Comparison of Evolutionary Algorithms for Synthesis of Non-Uniformly Spaced Linear Array of Unequal Length Parallel Dipole Antennas for Impedance Matching with low side lobe level

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***Abstract*— This work presents a comparative study of three evolutionary algorithms such as quantum particle swarm optimization (QPSO), firefly algorithm (FA) and cuckoo search algorithm (CS) for synthesis of linear array of non-uniformly spaced parallel unequal length very thin dipole antennas for impedance matching of all the antenna elements of an array with low side lobe level. Performance of the above three algorithms for impedance matching are compared here in terms of side lobe level as well as statistical parameters such as global best fitness value, worst fitness value, mean and standard deviation. Mutual coupling effect exists between the parallel dipole antennas and it is analyzed by induced electro-motive force (EMF) method, assuming Current distribution on each dipole to be sinusoidal. In addition to it, the obtained results from simulation of the entire optimization algorithm on Matlab is also validated by results obtained from FEKO analysis. One example is presented to show the effectiveness of the proposed approach. Moreover the applied method seems very effective for a linear array of dipole antennas; however, the principle can easily be extended to other type of arrays.**

***Index Terms*— Antennas Array; Cuckoo Search Algorithm; FEKO, Firefly Algorithm; Quantum Particle Swarm Optimization; Side Lobe Level.**

I. INTRODUCTION

Antenna arrays are one of the most vital terms used in communication and other applications. In which a linear antenna array is used to generate a sufficient narrow beam also the shape of the pattern can be change by changing the geometrical configuration and antenna parameters like inter element spacing between the elements, excitation amplitude and phase, relative pattern of the individual elements [1-2]. Many researchers have developed methods for generating radiation patterns for non-uniformly excited, non-uniformly spaced antenna arrays [3-10].Application of particle swarm algorithm in the optimization of unequally spaced antenna arrays to achieve the maximum difference between the peak of main lobe and the peak of highest side lobe is detailed in [3].Non-uniform antenna array and performance improvement in amplitude synthesis of unequally spaced array is detailed in [4]. A novel modified invasive weeds optimization for synthesis of non-uniformly spaced linear antenna array is stated in [5]. Optimal pattern synthesis of antenna array is described in the literature [6]. Side lobe reduction using non-uniform elements spacing was reported in [7]. Non-uniformly spaced linear antenna array design using firefly Algorithm is also detailed in [8].Moreover the mutual coupling consideration for non-uniformly spaced linear array is a difficult work. Neural networks for solving non uniform-antenna array problems with considering coupling effects is described in [9].A method for side lobe level control for non-uniformly spaced linear array with coupling considerations is stated in [10].

Here, QPSO, FA and CS are used for optimization to generate the radiation pattern with specified side lobe level (SLL) value by optimizing the excitation and geometry of the individual array element. Coupling effect is compensated by minimizing the real and imaginary part of the input impedance of the antenna element of a linear array to the value near to the specified value. All the above mentioned optimization algorithm (QPSO, CS and FA) are detailed in the article [11-19].

In addition to it, this paper also presents a validation of obtained results from simulation using FEKO Software. FEKO [20] is a comprehensive electromagnetic simulation software tool. It is used for the electromagnetic field analysis of 3D structures. The software is based on the Method of Moments (MoM).The software can be used to calculate radiation pattern, impedance, gain etc. of an antenna or antenna array [20].

II. MAJOR CONTRIBUTION OF THE PROPOSED WORK

In the introduced work, synthesis is done on a non-uniformly spaced linear array consists of unequal height antenna elements for a multi objective problem. The proposed technique is different from [3-10] in the sense that the authors here considered excitation amplitudes, length of antenna elements and spacing between the elements as design variables to obtain the desired requirements. Moreover, this technique is different from [3-8] in the sense that authors here considered real antennas including mutual coupling effect. In addition to it, coupling effect is also compensated by minimizing the real and imaginary parts of the input impedance of the antenna elements which is different from [9-10]. This work presents a comparative analysis between QPSO, FA and CS to generate the radiation pattern for impedance matching with low SLL. Here, the obtained results from simulation are also validated using FEKO Software.

