Gravitational Search Algorithm Used to synthesis a Planar Array Antenna for Nulling Control and Side Lobe Level Reduction

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Abstract_ planar array antenna synthesis is one of the most popular optimization problems in electromagnetic and antenna community. This paper introduces a recently algorithm, known as the Gravitational Search Algorithm (GSA), to the pattern synthesis of planar antenna array for imposing deeper nulls in the interfering direction and desired side lobe level (SLL) by position-only optimization. The results of GSA are validated by comparing with results obtained using PSO algorithm as reported in literature for planar array. The numerical results such as radiation pattern show the effectiveness of the proposed method.

Index Terms_ planar array antenna, particle swarm optimization (PSO), Gravitational search algorithm (GSA), array synthesis, Deeper Nulls, Side lobe level (SLL).

I. INTRODUCTION

An antenna array can be assumed as a spatial filter, which allows signal from a specific direction and prevents all other signals from other directions, after hitting array. There are plethora antenna arrays used for personal, commercial and military applications like radio, TV, mobile, radar, sonar, and etc.

Synthesis of radiation pattern includes the selection of number and type of the elements, geometrical configuration of the overall array [2, 3, and 17], determination of the individual element excitation [4-7] and relative distance between elements [8], which is required for attaining desired radiation characteristic. With these variables we have a multidimensional optimization problem that usually analytical methods wouldn’t resolve. On the other hand due to the limitation of analytical method, we are interested in utilizing the evolutionary algorithm (EA).

Today lots of EA are used to solve electromagnetics problems due to their robustness and easy adaptively. For example, in [9] the design of a non-uniformly excited symmetric linear antenna array with optimized inter element spacing has been described, using the optimization techniques of Real-coded Genetic Algorithm (RGA).[10] describes the planar antenna array synthesis, using cross entropy (CE) method to produce array responses with minimum peak side lobe level (SLL). In [3], the method of Cuckoo Optimization Algorithm (COA) is used to determine a set of parameters of antenna elements that provide the required radiation pattern. Firefly Algorithm (FA) is applied to synthesized antenna array for reduced SLL with keeping the first null beam width (FNBW) fixed in [11]. In [12] Wind Driven Optimization (WDO) is applied to three electromagnetics optimization problems, including the synthesis of a linear antenna array, a double sided magnetic conducting surface, and an E-shaped micro strip patch antenna.

With the advancement of technology and radiation from various sources that is not mean for the communication systems, we need an antenna to receive no signals from certain directions. It means an antenna with desired nulls directions is required. Reducing the effect of international interference or jamming is the other benefit of null. Here several methods for synthesis of array antenna pattern with prescribed nulls are reviewed. Reference [13] illustrated the application of Composite Differential Evolution algorithm, called CoDE, in designing a linear antenna array, having suppressed side lobe and efficient null control in a certain direction. In [7] the Invasive Weed Optimization algorithm (IWO) for pattern synthesis of planar array with prescribed pattern nulls and side lobe reduction by optimizing the amplitude-only and position-only are presented. Pattern synthesis of linear arrays using Accelerated PSO (APSO) is presented to minimize the SLL with constrain on beam width and to perform null steering for isotropic linear antenna arrays in reference [15].

In most papers mentioned above, the null depth is about 100 dB and they used greater than 10 elements to achieve the desired pattern. But in some application deeper nulls is needed in more angles. To overcome these requirement, we used Gravitational Search Algorithm (GSA), with position-only optimization and numbers of element are 10 or less, and also the good SLL is obtained. To reduce the mutual coupling between elements we defined the distance between any two elements is greater than or equal to 0.2λ. Furthermore in this paper the total number of element is 10, less number of parameter will cause energy saving and easier fabrication.
The rest of the paper is organized as follows: in section II, the theoretical formulations for planar arrays is presented. Section III describes the principle of the GSA. Numerical results for planar arrays are given and analyzed in section IV while the conclusion are discussed in section V.

