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Pattern Design of 2D Antenna Arrays using Biogeography Based Optimization

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Abstract— **In this work, the design of two dimensional antenna arrays using the biogeography based optimization (BBO) is considered. The purpose is to match a desired pattern while preserving acceptable properties as compared to the conventional arrays. Three array geometries considered in this work are: the rectangular array, the circular array, the concentric circular array and the hexagonal array. The parameters that are varied are the element excitation amplitude and the variation is continuous from 0 to 1. Examples are included to demonstrate the effectiveness of the optimization technique in solving the antenna array design problem**

Keywords-antenna arrays, BBO, optimization, directivity, sidelobe level

I. INTRODUCTION

An antenna array consists of more than one element. A single-element antenna is usually not enough to achieve some radiation characteristics needed for modern communication systems [1-3]. An antenna array acts as a spatial filter which permits signal from a certain direction while rejecting all other signals coming from other directions, impinging on the array. To attain this, an array must be designed with high gain at the desired look direction, and achieve maximum signal to noise plus interference ratio (SNIR) at the output. For linear array design, there are two important conventional types of arrays: the equi-spaced uniformly excited array and the Chebyshev excited array. The former is an array with high resolution but with a relatively high sidelobe, whereas the latter generally has a larger beam width as compared with the former, its sidelobes are controllable and of equi-height [4-6].

Array parameters such as output gain, input impedance and desired radiation pattern can be optimized by carefully choosing the design of antenna [7]. Optimized selection of these multiple parameters can be efficiently achieved. Pattern synthesis techniques are, in general, based on the variations of the array parameters such as the element excitations (amplitude and/or phase) and positions of array elements. The characteristics of the desired pattern can vary depending on the required application. Some synthesis methods are concerned with reducing the Sidelobe Level (SLL) while preserving the gain of the main beam [8]. Others deal with null control to eliminate the effects of interference and jamming. Other methods of controlling the array pattern use non-uniform excitation and phased arrays [9]

The Schelkunoff array polynomial method [10-12] has been used to synthesize the equispaced linear array pattern. In this method, the pattern synthesis problem is reduced to the determination of proper roots of the array polynomial for a desired pattern. From this the element excitations are determined. The works reported in literature considered large arrays based on various optimization techniques together with the Schelkunoff unit circle representation of the array polynomial for uniform linear array. A genetic algorithm has been used for the pattern synthesis by Monorchio et. al. [13]. Optimized low sidelobe levels have been presented by the F. Yu et al. in [14]. The optimization has been performed for different beamwidth values and the tradeoff between the sidelobe level and the main beam examined. Another genetic algorithm based optimizer has been proposed by A. Recioui et al and the results have been compared with other techniques [12].

Nature inspired evolutionary algorithms which have earned their place because of their simplicity, no mathematical analysis, larger solution space and faster convergence. In antenna array design problems, the evolutionary algorithms including Genetic Algorithm (GA) [15], Particle Swarm Optimization (PSO) [16], Ant-Colony-Optimization (ACO) [17] and Differential Evolution (DE) [18] have been deployed to find the optimum solutions. Haupt [15] has done a lot of research on the synthesis of antenna array using genetic algorithm. Recently more algorithms such as Invasive Weed Optimization algorithm [19], Tabu Search (TS) [20], Bees Algorithm (BA) [21], Bacteria Foraging Algorithm (BFA) [22], Taguchi's Algorithm [23] and Plant Growth Simulation Algorithm (PGSA) [12] have flourished to solve optimization problems. Guney et al. [22-24] proposed BFO, PGSA and Bees Algorithm to synthesize antenna pattern for reducing sidelobe levels with null control using the methods, amplitude-only and position control of elements.

In this work, the Biogeography Based Optimization is used as a technique to optimize the amplitude excitation, to get best reduction of SLL and the largest possible directivity. These two properties turn out to be conflicting as optimizing for one would automatically affect the other. In fact, optimizing for sidelobe level only means obtaining bad directivity and optimizing for directivity only would automatically worsen the sidelobe level. The indea of the

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present work is to use a mask to force the directivity and sidelobe levels to stay within the limits dictated by the user. The design concerns non-uniformly excited rectangular, circular, concentric circular and hexagonal antenna array geometries.