III. APPROACH

A linear array of 2N very thin wire dipole antennas has been considered along y-axis. All the dipoles are parallel to x- axis and assumed non-identical. The radiation pattern in the vertical (*Y-Z*) plane depends on the geometry and excitation currents applied at the centre of the dipoles. Elements of the array are located symmetrically on each side of the origin. The geometry of the array is given by the lengths l_n (n = 1... N) of the dipoles and the distance from origin to centre of dipole d_n (n = 1,. . . , N).The free-space far-field pattern [1] *FP (θ, ϕ)*in the vertical plane *(Y-Z)* with symmetric amplitude distributions is given by Equation (1).

$$FP(\theta,\varphi)=AF(\theta,\varphi)\times ELP(\theta,\varphi)=\left[\sum_{n=1}^{N}2I_n\cos[kd_n\sin(\theta)\sin(\varphi)\right]\times ELP(\theta,\varphi) \quad (1)$$

Where n=element number, d_n=distance from origin to centre of the n-th dipole, $k=2\pi/\lambda$ = the wave number, λ=wavelength, θ is the polar angle of far-field measured from z-axis(-90º to +90º),ϕ is the azimuth angle measured from x-axis (for vertical plane ϕ=90º), I_n= amplitude of the excitation current at n-th element, N is total number of elements from one side of the origin.*AF (θ, ϕ)* is the array factor. *ELP (θ, ϕ)* is element pattern of each x-directed horizontal thin dipole antenna. The element pattern of the horizontal dipole antenna is given below considering ϕ=90º for vertical plane:

$$ELP(\theta,\varphi)=\frac{\cos\left(\frac{kl_n\sin(\theta)\cos(\varphi)}{2}\right)-\cos\left(\frac{kl_n}{2}\right)}{\sqrt{(1-\sin(\theta)^2\cos(\varphi)^2)}} \quad (2)$$

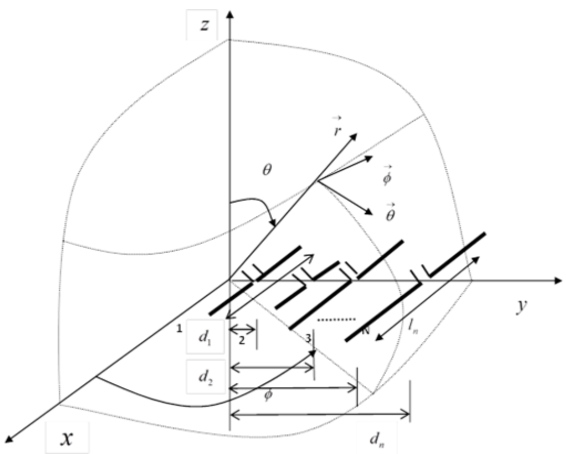

Figure 1: Geometry of linear array of x-directed parallel unequal length dipole antennas along y-axis.

The voltage distribution matrix of size (1×N) on the antenna is obtained by [1]:

$$V=IZ \quad (3)$$

Where, I is the current matrix of size (1× N) applied to dipole antennas and Z is the mutual coupling impedance matrix of size (N×N). Here N is the total number of elements. Self-impedances and mutual Impedances of Z are calculated by induced electro-motive force (EMF) method [1], which assumes the current distribution on the dipoles to be sinusoidal. The value of mutual coupling matrix Z depends on the geometry of the dipoles as well as distance between them.The integration is solved using 16-point Gauss-Legendre quadrature integration formula.

The voltage across the n-th dipole [1] is given by:

$$V_n=Z_{nn}I_n+\sum_{m\neq n}Z_{nm}I_m \quad (4)$$

Where Z_{nn} is the self-impedance of dipole n and Z_{nm} is the mutual impedance between dipoles n and m. The input impedance [1] of dipole n, Z_n^A is given by:

$$Z_n^A=V_n/I_n=Z_{nn}+\sum_{m\neq n}Z_{nm}(I_m/I_n) \quad (5)$$

In the end the real and imaginary part of the input impedance is calculated for all the elements.

We are considering that the characteristic impedance of the feed network is 50 ohm. The 50 ohm objective is taken because of the fact that it is the de-facto standard for characteristics impedance, input impedance and output impedance across all circuits and systems of telecommunications domain. For maximum power transfer real part of the input impedance should be equal to the characteristics impedance of the feed network (imaginary part equal to zero).

