].

D. Updation of locations

The remaining fireflies are made to move towards the brighter firefly *(gbest)* and their locations for the next iteration in the algorithm are updated based on their attraction towards the brighter firefly. The movement of firefly m towards brighter firefly n is summarized by:

$$v_m = v_m + \beta_o e^{-\gamma r_{mn}^2}(v_n - v_m) + \alpha \varepsilon_m, \quad (11)$$

where the product of β_o and $e^{-\gamma r_{mn}^2}$ in Equation (11) denotes the attractiveness between the two fireflies m and n. γ refers to the light absorption coefficient in a given medium. r_{mn} is the Cartesian distance between the two fireflies m and n at v_m and v_n, and is obtained from the following Equation (12).

$$r_{mn} = \|v_m - v_n\| = \sqrt{\sum_{j=1}^{w}\left(v_{m,j} - v_{n,j}\right)^2}. \quad (12)$$

Firefly algorithm disallows the motion of the brightest firefly to any other direction at current generation. In this juncture, the algorithm allows remaining fireflies other than the brightest one to modify their locations based on Equation (11) and saves the brightest firefly's location. Proceeding in this way, the global best (*gbest*) solution is updated regularly in the corresponding successive iterations of the algorithm. β_o is the value of the attractiveness at r=0 and $\alpha\varepsilon_m$ is for introducing randomization where α is the randomization parameter and ε_m is a vector of random numbers drawn from a Gaussian distribution or uniform distribution [12,13]. Repeat from steps *(B)* to *(D)* till the current iteration reaches specified number of iterations and the algorithm gives the location of the most brightest firefly (*gbest*) as the overall solution of the population. The value of brightness of that brightest firefly (*gbest*) is treated as the global fitness value of the objective function.

The following Table 1 shows the firefly algorithm settings.

Table 1: Firefly algorithm settings

Parameters	Value
Number of flies	20
Randomness	0.25
Minimum value of β	0.2
Absorption coefficient	1
Choice of initial population	Random
Maximum number of iterations	200

IV. SIMULATED RESULTS

A firefly (FF) optimized linear array of 20 parallel dipole antennas of length $\lambda/2$ and radius 0.005λ, spaced uniformly with $\lambda/2$ distance apart along x-axis has been taken for consideration to produce a radiation pattern in azimuth plane (x-y plane). The array is optimized for a side lobe level of -20 dB and maximum reflection coefficient (S_{11}) in dB of -15 dB using FF algorithm with various distances of *h* (distance between ground plane and array) at 0.10λ, 0.15λ, 0.20λ and 0.25λ. As for any evolutionary algorithm dealing with minimization problems, the lower the value of global fitness suggests the maximum fitness of the array to the desired specifications. Three elements namely, 5, 7 and 15^{th} are considered to be failed elements and their amplitudes (voltages) are made equal to zero for obtaining the damaged pattern. The above elements are chosen randomly for test purpose.

The FF algorithm is utilized here for recovering the radiation pattern closer to the original pattern for all the various distances used above. The algorithm minimizes the stated objective function and finally produces the voltage excitations of the remaining defective elements that will be used to obtain the radiation pattern with expected parameters. Or in other words, the values of obtained side lobe level and reflection coefficient (S_{11}) in dB are made approachable to the expected one. The terms used in connection to side lobe level and reflection coefficient (S_{11}) in dB fitness in equations (6) and (7) are made equal to zero when their corresponding values are lower when compared with expected values by multiplying Heaviside step function. Program is written in Matlab. Figure 2 shows corrected voltage distribution for various distances of array from ground plane with three element failures.

Table 2 shows the value of the voltage amplitude distribution of the 20 elements in the array with three failures at 5, 7 and 15^{th} positions with the effect of ground plane. The values of the original, damaged and corrected radiation pattern's SLL can be found from Table 3, which shows that the parameters reached the expected value. These values are obtained from the radiation pattern shown in Fig. 3 to Fig. 6.

As seen from Table 4, the maximum reflection coefficient (S_{11}) in dB for corrected pattern is better than the damaged pattern and it is proved for various distances between the ground plane and the array. Also, it can be found that the maximum absolute value of active impedance of the elements in the corrected pattern increases as the distance between the ground plane and array increases. For a distance of 0.1λ, the maximum absolute active impedance was found to be 67.09 ohms, and for a distance of 0.25λ it was found to be 134.64 ohms, which shows that the absolute value of maximum active impedance increases when the distance between array and ground plane increases. It becomes obvious from the Table 4 that the algorithm was effective in improving the cost function parameters to a good agreement between the damaged and corrected patterns.

A plot of fitness value with number of iterations in Fig. 7 shows that as the distance between the ground plane and antenna array increases, the fitness value converges but relatively at a higher value when compared to the ones with the least distances.