II. PROBLEM FORMULATION

To provide very directive patterns, it is necessary that the fields from the elements of the array interfere constructively in the desired directions and interfere destructively in the remaining space. Depending on the array geometry, different array factor expressions exist.

A. Rectangular arrays

If N linear arrays are placed at even intervals along the y direction, a rectangular array is formed. We assume again that they are equispaced at a distance and there is a progressive phase shift along each row. We also assume that the normalized current distribution along each of the x-directed arrays is the same but the absolute values correspond to a factor of $\mathbf{I_{1n}}$(n=1, …, N). Then, the Array Factor(AF) of the entire MN array is:

$$AF(\theta,\phi)=\sum_{n=1}^{N}\sum_{m=1}^{M}\begin{matrix} I_{nm}\exp(j(n-1)(kd_x\sin\theta\cos\phi+\beta_x \\ \times \\ \exp(j(m-1)(kd_y\sin\theta\sin\phi+\beta_y))\end{matrix} \tag{1}$$

B. Circular arrays

The array factor of circular antenna arrays is given as [7];

$$AF(\theta,\varphi)=\sum_{n=1}^{N} I_n e^{j(ka\sin(\theta)\cos(\varphi-\varphi_n)+\alpha_n)} \tag{2}$$

Where, I is the excitation amplitude of element n; φ_n is its position and α_n is the excitation phase. k is the wave number and a is the circle radius.

C. Concentric Circular Array

A concentric circular array antenna is an array that consists of many concentric rings of different radii and a number of elements on its circumference. For the concentric circular array with M rings and N_m elements in the corresponding m^{th} ring, the array factor is given as:

$$AF(\theta,\varphi)=\sum_{m=1}^{M}\sum_{n=1}^{N_M} I_{nm}\exp\{jka_m\sin(\theta)\cos(\varphi-\varphi_{nm})+\alpha_{nm}\} \tag{3}$$

D. The hexagonal array antenna

The hexagonal array (HA) can be treated as consisting of two concentric N -element circular arrays of different radii r_1, r_2 as the peripheral curve of its vertices is a circle [7]. The array factor of the hexagonal array is expressed by:

$$AF(\theta,\phi)=\sum_{n=1}^{N}\begin{matrix} A_n\exp(jr_1\sin\theta(\cos\phi_{1n}\cos\phi+\sin\phi_{1n}\sin\phi) \\ + \\ B_n\exp(jr_2\sin\theta(\cos\phi_{2n}\cos\phi+\sin\phi_{2n}\sin\phi)\end{matrix} \tag{4}$$

With $$r_2=r_1\cos(\frac{\pi}{n}) \text{ and } r_1=\frac{d_e}{\sin(\frac{\pi}{n})} \tag{5}$$

Where d_e is the inter-element spacing along any side of the hexagonal array.

E. The objective function

The objective function to be optimized is the least squares sum of differences between the produced Array Factor and the desired mask. Fig. shows an example of a Mask, Noting that the values of AF and $AFmin$ and the intervals of each one of them should be modified to adapt to the specific array factor of the 2D shape we want to optimize. For this, adjustment must be suitable to the sidelobes level (SLL) and the Directivity (Dir) of the uniform array factor of that specific shape.

The fitness function to be minimized is:

$$F=\frac{\sum_{n=1}^{N}\left|AF_d(\theta)-AF_p(\theta)\right|}{N} \tag{6}$$

$AF(\theta)_d$: The desired array factor which is represented by the mask shown above.

$AF(\theta)_p$: The produced array factor (using eqs 1 to 4).

N : Number of point. Throughout our work: N=36000.

