AN EFFICIENT BEAMFORMER FOR UNIFORM RECTANGULAR ARRAYS

MỘT BỘ ĐỊNH BÚP SÓNG HIỆU QUẢ CHO MẢNG HÌNH CHỮ NHẬT CÁCH ĐỀU

Tong Van Luyen[1,*], Nguyen Van Cuong[1]

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ABSTRACT

This paper proposes an efficient beamformer based on the binary bat algorithm for uniform rectangular arrays of half-wavelength dipoles. The proposed beamformer utilizes the technique of controlling only the amplitude of excitation weights to produce optimal patterns with minimal distortions in sidelobe regions while maintaining the main beam and imposing nulls in the directions of interfering signals. To demonstrate this ability, the proposed beamformer is evaluated through various scenarios and compared to a beamformer based on binary particle swarm optimization.

Keywords: *Beamforming, binary bat algorithm, optimum array processing, interference mitigation, array pattern synthesis.*

TÓM TẮT

Bài báo này đề xuất một bộ định dạng búp sóng hiệu quả cho mảng anten lưỡng cực nửa bước sóng hình chữ nhật cách đều dựa trên thuật toán đàn dơi nhị phân. Bộ định dạng búp sóng đề xuất tận dụng kỹ thuật chỉ điều khiển biên độ của trọng số kích thích để tạo ra giản đồ bức xạ tối ưu với sự biến dạng tối thiểu tại các vùng búp sóng phụ trong khi duy trì búp sóng chính và đặt điểm "KHÔNG" tại hướng của tín hiệu nhiễu. Để minh họa khả năng này, bộ định dạng búp sóng đề xuất được đánh giá qua các kịch bản đa dạng khác nhau và được so sánh với bộ định dạng búp sóng dựa trên thuật toán tối ưu hoá bầy đàn.

Từ khóa: *Định dạng búp sóng, thuật toán đàn dơi nhị phân, xử lý mảng tối ưu, giảm thiểu nhiễu, tổng hợp giản đồ bức xạ của mảng anten.*

[1]Hanoi University of Industry
[*]Email: luyentv@haui.edu.vn
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1. INTRODUCTION

Due to the increasing pollution of the electromagnetic environment, various kinds of interferences are serious concerns in communication system design and operation. To improve the ability of interference mitigation and spectrum utilization in radar and wireless communications applications, array pattern synthesis and pattern nulling have been taken into account in numerous research papers. Several pattern nulling techniques including weight control, position-only control, and array thinning have been adopted to mitigate interferences with their merits and demerits. In smart antenna systems, adaptive beamformers based on weight controls for interference mitigation are of great interest and becoming important [1-3].

In excitation weight-based controls, the complex weight control, which simultaneously adjusts both the amplitudes and phases, has been deemed to be the best performance for steering nulls and maintaining sidelobes. However, this control has been proved to be slow and comes at a high cost because of requiring a set of an attenuator, and a phase shifter for each element [4]. In contrast, the simpler controls are the amplitude-only control and the phase-only control. Although the phase-only control technique can be applied to existing phased array systems without incurring additional costs, it cannot place two nulls symmetrically across the main beam in the array pattern without large phase shifters; various kinds of nulls are placed less flexibly as well [3, 5]. Meanwhile, the only amplitude-only control is less vulnerable to quantization errors and easier to implement than the phase-only one [6].

Recently, metaheuristic algorithms for optimization such as bat algorithm (BA), particle swarm optimization (PSO), and genetic algorithm (GA) to solve continuous optimization problems or binary particle swarm optimization (BPSO) and binary bat algorithm (BBA) to solve discrete optimization problems, which outperform classical optimization techniques, have all been proved to be effective global optimization algorithms to obtain optimal patterns [4-9]. Among those, BA and BBA were superior to the other algorithms on the different types of benchmark functions as well as multiple engineering problems. In [4-6], specifically, adaptive beamformers utilizing BA were successfully performed for uniform linear arrays (ULAs), and the results show that BA-based beamformers have been proved to be completely superior to GA and accelerated PSO-based ones in respect of pattern nulling. However, weight vectors optimized in these beamformers are in the real number format while the excitation amplitude or phase of elements are commonly adjusted by digital attenuators and/or digital phase shifters. Therefore, real weight vectors necessitate quantizing before applying them to the digital attenuators or digital phase shifters, which leads to the quantization error of optimized weights and the perturbation of array patterns.

