Null-Steering Beamformer Using Bat Algorithm

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Abstract ─ This paper proposes an adaptive null-steering beamformer based on Bat Algorithm (BA) for Uniform Linear Array (ULA) antennas to suppress the interference. The beamformer is targeted at steering nulls of ULA pattern in the directions of the interferences. The amplitude-only nulling method has been utilized for adjusting excitation weight of each array element. In order to validate the proposal, several scenarios of ULA array pattern imposed with the prescribed nulls have been investigated and compared with those of accelerated particle optimization (APSO) and genetic algorithm (GA). The proposed beamformer has shown the ability to suppress sidelobes and to place precisely single, multiple, and broad nulls at arbitrary interference directions. Furthermore, the beamformer is much faster and more effective than APSO and GA-based ones.

Index Terms ─ Array pattern synthesis, bat algorithm, beamformer, beamforming, interference suppression, null-steering, ULA antennas.

I. INTRODUCTION

Adaptive beamformers for smart antennas are widely applied in wireless communication systems to enhance the performance by increasing the effectiveness of radio spectrum utilizing, interference suppression, and saving power consumption. In order to obtain the desired pattern of the array, the beamformers create appropriate weights for array antenna elements [1].

Nowadays, the increasing number of wireless devices causes serious pollution in the electromagnetic propagation environment. In this context, smart antennas with null-steering capabilities emerge as promising solution for interference suppression in wireless communications and radar applications.

Several nulling methods such as controlling the amplitude-only, the phase-only, position-only, and the complex weights (both the amplitude and the phase) have been widely studied and implemented [1,2]. All of these methods have their own advantages and limitations.

Among those, the complex weights method has been considered as the most flexible and efficient one because it allows to adjust amplitude and phase simultaneously [3-6]. Nonetheless, it is the most complicated and expensive due to the fact that each array element must have controllers, phase shifters and attenuators. Especially, the computational time will be a considerable issue in large array antennas.

Indeed, the problem for the phase-only and position-only nulling methods is inherently nonlinear [7]. The position-only method [8-10] requires a mechanical driving system such as servomotors for adjusting the array element position. This makes the system more complicated, and has difficulty in accuracy control. Phase-only null synthesizing is less complex and more attractive for the phased arrays since the required controls are available at no extra cost, but it still has common problems [11-14].

The amplitude-only control [7], [15-17] is the simple method, compared to the others as it only changes the amplitude excited at each array element. Specifically, in the case of even number of elements that is symmetrical at the center of the array, the number of attenuators and the computational time will be reduced by half.

In recent years, optimization techniques have been widely applied in beamforming for antenna array pattern synthesis including null steering. The classical optimization techniques used for the array pattern synthesis are likely to be stuck in local minima if the initial guesses are not reasonably close to the final solution. Most of the classical optimization techniques and analytical approaches also suffer from the lack of producing flexible solutions for a given antenna pattern synthesis problem. To overcome these issues, various nature-inspired optimization algorithms based on computational intelligence approaches have been developed. These algorithms such as ant colony

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optimization [5], bacterial foraging algorithm [7], differential evolution [16], clonal selection [17], bees algorithm [18], especially the genetic algorithm (GA) [2,6, 19-21] and particle swarm optimization (PSO) [20, 22,23] have been proved to be better and more flexible solutions than the classical techniques. These techniques have been proposed and implemented with their own benefits and limitations in the array pattern synthesis.

BA is a new nature-inspired computation technique based on the bat behavior of using echolocation to detect prey, avoid obstacles, and locate their roosting crevices in the dark. It has been successfully used to solve various kinds of engineering problems [24,25]. BA is better than PSO and GA optimization in terms of convergence, robustness and precision [24]. This algorithm has been applied for the first time for beamforming in [26]. The authors of [26] showed that the BA is a promising optimization tool for adaptive beamforming in terms of computation time. Nevertheless, this work was still in preliminary phase and thus, it lacked adequate analysis on the application of BA in beamforming.