The aim is now to find the set of excitation current amplitude, spacing between the elements and the length of antenna elements using quantum particle swarm optimization (QPSO), firefly algorithm (FA) and cuckoo search algorithm (CS) that will minimize the following cost function to generate the free space far-field pattern with low value of SLL for impedance matching.

$$\mathrm{Cost}=\left[wet_1\times(mse(F_1))^{0.5}+wet_2\times(mse(F_2))^{0.5}+wet_3\times F_3^{\,2}\right] \quad (6)$$

Where

$$F_1=\begin{cases}\left|\mathrm{Re}\,alZA^o-\mathrm{Re}\,alZA^d\right|,if\rightarrow\mathrm{Re}\,alZA^o\neq\mathrm{Re}\,alZA^d\\0,if\rightarrow\mathrm{Re}\,alZA^o=\mathrm{Re}\,alZA^d\end{cases} \quad (7)$$

$$F_2=\begin{cases}\left|\mathrm{Im}\,agZA^o-\mathrm{Im}\,agZA^d\right|,if\rightarrow\mathrm{Im}\,agZA^o\neq\mathrm{Im}\,agZA^d\\0,if\rightarrow\mathrm{Im}\,agZA^o=\mathrm{Im}\,agZA^d\end{cases} \quad (8)$$

$$F_3=\begin{cases}SLL_0-SLL_d\,,if\rightarrow SLL_o>SLL_d\\0,if\rightarrow SLL_o\leq SLL_d\end{cases} \quad (9)$$

The coefficients wet_1, wet_2 and wet_3 are the relative weight applied to each term in Equation (6).

Where $\mathrm{Re}\,alZA^{o}$ and $\mathrm{Re}\,alZA^{d}$ are the obtained and desired value of real part of the input impedance, $\mathrm{Im}\,agZA^{o}$ and $\mathrm{Im}\,agZA^{d}$ are the obtained and desired value of imaginary part of the input impedance, SLL_o and SLL_d are the obtained and desired value of side lobe level respectively. mse is a network performance function. It measures the network's performance according to the mean of squared errors.

In our work, we have calculated simultaneous current excitation and geometry of the individual linear array elements from optimization for impedance matching with low side lobe level (SLL). The geometry represents the lengths of antenna elements and the distance from origin to the centre of dipole, while the excitation represents the current amplitudes applied to the array elements by proper feeding network. The power pattern is generated by considering the excitation and geometry symmetric from the centre of the array.

IV. Overview Of QPSO, CS And FA

The QPSO algorithm was introduced in [11-13], is a novel optimization algorithm founded on the primordial law of particle swarm and properties of quantum mechanics. QPSO has one controlling parameter α. α=0.75, is the contraction and expansion coefficient used for controlling convergence speed and performance of the particle [12-13]. Flow chart of QPSO algorithm is detailed in Figure 2.

Cuckoo search (CS) is a new meta-heuristic algorithm proposed by Xin-she Yang and S. Deb in 2009 [14-16].It is inspired by the constrained children parasitism of some cuckoo species by laying their eggs in the nests of other species. CS has two control parameters; one is population size, and discovery rate. P_a (discovery rate) controls the elitism and the balance of the randomization and local search. In our case P_a is set as 0.25 [16]. It is also discovered by Yang and Deb that the random-walk style search performance is better represents by Lévy flights rather than simple random walk.

CS is founded on three idealized principles:

1. Each cuckoo gives one egg at a time, and dumps it in a randomly chosen other Cuckoo’s nest.
2. The high quality eggs of best nests will get forwarded to the next generation.
3. The number of available host’s nests or other species is fixed. The egg put by a cuckoo is searched by the host bird with a probability $P_a \in (0,1)$. For further calculations, the host birds will abandon the set of worst nests or solutions.

Flow chart of CS algorithm is described in Figure 3.

