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COMPARATIVE STUDY OF EVOLUTIONARY ALGORITHMS TO GENERATE FLAT-TOP BEAM PATTERN FOR SYNTHESIS OF A LINEAR ANTENNA ARRAY

Hemant Patidar[1], Vikas Maheshwari[2], Rajib Kar[3], Prasanna Kumar Singh[4] and Vijay Kumar Sahu[5]
[1]Department of Electrical and Electronics Engineering, Oriental University, India
[2]Department of Electronics and Communication Engineering, Guru Nanak Institutions, India
[3]Department of Electronics and Communication Engineering, National Institute of Technology, Durgapur, India
[4]Department of Electronics and Communication Engineering, Noida Institute of Engineering and Technology, India
[5]Department of Electronics and Communication Engineering, Anil Neerukonda Institute of Technology and Sciences, India

Abstract

In the present paper three evolutionary algorithms are compared and discussed for synthesizing a linear array of dipole antenna of half-wavelength oriented horizontally. All the dipoles are mutually coupled and designed to radiate the flat-top beam (FTB) pattern including multiple single null steering with little ripple deviation. The adopted evolutionary algorithms are; flower pollination algorithm (FPA), firefly algorithm (FA) and back tracking search algorithm (BSA), respectively. These algorithms are then combined with an efficient Inverse Fast Fourier Transform (IFFT) for reduction in the computation of evaluating time meaningfully. The required synthesis is attained by generating the current amplitudes at 00 and 1800 using binary phase shifters for the antenna array. The performance analysis of key antenna parameters along with the statistical parameters is achieved with the help of the optimization process and compared. In this paper, the MATLAB tool is used as a validation tool and the obtained simulation results are very satisfying and acceptable.

Keywords:

Antenna Array, Backtracking Search Algorithm, Firefly Algorithm, Flower Pollination Algorithm, Flat- Beam Pattern, Side Lobe Level, Single Null Placement, Ripple, VSWR

1. INTRODUCTION

To find the application of radiation patterns in mobile, radar, satellite and wireless communication, antenna array synthesis is required. Also, it is important to increase the quality of the signal and the spectral efficiency. Flat-top power pattern finds many applications in wireless communication and in broadcasting where requires uniform illumination for more than one sector of the region from the satellite. It is also used in the study of the propagation of sound in the water and the interaction of the mechanical waves (underwater acoustics). Generally, the desirable shaped beam pattern can be easily achieved by modifying either or both the phase and amplitude excitation of every element [1]-[7]. Among the several shaped beam patterns, the FTB has a very smaller number of ripples in the FTB characteristics. But this beam has a high probability of Side Lobe Level (SLL) in the remaining regions [1]. The SLL, ripple and transition width are the main radiation parameters of the FTB pattern which are contradictory to each other which is described in the paper [2]. Chatterjee proposes in his paper, a technique that produces two different beams using the gravitational search algorithm based on the phase-only control method [3]. Furthermore, he proposed [4] that the dual-beam pair can be attain using modified FA in addition to the “on/off” states of the array elements [4]. O.M. Bucci suggested an alternative method for the shaped beam pattern synthesis [5]. For the concentric ring isotropic antenna array, the steered FTB pattern is properly synthesized and is described in [6]. Antenna array failure correction for shaped beam pattern is detailed in the article [7]. Synthesis of FTB [8] from a linear antenna array of isotropic element is performed by the polynomial approximated phase-only. In articles [9]-[10], the clonal selection algorithm is used in a reconfigurable antenna array and their shaped beam pattern syntheses are illustrated appropriately.

When using realistic antennas rather than isotropic antennas to understand the mutual coupling (MC) effect, MC analysis is required prior to implementation for each application. These articles [11]-[12] also covered the synthesis of parasitic antenna arrays and antenna arrays, including the existence of MC, as well as a finite array of dipoles and its feeding network. In the literature survey, it is found that the MC effect considered a vital part of many antenna array synthesis practices which have been reported in various papers [11]-[14]. Moreover, the phase-only reconfigurable antenna array is designed in consideration of the MC effect in [13]. Linear antenna array failure correction using FPA is given in [14].

