Progress In Electromagnetics Research M, Vol. 54, 9–18, 2017

A Linear Mutually Coupled Parallel Dipole Antenna Array Failure Correction Using Bat Algorithm

Narwant S. Grewal[1, 2, *], Munish Rattan[2], and Manjeet S. Patterh[3]

Abstract—In this work, the problem of mutually coupled dipole antenna array failure has been solved using bat algorithm by adjusting only the amplitude excitation of good array elements. The element failure causes the degradation of side-lobe power level to an improper level. A fitness function is formulated to obtain the difference between degraded side-lobe pattern and measured side-lobe pattern, and a flexible approach using bat algorithm is used to minimize this function. Numerical examples of single and multiple element failure correction under mutual coupling conditions are discussed to show the capability of this proposed approach.

1. INTRODUCTION

Antenna array is an important part of communication system that improves its spectral efficiency and system capacity. It is used in wireless applications such as radio system, sonar, and satellite communication for signal acquisition process. The dipole antenna array mostly consists of large number of active elements, which always has a chance of failure of one or more elements in such a system. Single or multiple element failure of an antenna array system causes unacceptable distortion of side-lobe level, null pattern displacement and sharp variation in field intensity across the antenna array. It is realistic to recover the radiation pattern of a dipole antenna array system with approximately same quality without replacing the failed element by readjusting the excitations of the healthy elements of the antenna array system. Researchers have proposed various techniques to recover the array system in presence of defective elements such as an orthogonal method [1], conjugate gradient based method [2, 3], applying genetic algorithm (GA) [4, 5], with the hybridization of GA and fast fourier transform (FFT) [6], applying an adaptive neuronal system [7], with simulated annealing (SA) [8, 9], particle swarm optimization (PSO) [10–12], and firefly algorithm (FA) [13, 14]. These above mentioned methods are either having large number of control parameters to set for the operation or showing slow convergence characteristics.

For a practical antenna system, mutual coupling effect [15–19] plays an important role. It may deteriorate the antenna radiation pattern and matching characteristics of antenna system. In this paper, a mutual coupling between elements is considered, and an effective optimization method based on the Bat Algorithm (BA) is proposed for array failure correction of linear dipole antenna array. It is observed that bat algorithm has the capability to provide effective solutions for continuous constrained optimization problems [20]. It naturally has edge over harmony search (HA), particle swarm optimization (PSO) and genetic algorithm (GA) because bat algorithm adopts good features of these algorithms. Moreover, harmony search and PSO are taken as a special case of the bat algorithm.

Received 2 December 2016, Accepted 11 January 2017, Scheduled 2 February 2017

* Corresponding author: Narwant Singh Grewal (ernarwant@gmail.com).
[1] IKG Punjab Technical University, Kapurthala, Punjab, India. [2] Department of Electronics & Communication Engineering, Guru Nanak Dev Engineering College, Ludhiana, Punjab, India. [3] Department of Electronics & Communication Engineering, University College of Engineering, Punjabi University, Patiala, Punjab, India.

For a uniformly spaced linear parallel dipole antenna array system, the array-failure correction is a complicated problem compared with simple side-lobe suppression in antenna array system. The complexity of the array failure problem further increases under mutual coupling conditions. A recently developed bat algorithm [21] has shown its ability to provide effective solutions to the problems with variables in complex multi-dimensional search spaces. In this work, bat algorithm is successfully applied to the linear dipole antenna array failure problem under mutual coupling conditions, and the restoration of antenna array pattern is done by readjusting the amplitude excitations of healthy antenna array elements. The amplitude only control is preferred to use for excitation of antenna elements because it is simple to implement compared with amplitude and phase control [22]. The single and multiple failure conditions in antenna array system has been considered to show the effectiveness of this algorithm.

The second section describes the problem formulation, and cost function of the problem is modeled in the same section. The third section of the paper discusses a brief description of bat algorithm. Simulation results and discussion of a dipole antenna array are presented in Section 4, and the proposed method is concluded in the last section.

2. PROBLEM FORMULATION

The linear dipole antenna array consists of N identical elements which is shown in Figure 1, and the adjacent elements of the array are placed at uniform spacing of half a wavelength. The array factor of an arbitrary dipole antenna array can be represented [4] as,

$$AF = W\, S_v(\theta, \theta_B) \tag{1}$$

$$W = \{w_1, w_2, w_3 \ldots w_N\}^T, \quad w_n \in C^C, \quad n = 1, 2, 3, 4 \ldots N \tag{2}$$

The symbols θ and θ_B used in Equation (1) represent the direction variable and main beam direction, respectively, whereas W is the weighting vector as given in Equation (2) and S_v the steering vector of dipole antenna array. The symbol C^C represents a subset or set of all the real numbers which are used as weights of the linear dipole antenna element.