The firefly algorithm [17-19] was proposed by Xin-She Yang in 2010. It is a nature inspired metaheuristic search algorithm based on the flashing behaviour of the fireflies [17-19]. It is used for solving various engineering optimization problems. The main purpose of a firefly flash is to use flash as a signal to attract other fire flies. The characteristics of the fireflies are given below by following rules:

1. Because of all fireflies are unisexual, so each firefly will be attracted by all other fireflies.
2. The attractiveness between two fireflies is proportional to their brightness. For any two fireflies, the less bright one will be naturally attracted by the brighter one and the intensity of attractiveness decreases when the distance between two fireflies increases.
3. If there are no fireflies flies brighter than a particular firefly then it follows its own choice of direction and movement. Flow chart of firefly algorithm (FA) is given in Figure 4.

Details of the above three algorithms are available in the articles [11-19].

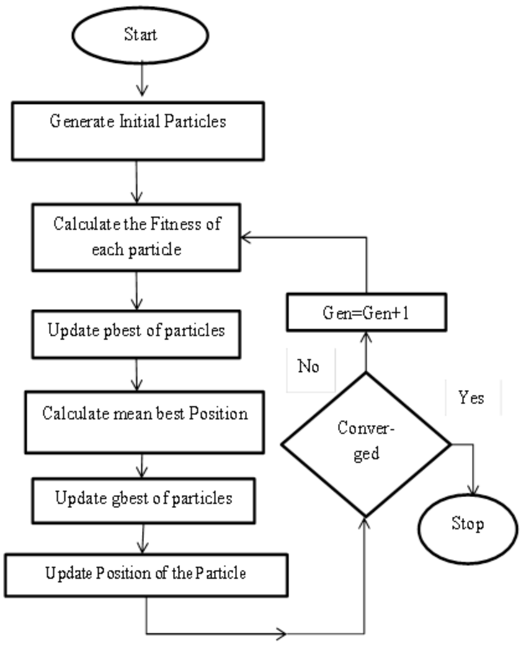

Figure 2: Flow chart of QPSO algorithm.

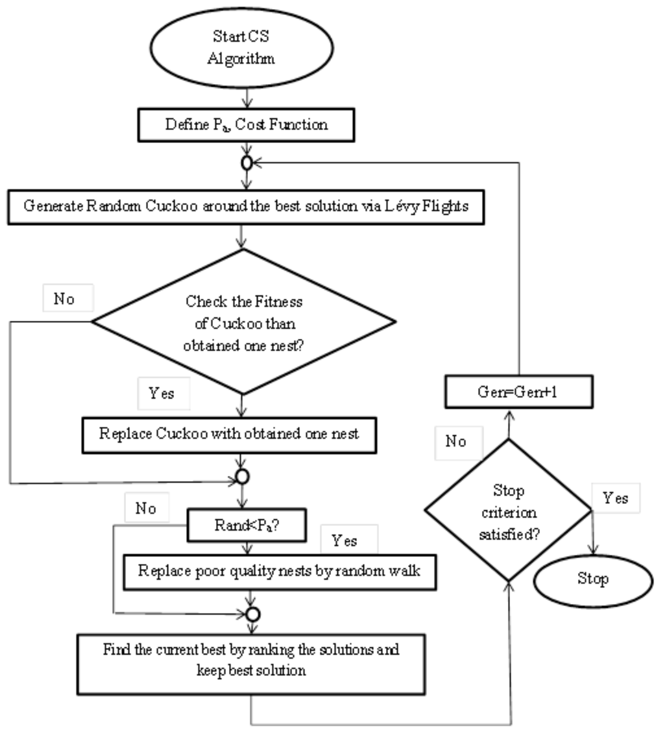

Figure 3: Flow chart of CS algorithm.