Sometimes, it also becomes evident to offer nulls or reject lobes at any identified directions in the radiation pattern. These null steering features are desirable for increasing the SNR performance for avoiding undesirable interference in many secured communication systems. It is also illustrated in the literature survey, that the numerous techniques involved beamforming with multiple or single and wide nulls in the desired directions. In paper [15], the null control approaches and their effect on the radiation performances are explained thoroughly. To avoid interference, the nulls can be oriented along any required direction of the antenna array as mentioned in [16]. Synthesis of null for antenna arrays by controlling phase only is detailed in [17]. The [18] paper utilizes quantum particle swarm optimization (QPSO) which helped in designing the linear antenna array with its elements spaced uniformly and beam scanned away from the broad side direction while imposing constraints on SLL, broad null depth and first null beamwidth. Also, in paper [19], the QPSO algorithm is used for generating the flattop beam from a linear isotropic antenna array. Under this development, the multiple nulls are placed with minimum deviation in flattop beam ripple are effectively generated by varying the excitation current amplitude and phases at either at 0^0 or 180^0 of some elements. In most of the methods, null steering is achieved by varying any of these components like complex weights, phase-only, amplitude-only, and position only of the elements. For efficient computational time or speed, the IFFT has been successfully used for synthesizing the power pattern as mentioned in [20]-[21].

The present paper discusses a comparative study of above stated three algorithms to generate the FTB pattern including the MC effect. The present paper aims to determine the excitation current amplitudes with 0^0 and 180^0using binary phase shifters by considering all the stated optimization algorithms. IFFT has been used here to minimize the computation time. This paper compares the performance BSA, FPA and FA algorithm with respect to the antenna parameters and its statistical analysis. BSA has been used for the numerical optimization problems is detailed in the article [22]-[24]. FPA is a global optimization algorithm inspired from flowering plants was described in [25]-[26]. Xin-She Yang stated about the FA in the articles [27]-[28], which is an iterative based meta-heuristic optimization algorithm inspired from nature. The present study is given importance in the succeeding means:

By comparing the other studies, the current aim is focused directly on the implementation of the practical antennas, instead of an ideal or isotropic antenna. Effects of MC are also part of the present study because of the degradation in performance while implementing the array with the real antenna. Here, the amplitude excitations alone are considered for the pattern generation which in turn impressively decreases the computational complexity. Generally, feed network designing is one of the crucial parts of any antenna structure. So, an effective approach to minimize the complexity level of the feed network is by removing the non-uniform phase introduction part in the feed network. Also, a desirable impedance matching between a feed network and an antenna can be achieved by decreasing the VSWR value of the antenna elements.

2. THEORETICAL FORMULATION

A linear array of parallel dipole antennas has been considered along the y-axis for generating the free-space far-field pattern *FFP* (u) in the vertical (Y-Z) plane. It is expressed by Eq.(1). From Fig.1, the array elements are arranged linearly and are uniformly separated with a gap d.

$$FFP(u) = AF(u)\times EP(u_1) = \left[\sum_{n=1}^{N} A_n e^{j(n-1)kdu}\right]\times EP(u_1) \quad (1)$$

where, $u=\sin\theta$, θ is the polar angle from z-axis (-90º to +90º), n is the element number, AF (u) is the array factor in u-space, $A_n = n^{\text{th}}$ antenna's amplitude of the excitation current, d=0.5λ is the spacing between elements, k=2π/λ is the wave number, λ is the wavelength, j is the imaginary unit, and the total elements in an array configuration as N. The IFFT is used in calculating the array factor.