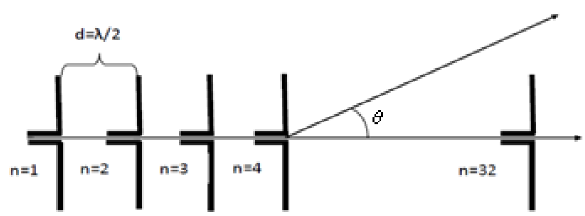

Figure 1. Linear dipole antenna array.

The steering vector S_v plays an important role in deciding the main-lobe direction of the linear dipole antenna array, and it is represented by the following equation for antenna array system having N identical elements with d spacing between them,

$$S_v = \exp\left\{jkd\left(n - \frac{N-1}{2}\right) \cdot (\cos\theta - \cos\theta_B)\right\} \quad n = 1, 2, 3 \ldots N \tag{3}$$

Assume that the thickness of dipole antenna element is very small and produces an omnidirectional pattern. The voltage distribution across kth element of dipole [19] is given as

$$V_k = I_k Z_{kk} + \sum_{n \neq k} I_n Z_{nk} \tag{4}$$

where I_k represents the amplitude of current, Z_{kk} the self-impedance of kth dipole and Z_{nk} the mutual impedance between kth and nth dipoles in Equation (4). The active impedance of each element of an array is determined by

$$Z_k^A = \frac{V_k}{I_k} = Z_{kk} + \sum_{n \neq k} \left(\frac{I_n}{I_k}\right) Z_{nk} \tag{5}$$

The failure condition of the zth element of the dipole antenna array is generated by applying zero value to weight w_z in Equation (1). The active impedance of failed element is considered zero value. Further, the voltage excitation at input of failed element is also zero, and these elements do not contribute in the calculation of voltage standing wave ratio [19]. The failed elements behave as parasitic radiators, and the current through the faulty elements has not ceased to be zero because of mutual coupling effect. The main beam and side-lobe level (SLL) of mutually coupled dipole antenna array disturbed under failure conditions of antenna elements which is recovered by recalculating the amplitude of healthy elements are obtained with the bat algorithm.

The aim of the work is to recover side-lobe level of the original array pattern and maximizes the directivity. To achieve this, a template based on specified SLL and shape of main lobe of array pattern is formed as shown in Figure 2. This reference template is compared with the antenna array pattern which is determined by each solution of the bat algorithm to calculate their cumulative difference. This cumulate difference is taken as a fitness value of the problem.

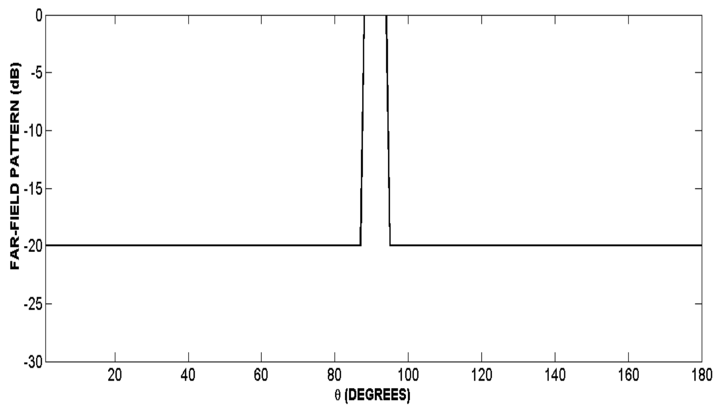

Figure 2. Template used as reference.

3. BAT ALGORITHM

The basic bat algorithm discussed in [20, 21] is based on the echolocation behavior used by bats. Bats exploit echolocation behavior for different activities such as sensing their roosting crevices, searching their food and detecting obstacles. The bat algorithm uses the idealized conditions of echolocation behavior of bats with the following rules: 1) All of the bats exploit echo signal for the detection of distance only and assume that they have the knowledge about the difference between prey and background barriers; 2) The movements of bats are random in order to search the food. They are moving with velocity v_i at position s_i with a frequency f_g, and varying loudness A_o. Bats can automatically adjust the wavelength and emitted pulse rate based on the location of the prey; 3) Loudness varies between a high positive value A_o and low fixed value A_l.

