Null-Steering Beamformers for Suppressing Unknown Direction Interferences in Sidelobes

Luyen V. Tong[1], Kha M. Kha[1], Cuong V. Nguyen[1], Trung L. Nguyen[2], and Giang B. V. Truong[2]
[1] Hanoi University of Industry, Hanoi, 100000, Vietnam
[2] Vietnam National University, Hanoi, 100000, Vietnam
Email: luyentv@haui.edu.vn; khahoang@haui.edu.vn; cnv.cuong@gmail.com; linhtrung@vnu.edu.vn; giangtvb@vnu.edu.vn

Abstract—This paper proposes an efficient null-steering beamformer for adaptive pattern synthesis of uniform linear arrays based on binary bat algorithm (BBA) and the amplitude-only control of array excitation weights. The proposed beamformer is able to suppress unknown direction interferences in the sidelobes while simultaneously maintaining the main lobe and suppressing the sidelobes. The performance of the proposal has been investigated via a couple of scenarios including operation speed and adaptive null-steering ability with or without the effect of mutual coupling in half-wave dipole uniform linear arrays (DULA). The simulation results have proved that the proposed beamformer is a promising approach for adaptive pattern synthesis in the case of interference suppression. In addition, this proposal outperforms those using binary particle swarm optimization (BPSO) on the operation speed and null-steering efficiency.

Index Terms—Array pattern synthesis, bat algorithm, beamforming, interference suppression, null-steering, pattern nulling, ULA antennas

I. Introduction

Array pattern synthesis to enhance the ability of smart antennas for interference suppression, spectrum utilization and energy saving in wireless communications and radar applications have been taken into account in numerous research papers. Several pattern nulling techniques, which are array thinning, excitation weights control, and position-only control, have been developed and implemented for interference suppression with their advantages and limitations. Among those, interference suppression utilizing pattern nulling approaches such as excitation weights control based on null-steering beamformers is of particular interest [1]–[3].

In excitation weight-based control proposals, the amplitude-only control is the simplest one because the amplitudes of the weights are the only control parameters [3], [4]. Besides, when the number of elements is even and symmetrical around the center of the array, the number of attenuators and the computational time will be reduced by half [4]. The phase-only control is another simple approach since it controls only phases. The advantages of phase control approaches are the utilization of existing deployed phased arrays and the ease of controlling the main lobe [3], [5]. However, the problem of the phase-only nulling methods is inherently nonlinear. The complex weight control which simultaneously controls both the amplitude and the phase of the weight have been considered to produce the best performance in terms of array pattern synthesis compared to the two mentioned above approaches. However, it is more complicated and expensive than amplitude-only control and phase-only control since a complete set of a phase shifter, an attenuator, and a controller is required for each element in arrays [3], [6]. Especially, the computational time will be a considerable issue in large antenna arrays.

Recently, nature-inspired optimization approaches such as genetic algorithm (GA) [7], [8], particle swarm optimization (PSO) [8], [9], ant colony optimization [10], backtracking search [11], and bat algorithm (BA), [4]–[6], [12] have been proven to be promising global optimization solutions to achieve the optimal pattern synthesis in terms of flexibility and effectiveness. Among the most popular nature-inspired optimization algorithm, BA shows its best performance on various benchmark functions as well as multiple engineering problems [13], [14]. Adaptive beamformer employing BA was first presented in [15], then it was successfully implemented for uniform linear arrays in [4]–[6], [16]. The presented results in [4]–[6], [16] proved that BA-based beamformers outperform GA and accelerated particle swarm optimization-based ones in terms of the pattern nulling. Although the proposals in [4]–[6], [16] are fast nulling approaches, they are limited to the known directions of interferences. Furthermore, except for proposal in [16], weight vectors optimized by these beamformers are in the real number format while the amplitudes or phases of the excitations of array elements are commonly adjusted by digital attenuators or digital phase shifters. Therefore, it is necessary to quantize the real weight vector before applying to the digital attenuators or digital phase shifters. This leads to the quantization error, which in turn perturbs the ideal array pattern.

In this study, a simple null-steering beamformer (NSBF) based on amplitude-only control has been proposed. This estimates the weight amplitudes in binary numbers based on the minimization of the total output power of the array utilizing binary bat algorithm (BBA) [17]. The proposed BBA-based NSBF is to suppress interference at sidelobes while simultaneously maintaining the main lobe and keeping the sidelobes at low levels. The effectiveness of

Manuscript received December 10, 2021; revised July 14, 2022.
Corresponding author email: luyentv@haui.edu.vn.
doi:10.12720/jcm.17.8.600-607

the proposal has been verified through five scenarios. For array pattern synthesis, PSO has been proven to perform much better than GA [4], [5], [16]. Therefore, the Binary Particle Swarm Optimization (BPSO) [18] has been selected to be the reference to compare with this proposal for producing the optimal binary excitation weights.

The main contribution of this work can be stated as follows:

- An efficient null-steering beamformer for the suppression of unknown direction interferences in sidelobes while suppressing the sidelobes and maintaining the main lobe. The proposed beamformer attains good performance at high convergence speed;
- Evaluation of the proposed beamformer for DULA, in which binary weights have been optimized for digital attenuators, and the mutual coupling effect has been taken into account.

This paper is organized as follows. After the introduction, in Section II, the problem formulation is presented. The derivation and implementation of the proposal of null-steering beamformer are shown in Section III. The numerical results of the proposal and discussions are in Section IV. Finally, the conclusions of the work are given in Section V.