The dipoles are oriented along x-axis have the element pattern (EP (u_1)) expressed by the equation as below:

$$EP(u_1) = \frac{\cos\left(\frac{\pi}{2}u_1\right)}{\sqrt{1-u_1^2}}$$

where, $u_1 = \sin\theta\cos\varphi$ the element pattern of horizontal half-wavelength thin dipole antenna is assumed to be omnidirectional in Y-Zplane (φ=90°), i.e., EP (u_1) =1. For a dipole antenna, the voltage distribution matrix (1×N) is obtained by the given below Eq.(1):

$$V = I\,Z$$

where, I and Z are the (1×N) sized current matrix and (N×N) sized MC impedance matrix of the dipole antennas in the array. For the n^{th} dipole antenna, the voltage is expressed by [1]:

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

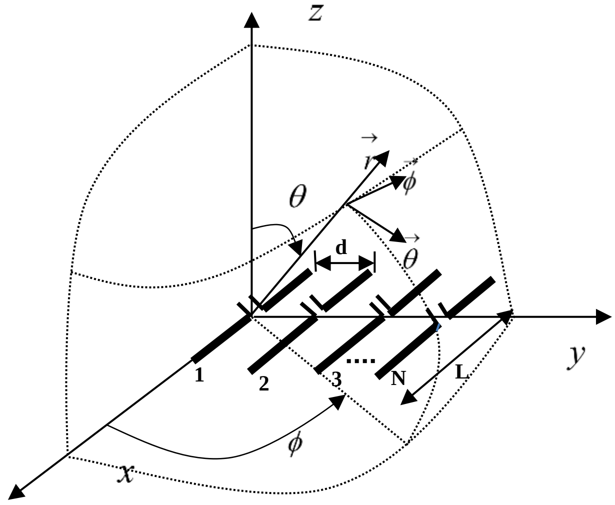

Fig.1. Geometry of Linear antenna array along the y-axis

where Z_{nn} is the self-impedance of n^{th} antenna and Z_{nm} be and mutual impedance between the n^{th} and m^{th} antennas [1] respectively and is used by imposing the distribution of sinusoidal on each of the element. The obtained equations are solved by using the 16-point Gauss-Legendre quadrature integration formula. Also, Z_n^A is the active impedance of the antenna n and computed by:

$$Z_n^A = \frac{V_n}{I_n} = Z_{nn} + \sum_{m\neq n} Z_{nm}\left(\frac{I_m}{I_n}\right) \quad (3)$$

Assuming Z_0 as the characteristic impedance of 50 ohm, Γ_n reflection coefficient at the input of n^{th} dipole [1] is then expressed by

$$\Gamma_n = \left[\frac{\left|Z_n^A\right| - Z_0}{\left|Z_n^A\right| + Z_0}\right] \quad (4)$$

At the end, after calculating the reflection coefficients, the maximum of the reflection coefficients noted which is designated by Γ_{max}.

Finally, the maximum VSWR is obtained by the given standard expression:

$$VSWR_{\max} = \left[\frac{1+|\Gamma|_{\max}}{1-|\Gamma|_{\max}}\right] \quad (5)$$

Now, the next step is to make use of FPA, FA and BSA algorithms and discover the set of amplitude of current along with binary phase shifters of 0^0 and 180^0 provided to each of the elements while minimize the succeeding fitness function to obtain the required goals.

$$Fitness = \begin{bmatrix} wtt_1 \times Ft_1^2 \\ +wtt_2 \times Ft_2^2 \\ +wtt_3 \times Ft_3^2 \\ +wtt_4 \times Ft_4^2 \\ +wtt_5 \times Ft_5 \end{bmatrix} \tag{6}$$

where,

$$Ft_1 = \begin{cases} SL_o - SL_d & if \rightarrow SL_o > SL_d \\ 0 & if \rightarrow SL_o \le SL_d \end{cases} \tag{7}$$

$$Ft_2 = Ft_3 = \begin{cases} SN_{\max}^o - SN_{\max}^d & if \rightarrow SN_{\max}^o > SN_{\max}^d \\ 0 & if \rightarrow SN_{\max}^o \le SN_{\max}^d \end{cases} \tag{8}$$

$$Ft_4 = \begin{cases} \left|ripple_{\max}^o\right| - ripple_{\max}^d & if \rightarrow \left|ripple_{\max}^o\right| > ripple_{\max}^d \\ 0 & if \rightarrow \left|ripple_{\max}^0\right| \le ripple_{\max}^d \end{cases} \tag{9}$$

$$Ft_5 = \begin{cases} \left|VSWR_{\max}^o - VSWR_{\max}^d\right| & if \rightarrow VSWR_{\max}^o > VSWR_{\max}^d \\ 0 & if \rightarrow VSWR_{\max}^o \le VSWR_{\max}^d \end{cases} \tag{10}$$

The SL_d and SL_0 are specified and achieved sidelobe levels. $SN_{\max}^0$ and $SN_{\max}^d$ are the achieved and specified value of maximum single null depth for Ft_2 and Ft_3 articulated in Eq.(8). The coefficients wtt_1, wtt_2, wtt_3, $wtt_4$and wtt_5 are the relative weights used to quantify the term in Eq.(6).