The aforementioned beamformers were used for ULAs, but this type of array lacks the capability of scanning in 3-D space [4-12]. In contrast, the main beam of the pattern of uniform rectangular arrays (URA) can be steered toward any direction of elevation and azimuth in space. In addition, URAs are more adaptable and can produce more symmetrical patterns with deeper sidelobes. In particular, these arrays are more attractive for these mobile devices and applications including tracking radar, search radar, remote sensing, and communications [13].

Understanding these challenges and characteristics, this paper proposes an efficient beamformer utilizing the amplitude control and the basic BBA in [14] for a URA of half-wavelength dipoles. The binary weights optimized by BBA are directly applied to digital attenuators to obtain optimized patterns, which are compared to the patterns optimized by a BPSO-based beamformer.

2. PROBLEM FORMULATION

This paper considers a URA of U x V half-wavelength dipoles illustrated in Figure 1.

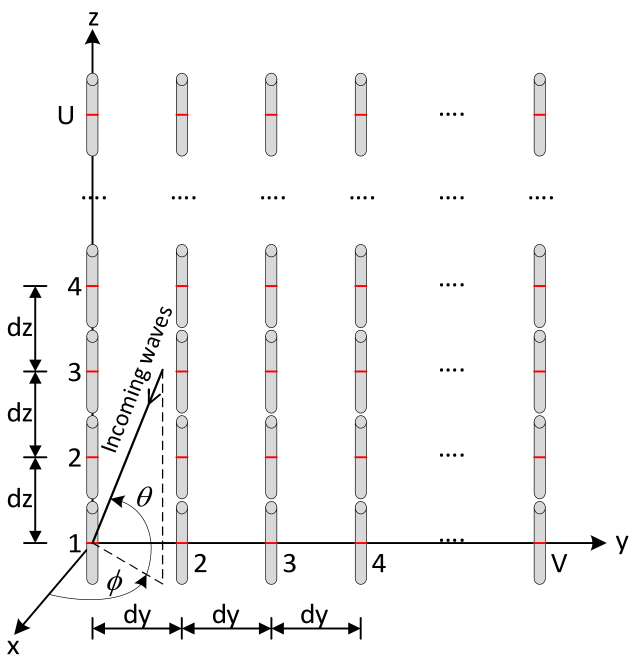

Figure 1. A planar dipole array with uniformly spaced elements

The array pattern can be expressed as [13]:

$$P(\phi,\theta) = EF \cdot AF = EF\sum_{u=0}^{U-1}\sum_{v=0}^{V-1} w_{u,v}e^{j(u\psi_z + v\psi_y)}, \quad (1)$$

where:

- EF is the element factor of the dipole, and AF is the array factor of the array at (ϕ,θ);
- $\psi_z = kd_z\cos(90-\theta)$.
- $\psi_y = kd_y\sin(90-\theta)\sin(\phi)$.
- $k = 2\pi/\lambda$ is the wavenumber; d_y = d_z = λ/2 is the distance between elements.
- The dipole has a length slightly lower than λ/2 and a radius of approximately λ/150. The operating frequency is 70MHz.
- $w_{u,v} = a_{u,v}e^{j\delta u,v}$ is the complex weight at the $(u,v)^{th}$ element with $a_{u,v}$ and $\delta_{u,v}$ are the amplitude and the phase, respectively.

To steer the main beam toward the direction of (ϕ_0,θ_0), the phase shift of the $(u,v)^{th}$ antenna element is equal to [13]:

$$\delta_{u,v} = -k\left(ud_z\cos(90-\theta_0) + vd_y\sin(90-\theta_0)\sin(\phi_0)\right) \quad (2)$$

The proposed beamformer utilizes the amplitude-only control to obtain nulled patterns, so the approach to obtain these patterns will be presented in the next section.