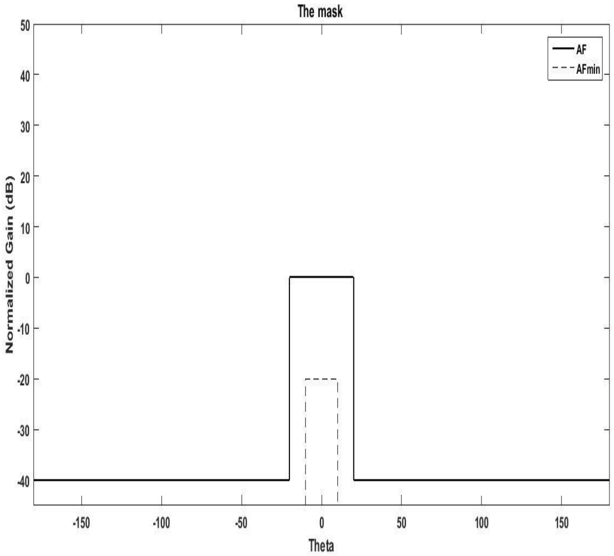

Fig. 1 The shape of the mask used in the optimization

III. THE BIOGEOGRAPHY BASED OPTIMIZATION

Biogeography based optimization (BBO) is an evolutionary algorithm (EA) that optimizes a function by stochastically and iteratively improving candidate solutions with regard to a given measure of quality or fitness function, since it does not make any assumptions about the problem, it can be applied to a wide class of problems [25]. It is typically used to optimize multidimensional real-valued functions and It does not require the function to be differentiable therefore it can be used on discontinuous functions.

Like many Evolutionary Algorithms, BBO was motivated by a natural processing particular, BBO was motivated by biogeography, which is the study of the distribution of biological species through time and space, it has been introduced by Dan Simon in 2008 [25]. Generally, Mathematical models of biogeography describe how species migrate from one island to another, how new species arise, and how species become extinct. The term "**island**" here is used descriptively rather than literally. That is, an island is any habitat that is geographically isolated from other habitats. So, Geographical areas that are well suited as residences for biological species are said to have a high **habitat suitability index** "HIS". and the variables that characterize habitability are called **suitability index variables** "SIVs", SIVs can be considered the independent variables of the habitat, and HSI can be considered the dependent variable [6]. Candidate solutions of a problem are represented by an array of integers as:

$$Habitat = \left[SIV_1, SIV_2, ..., SIV_N\right] \quad (7)$$

The Habitat suitability index (HSI) can be also referred to as the value of the fitness function since it is directly proportional to it [25,26], and it is found by evaluating the fitness function:

$$Fitness(habitat) = f([SIV_1, SIV_2, ..., SIV_N]) \quad (8)$$

A. BBO Main Operators

The BBO algorithm is based on two main operators **Migration** and **Mutation**

- **Migration Operator**

In BBO algorithm each habitat (H_i) is a solution candidate for the optimization problem and the position of each habitat (H_i) is an n-dimensional search space represented by **(SIVs)** which is an n-dimensional vector, and the quality of each habitat is measured by the "HSI" which is directly proportional to the fitness function value. This algorithm uses **Migration** operator as a powerful tool to share information between habitats in the solution space. **The Migration operator** shares information between habitats based on **immigration and emigration rates**, probabilistically. Ea0ch habitat has its own immigrationλ_i and emigration rates $\mu_i$which are the functions of species in the habitat.

For a given habitat, the immigration λ_i rate is inversely proportional to the HSI (fitness) value, while the emigration μ_i rate is directly proportional to HSI value. The habitats with high immigration rates (poor solutions) are more likely to accept information from the other habitats with high HSI values, while the habitats with low immigration rates (good solutions) share their information with other poor habitats with a high probability [25,26]. The immigration and emigration rates are calculated for each habitat as follows:

$$\mu_i = E(\frac{K}{S_{\max}}) \quad (9)$$

$$\lambda_i = I(1 - \frac{K}{S_{\max}}) \quad (10)$$

I: Maximum possible immigration rate
E: Maximum possible emigration rate
K: Number of species in the ith habitat
S_{max} : Maximum number of species