The $VSWR_{\max}^0$ and $VSWR_{\max}^d$ are achieved and specified value of maximum voltage standing wave ratio expressed in Eq.(10). The $ripple_{\max}^0$ and $ripple_{\max}^d$ are the achieved and specified value of maximum ripple from u =0 to 0.3 for the flat-top region.

3. OVERVIEW OF BSA, FA AND FPA

Civicioglu has proposed a stochastic based search algorithm called BSA. It is a population based evolutionary algorithm with dim_rate as the single controlling parameter [22]-[24]. The three core genetic operators used by BSA for test generation of individuals are selection, mutation, and crossover. It is primarily applied to solve complex, nonlinear, and non-differentiable numerical optimization problems. Details of BSA are available in the article [22]-[24]. The BSA is described in the flow chart as shown in Fig.2.

Xin-She Yang proposed the FPA by using the concept of flower pollination [25-26]. The four rules are described below:

Step 1: The global pollination process is regarded with cross-pollination and biotic processes, and pollen movements are allied with the flight of Levy.

Step 2: Abiotic and self-pollination are used for local pollination.

Step 3: The flora constant that's a pollinator type, may develop by insects. The probability of reproduction and the similarity of the two involved flowers are equivalent.

Step 4: The probability change p[0, 1] controls the whole interaction between local and globalized pollination with a slight change in local populations.

Details of FPA are available in the article [25-26]. The Fig.3 depicted a flow chart of FPA.

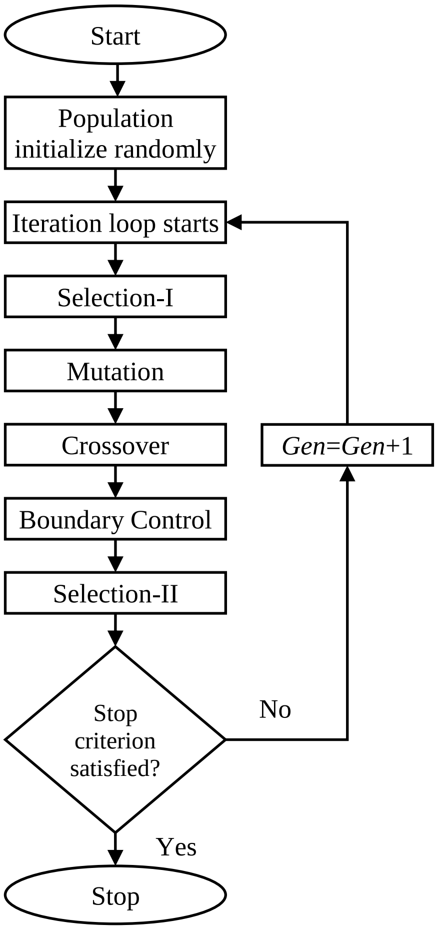

Fig.2. Flow chart of BSA algorithm

In 2010, Xin-She Yang has suggested a stochastic meta-heuristic algorithm called the firefly algorithm which is used to solve various engineering optimization problem. It is a nature motivated computing optimization algorithm established on the exclusive attribute of the fireflies' flash [27]-[28]. It uses flash as a signal to attract other fireflies.

Following are the flashing attributes of the fireflies:

- Because of their unisex property fireflies attract each other.
- A firefly takes its own path (random direction and movement) if none of the fireflies are brighter than it
- If it finds a firefly brighter that it, then it naturally gets involved with it. The attractiveness between then is proportional to their brightness
- Attractiveness between two fireflies decreases as the fireflies start moving apart from each other.
- The brightness of the any fire fly can be improved by improvement in the cost function [27].