The movement of a bat in order to catch the prey causes change of the bat's location. This location of bat provides the solution of problem. The fitness function is inversely proportional to the location of bat for maximization problem, and it is directly proportional to the location for minimization problem. The pseudo-code for basic bat algorithm is shown in Figure 3, and the steps involved in implementation of algorithm are summarized as below:

Step 1 (Initialization): In this step, a random population of J bats is generated to initialize bat algorithm and given as

$$x_j(0) = rand_j(0,1)(x_j^U - x_j^L) + x_j^J, \quad j = 1, 2, \ldots, J \tag{6}$$

where $rand_j(0,1)$ is a uniformly distributed random variable which has the range between 0 and 1. Variables x_j^U and x_j^L represent the upper and lower bounds in the bat population respectively given in Equation (6). Velocity vector v_j and a position (solution) vector x_j are the two attributes associated

Initialization of the population with J bats

$x_j(0) \leftarrow \{x_1(0), x_2(0)..x_J(0)\}$

Set echo pulse frequency f_j at position x_j

Initialize loudness A_j and pulse rate r_j

$m \leftarrow 0$

while the iterations attains maximum value or desired fitness value (terminating conditions) is not true **do**

Calculation of velocity parameter of each bat using Equation (10)

Calculation of position parameter (solution) of bat using Equation (11)

Reloading of new solutions by variation of frequency

Modifying velocities and position parameters

Evaluate fitness function: $\{f(x_1(m)), f(x_2(m))... f(x_J(m))\}$

If (*random* > r_j)

Select the best solution from the available solutions

Local search by the randomly movement of bat around a selected best location (solution)

end if

Generate a new solution by flying randomly

If (*random* < A_j *and* $f(x_j) < f(x^*)$)

Respond to the new solutions

Decrease A_j and increase r_j

end if

Ranks the bats and find the global best position x^*

$m \leftarrow m - 1$

end while

Figure 3. Pseudo code of the bat algorithm.

with each bat in the population. During the search operation, the velocity vector is responsible for changing the position of the bat, and the values of the design variables are associated with the position vector of the bat. The counter is set to zero at the start of iteration loop.

Step 2 (Parametric evaluation of echolocation): In this step, the three parameters, pulse rate r_j, frequency f_j, and loudness A_j associated with echolocation, are initialized to compute the location of the bat (solution of the problem). These parameters are computed and updated as per the following equations [20],

$$r_j^m = r_j^0\,[1 - \exp(-\gamma m)] \tag{7}$$

$$f_j = \beta_0\,(f_{\max} - f_{min}) + f_{\min} \tag{8}$$

$$A_j^{m+1} = \alpha\, A_j^m \tag{9}$$

The pulse rate r_j^0 varies in the range of 0 and 1, which depends on the proximity of the prey. The value of pulse rate r_j^m approaches r_j^0 at large value of iteration m as per Equation (7). The maximum and minimum values of frequency in Equation (8) are represented by $f_{\min}$ and $f_{\max}$ with values 0 and 1, respectively, and random vector β_0 is a uniform distribution. The constant parameter γ is greater than zero and depends upon parameter α, whose value is in the range [0, 1]. It is clear from Equation (9) that the loudness parameter of each bat is updated at every iteration m.

Step 3 (Positional update of bat): In this step, each bat in the population moves toward the prey, and this movement of bat is updated by its velocity in the current iteration. The bat velocity is updated in every iteration according to the location and frequency of the bat with respect to the current global bat position. The velocity and position of the bat are evaluated and updated as:

$$v_j^m = v_j^{m-1} + f_j \left(x_j^m - x^*\right) \tag{10}$$

$$x_j^m = x_j^{m-1} + v_j^m \tag{11}$$

where x^* indicates the global position (solution of the problem) in current iteration. The fitness value of each bat is evaluated, and the bat with best position value out of current bat population is selected. For the local search process, the selected best solution is modified with random walk which is given as,

$$x_{mod} = x_{old} + \varepsilon \overline{A^m} \tag{12}$$

where $\overline{A^m}$ is the mean loudness value of the bat population, and random number ε indicates the magnitude and direction of random-walk process. The value of ε varies in the range between 0 and 1.

Step 4 (Evaluation of current global best): The bats in the population are ranked and placed in a list based on their fitness or cost value. The fitness of each bat is evaluated by its location in the current generation. The current global best ($x*$) value is determined by the bat which has the best position in the population.