3. THE PROPOSAL OF AN EFFICIENT BEAMFORMER

3.1. The fitness function

The fitness function in this proposal is developed for the receiver, but this development is similar for the transmitter. The proposed beamformer requires mitigating interferences while keeping the main beam and sidelobes at a predefined level. This means that a problem required to solve is a constrained optimization problem. Moreover, since only the amplitude of weight excitations is controlled, i.e. ($\delta_{u,v}$ = 0), the main beam will be steered toward $(\phi_0,\theta_0) = (0°,0°)$. This means that most of the high-magnitude sidelobes occur at $(\phi = -90° : 90°, \theta = 0°)$ and $(\phi = 0°, \theta = -90° : 90°)$. Nulls can be arbitrarily placed in 3-D space; however, interferences emerging in high-magnitude sidelobes are the most undesirable, so this paper assumes that interferences only emerge at the azimuth plane (θ = 0°). By applying the penalty method in [15], therefore, the constrained problem is converted to the unconstrained problem, and the fitness function to solve this unconstrained problem can be formulated as [4 - 6]:

$$F(a_{u,v}) = \frac{1}{\xi}\left[\begin{array}{l}\xi\sum_{i=1}^{I}\left[\left|P_o(\phi_i,\theta_i)\right|^2\right] + \\ \sum_{\phi=0°,\theta=-90°}^{\theta=90°}\left[\left|P_o(\phi,\theta) - P_d(\phi,\theta)\right|^2\right] + \\ \sum_{\theta=0°,\phi=-90°}^{\phi=90°}\left[\left|P_o(\phi,\theta) - P_d(\phi,\theta)\right|^2\right]\end{array}\right], \quad (3)$$

where:

- ξ = 1000, this penalty parameter is chosen based on approaches presented in [4 - 6].

- I is the total number of interfering signals.
- (ϕ,θ_i) is the direction of the i[th] interfering signal.
- $\xi\sum_{i=1}^{I}\left[\left|P_o(\phi,\theta_i)\right|^2\right]$ is to place I nulls at (ϕ,θ_i).
- $\sum_{\phi=0^\circ,\theta=-90^\circ}^{\theta=90^\circ}\left[\left|P_o(\phi,\theta)-P_d(\phi,\theta)\right|^2\right]+\sum_{\theta=0^\circ,\phi=-90^\circ}^{\phi=90^\circ}\left[\left|P_o(\phi,\theta)-P_d(\phi,\theta)\right|^2\right]$

for $(\phi,\theta)\neq(\phi,\theta_i)$ are used to maintain the optimized pattern $P_o(\phi,\theta)$ with as little disturbance as possible concerning the reference pattern $P_d(\phi,\theta)$.

- $P_o(\phi,\theta)$ and $P_o(\phi,\theta_i)$ are the patterns optimized by BPSO or BBA at (ϕ,θ) and (ϕ,θ_i), respectively.

3.2. The proposed algorithm

To obtain optimized weights, the proposed algorithm which is displayed in Figure 2 is implemented. This algorithm can be explained as follows: firstly, the parameters of the array and of BBA (block with a red border) are initialized such as the number of antenna elements, fitness function (F) described in the previous subsection, the number of bat population and their characteristics including solution/position (xi or $a_{u,v}$ in the fitness function), frequency (fi), velocity (vi), pulse rate (ri), and loudness (Ai). After that, BBA's mechanism (blocks with a green border) is implemented (see more details in [14]) and eventually optimized weights are acquired to form nulled patterns (block with a blue border). In the process of finding the optimal solution, optimized bits in Gbest can be directly applied to digital attenuators.

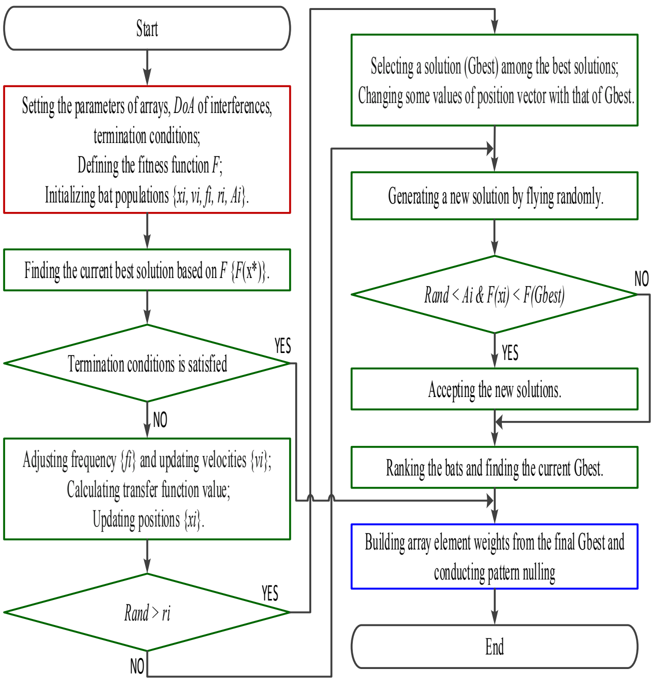

Figure 2. The flowchart of the efficient beamformer

4. NUMERICAL RESULTS

The performance of the proposal for interference mitigation is evaluated via three scenarios in this section. Common parameters for all scenario simulations:

- The URA of half-wavelength dipoles has U = V = 24 for the first two scenarios and U = V = 25 for the last scenario; The 5-bit digital attenuators are adopted.
- The reference pattern $P_d(\phi,\theta)$ is chosen as the Chebyshev pattern with SLL = -25dB.
- The population of BBA and BPSO are randomly initialized apart from the first solution initialized by the weights of the Chebyshev pattern. Apart from the iteration iter = 200 for the first scenario, the iteration for the other scenarios is 3, and the population is pop = 50. the results for all scenarios are average values of Monte Carlo simulations with 200 times.
- BBA: A = 0.25; r = 0.1; f_{min} = 1 and f_{max} = 2 [14].
- BPSO: C_1 = C_2 = 2; w = [0.4, 0.9]; V_{max} = 6; the transfer function is V-shaped [16].

4.1. Convergence characteristics

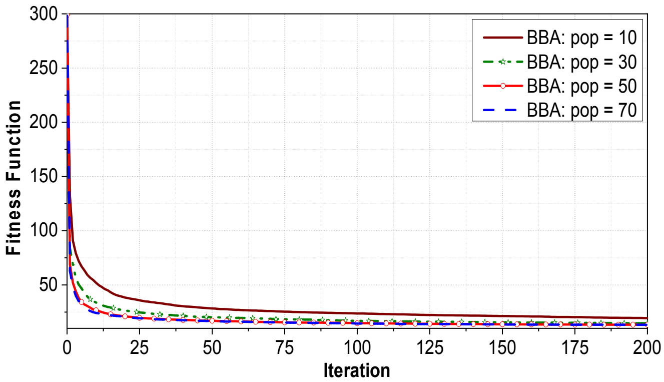

Figure 3. The fitness function of BBA-based BF with different population sizes

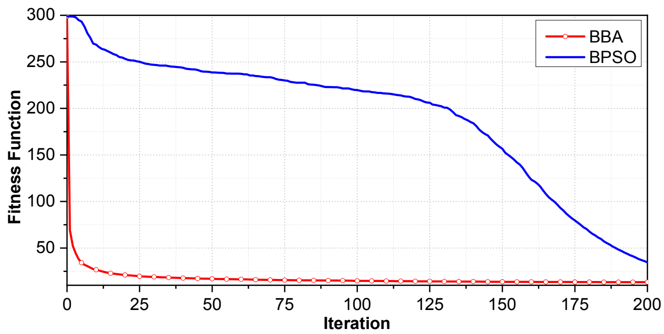

Figure 4. The comparison of the fitness function between BBA-based BF and BPSO-based BF

This scenario compares the value of the fitness function in the case of placing a single null at a peak of the Chebyshev pattern $(\phi,\theta_i)=(21^\circ,0^\circ)$. The BBA-based BF has been investigated with different population sizes, which is shown in Figure 3. This beamformer has taken 15, 6, 3, and 3 iterations to approximately achieve F ≤ 21 corresponding to pop = 10, 30, 50 and 70, respectively. For illustrative purposes, pop = 50 and iter = 3 have been chosen for the next scenarios.

In addition, the simulation result of the fitness function with pop = 50 and iter = 3 is displayed in Figure 4. The beamformer based on BBA has clearly converged much more quickly than that based on BPSO.

4.2. Efficient null-steering ability

This scenario presents the adaptive null-steering ability of the proposed beamformer. Figure 5 and Figure 6 show the 2-D and 3-D optimized pattern with a single null at $(\phi_i, \theta_i) = (21^\circ, 0^\circ)$ obtained by BBA-based BF. In both cutting planes with $\phi = 0^\circ$ and θ = 0°, the optimized pattern has preserved almost all characteristics of the reference pattern including first null beamwidth (FNBW = 12°), half-power beamwidth (HPBW = 4.8°), and the sidelobe levels (SLL = -30dB) except for the maximum SLL = -21.49dB and NDL = -58.49dB. Interestingly, there is an additional null at $(\phi, \theta) = (-21^\circ, 0^\circ)$ which is symmetrical to a pre-intended null across the main beam because of the characteristic of only amplitude control.