The FA is described in the flow chart as shown in above Fig.4.

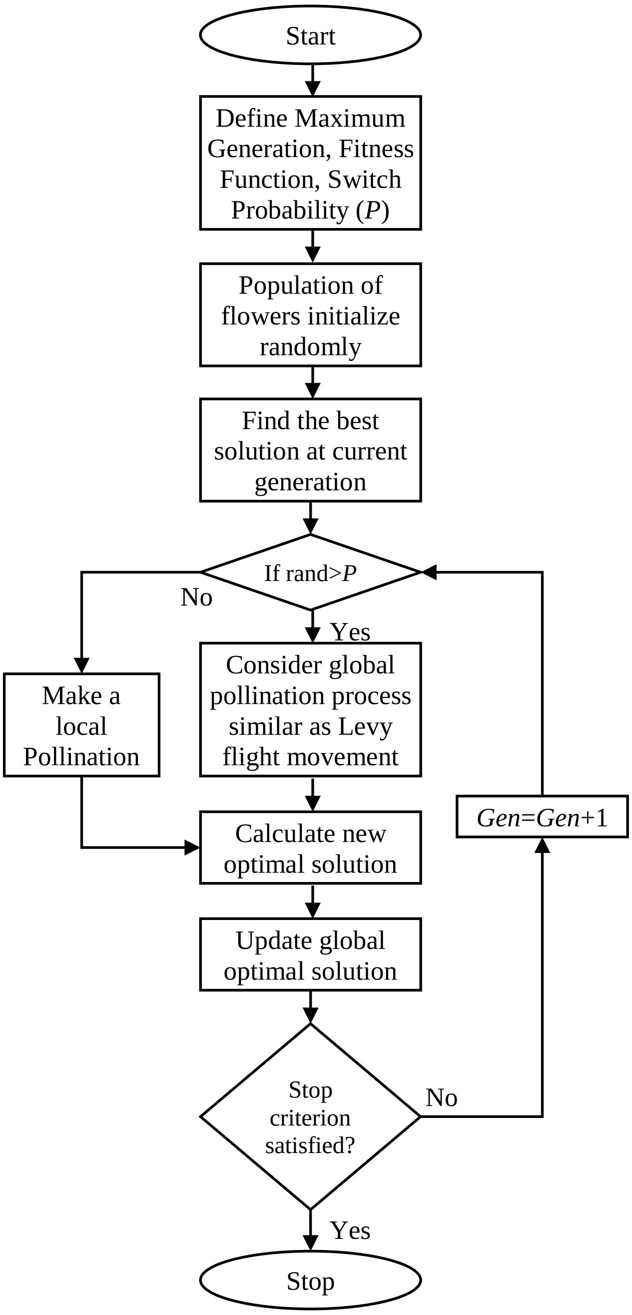

Fig.3. Flow chart of FPA algorithm

4. RESULTS AND DISCUSSIONS

The synthesis of the flat-top beam (FTB) pattern from a linear array of 26 dipole antenna equally spaced by 0.5λ along y-axis is considered and comparison of achieved outcomes of all the evolutionary optimization methods are performed very thoroughly and obtained satisfactory results. The achieved free-space FTB pattern is broadside in the vertical plane with the peak SLL of -25dB or less, ripple of 1dB or less, depth of null -48dB or less at u=0.6601and u=0.7578 and VSWR of 2 or less as predetermined. The diameters of each dipole are 0.006λ and are excited with asymmetric amplitude distribution of current excitation. 4096-point IFFT is used in coding in combination with the above-mentioned algorithms for calculating the array factor that it is effective in terms of computation time [20]-[21]. The computed processing time for all the algorithms used has been compared. Here, a comparison is also done between the algorithms on the process with IFFT. One case is discussed here.