Habitats with a high HSI value tend to have a large number of species, while those with a low HSI have a small number of species. from Figure 1, it can be concluded that the habitat with few species (poor solution, low HSI) like S_1, has a low emigration rate and a high immigration rate. This means that the habitat with low HSI tends to take information about the good habitats with the high probability, while the probability of sharing its information for other habitats is relatively low. On the other hand, the habitat which has more species (good solution, high HSI) like S_2, has a low immigration rate and a high emigration rate. Such habitats with high HSI values share their information with the other habitats with a high probability. By utilizing this mechanism [25,26], the Migration Operator of the BBO algorithm can achieve adequate exploitation ability between the habitats in the search space. For each variable of a given solution (H_i), the immigration λ_i rate decides whether or not to immigrate.

- **Mutation Operator**

In most cases, it is possible that a meta-heuristic algorithm is trapped to the local optimum by lapse of the iteration. In order to escape from the local traps in the search space, the BBO algorithm utilizes a **Mutation Operator**. Which is a probabilistic operator that modifies a habitat's SIV randomly based on mutation rate (*pMutate*) [25], which is related to the habitat's probability. The mutation rate (*pMutate*) for each habitat is calculated as follows:

$$pMutate = m_{\max}(\frac{1 - P_i}{P_{\max}}) \quad (11)$$

m_{max}: user-defined parameter.
P_{max}: max{ P_i }
P_{i} =probability of the number of each species

Based on this equation a variable of each habitat mutates randomly in search space with a given probability.

Another feature of the BBO algorithm is that the elitehabitats with high HSI values are selected to keep and transfer from previous generation to the current one. Therefore, the ***"Keeprate"*** parameter is defined for this purpose. For Example, 20% of habitats with high HSI values are selected to keep in each generation. It means that the 20% of elite habitats from the previous population are transferred to the current generation and combined with new habitats (*Keeprate=0.2)*. Finally, the habitats with high HSI values are selected from the combined population of habitats to form a new population.

Fig. 2 shows the flowchart that describe the simplified algorithm of the BBO. The algorithm starts by generating random habitats and evaluating the cost function then the migration rates are calculated to be used in formulating the migration operator after that the mutation operator is applied to save the algorithm from trapping in a local minima, at the end the habitats with high HSI would be conserved to pass to the next generation. The same steps will be repeated until the termination criterion will be satisfied.

IV. RESULTS AND DISCUSSIONS

The following BBO parameters has been used: Number of population: 60,KeepRate=0.2, Number of iterations =100, Maximum migration rates E=1 and I=1, Mutation probability = 0.04.

A. Rectangular Planar Array

It is seen from figure 3 that the side lobes level and the Directivity of the uniform array are -12.65dB, 18.34dB respectively, and after optimizing the values obtained are SLL= -20.96dB , Directivity=17.14dB. From figure 4 by varying the amplitude, the side lobes level and the Directivity of the uniform array are -12.96dB to 21.70dB respectively, and after optimizing the values obtained are SLL= -20.82dB , Directivity=20.27dB.

When optimizing with 49 elements and 100 elements, for the 7 x 7 arraythe uniform one has a ratioDIR/SLLof 1.4498, we have optimized it to 0.8177,for the 10 x 10 array the uniform one has a ratioDIR/SLL1.6744, we have optimized it to 0.9736 and although we have obtained a better SLL for both cases but we had a decrease in directivity.

B. Concentric Circular array

We have used a 92 elements concentric circular array consisting of 5 rings, each ring hold a specific number of element Nm= [6 12 18 2531]. The results obtained are shown in Fig. 7 for the uniform array we have got SLL = -15.10dB, and Directivity=16.23dB and after optimizing we have a got a reduction of sidelobes level to-34.2dB, and a decrease in Directivity to 15.29dB.

We have used also a 168 elements concentric circular array consisting of 7 rings, with: Nm= [8 16 24 32 40 48].