Step 5: In this step, the terminating condition is checked and the process repeated through steps 2 to 4, if the terminating condition is not satisfied as shown in Figure 3. At the end of process, the best location of bat ($x*$) provides the optimum solution of the problem.

4. SIMULATION RESULTS AND DISCUSSION

The algorithmic steps of bat algorithm (BA) has been implemented in MatLab and applied to solve the multi-dimensional complex array failure problem of mutually coupled linear dipole antenna arrays. The result of the proposed algorithm is compared with the other computationally efficient optimization techniques such as biogeography-based optimization (BBO), differential evolution (DE) and genetic algorithm (GA). The parametric settings used for the bat algorithm (BA) and other algorithms are summarized in Table 1.

Consider a Dolph-Chebyshev linear array of 32 parallel dipoles along x-axis with half-wavelength uniform inter-element spacing and side-lobe level (SLL) of -20 dB. For this array, four cases of element failure at different locations are considered and simulated in order to demonstrate the effectiveness of this method. Figure 4 shows the pattern of 32-element array under mutual coupling condition along with original array pattern without coupling effect. The mutual coupling of array elements causes change in the side-lobe pattern, but fortunately the pattern is not adversely affected. On the other hand, it is a very difficult task to recover the failed-element array under mutual coupling effect because the faulty element is not completely off and behaves as a passive element.

Case-1: In the first case, the failed elements are located at 5th and 13th element positions in a 32-dipole antenna array. The array pattern is disturbed, and the side-lobe level is increased to an unacceptable maximum level of -16.55 dB at 74.57° and 105.4° under failed conditions. The proposed method is executed, and new optimized excitations are provided to the healthy elements of the array. The array pattern is recovered from the value of -16.55 dB to -19.63 dB as shown in Figure 5(a).

Case-2: In this case, asymmetric array with the 5th, 10th, 20th and 29th element failure condition is considered. The damaged pattern is realized by replacing the voltage excitation of the respective dipole with zero as indicated in Table 2. Figure 5(b) shows that the SLL of the damaged pattern achieves an unaccepted value of -15.76 dB at 66.09° and 113.7°. The corrected pattern shown in Figure 5(b) indicates the recovery of SLL to the reasonable value of -19.66 dB.

Case-3: Consider an asymmetric 32-dipole antenna array with five failed elements located at 3rd, 6th, 13th, 19th and 22th. The SLL of failed antenna array disturbs and achieves the maximum value of -14.78 dB as shown in Figure 5(c). The proposed method redistributes the excitation of good elements, which results in the recovery of SLL to maximum value of -19.78 dB. The recovered SLL along with the original and failed patterns is shown in Figure 5(c).

Case-4: In this case, the complex scenario of array failure problem is considered by taking six failed elements at 3rd, 8th, 13th, 19th, 24th and 28th locations in the asymmetric 32-dipole antenna array. Figure 5(d) shows SLL of the array which is distorted to the maximum value of -12.49 dB

Table 1. Parametric setting for BBO, DE, GA and BA.

Algorithm	Parameter	Parametric value
BBO	Population Size	45
	Max. Iterations	50
	Mutation probability	0.0012
	Elitism	2
	Habitat modification	1
DE	Population Size	50
	Max. Iterations	50
	Crossover probability	0.50
	Habitat modification	1
	Weighting factor	0.51
GA	Population Size	45
	Max. Iterations	50
	Mutation probability	0.012
	Crossover probability	1
	Elitism	2
BA	Population Size	50
	Max. Iteration	50
	Echo Loudness	0.5
	Echo Pulse rate	0.5
	Minimum frequency	0
	Maximum frequency	2

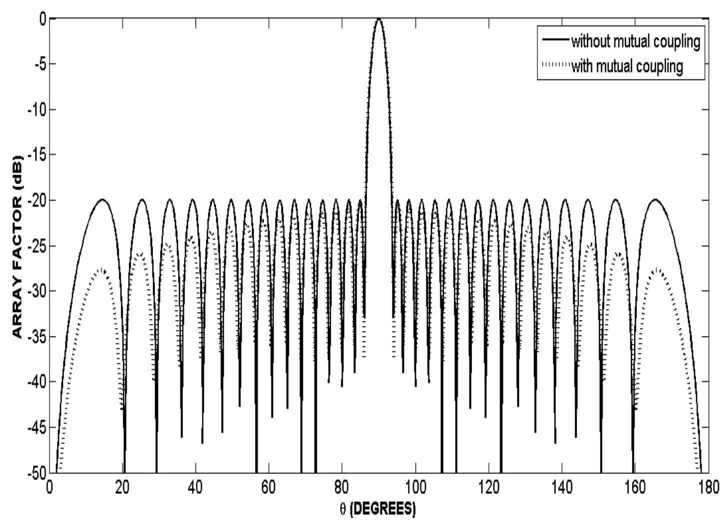

Figure 4. Original array pattern of 32 element antenna array with and without mutual coupling effect.