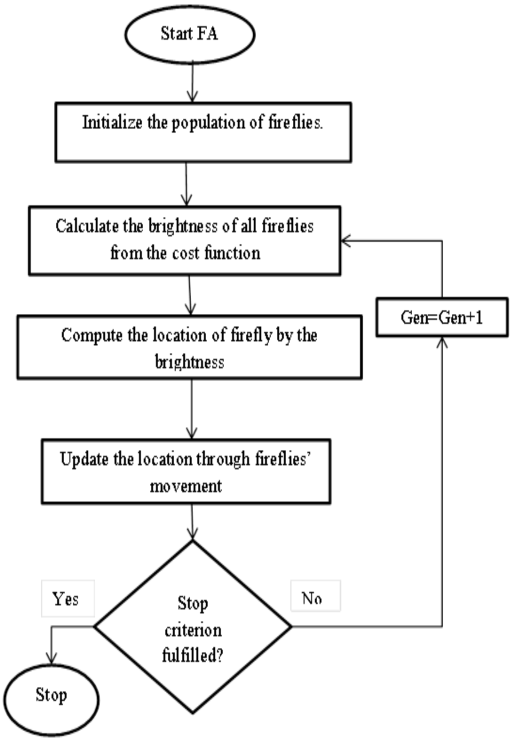

Figure 4: Flow chart of Firefly algorithm.

For comparison purpose the value of wet_1, wet_2 and wet_3 for each of the evolutionary algorithm are chosen in such a way so as to get the best possible desired results from same fitness function by Equation (6). All the internal parameters are tuned by linear variation in between their minimum and maximum values or by trial and error method and then assigned a suitable value to the parameters for obtaining the far-field pattern with impedance matching.

A report of parametric setup (tuning parameters) for all the evolutionary algorithms (QPSO, CS and FA) applied in the problem is detailed in the Table 1 below:

Table 1
Setting of tuning parameters for all the evolutionary algorithms

Parameters	QPSO	CS	FA
Population size	30	30	30
Iteration	500	500	500
Run number	10	10	10
wet_1,wet_2, wet_3	3,1,1	3,1,1	3,1,1
α	0.75	—	—
P_a	—	0.25	—
Minimum value of attractiveness	—	—	0.21
Absorption coefficient	—	—	1
Randomization parameter	—	—	1

V. RESULTS

A. Simulation

A linear array of 20 dipole antennas of radius 0.003λ has been considered along y-axis. Excitation current amplitudes is allowed to vary between 0 and 1, spacing between the elements is allowed to vary between 0.5λ and 1.1λ, and the length of each antenna element is allowed to vary between 0.4λ and 0.6λ respectively. All the current excitation phases are kept fixed at 0 degree. Due to symmetry, only ten current amplitudes, ten element spacing and ten antenna heights are to be optimized using QPSO, CS and FA. All the algorithms are designed to generate a vector of 30 real values, first 10 values to obtain the element spacing; next ten values for antenna length and last ten values are for current amplitude. For generation of far-field pattern and to compare the performance of the above mentioned algorithms in terms of different antenna parameters as well as statistical parameters all the evolutionary algorithms are run 10 times each with 500 generations with a population size of 30. All algorithms generate one best scoring individual in each run. A global best individual is regarded as best among such ten best scoring individuals (best fitness values). Mean and standard deviation of ten best scoring individuals are then calculated.

B. FEKO Assessment

1. Build antenna array geometry in CADFEKO.
2. Build geometry to describe surrounding geometry in CADFEKO.
3. Meshing of designed antenna array and the surrounding geometries.
4. Request for types of solution and setting solution parameters.
5. Run the FEKO solver.
6. Read in and illustrate results using PostFEKO.

All the steps are detailed in FEKO tutorial [20].

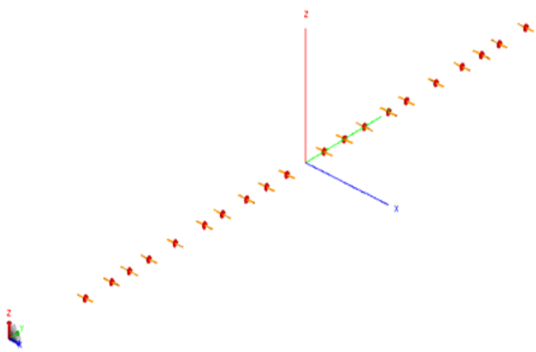

Figure 5: Constructing geometry of linear array of x-directed non-uniformly spaced unequal length center-fed dipole antennas along y-axis on CADFEKO.

Voltage excitation on the antenna elements is calculated from simulation is shown in Equation (3). Here we consider voltage excitations, length of antenna elements and distance from the origin to the centre of antenna elements obtained from simulation of the above algorithms on Matlab as excitation voltage, length and distance of antenna elements from origin to create geometry of linear antenna array on CADFEKO. Now, the far-field pattern is generated in PostFEKO after taking the same voltage excitations, length of antenna elements and distance from the origin to the centre of antenna elements obtained from simulation.