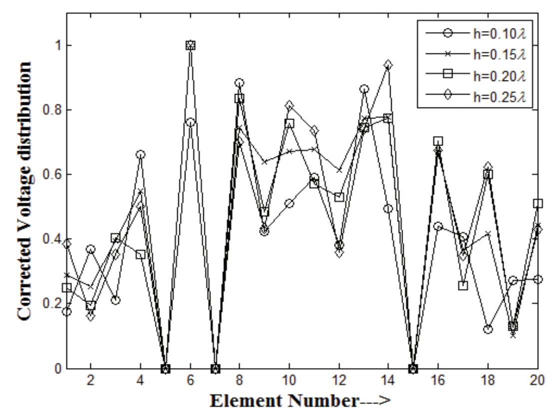

Fig. 2. Corrected voltage distribution with three element failures at 5, 7 and 15^{th} positions with various distances of array from ground plane.

Table 2: Obtained voltage distribution for corrected pattern with 3 failures using firefly algorithm

Distance of Antenna Array from the Ground Plane	Voltage Distribution of 20 Elements for Corrected Pattern with 3 Failures at 5, 7 and 15^{th} Positions					
	0.1741	0.3690	0.2092	0.6594	0.0000	0.7613	0.0000
h=0.10λ	0.8825	0.4245	0.5089	0.5900	0.3809	0.8650	0.4936
	0.0000	0.4392	0.4060	0.1197	0.2715	0.2751	
	0.2880	0.2532	0.3950	0.5495	0.0000	1.0000	0.0000
h=0.15λ	0.7452	0.6395	0.6697	0.6758	0.6119	0.7749	0.7758
	0.0000	0.6675	0.3639	0.4159	0.1028	0.4424	
	0.2507	0.1938	0.4042	0.3512	0.0000	1.0000	0.0000
h=0.20λ	0.8336	0.4849	0.7574	0.5711	0.5299	0.7456	0.7720
	0.0000	0.7020	0.2546	0.5995	0.1292	0.5113	
	0.3836	0.1632	0.3506	0.4996	0.0000	1.0000	0.0000
h=0.25λ	0.6992	0.4335	0.8129	0.7345	0.3590	0.7405	0.9363
	0.0000	0.6751	0.3486	0.6214	0.1265	0.4297	

Table 3: Value of side lobe level in dB for original, damaged and corrected patterns with 3 failures using firefly algorithm

Distance h	Patterns	SLL (dB)
Ground plane with h=0.10λ	Original	-20.12
	Damaged	-14.78
	Corrected	-20.04
Ground plane with h=0.15λ	Original	-20.49
	Damaged	-16.12
	Corrected	-20.00
Ground plane with h=0.20λ	Original	-20.42
	Damaged	-16.27
	Corrected	-20.00
Ground plane with h=0.25λ	Original	-20.29
	Damaged	-16.19
	Corrected	-20.66

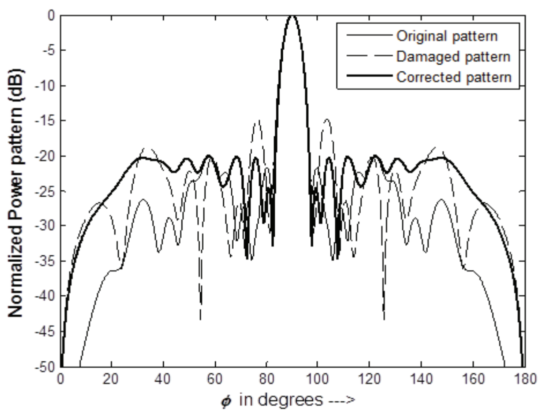

Fig. 3. Original (no failures), damaged and corrected normalized power pattern with three element failures at 5, 7 and 15th positions with a distance of h=0.10λ from ground plane.

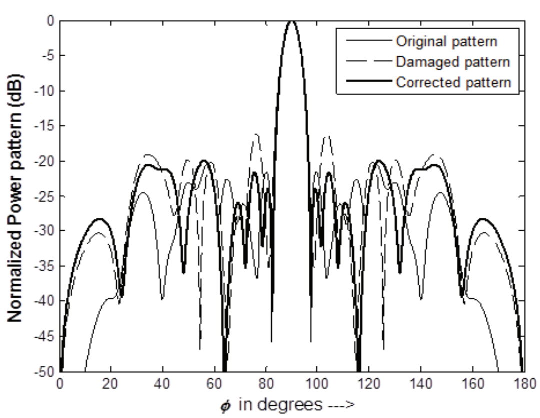

Fig. 4. Original (no failures), damaged and corrected normalized power pattern with three element failures at 5, 7 and 15th positions with a distance of h=0.15λ from ground plane.