under the considered failure conditions. The bat algorithm provides excitations to healthy elements of the antenna array under failed condition which recovers the SLL to maximum value of -19.97 dB. The damaged pattern is also shown in Figure 5(d), and the numerical values of original, damaged and corrected patterns of the array are summarized in Table 4.

The original and corrected normalized excitation coefficients of all four cases of 32-dipole antenna array are given in Table 2. The failed conditions of the antenna array are implemented by replacing the normalized excitation with value zero in the respective locations. The excitation coefficients shown in Table 2 are modified with active impedance as per Equation (5) in order to include the self and mutual coupling effect and applied to elements of the considered antenna array. Figure 6 depicts the cost function curves of case 1 and case 3 of 32 parallel dipole antenna array, which indicate that the bat algorithm converges in around 18 generations in the first case and 34 generations in the third

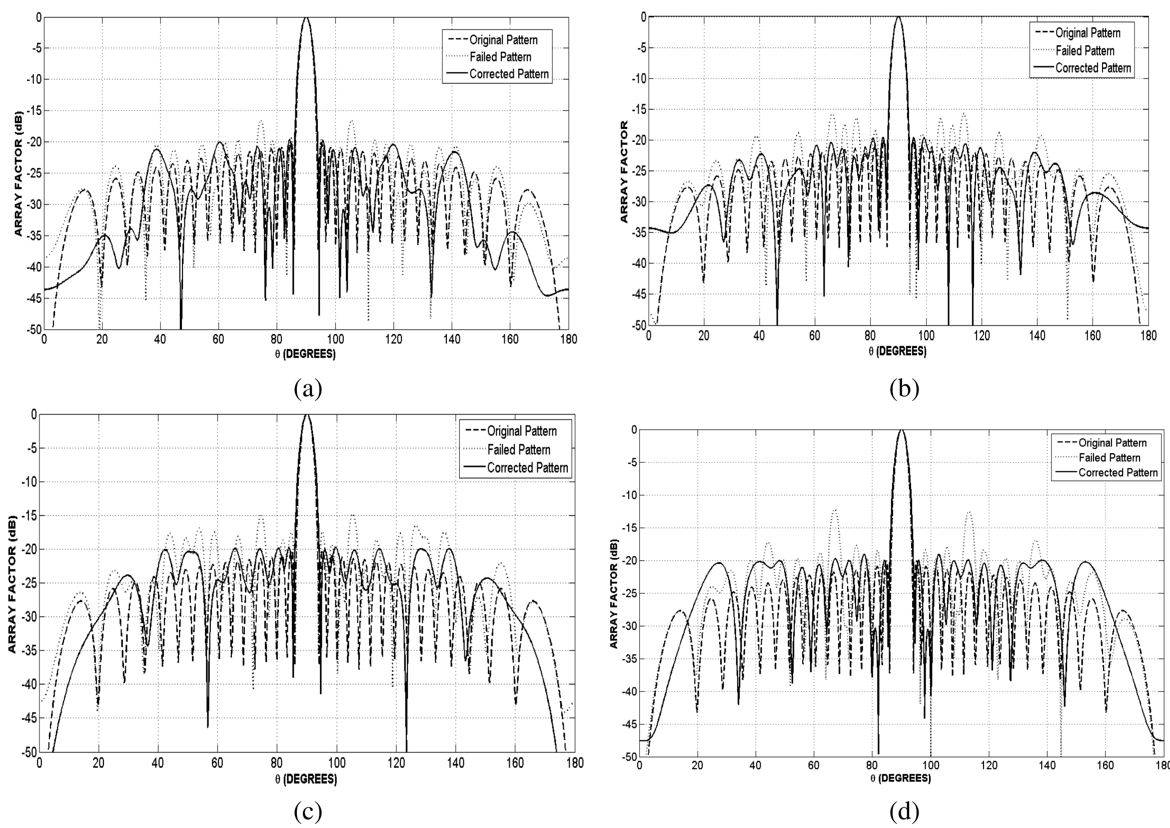

Figure 5. The original, damaged, and corrected array patterns of the 32-dipole-linear array with main beam at 90°: (a) asymmetric array with 5th and 13th element failure condition (case-1), (b) asymmetric array with 5th, 10th, 20th and 29th element failure condition (case-2), (c) asymmetric array with 3rd, 6th, 13th, 19th and 22th element failure condition (case-3) and (d) asymmetric array with 3rd, 8th, 13th, 19th, 24th and 28th element failure condition (case-4).