II. PROBLEM STATEMENTS

A. Planar Array Formulation

Linear array is an appropriate way to achieve desired radiation characteristic while the planar arrays have more variables which can be used to control and shape the pattern of the array. In this paper individual radiators (isotropic antenna) are position along a rectangular grid to form a planar array.

Planar array can provide deeper null with smaller number of elements and steered electronically in both azimuth and elevation. Figure 1 shows a planar antenna array (PAA) that consists of N elements. Assuming that the elements are located over the x-y plane, the far-field pattern can be calculated using the following expression [1]:

\[
AF (\theta, \phi) = \sum_{i=1}^{N} a_i e^{j k_1 d_x \sin \theta \sin \phi} e^{j k_2 d_y \sin \theta \cos \phi}
\]

(1)

Where \( i \) is the number of elements, \( a_i \) and \( \beta_i \) are the amplitude and phase of excitation of the \( i \)th element. \( dx \) and \( dy \) are the locations of elements in x and y directions, respectively. \( \theta \) is the elevation angle with respect to the z-axis and \( \phi \) the azimuth angle with respect to the x-axis.

There are three parameters controlling the AF: the amplitude, the phase and the position of the elements.

The normalized array factor in dB can be expressed as follows:

\[
p (\theta, \phi) = 20 \log_{10} \left[ \frac{|AF (\theta, \phi)|}{|AF_{max} (\theta, \phi)|} \right]
\]

(2)

The distance between any two elements is constrained to be greater than or equal to 0.3, such that the minimum distance is never less than 0.3\( \lambda \), in order to reduce the mutual coupling between elements.

B. Cost Function Definition

We now need to formulate the objective function we want to minimize. The objective function is to be defined in such a way using array factor so that the objective of the optimization is satisfied. For the optimization problem of null placement in the far field pattern of the array, the array factor value at the particular null position must be less. Similarly, for side lobe reduction problem, the array factor values at the side lobe peaks must be less than the reference pattern. To satisfy the objective of this work the array factor is included in the cost function expression. The objective function “Cost function” (CF) to be minimized with algorithms for introducing deeper null and the relative SLL reduction is given in the following equation:

\[
f = \left[ \sum_{k=1}^{K} w_k \left( \left| -ND_k \right|^2 \right) \right] + w_s \left[ |d - d_{min}|^2 + |SLL_{max} - SLL_{min}| \right]^{-1/2}
\]

(1)

Where \( K \) is the number of desired nulls, \( AF_k \) is the value of the array factor for the \( k \)th direction to be suppressed and \( ND_k \) is the desired null depth for the \( k \)th null. The weight \( w_k \) (\( k=1, \ldots, K \)) is set to zero (i.e., \( w_{null} \)) if the condition \( |AF_k| \leq ND_k \) is satisfied. \( d \) and \( d_{min} \) are the minimum distance and the desired minimum distance between the array elements, respectively. If the condition \( d \geq d_{min} \) is satisfied then the weight \( w_d \) is set to zero.

The third term in the CF is added to reduce the side lobe up to a desired level. \( SLL \) and \( SLL_{max} \) are side lobe level and desired maximum side lobe level for the overall pattern of the antenna array, respectively. The weight \( w_s \) is set to zero if the obtained side lobe level \( SLL \) is smaller than the desired maximum side lobe level \( SLL_{max} \).

In this paper, Gravitational search algorithm is used to find the location of each elements that will result in an antenna pattern with desired null depth in specific direction and side lobe level reduction.