The program is written in Matlab. Computational time is measured here using a PC with Intel(R) Core(TM) i5-4690 processor of clock frequency 3.50 GHz and 4 GB of RAM.

Table 2 shows the desired and obtained comparative results from simulation using QPSO, CS, FA and the results obtained from FEKO analysis. It gives the complete comparative details about the results obtained using simulations. It shows that QPSO is better than CS and FA in terms of the statistical parameters as well as computational time.

Table 3 shows the excitation current amplitudes, length of the each antenna element (in λ) and the distance from origin to the center of the antenna elements (in λ) obtained from QPSO, CS and FA to generate the power pattern with above requirements. Length and spacing of antenna elements obtained from simulation have been used to create the geometry of antenna array on CADFEKO.

Table 4 shows the voltage excitation obtained from Equation (3) from simulation using evolutionary algorithms. These voltage excitations have been used during FEKO analysis as excitations to generate the radiation pattern for validation of the results.

Table 5 shows the real and imaginary value of input impedance of all the elements obtained from simulation and FEKO analysis. Obtained values from simulation and FEKO analysis shows that the impedance matching was well under control for all the antenna elements of an array and it is well obtained by QPSO compared to CS and FA.

Figure 6 shows the mean fitness value of ten runs versus iteration number obtained by all the evolutionary algorithms. It shows that QPSO converged well as compared to CS and FA. Figure 7 shows the normalized power pattern in dB obtained from QPSO and FEKO analysis. Figure 8 shows the normalized power pattern in dB using CS and FEKO analysis. Figure 9 shows the normalized power pattern in dB using FA and FEKO analysis. From the obtained pattern in figure 7 to 9, it is observed that the objective of low side lobe levels has been achieved and the error is less in obtained pattern from simulation and FEKO analysis.

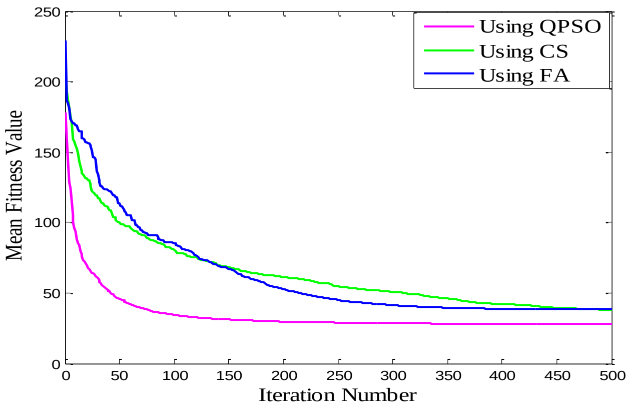

Figure 6: Mean fitness value of ten runs versus iteration number obtained from QPSO, CS and FA.

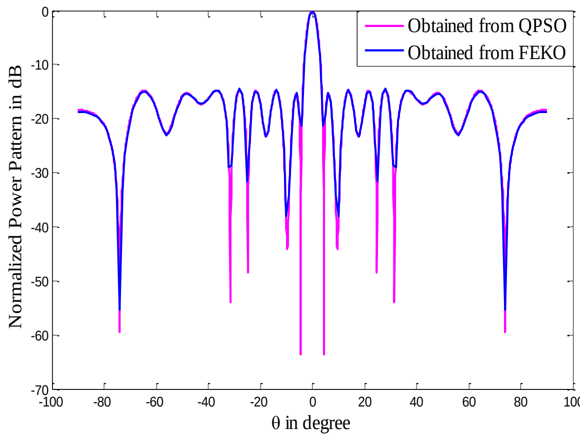

Figure 7: Normalized power pattern in dB obtained from QPSO algorithm and FEKO analysis.