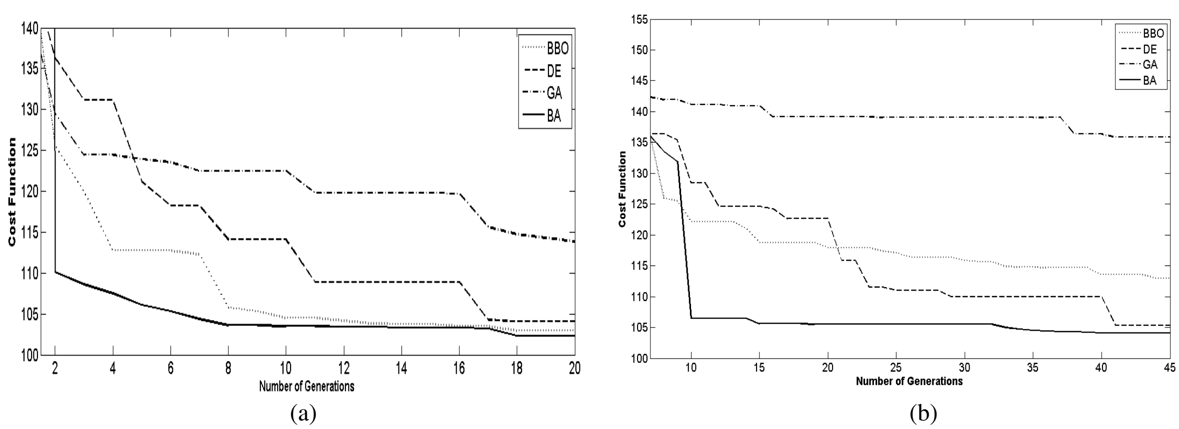

Figure 6. Fitness curve (a) asymmetric array with 5th and 13th element failure condition and (b) asymmetric array with 3rd, 6th, 13th, 19th and 22th element failure condition.

case. The performances of bat algorithm and the other optimization techniques (BBO, DE, GA) are observed and compared as shown in Figure 6. It is observed that the bat algorithm is more efficient than its counterparts in terms convergence speed and accuracy. Table 3 shows the optimum cost value of four considered cases obtained with different optimization techniques, which indicates that the bat algorithm provides more accurate results than other techniques (BBO, DE and GA) in array failure problem. The side-lobe level and beam-width of original, degraded and corrected patterns of 32-dipole antenna array under four considered cases of array failure problem are summarized in Table 4. The beam-width of corrected pattern in all cases is higher than the expected value because this parameter has to compromise with the recovery of SLL. The algorithms used in this work have been executed 25 times for 50 iterations and best result accepted in Tables 3 and 4. During simulation process, it is observed that the bandwidth and SLL of the considered array remain reliable and effective when the number of faulty elements in the array does not exceed the maximum limit of 6 elements.

Table 2. Original and corrected normalized excitation coefficients of 32-dipole antenna array.