In this paper, a beamformer based on BA is proposed for ULA antennas pattern synthesis with null-steering abilities. In our proposal, the amplitudes of excitation for array elements are the only controlling parameters, and the main aim is to synthesize array patterns with nulls imposed on directions of interferences. The proposed beamformer will be verified in five scenarios, and compared with accelerated particle swarm optimization (APSO) and GA-based ones. The results show that the beamformer operates well in terms of steering the nulls to interference directions, sidelobe suppression, and more efficiently than those of APSO and GA-based ones.

II. PROBLEM FORMULATION

Null-steering for interference suppression is achieved by adjusting the weights of array elements. Simultaneously, it is always desirable to keep the beamwidth and the peak sidelobe level (SLL) within a required level. This is realized by solving min optimization problem subjected to three constrains, namely, SLL limits, the prescribed location of the null points and acceptable broadening of the main lobe. The problem can be described as follows:

$$\left\{\begin{matrix} min(|AF_o(\omega_n,\theta,d)|) & at\ \theta=\theta_i \\ min(|AF_o-AF_d|) & at\ \theta\neq\theta_i \end{matrix}\right\}, \quad (1)$$

where: $AF(\omega_n,\theta,d)$ is the array factor, which is a function of weights (ω_n); θ is the elevation angle of incident wave with respect to the direction of the antenna array; and d is the distance between adjacent elements. AF_0 and AF_d are the optimization patterns obtained by using an optimization, which will be BA in this paper, and the desired pattern, respectively. θ_i are the angles of null points.

The ULA antenna of $2N$ isotropic elements is considered and presented in Fig. 1. The array is positioned symmetrically along the x axis, and the array factor can be expressed as:

$$AF(\theta) = \sum_{n=-N}^{N} \omega_n\, e^{jndksin(\theta)}, \quad (2)$$

where: $\omega_n = \omega_n^{re} + j\omega_n^{im}$, $\{n=(-N,\ldots,-2,-1,1,2,\ldots,N)\}$, is the complex weight of n^{th} array element; $k=\frac{2\pi}{\lambda}$ is the wave number; λ is wave length. In our study, the imaginary parts of weight (ω_n^{im}) are zero, and $\omega_{-n}^{re}=\omega_n^{re}$. Therefore, the weights are real and symmetrical around the center of the array. This means the number of attenuators and computation time are halved, and the array pattern is symmetrical around the main lobe at θ=0.

Since $\omega_n^{im}=0$ and $sin(-ndksin(\theta)) = -sin(ndksin(\theta))$, the array factor in (1) can be rewritten as:

$$AF(\theta) = 2\sum_{n=1}^{N} \omega_n^{re}\cos(ndksin(\theta)). \quad (3)$$

According to (3), the array factor is symmetrical around the center of the array (or about theta angle θ=0).

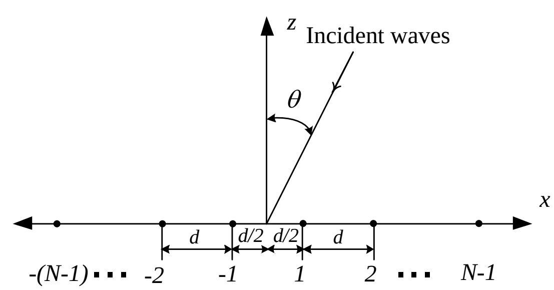

Fig. 1. Geometry of ULA antennas of $2N$ elements.

For the investigated ULA, to put a null at a given angle θ_i, we need [3]:

$$AF(\theta_i) = W^T v(\theta_i) = 0, \quad (4)$$

where: W is $N\times 1$ vector, which is defined as:

$$W = [\omega_{-N}, \omega_{-(N-1)}, \ldots, \omega_{N-1}, \omega_N]^T,$$

and

$$v(\theta_i) = \begin{bmatrix} e^{-jNdksin(\theta)} \\ e^{-j(N-1)dksin(\theta)} \\ . \\ . \\ . \\ e^{j(N-1)dksin(\theta)} \\ e^{jNdksin(\theta)} \end{bmatrix}_{N\times 1}.$$

Additionally, inspired by the objective function implemented previously in [7,27], a new objective function F, which meets the requirements in (1), has been developed as follows:

$$F_1 = \sum_{\theta=-90^0}^{90^0} [|AF_o(\theta) - AF_d(\theta)|^2],\ with\ \theta \neq \theta_i, \quad (5)$$

$$F_2 = \sum_{i=1}^{I} [|AF_o(\theta_i)|^2], \quad (6)$$

where: F_1 is used to reduce SLL and to keep beamwidth of main lobe within a maximum allowable change; F_2 is for placing the null points.