III. Gravitational Search Algorithm

The Standard Gravitational Search Algorithm uses the Newtonian laws of gravity and motion to find optimum solutions [16]. In the proposed method they considered an isolated universe in which only gravity force plays rule. Each particle in such isolated universe attract other particle by a gravitational force that can be stated as follows:

\[
F = \frac{G(M_1 M_2)}{R^2}
\]

(4)

where \( F \) is the magnitude of gravitational force between the two particles, \( G \) is the "Gravitational Constant", \( M_1 \) and \( M_2 \) are the masses of first and second particles respectively and \( R \) is the Euclidean distance between the two particles. According to Newton’s second law, when a force is applied to an object its acceleration, \( a \), depends only on the force and its mass:

\[
a = \frac{F}{M}
\]

(5)
Where \( F \) and \( M \) is the applied force and the mass of the object respectively. According to (5) heavier particle which corresponds to better solution has less acceleration than lighter particles. In physics, the gravitational constant is not actually constant, instead it depends on the age of universe and is decreased by elapsing the time:

\[
G(t) = G(t_0) \times \left(\frac{t_0}{t}\right)^{\beta} \quad \beta < 1
\]  

(6)

Where \( G(t) \) is the value of gravitational constant at time \( t \), \( G(t_0) \) is the value of the gravitational constant at the first cosmic quantum-interval of time \( t_0 \), and \( \beta \) is a constant less than one. In GSA algorithm the gravitational constant has an exponential behavior and can be stated as follows:

\[
G(t) = G_0 e^{a T}
\]  

(7)

Where \( G_0 = 100, \alpha = 20 \) and \( T \) is the total number of iteration.

Now, consider a system with \( N \) agents (masses). We define the position of the \( i \)th agent by:

\[
X_i = (x_{i1}, x_{i2}, ..., x_{in}), \quad i = 1, ..., N
\]  

(8)

Where \( x_{id} \) is the position of \( i \)th particle in the \( d \)th dimension.

At specific time \( t \), we define the force acting on mass \( i \) from mass \( j \) as following:

\[
F_{ij}^d = G(t) \times \frac{M_i \times M_j}{R_{ij}(t)} \times \left( x_{ij}^d(t) - x_{id}^d(t) \right)
\]  

(9)

Where \( F_{ij}^d \) is the force acting on mass \( i \) from mass \( j \) in dimension \( d \), \( M_i \) and \( M_j \) are the masses of particles \( i \) and \( j \) respectively, \( \epsilon \) is a small constant and \( R_{ij}(t) \) is the Euclidean distance between two particles which can be calculated as follows:

\[
R_{ij}(t) = |X_i(t), X_j(t)|_2
\]  

(10)

To give a stochastic characteristic to the SGA algorithm, the total force which acts on agent \( i \) in a dimension \( d \) can be a random weighted sum of \( d_{ab} \) components of the forces exerted from other agents:

\[
F_i^d(t) = \sum_{j=1, j \neq i}^{N} rand_i F_{ij}^d(t)
\]  

(11)

Where \( F_i^d(t) \) is total applied force on agent \( i \) in dimension \( d \), \( rand_i \) is a random number generator and \( N \) is total number of agents act on agent \( i \).

Hence, the acceleration of the agent \( i \) at time \( t \), and in direction \( d \) can be stated as follows:

\[
a_i^d(t) = \frac{F_i^d(t)}{M_i}
\]  

(12)

By calculating the acceleration in different directions, the particles velocity and position can be updated as follows:

\[
v_{i1}^d(t + 1) = v_{i1}^d(t) + rand \times a_i^d(t)
\]  

(13)

\[
x_{i1}^d(t + 1) = x_{i1}^d(t) + v_{i1}^d(t + 1)
\]  

(14)

Where \( rand \) is a randomly distributed number in the interval \([0,1]\). This random number plays an important role in increasing the exploration power of the search algorithm.