Element location	**Original weights**	**Corrected weights obtained by BA**			
		Case-1	**Case-2**	**Case-3**	**Case-4**
1.	*1.000*	0.0992	0.3219	0.0969	0.1000
2.	*0.2872*	0.2999	0.4351	0.3000	0.2993
3.	0.3245	0.2397	0.5542	**0**	**0**
4.	0.3620	0.5311	0.5132	0.3000	0.2498
5.	0.3992	*0*	*0*	0.2983	0.6162
6.	0.4356	0.2643	0.7180	*0*	0.2236
7.	0.4708	0.6365	0.6345	0.4901	0.2539
8.	0.5041	0.2424	0.4864	0.3799	*0*
9.	0.5352	0.3639	0.6125	0.2861	0.6890
10.	0.5635	0.4631	*0*	0.3840	0.4655
11.	0.5887	0.4487	0.9879	0.3810	0.3963
12.	0.6103	0.4975	0.4954	0.6480	0.7537
13.	0.6280	*0*	0.6653	*0*	*0*
14.	0.6415	0.5915	0.9100	0.5971	0.6889
15.	0.6506	0.6262	0.7389	0.6095	0.4331
16.	0.6552	0.4586	0.5493	0.6598	0.5165
17.	0.6552	0.5844	0.7302	0.6544	0.3758
18.	0.6506	0.3093	0.5767	0.4429	0.5778
19.	0.6415	0.5311	0.7945	***0***	***0***
20.	0.6280	0.5168	*0*	0.3932	0.7575
21.	0.6103	0.3357	0.6734	0.6986	0.3843
22.	0.5887	0.4307	0.4691	*0*	0.3915
23.	0.5635	0.4637	0.7108	0.6619	0.8821
24.	0.5352	0.3253	0.4370	0.3014	*0*
25.	0.5041	0.4160	0.7280	0.5121	0.4268
26.	0.4708	0.2693	0.2321	0.4622	0.1855
27.	0.4356	0.3504	0.5077	0.3569	0.4433
28.	0.3992	0.2224	0.4691	0.2922	*0*
29.	0.3620	0.2971	*0*	0.2837	0.3905
30.	0.3245	0.3000	0.5053	0.1458	0.3000
31.	*0.2872*	0.1987	0.3499	0.2454	0.2913
32.	*1.000*	0.1700	0.3334	0.1700	0.0991

Table 3. Optimum fitness value obtained with different algorithms.

Case	Array design	DE	BBO	GA	BA
1	Asymmetric array with 5th and 13th element failure condition	104.1	102.9	113.8	102.3
2	Asymmetric array with 5th, 10th, 20th and 29th element failure condition	103.3	103.9	106.5	102.7
3	Asymmetric array with 3rd, 6th, 13th, 19th and 22th element failure condition	105.3	113.0	135.8	104.1
4.	Asymmetric array with 3rd, 8th, 13th, 19th, 24th and 28th element failure condition	104.1	103.9	119.5	102.5

Table 4. Beam width and side lobe level (SLL) of original, damaged, and corrected patterns of 32-element antenna array obtained with proposed algorithm.

Case	Array Design	SLL (dB)			Beam width		
		Original	Damaged	Corrected	Original	Damaged	Corrected
1	Asymmetric array with 5th and 13th element failure condition	−20.14	−16.55	−19.63	3.34°	3.34°	3.6°
2	Asymmetric array with 5th, 10th, 20th and 29th element failure condition	−20.14	−15.76	−19.66	3.34°	3.34°	3.6°
3	Asymmetric array with 3rd, 6th, 13th, 19th and 22th element failure condition	−20.14	−14.78	−19.78	3.34°	3.34°	3.87°
4	Asymmetric array with 3rd, 8th, 13th, 19th, 24th and 28th element failure condition	−20.14	−12.49	−19.97	3.34°	3.34°	3.7°

5. CONCLUSION

The field intensity of mutually coupled active antenna array can be degraded to an unacceptable level in antenna failure problem. In this paper, the bat algorithm is proposed for solving array failure problem of mutually coupled asymmetric linear antenna array by applying a new set of amplitude excitations to the array elements. The array field pattern obtained with the proposed algorithm is compared with the template of an ideal array field pattern of asymmetric linear array to correct the faulty antenna array pattern. The proposed method effectively solves the practical problem of parallel dipole antenna array failure by suppressing the side-lobe level to an acceptable level under different failure conditions. The amplitude only control used in the work reduces the complexity of the system implementation process because it needs only the attenuators and not phase shifters which is required in amplitude and phase control method. The proposed method can be extended to mutually coupled circular or other conformal antenna arrays.

ACKNOWLEDGMENT

This paper is the outcome of PhD work at I. K. Gujral Punjab Technical University, Kapurthala, Punjab. The authors would like to thanks Dean RIC, IKGPTU Kapurthala and Director, Guru Nanak Dev Engineering College, Ludhiana for required facilities provided for this work.

REFERENCES

1. Zainud-Deen, S. H., M. S. Ibrahem, H. A. Sharshar, and S. M. M. Ibrahem, "Array failure correction with orthogonal method," *Proceedings of the Twenty-First National Radio Science Conference*, B7-1-9, Cairo, Egypt, Mar. 16–18, 2004.