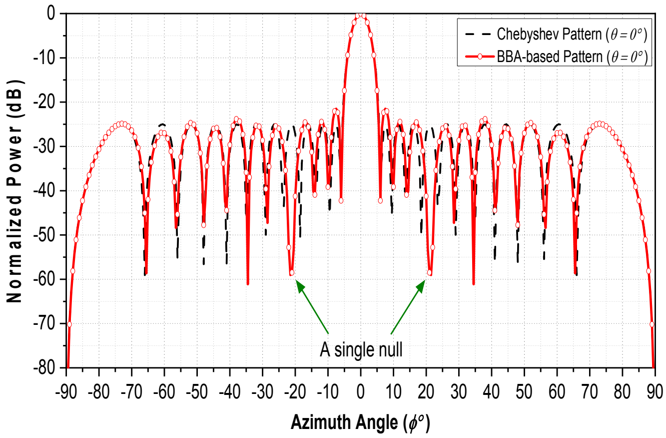

Figure 5. The 2-D optimized pattern with a single null

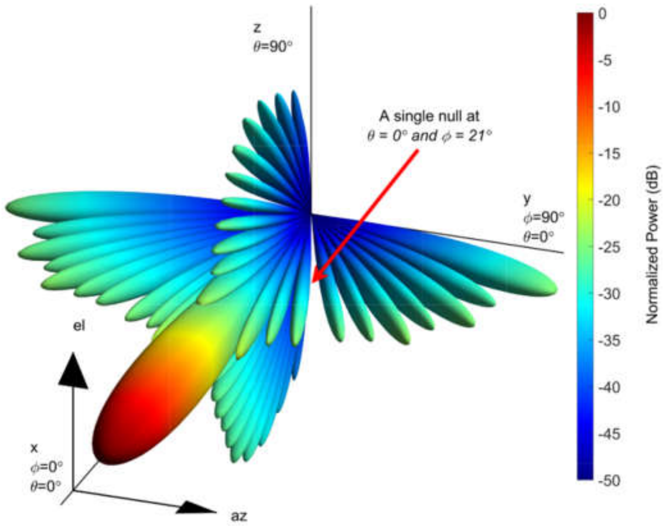

Figure 6. The 3-D optimized pattern with a single null

Besides, Figure 7 compares the patterns with a single null optimized by BBA and BPSO-based BF. Both the optimized patterns have been maintained in respect of HPBW, FNBW, and most of SLLs, but the null in the BBA-based pattern has been deeper than that in the BPSO-based pattern.

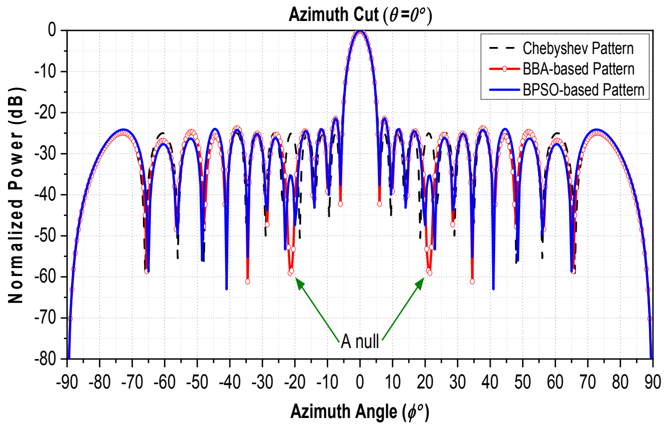

Figure 7. The 2-D optimized patterns with a single null optimized by BBA and BPSO