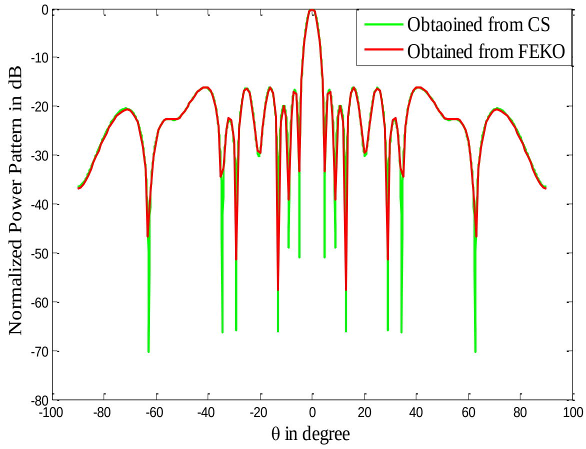

Figure 8: Normalized power pattern in dB obtained from CS algorithm and FEKO analysis.

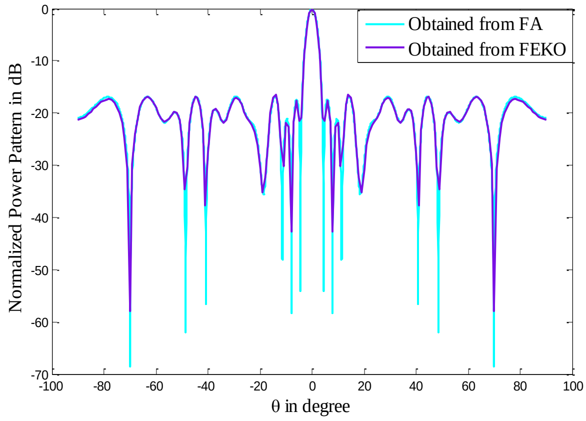

Figure 9: Normalized power pattern in dB obtained from FA and FEKO analysis.

Table 2
Desired and comparative obtained results from simulation and FEKO

Design Parameters	Desired Value	Obtained from QPSO	Obtained from CS	Obtained from FA	Obtained from FEKO (QPSO)	Obtained from FEKO (CS)	Obtained from FEKO (FA)
Global Best Fitness Value	—	20.4547	27.8186	31.8344	—	—	—
Worst Fitness Value	—	36.7495	44.9419	46.5389	—	—	—
Standard Deviation	—	4.8347	5.3661	4.4807	—	—	—
Mean Fitness Value of Ten Runs	—	27.9358	37.7535	38.3936	—		—
Peak Side Lobe Level (dB)	-18	-14.8303	-16.1748	-16.8033	-14.54	-16.11	-16.40
Computation Time (Seconds)	—	67806.35	136792.94	68594.24	—	—	—

Table 3
Excitation current amplitude, antenna height and spacing for the array

Element No	Obtained From QPSO			Obtained From CS			Obtained From FA		
	Current Excitation	Length of Antenna	Spacing	Current Excitation	Length of Antenna	Spacing	Current Excitation	Length of Antenna	Spacing
±1	0.9229	0.4697	0.8192	0.7920	0.4840	0.5429	0.6418	0.4801	0.5987
±2	0.9197	0.4736	1.7585	0.9278	0.4917	1.1259	0.8372	0.4807	1.2472
±3	0.7090	0.5060	2.3224	0.8683	0.4843	1.8455	0.5246	0.4854	1.8874
±4	0.4181	0.4694	2.8806	0.6090	0.4882	2.3748	0.5885	0.4922	2.6583
±5	0.5438	0.4798	3.7418	0.5625	0.4750	3.1708	0.5534	0.4746	3.2331
±6	0.6036	0.4966	4.2926	0.6184	0.5015	3.7539	0.6329	0.4639	4.1771
±7	0.4107	0.4691	4.9098	0.5459	0.4800	4.3119	0.4764	0.4655	5.0130
±8	0.3908	0.4799	5.8197	0.5435	0.4863	5.0488	0.4365	0.5111	5.6368
±9	0.4567	0.4956	6.3474	0.6599	0.4840	5.6052	0.4274	0.4707	6.2044
±10	0.2914	0.4669	7.0188	0.3510	0.4882	6.2214	0.3975	0.4620	7.0528