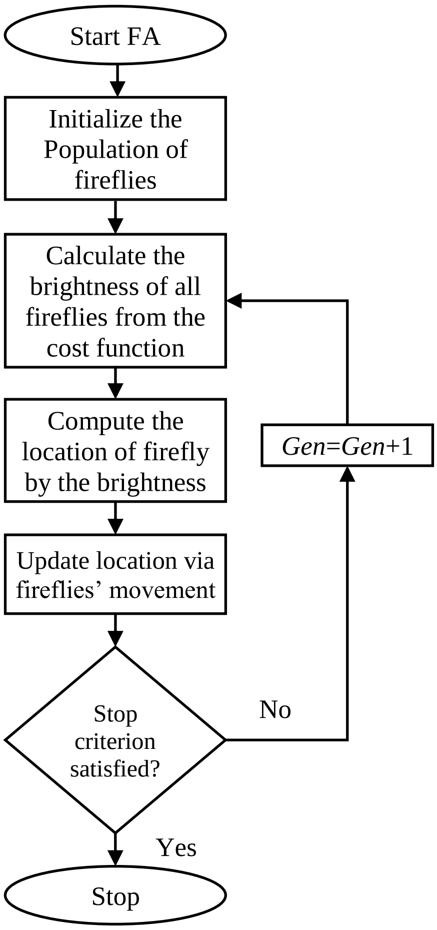

Fig.4. Flow chart of FA algorithm

Case 1: To perform the comparison of the above algorithms for FTB pattern synthesis with the different antenna parameters and statistical parameters, every algorithm is simulated for 20 times with 6000 iterations in each simulation and the population size of 60. The selection of current excitations is based on their contribution to achieve lowest value of global fitness in every run. These least value of global fitness for all the 20 simulation runs are collected and calculated for their mean and Standard deviation values.

Details of weighting parameters of the evolutionary algorithms are shown in Table.1. For comparison purposes, the value of wtt_1, wtt_2, wtt_3, wtt_4 and wtt_5 for each of the optimization algorithms is selected in such a way that the best possible anticipated outcomes from the same fitness function can be achieved. Firstly, all the internal parameters are randomly searched individually in the algorithm in between their minimum and maximum value and then allocated an appropriate value to the parameters for attaining the flat-top power beam with preferred values. The values of the tuning parameters assigned to the parameters of antenna show the priority of those parameters. If higher the value of these weights higher the priority given to the parameters compared to the others.

Table.1. Comparison of evolutionary algorithms w.r.t. its tuning parameters

Parameters	BSA	FPA	FA
Size of Population	60	60	60
Iteration	6000	6000	6000
Total Run	20	20	20
wtt_1, wtt_2, wtt_3, wtt_4, wtt_5	10,1,1,25,1	10,1,1,25,1	10,1,1,25,1
Dim_Rate [24]	1	—	—
Scale Factor [22]	1./ gamrnd(1,0.5)	—	—
attractiveness factor (Minimum value of β) [27]	—	—	0.2
Switch Probability P [25]	—	0.555	—
Absorption Coefficient [27]	—	—	1
Randomization Parameter (α) [27]	—	—	0.9

Table.2. Comparative results of BSA, FPA and FA

Design Parameters	Desired Value	Achieved by BSA	Achieved by FPA	Achieved by FA
Global Best Fitness Value	–	0	0.018	0.054
Worst Fitness Value	–	432.0448	947.3292	1373.6
Standard Deviation	–	96.2491	316.2621	555.63
Mean fitness value of 20 runs	–	36.7656	339.01	530.01
Peak SLL (dB)	-25	-25.3912	-24.984	-25.06
Ripple in dB	±0.50	±0.4981	±0.4777	±0.5031
Maximum VSWR	2	1.6992	1.6509	1.8909
Depth of Single null (dB)	-48 (u= 0.6601)	-49.2689	-48.3205	-51.8300
Depth of Single null (dB)	-48 (u= 0.7578)	-49.7889	-48.3288	-55.4977
Computation Time (s)	–	30252.55	31416.89	32699.16