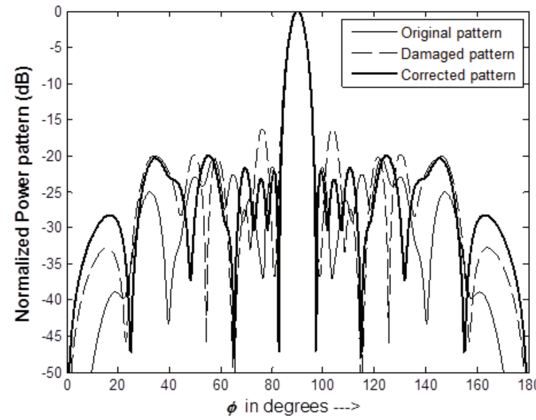

Fig. 5. Original (no failures), damaged and corrected normalized power pattern with three element failures at 5, 7 and 15th positions with a distance of h=0.20λ from ground plane.

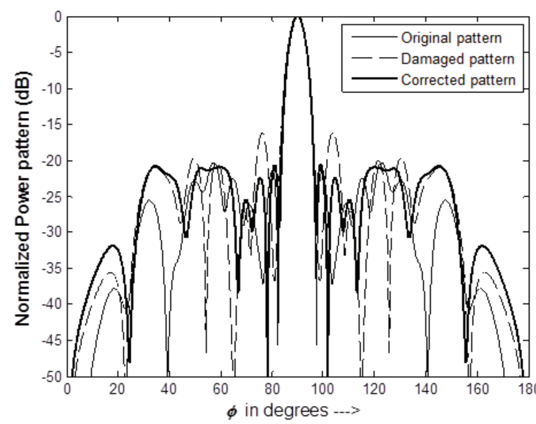

Fig. 6. Original (no failures), damaged and corrected normalized power pattern with three element failures at 5, 7 and 15th positions with a distance of h=0.25λ from ground plane.

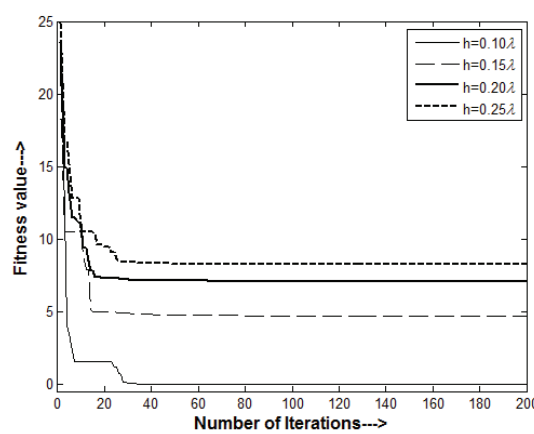

Fig. 7. Fitness value versus number of iterations.

In order to get a global magnitude that can tell how well is the agreement between the original and corrected patterns in relation with the original and damaged patterns, the following equation (13) is used. If *NPPO* being original normalized power pattern, *NPPC* being corrected normalized power pattern and *NPPD* being damaged normalized power pattern, the root mean square error *Err* is given by:

$$Err = \sqrt{\frac{\int_0^{\pi}\left(NPPO(\varnothing)-NPPC(\varnothing)\right)^2 d\varnothing}{\int_0^{\pi}\left(NPPD(\varnothing)-NPPC(\varnothing)\right)^2 d\varnothing}}. \quad (13)$$

The root mean square error has been found to be 2.0624 (when h=0.10λ), 1.5439 (when h=0.15λ), 1.3210 (when h=0.20λ) and 1.1810 (when h=0.25λ).

Table 4. Maximum reflection coefficient (S_{11}) in dB and maximum absolute value of active impedance for the original (without failures), damaged and corrected pattern with 3 failures

Distance of Antenna Array from Ground Plane	Maximum Absolute Value of Active Impedance (ohms)			Maximum Reflection Coefficient (S_{11}) in dB		
	Original Pattern	Damaged Pattern	Corrected Pattern	Original Pattern	Damaged Pattern	Corrected Pattern
h=0.10λ	64.77	67.57	67.09	-17.81	-16.51	-16.71
h=0.15λ	88.56	97.53	94.01	-11.11	-09.84	-10.30
h=0.20λ	107.20	124.58	117.06	-8.78	-7.39	-7.93
h=0.25λ	119.62	147.97	134.64	-7.73	-6.11	-6.78

V. CONCLUSIONS

This paper presents a technique based on firefly algorithm optimization for failure correction of three elements out of 20 element linear array of parallel half-wave length dipole antennas in presence of ground plane with fixed side lobe level and maximum reflection coefficient (S_{11}) in dB. Instead of isotropic radiators, realistic antennas with mutual coupling are used in the simulations. The paper also takes care of matching between antenna and the feed network by minimizing maximum reflection coefficient (S_{11}) in dB. Results have been simulated for the original, damaged and corrected patterns and they depicted that the corrected radiation pattern approached the expected pattern in a span of 200 iterations to an acceptable level of the parameters like SLL and reflection coefficient (S_{11}) in dB; or in other words, they clearly show a very good level of improvement of corrected pattern when compared with damaged one. To extend this research work, importance can be given to fine tuning of setting of parameters like attractiveness parameter, absorption coefficient, etc. for firefly algorithm. This work can also be extended with a modification in the cost function, different number of failures, varying dynamic range ratio, change in number of elements considered, various steering angles and for other array configurations.

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