Table 4
Voltage excitation obtained from simulation

Element No	Using QPSO		Using CS		Using FA	
	Magnitude	Phase in degree	Magnitude	Phase in degree	Magnitude	Phase in degree
±1	44.9584	0.0310	36.2880	-3.8610	28.6947	-0.3793
±2	43.4918	0.1420	41.3791	20.5230	26.5285	2.9777
±3	32.1164	0.0780	42.6033	-4.3296	25.5713	1.9969
±4	18.9121	0.0171	26.2264	-3.7875	26.3020	-0.0085
±5	25.6927	0.0393	26.7182	-1.3351	19.8908	4.0033
±6	26.3024	0.0152	26.5793	7.0566	30.0532	0.1338
±7	19.4901	0.0457	25.6324	-2.3854	16.6671	4.3393
±8	18.3648	-0.0947	22.9689	4.6136	17.9808	1.1426
±9	22.4370	0.0429	29.9354	-12.1458	19.9033	3.1726
±10	14.3785	0.0382	17.2078	16.6066	19.6548	0.4749

Table 5
Real and imaginary value of the input impedance obtained from simulation and FEKO analysis

Element No	Obtained From Simulation (QPSO)		Obtained From FEKO (QPSO)		Obtained From Simulation(CS)		Obtained From FEKO (CS)		Obtained From Simulation (FA)		Obtained From FEKO (FA)	
	Real Value	Imaginary Value	Real Value	Imaginary Value	Real Value	Imaginary Value	Real Value	Imaginary Value	Real Value	Imaginary Value	Real Value	Imaginary Value
±1	48.7143	0.0263	56.47	2.879	45.7142	3.0852	51.18	-2.151	44.7087	0.2960	51.06	2.377
±2	47.2890	0.1172	54.06	2.214	41.7685	15.6357	46.84	18.75	31.6444	1.6460	35.77	4.525
±3	45.2981	0.0617	48.13	1.689	48.9251	3.7041	54.00	-2.952	48.7147	1.6985	53.38	3.748
±4	45.2334	0.0135	52.15	1.671	42.9706	2.8447	47.58	-1.779	44.6933	0.0066	48.68	2.292
±5	47.2466	0.0324	53.31	1.170	47.4862	1.1067	53.90	0.698	35.8552	2.5093	41.48	5.683
±6	43.5759	0.0116	47.39	1.618	42.6552	5.2802	46.08	6.894	47.4848	0.1109	56.21	4.026
±7	47.4559	0.0379	54.64	2.279	46.9138	1.9543	52.65	-0.973	34.8853	2.6471	40.59	7.404
±8	46.9929	0.0777	53.10	0.7813	42.1241	3.3993	46.94	5.368	41.1850	0.8214	43.73	3.635
±9	49.1285	0.0367	53.38	1.278	44.3482	9.5445	48.84	-8.682	46.4969	2.5773	53.86	4.788
±10	49.3427	0.0329	56.68	2.798	46.9803	14.0113	52.87	16.72	49.4444	0.4098	58.79	4.013

VI. CONCLUSIONS

This paper presents a comparative study of three evolutionary algorithms (QPSO, CS and FA) in terms of antenna parameters as well as statistical parameters for impedance matching to generate a far-field pattern. Results obtained from above tables describes that all the algorithms are well suitable for synthesis of power pattern in presence of mutual coupling. Computation time taken for simulation by CS is more than QPSO and FA; While, FA takes more time than QPSO. From above Table 2 we conclude that all the algorithms are applicable to reduce the peak side lobe level. Impedance matching is well obtained by QPSO for all the antenna elements of an array by matching the real and imaginary part of the input impedance to the specified value compared to CS and FA; it is shown by the obtained values from simulation and FEKO analysis in Table 5. In case of statistical parameters, QPSO gives best results for global best fitness value and mean fitness value. FA gives best result for standard deviation and generates maximum worst fitness value. For validating the obtained results from simulation of all the evolutionary algorithms, FEKO is successfully utilized here to generate the free space far-field pattern. It is shown from the obtained results by FEKO analysis in above Table 2 and Table 5. Results obtained from simulation (QPSO, CS and FA) and FEKO analysis nearly matches to each other. Overall from the obtained results of above tables, it was found that QPSO was more suitable for generation of far-field pattern with proper impedance matching of all the antenna elements of a linear array. This comparative analysis can be extended to other antenna array configurations also.

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