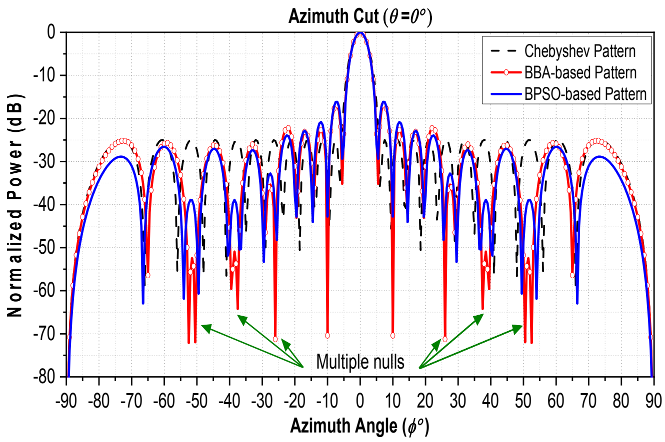

Figure 8. The 2-D optimized patterns with separate nulls

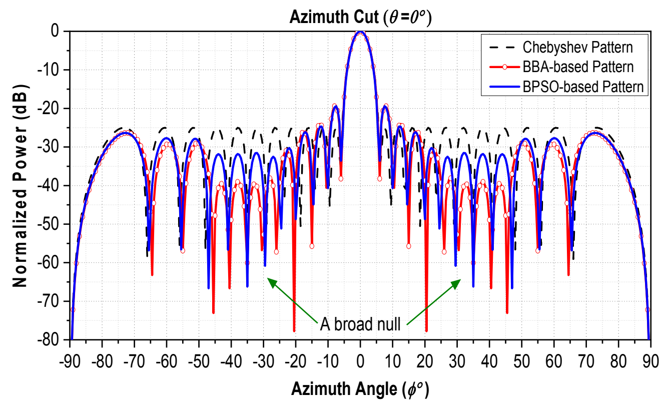

Figure 9. The 2-D optimized patterns with a broad null

In other cases, the proposal will be evaluated to separately impose nulls at $(\phi_i = 26^\circ; 38^\circ; 51^\circ, \theta_i = 0^\circ)$ and a predefined broad null at $(\phi_i = [25^\circ : 45^\circ], \theta_i = 0^\circ)$. As shown in Figure 8 and Figure 9, corresponding to placing multiple nulls and a broad null, all nulls have been successfully imposed; most of the sidelobes have been kept less than -25dB as well. Again, BBA-based BF has outperformed the BPSO-based one in terms of pattern nulling.

4.3. Optimized patterns in a frequency range

In this scenario, the effectiveness of BBA-based BF has been evaluated on a frequency range with the frequency band from 60 to 80MHz and the center frequency of 70MHz. Figure 10 illustrates the pattern of the 25x25 array with a broad null at $(\phi_i = [25° : 45°], \theta_i = 0°)$. It is apparent that the main beam and the SLLs have been preserved while suppressing the sidelobes in the given directions over the 20MHz bandwidth. Thus, this beamformer can be considered as a promising solution for wideband beamforming in reality.

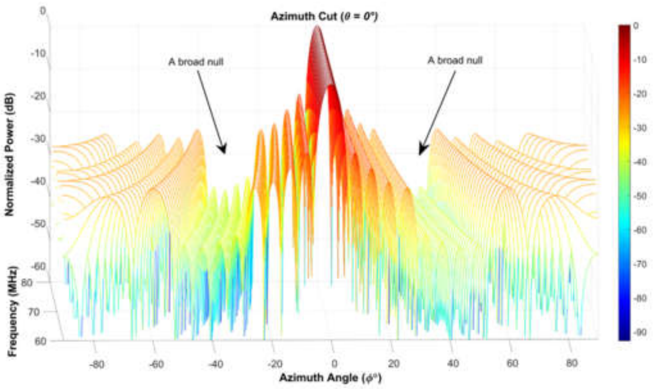

Figure 10. The optimized patterns over the bandwidth of 20MHz

5. CONCLUSION

In this paper, the beamformer using BBA for a URA of half-wavelength dipoles has been proposed. The ability to set nulls in sidelobes of the proposal has been verified via various simulation results, which have proven that the proposed beamformer outperforms the BPSO-based one in terms of adaptive nulling and maintaining the characteristics of the reference pattern. For future works, unknown interferences, interferences entering the main beam, or approaches for reducing the hardware requirements such as phase-only nulling, subarray nulling, partial adaptive nulling, and compressed sensing should be considered.

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THÔNG TIN TÁC GIẢ

Tống Văn Luyên, Nguyễn Văn Cường

Trường Đại học Công nghiệp Hà Nội