The objective function F has been built from F_1 and F_2 as follows:

$$F = \begin{cases} N(\theta)F_2, & \text{for } \theta = \theta_i \\ F_1\ , & \text{elsewhere} \end{cases}, \quad (7)$$

where: $N(\theta)$ is a parameter, which is defined by simulations during the investigation of the proposal (see Section IV).

III. PROPOSAL OF THE BEAMFORMER

A. Bat algorithm

The Bat algorithm is a new swarm intelligence optimization method developed by Yang in 2010 [24], in which the fundamental principle is inspired by the social behavior of bats and the phenomenon of echolocation to sense distance.

In BA [24,25], each bat (i) is defined by its position x_i^t, velocity v_i^t, frequency f_i, loudness A_i^t, and the emission pulse rate r_i^t in a d-dimensional search space. The new solutions x_i^t and velocities v_i^t at time step t are given by:

$$f_i = f_{min} + (f_{max} - f_{min})\beta,$$
$$v_i^t = v_i^{t-1} + (x_i^t - x_*)f_i, \quad (8)$$
$$x_i^t = x_i^{t-1} + v_i^t,$$

where $\beta \in [0,1]$ is a random vector drawn from a uniform distribution. Here x_* is the current global best location (solution) which is located after comparing all the solutions among all n bats. Frequency range is defined by f_{min} and f_{max}, which are chosen depending on the domain size of the problem of interest. Initially, each bat is randomly given a frequency which is drawn uniformly from $[f_{min}, f_{max}]$. For the local search part, once a solution is selected among the current best solutions, a new solution for each bat is generated locally using random walk as:

$$x_{new} = x_{old} + \varepsilon A^t, \quad (9)$$

where $\varepsilon \in [0,1]$ is a random number, while A^t is the average loudness of all the bats at time step t.

Furthermore, in consecutive iterations, the loudness A_i and the rate r_i of emission pulse can be updated by:

$$A_i^{t+1} = \alpha A_i^t, \quad (10)$$

$$r_i^{t+1} = r_i^0[1 - \exp(-\gamma t)], \quad (11)$$

where $0<\alpha<1$ and $0<\gamma$ are constants.

B. Bat algorithm based beamformer

The basic principle of the beamformers has been presented in [28]. Additionally, in our previous papers [29-31], the adaptive beamformer for ULA antennas with detailed design and verification procedure has been given. Inspired by these beamfomers and BA, a null-steering beamformer for interference suppression is being proposed and presented in Fig. 2. Operation of the beamformer is described as follows.