For the second case the results obtained are shown in Figure 6, for the uniform array we have got SLL = -15 dB, and Directivity=18.95dB and after optimizing we have a got a reduction of sidelobes level to-34.09dB, and a decrease in Directivity to 16.95dB.

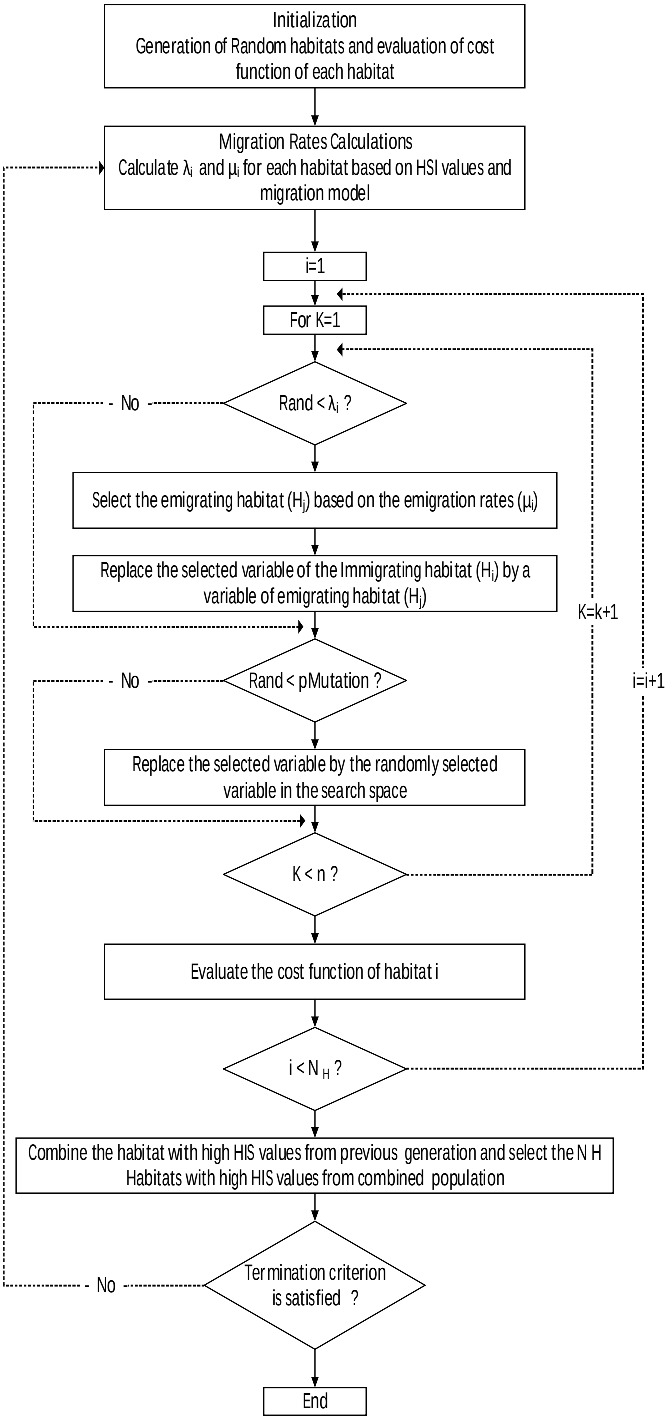

Fig. 2 the flowchart of the main BBO Algorithm

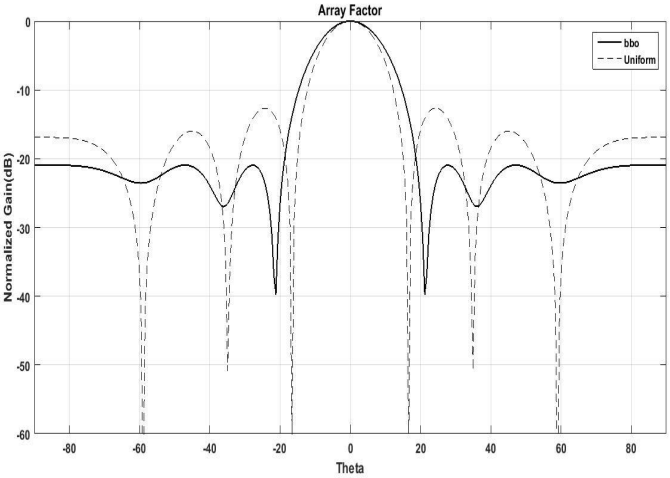

Fig. 3 Array factor of 7 x 7 Planar Rectangular Array optimization

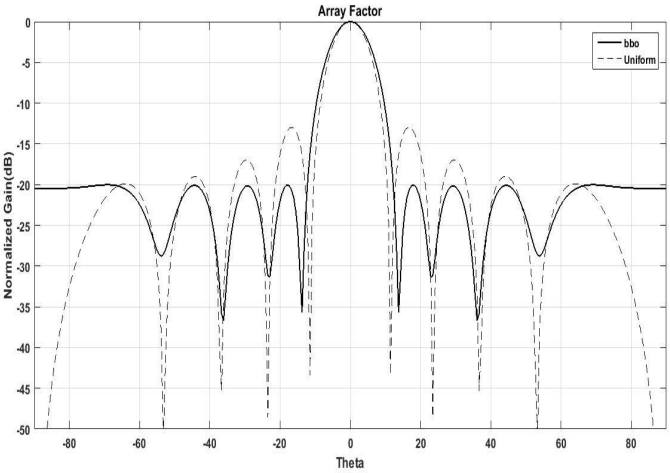

Fig. 4 Array factor of 10 x 10 Planar Rectangular Array optimization