Table.3. Current excitations with 0° and 180° binary phase shift

Element No	Using BSA	Using FPA	Using FA	Element No	Using BSA	Using FPA	Using FA
1	0.0194	0.0328	-0.1106	14	-0.0973	0.1074	0.0262
2	0.0120	0.0551	-0.1276	15	-0.1985	0.6249	-0.1758
3	-0.0095	0.0609	0.1114	16	0.0292	0.9769	-0.1964
4	-0.0561	0.0514	0.3223	17	0.3135	0.9761	-0.1951
5	-0.1440	-0.0037	0.3804	18	0.2981	0.5984	-0.1557
6	-0.1999	-0.0795	0.1084	19	0.0650	0.0917	-0.0822
7	-0.1869	-0.1269	-0.1727	20	-0.1256	-0.1815	0.0288
8	0.0760	-0.0656	-0.1840	21	-0.1507	-0.1460	0.0468
9	0.4444	-0.0449	0.2514	22	-0.0126	0.1296	0.0600
10	0.9042	-0.0503	0.7534	23	0.1052	0.2286	0.0722
11	0.9997	-0.1046	0.9763	24	0.0847	0.2077	0.0404
12	0.8120	-0.1865	0.7853	25	-0.0272	0.0724	0.0464
13	0.3411	-0.1422	0.3558	26	-0.0862	0.0150	0.0468

The MATLAB™ software is used as a simulation tool for verifying the experiment's results. Both the radiation pattern and the statistical parameters are found as well as analyzed using this software. Table.2 represents the results obtained using BSA, FPA and, FA for comparison. The time to compute is calculated utilizing a PC with internal configurations areas 2 GB of RAM and an Intel core2 duo processor of clock frequency 2.93GHz.

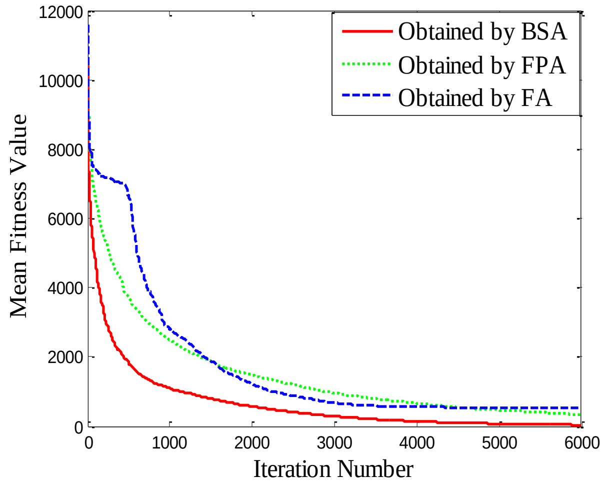

Fig.5. Mean fitness value versus Iteration number

The Table.3 shows the current excitation values. Fig.5 depicts the average value of fitness for twenty runs versus number of iterations realized by BSA, FPA, and FA. The standardized dB power patterns achieved with BSA, FPA and FA can be displayed from Fig.6 to Fig.8.

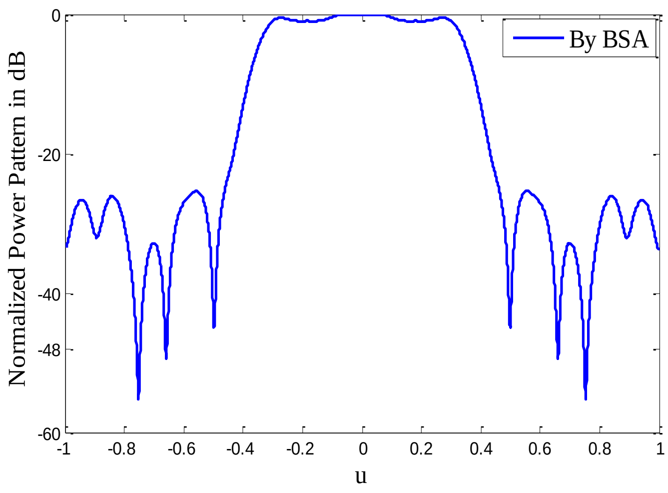

Fig.6. Normalized FTB pattern in dB with two prescribed nulls in the desired directions obtained by BSA