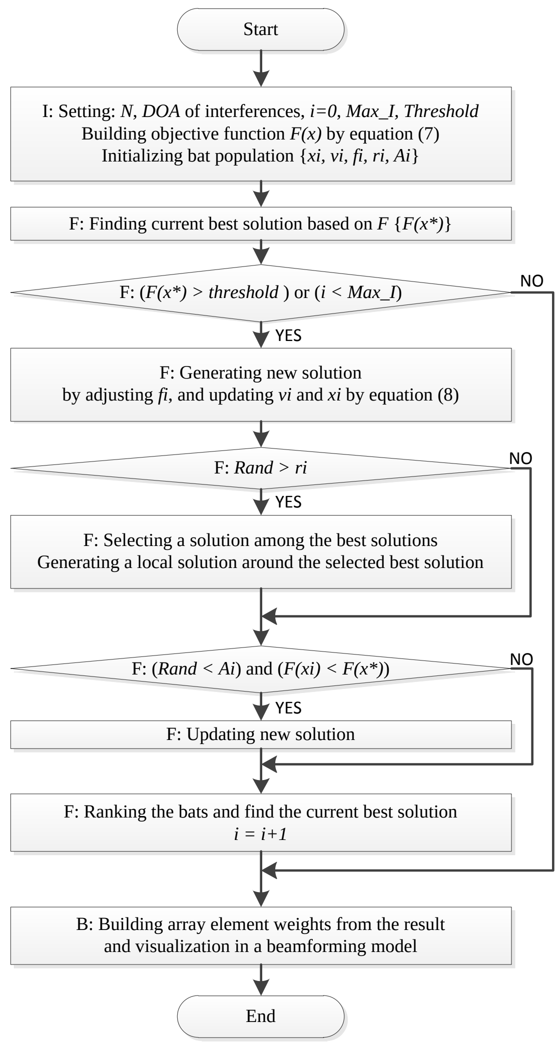

Fig. 2. Flowchart of the proposed beamformer.

Initializations (I):

- Setting the input data such as: number of array elements (N), Direction of Arrival (DOA) of interferences; number of iteration (i); maximum number of iterations (Max_I); and the termination criterion (*Threshold*).
- Initializing bat population in which parameters of each bat are: location x_i; velocity v_i; pulse frequency f_i; pulse rate r_i; and loudness A_i. Each bat is corresponding to a

potential solution.

Finding the best solution (F):

- The beamformer consecutively calculates and searches for the current best solution based on the BA. The operation is finished when the termination criterion or maximum number of iterations is satisfied. Then, the final best solution is obtained.

Building of the amplitude of excitations for array elements (B):

- From the best solution, the beamformer calculates the corresponding amplitude excited at each element of ULA antenna. These parameters will be used for null-steering.

IV. NUMERICAL RESULTS

To demonstrate the capability and flexibility of the proposal for sidelobe suppression and null steering, five scenarios will be investigated. It is well-known that the Chebyshev array weights distribution produces the optimum pattern in terms of tradeoff between the sidelobe level and the first-null beamwidth of main lobe for equally spaced arrays [32]. Therefore, in this paper, array factor of Chebyshev array has been chosen as a desired one to control the sidelobe level and the beamwidth. A -30 dB Chebyshev array pattern for 20 isotropic elements with $\lambda/2$ inter-element spacing has been utilized as the initial pattern.

The initial parameters for BA have been chosen for all investigation scenarios as: population size is 1000 and number of iterations is 20 (except for the first scenarios); step size of random walk is 0.01; boundary frequency values: f_{min}=0 and f_{max}=1; search value x_i in the range of 0 to 1; $A = r = 0.5$.

Parameters for GA: selection rate: 50%; mutation rate: 20%; crossover type: roulette wheel; crossover rate: 90%; and elitism: 1.

Due to the simplicity and improved convergence speed, APSO by Yang [25] has been considered as a good choice, and the parameters have been chosen as α = 0.2 and β = 0.5 [23,25].

The values of the objective function parameters given in Equation (7) are selected as follows:

$$AF_d = \begin{cases} 0, & \text{for } \theta = \theta_i \\ \text{Initial pattern}, & \text{elsewhere} \end{cases}, \quad (12)$$

$$N(\theta) = \begin{cases} 10000, & \text{for } \theta = \theta_i \\ 1, & \text{otherwise} \end{cases}. \quad (13)$$

In order to show the ability of our proposed beamformer for interference suppression, five scenarios have been built as Convergence Characteristics, Single Null, Multiple Nulls and Broad Null. The simulation results of all scenarios have been compared and presented in Figs. 3-7, in which the results are averaged values of Monte Carlo simulations with 1000 times for the first scenario, and 100 times for the others.

A. Convergence characteristics

In the first scenario, convergence rate of the proposed beamformer has been investigated and compared with those of APSO and GA-based ones. In order to do that, these beamformer have been applied to obtain the desired optimization pattern as -30 dB Chebyshev array pattern. Additionally, the initial population has been randomly generated, number of iteration is 100. Their convergence rates have been illustrated in Fig. 3. It can be seen that BA-based beamformer converges much faster than APSO and GA-based ones.