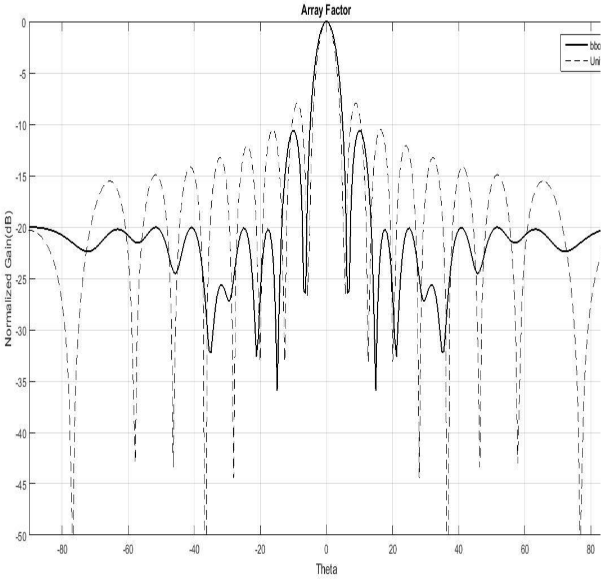

Fig. 5 Array factor of 92 element Concentric Circular array

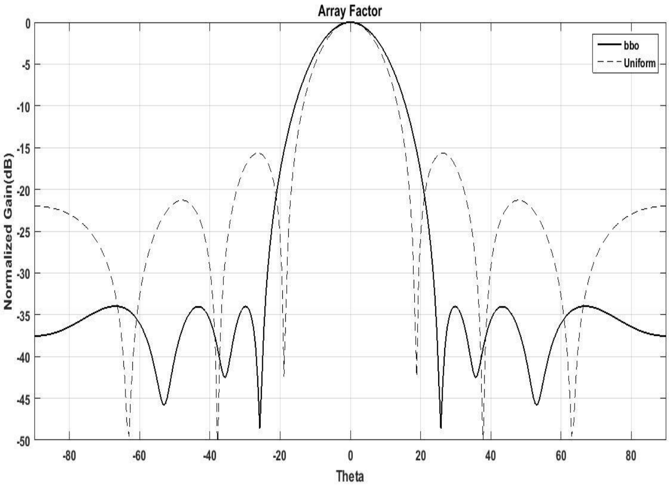

Fig. 6 Array factor of 168 element Concentric Circular array

C. The hexagonal array

A 20 elements hexagonal array is used, in the figure 7 the uniform and a non-uniformly excited hexagonal array are shown, for the uniform array we have got SLL = -07.91dB, and Directivity=15.51dB and after optimizing we have a got a reduction of SLL to-20.48dB, and a decrease in Directivity to 13.53dB.