Particles masses are a map from their fitness function such that better solutions have heavier masses. The masses are updated by the following equation:

\[
m_i(t) = \frac{fit_i(t) - \text{worst}(t)}{\text{best}(t) - \text{worst}(t)} \quad \text{best}(t) = \min_{j \in [1, ..., N]} fit_j(t) \quad \text{worst}(t) = \max_{j \in [1, ..., N]} fit_j(t)
\]  

(15)

(16)

(17)

Calculating gravitational force of all particles which effect a specific particle is a wasteful and time consuming. In order hand, in order to reduce the computation time, the exploration power should be decreased and the exploitation must be increased by elapsing the time. So, the total force which effects a specific particle can be a function of time, that is, only \( K_{best} \) number of particles which is a function of time can applies their force each other, therefore the total applied force on particle \( i \) can be calculated as follows:

\[
F_i^d(t) = \sum_{j=1, j \neq i}^{K_{best}} rand_i F_{ij}^d(t)
\]  

(18)

IV. SIMULATION RESULTS

In this section, numerical result of rectangular array optimization is presented. A planar array of 10 isotropic elements with uniform excitation and zero phase is considered, with the aperture of \( 2 \lambda \times 2 \lambda \). The position of each elements is optimized by GSA algorithm to achieve a desired value of null depth and acceptable side lobe level. The necessary parameters of the GSA are taken as follows:

The population size equals 50; the maximum number of iteration equals 2500. The programming has been written in MATLAB language using MATLAB 8.3.0 (R 2014a) version on core (TM) 2 duo processor, 3.00 GHz with 2 GB RAM.

As mentioned, by increase in the communication noise, we need to have nulls in more angles. At the first case we are considered two symmetric nulls at 30° and 60°. As shown in fig.2 the PSO algorithm is works but the GSA depth is greater than the PSO. The null depth that obtained with GSA is -220dB and -197dB at 60° and 40° respectively and the SLL is less than -20dB. The position coordinate of the array elements (normalized to lambda) are shown in fig.2 for imposing 2 double nulls. In the next case, we set three separate symmetric nulls at 20, 40 and 60. Fig.3 clearly shows that the placement
is successful with the null depth is at least -189dB down the main beam and the side lobe level value of -20dB.

Fig. 2. The produced radiation pattern with 2 symmetric nulls imposed at 40 and 60.

Fig. 3. Normalized positions of the elements in wavelengths synthesized for double nulls pattern using GSA & PSO.

Fig. 4. The produced radiation pattern with 3 nulls imposed at 20, 40 and 60.

The position of elements are shown in fig. 5 for imposing three nulls. In the third case it is attempted to place four separate symmetric nulls at 20, 40, 60 and 80. As shown in fig. 6 the GSA reached our desired objective by placing the four nulls at exactly their corresponding angles with null depths reaching even -200dB. Fig. 7 concerns placing four separate symmetric nulls at 20, 40, 60 and 80.

Fig. 5. Normalized positions of the elements in wavelengths synthesized for three nulls pattern using GSA & PSO.

Figure 6. The produced radiation pattern with 4 symmetric nulls imposed at 20, 40, 60 and 80.

Fig. 6. Normalized positions of the elements in wavelengths synthesized for four nulls pattern using GSA & PSO.

From figure 6, it is evident that GSA imposes deeper nulls over 4 symmetric nulls. It can be seen that by increasing the number of nulls, the PSO algorithm loses its ability but GSA works fine.

V. Conclusion

Design of planar antenna arrays with deeper nulls and SLL reduction is an important optimization problem in computational electromagnetics. In this paper, we proposed recently inspired met heuristic algorithm called Gravitational Search Algorithm (GSA) and demonstrated through simulation experiments, the efficiency of the proposed
technique in comparison with the PSO. To reduce the coupling effects between elements, we considered the desired minimum distance between array elements. In this work we implemented the algorithm to constrain synthesis of planar array with isotropic elements, but it is not limited to this case. It can easily be implemented to non-isotropic elements antenna array with different geometrics for the design of different array patterns.

REFERENCES

[9] Bipul Goswami, and Durbadal Mandal, “Introducing Deeper Null and Reduction of Sidelobe Levels in a Symmetric Linear Antenna Array Using Genetic Algorithm,”