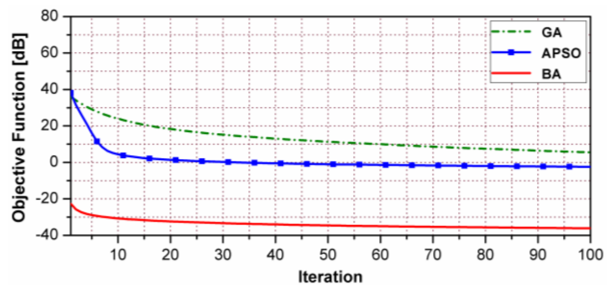

Fig. 3. Objective function comparisons of BA, APSO, and GA.

B. Single null

In the second scenario, the optimized patterns with single null have been demonstrated. This null is arbitrarily set at any angle, which is chosen at peak of the second sidelobe (14^0) in this test case. The population has been initialized as -30 dB Chebyshev array weights. As shown in Fig. 4, the optimized pattern by the proposed beamformer (BA pattern) preserves almost characteristics of the initial Chebyshev pattern such as approximately equal half power beam width (HPBW = $7{,}64^0$) and sidelobe level (-30 dB) except for first sidelobe level of -27 dB and the nulling location (θ_i=14^0) of -90.6 dB. It should be noted that a symmetric null is also observed at θ_i = -14^0 due to the symmetry of the array factor in (3). Additionally, the single null pattern optimized by our proposal is better than that of APSO and GA in the context of null depth level (NDL).

C. Multiple nulls

In the third scenario, the optimized patterns imposed with multiple nulls, which are set at 14^0, 26^0, and 33^0 corresponding to the peaks of the second, the fourth and the fifth sidelobe next to the main lobe of Chebyshev array pattern, has been given in Fig. 5. It can be seen that the nulls of optimized pattern have been exactly obtained at the predefined locations. All the NDLs are deeper than -71 dB and most sidelobe levels are nearly equal to that of Chebyshev pattern excluding the first and second sidelobe (maximum SLL is -20.5 dB). The BA pattern shows advantages over the APSO and GA patterns in terms of NDL and SLL.

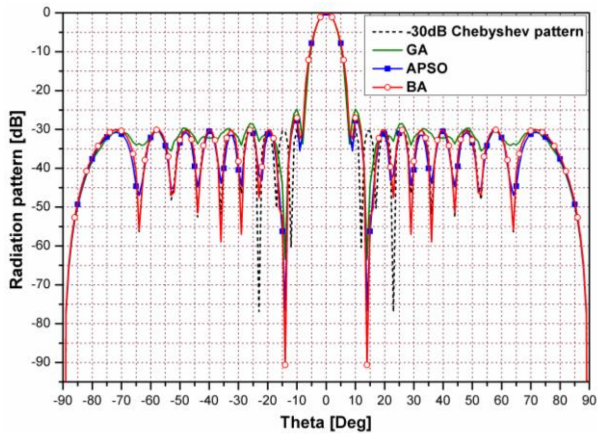

Fig. 4. Optimized pattern with single symmetric null at 14^0.

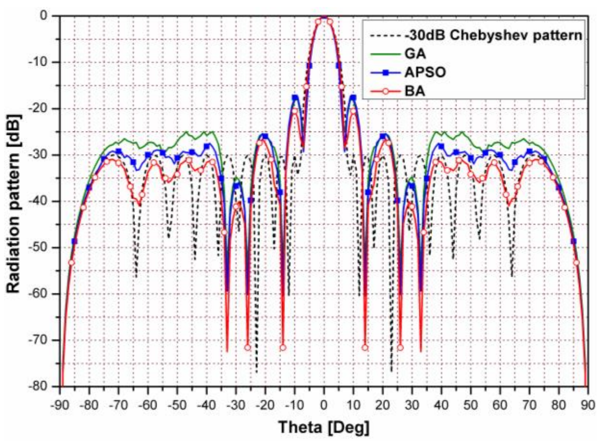

Fig. 5. Optimized patterns with three symmetric multiple nulls at 14^0, 26^0, and 33^0.