A 50 elements hexagonal array is used, the results obtained are shown in Figure 8, for the uniform array we have got SLL =-08.01dB, and Directivity=20.34dB and after optimizing we have a got a reduction of sidelobes level to=-13.99dB, and a decrease in Directivity to 18.31dB.

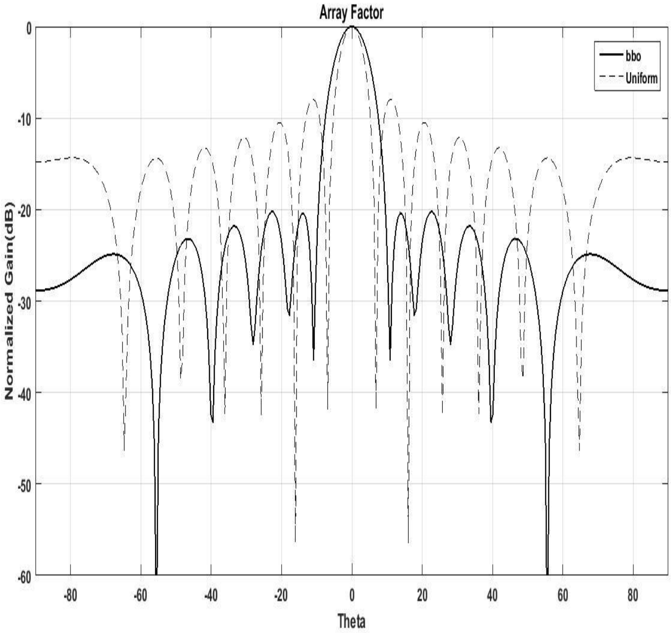

Fig. 7 Array factor of 20 element hexagonal array with optimization

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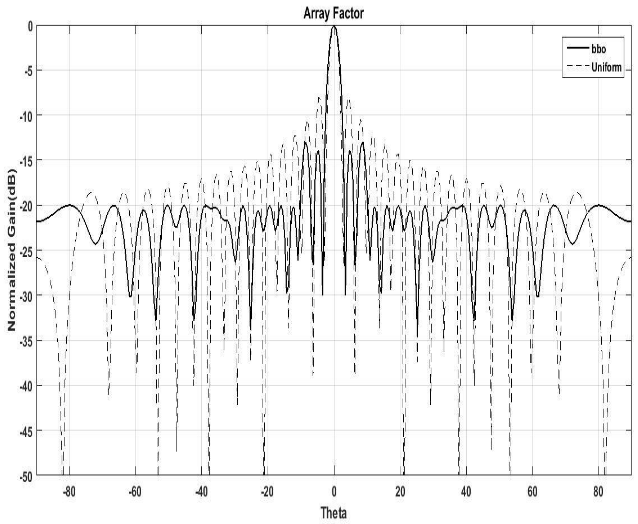

Fig. 8 Array factor of 50 element hexagonal array with optimization

V. CONCLUSION

This paper presented the optimization of a planar rectangular array, Concentric Circular and the hexagonal antenna arrays through varying the excitation amplitudes. The optimization was handled using a new nature-inspired global optimization technique which is the Biogeography based algorithm (BBO). The objective was to minimize the SLL using a designed mask while the fitness function to be used in the optimizations is the sum of the differences between the array factor treated and a specific mask made for it.

The obtained results were fairly noticeable in terms of sidelobe levels reduction. However, we noticed a decrease in directivity in all the array shapes but in many cases it was negligible due to the considered uniform array which is known to possess high directivity already as it is a common property in array antennas. The proposed mask method was just as efficient as or better than SLL objective functions implemented in literature.

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