The obtained results are properly tabulated in the above tables which show the above-mentioned algorithms appropriate for flat-top power beam synthesis by including the effect of MC. It is also been observed that the computation time taken by BSA is lesser compared to FPA and FA; here, BSA is slightly faster than FPA. Also, the obtained results demonstrate that all the algorithms are quite suiTable.to decrease the peak SLL with minimum ripple in the flat-top region. Null depth value has attained at two different positions. The obtained values of VSWR show that a small value of maximum VSWR guarantees the sufficiently agreed impedance matching condition in an antenna array. Statistical parameters like, Standard deviation, mean and best fitness value are the best while optimizing with the BSA when compared with the FA and FPA which have poor value. The obtained results of the antenna parameters, statistical parameters and computational time depicted in the above figures and tables it is concluded that the BSA algorithm is more suitable and efficient for the design of flat-top beam pattern with IFFT in the linear antenna array problem. The calculated or/and simulated values of VSWR show the acceptable matching between the antenna and feed network.

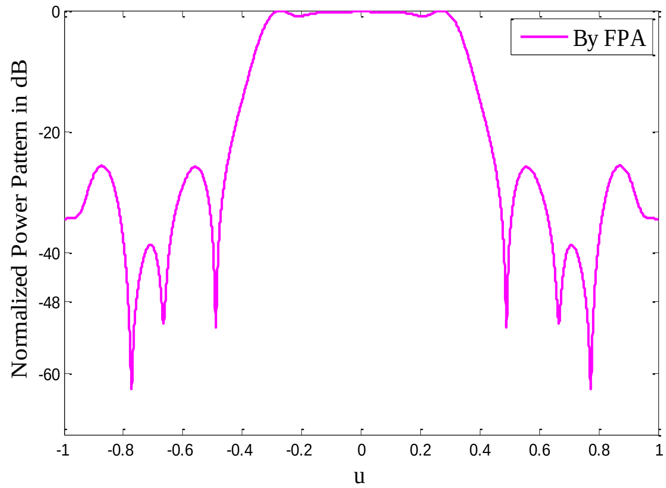

Fig.7. Normalized FTB pattern in dB with two prescribed nulls obtained by FPA

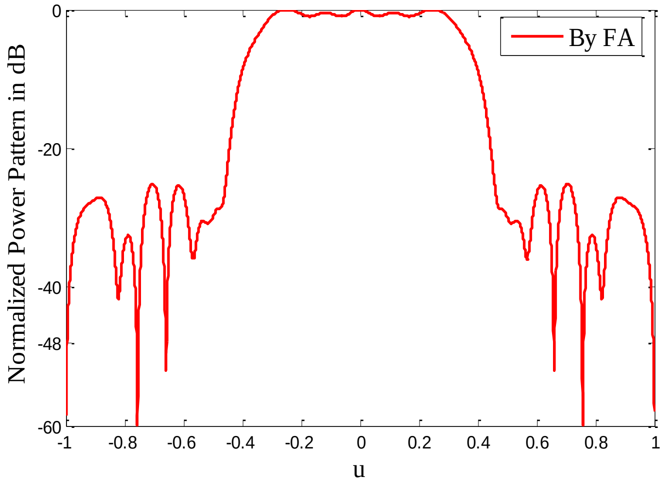

Fig.8. Normalized FTB pattern in dB with two nulls obtained by FA

5. CONCLUSIONS

All the three evolutionary algorithms; BSA, FPA and, FA respectively have shown satisfactory results and their comparative study are properly and accomplished. The antenna parameters and statistical parameters are generated and analyzed for the FTB pattern using MATLAB™. The pattern synthesis is magnificently achieved while the obtained antenna parameters values are in good agreement with the desired ones which are acceptable. The performance analysis of these algorithms for all antenna parameters and statistical parameters is given in Table.2. Additionally, it is also justified that the suggested method is a good substitute to earlier adopted methods where, non-uniform phase excitations were used for synthesizing a flat-top beam. Furthermore, this technique also minimizes the computational time and complexity in case of the large array, which requires non-uniform phase and amplitude excitations for synthesizing the flat-top beam pattern. Instead of having a complete non-uniform phase value, the phases are restricted to just two values. This will greatly reduce the feed network in terms of phase excitations. Just a phase shifter with two values is sufficient. This effect will make it easy to use the network components. The current work can be further extended by including the ground plane impact in one of its future scopes for the other type of arrays.

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