D. Broad null

In interference suppression application, if the directions of arrival of undesired interferences vary slightly with time or not be known exactly, or a null is continuously steered for obtaining an appropriate signal-to-noise ratio, a broad null is required. To give a demonstration of broad interference suppression capability, in the fourth scenario, the pattern with an imposed broad null locating at 35^0 with angular width ($\Delta\theta_i = 30^0$) has been obtained and illustrated in Fig. 6. It can be observed that a broad null (minimum NDL < -63 dB) on the BA pattern at the target sector has been obtained. The beamwidth stays the same without significant changes, and maximum SLL is -18.3 dB. According to the results, the BA pattern surpasses the APSO and GA ones in terms of NDL.

In all of the above scenarios, the null points of the patterns have been set accurately and the beamwidths have been approximately preserved. Notwithstanding this, SLLs were bigger than -30 dB. To hold maximum SLL at a predefined value (for example, -30 dB) and a symmetric broad null at the target sectors of [20^0, 50^0] as well, the fifth scenario has been conducted, in which AF_d has been substituted by the array factor of Chebyshev array with SLL of -49 dB. Optimized patterns have been shown in Fig. 7.

There exists a trade-off between the SLL and the beamwidth of the patterns, which possess maximum SLL of -30 dB and a broadened HPBW.

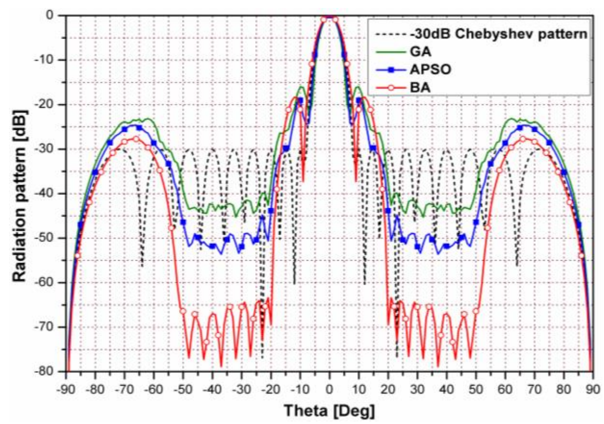

Fig. 6. Optimized patterns with a symmetric broad null from 20^0 to 50^0, unchanged main lobe and maximum SLL = -18.3 dB.

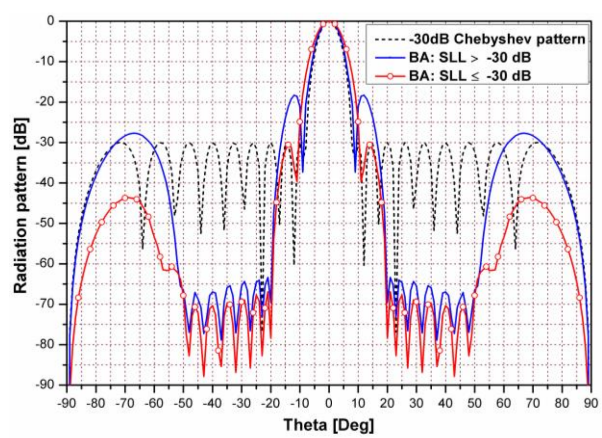

Fig. 7. Optimized pattern with a symmetric broad null from 20^0 to 50^0, broadened main lobe and SLL ≤ -30 dB.

V. CONCLUSION

In this paper, a BA-based beamformer has been proposed for adaptive steering nulls of ULA antennas patterns. The nulls steering capability of the beamformer has been verified by five scenarios including operation speed, null steering with single, multiple and broad nulls. The results show that the above mentioned nulls can be precisely imposed to arbitrary interference directions using our proposed beamformer, while the patterns have maintained the HPBW and low SLL. Furthermore, compared with APSO and GA-based beamformers, our proposal is more efficient in terms of operation speed and adaptive null steering in array pattern synthesis.

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