2. Peters, T. J., "A conjugate gradient based algorithm to minimize the side lobe level of planar arrays with element failure," *IEEE Transactions on Antennas and Propagation*, Vol. 39, No. 10, 1497–1504, Oct. 1991.
3. Mailloux, R. J., "Array failure correction with a digitally beamformed array," *IEEE Transactions on Antennas and Propagation*, Vol. 44, No. 12, 1543–1550, Dec. 1996.
4. Yeo, B. K. and Y. Lu, "Array failure correction with a genetic algorithm," *IEEE Transactions on Antennas and Propagation*, Vol. 47, No. 5, 823–828, May 1999.
5. Rodriquez, J. A., F. Ares, and E. Moreno, "Genetic algorithm procedure for linear array failure correction," *Electronic Letters*, Vol. 36, No. 3, 196–198, Feb. 2000.
6. Wang, L. and D. Fang, "Combination of genetic algorithm and fast fourier transform for array failure correction," *6th International Symposium on Antennas, Propagation and EM Theory*, 234–237, Beijing, China, Oct. 28–Nov. 1, 2003.
7. Padron, A. and J. L. Garduno, "Antenna array adjust with adaptive neuronal system," *Journal of Applied Research and Technology*, Vol. 2, No. 3, 189–198, Dec. 2004.
8. Lozano, M. V. and J. A. Rodriquez, "Recalculating linear array antennas to compensate for failed elements while maintaining fixed nulls," *IEEE International Symposium on Antennas and Propagation*, Vol. 3, 2048–2051, Orlando, FL, USA, Jul. 11–16, 1999.
9. Redvik, J., "Simulated annealing optimization applied to antenna arrays with failed elements," *IEEE International Symposium on Antennas and Propagation*, Vol. 1, 458–461, Orlando, FL , USA, Jul. 11–16, 1999.
10. Yeo, B. K. and Y. Lu, " Fast array failure correction using improved particle swarm optimization," *Asia Pacific Microwave Conference*, 1537–1540, Singapore, Dec. 7–10, 2009.
11. Acharya, O. P., A. Patnaik, and S. N. Sinha, "Null steering in failed antenna array," *National Conference on Communication*, 1–4, Bangalore, Jan. 28–30, 2011.
12. Acharya, O. P., A. Patnaik, and S. N. Sinha, "Null steering in failed antenna array," *Journal Applied Computational Intelligence and Soft Computing*, Vol. 2011, 1–9, 2011.
13. Grewal, N. S., M. Rattan, and M. S. Patterh, "A Linear antenna array failure correction using firefly algorithm," *Progress In Electromagnetics Research M*, Vol. 27, 241–254, 2012.
14. Grewal, N. S., M. Rattan, and M. S. Patterh, "A linear antenna array failure correction with null steering using firefly algorithm," *Defence Science Journal*, Vol. 64, No. 2, 136–142, Mar. 2014.
15. Pathak, N., B. Basu, and G. K. Mahanti, "Combination of inverse fast Fourier transform and modified particle swarm optimization for synthesis of thinned mutually coupled linear array of parallel half wave length dipole antennas," *Progress In Electromagnetics Research M*, Vol. 16, 105–115, 2011.
16. Keizer, W. P. M. N., "Low-sidelobe pattern synthesis using iterative fourier techniques coded in MATLAB," *IEEE Antennas and Propagation Magazine*, Vol. 51, No. 2, 137–150, 2009.
17. Elliott, R. S., *Antenna Theory and Design*, Prentice-Hall, New York, NY, USA, 1981.
18. Rodriguez, J. A., F. Ares, and E. Moreno, "Feeding in-phase dipole arrays: A tutorial and a MATLAB program," *IEEE Antennas and Propagation Magazine*, Vol. 47, No. 5, 169–173, 2005.
19. Muralidharan, R., V. Athinarayanan, G. K. Mahanti, and A. Mahanti, "QPSO versus BSA for failure correction of linear array of mutually coupled parallel dipole antennas with fixed side lobe level and VSWR," *Journal of Advances in Electrical Engineering*, Vol. 2014, 1–7, Hindawi, Sep. 2014.
20. Yang, X.-S., "A new metaheuristic bat-inspired algorithm," *Nature Inspired Cooperative Strategies for Optimization (NISCO 2010) (Gonzalez, J. R. et al., editors), Springer, SCI*, Vol. 284, 65–74, 2010.
21. Yang, X.-S., "Bat algorithm for multiobjective optimization," *International Journal Bio-Inspired Computation*, Vol. 3, 267–274, 2011.
22. Guney, K. and A. Akdagli, "Null steering of linear antenna array using modified tabu search algorithm," *Progress In Electromagnetic Research*, Vol. 33, 167–182, 2001.