II. Problem Formulation

In this study, the half-wave M elements DULA as illustrated in Fig. 1 has been considered.

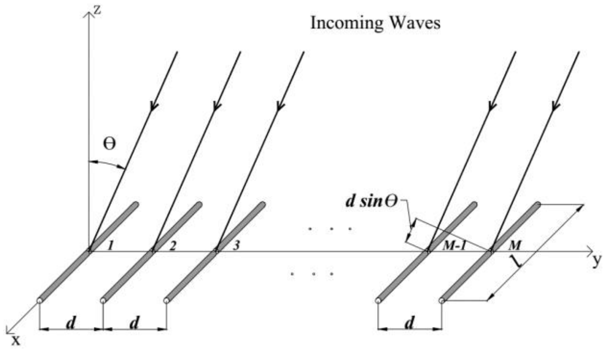

Fig. 1. Geometry of a $1 \times M$ DULA.

The array factor of the DULA can be expressed as [19], [20]:

$$AF(\theta) = \sum_{m=1}^{M} I_m \, e^{j(m-1)dksin(\theta)} \tag{1}$$

where: $I_m = a_m e^{j\delta_m}$ is the complex current (complex weight) excited at m^{th} array element; a_m and δ_m are the amplitude and the phase, respectively, of the current; M is the total number of array element antenna; $k = 2\pi/\lambda$ is the wavenumber; λ is wavelength; $d = 0.5\lambda$ is the distance between adjacent elements. The array factor in (1) becomes:

$$AF(\theta) = \sum_{m=1}^{M} a_m \, e^{j((m-1)dksin(\theta)+\delta_m)} \tag{2}$$

Then, the pattern of the DULA ($P(\theta)$) is given by:

$$P(\theta) = EP(\theta)AF(\theta) \tag{3}$$

where $EP(\theta)$ is the element pattern of the dipole.

The pattern nulling for interference suppression needs to be attained while keeping the main lobe, and the peak sidelobes level (SLL) within a required level. Therefore, this must be realized by solving constrained optimization problems.

In general, a constrained optimization problem with n-dimensional variables is normally formulated as a nonlinear optimization one as follows [21]:

$$\begin{gathered} Minimize\ f(\boldsymbol{x}) \\ subject\ to\ \boldsymbol{x} = (x_1, x_2, \dots, x_n) \in S \subseteq \Re^n \end{gathered} \tag{4}$$

where $f(\boldsymbol{x})$ is a continuous function on $\Re^n$ and S is a constraint set in $\Re^n$. According to the penalty function methods [22], a constrained problem in (4) can be transformed into a non-constrained one as follows:

$$Minimize\ \{f(\boldsymbol{x}) + \xi P_e(\boldsymbol{x})\} \tag{5}$$

where: $\xi P_e(\boldsymbol{x})$ presents a penalty term. If no violation occurs, $\xi P_e(\boldsymbol{x})$ will be zero and positive otherwise; ξ is a positive constant (*penalty parameter*) and P_e is a function on $\Re^n$ satisfying (i) $P_e(\boldsymbol{x})$ is continuous, (ii) $P_e(\boldsymbol{x}) \geq 0$ for all $\boldsymbol{x} \in \Re^n$, and (iii) $P_e(\boldsymbol{x}) = 0$ if and only if $\boldsymbol{x} \in S$.

Inspiring from the optimization in (5), the fitness function of the optimization in this study is defined as

$$F(\boldsymbol{x}, \xi) = f(\boldsymbol{x}) + \xi P_e(\boldsymbol{x}) \tag{6}$$

Here, each unsatisfied constraint influences $\boldsymbol{x}$ by adding a penalty, which equals to the square of the violation. These influences are summed and multiplied by ξ, the penalty parameter, and counterbalanced by $f(\boldsymbol{x})$. Hence, if the magnitude of the penalty term is small in comparison with the magnitude of $f(\boldsymbol{x})$, it is nearly certain that minimization of $F(\boldsymbol{x}, \xi)$ will not result in an $\boldsymbol{x}$ that would be feasible to the original problem. However, if the value of ξ is suitably large, the penalty term will result in such a heavy cost for any constraint violation that the minimization of the fitness function will give a feasible solution.

In antenna arrays, mutual coupling effects are caused by the interaction among array elements due to electromagnetic energy transferring. These effects influence the array pattern such as the sidelobes, the main lobe direction, and the depth of nulls. Therefore, taking mutual coupling effects into consideration during the design of adaptive beamformers for pattern nulling is very necessary.

To characterize mutual coupling, mutual impedance, S-parameters, a coupling matrix, or an embedded element pattern are commonly utilized [19, 20]. In this study, the mutual impedance approach has been chosen.

In mutual impedance-based mutual coupling, if the feeding voltages are $\boldsymbol{V} = [V_1, V_2, \dots, V_M]^{\boldsymbol{T}}$, the excitation currents $\boldsymbol{I} = [I_1, I_2, \dots, I_M]^{\boldsymbol{T}}$ will be calculated by

$$\boldsymbol{Z}\boldsymbol{I} = \boldsymbol{V} \tag{7}$$

where $\mathbb{Z}$ is the mutual impedance matrix which can be calculated by the induced electromotive force method presented in [19, 20]:

$$\mathbb{Z} = \begin{bmatrix} \mathbb{Z}_{11} & \mathbb{Z}_{12} \dots \mathbb{Z}_{1M} \\ \mathbb{Z}_{21} & \mathbb{Z}_{22} \dots \mathbb{Z}_{2M} \\ & \dots \\ \mathbb{Z}_{M1} & \mathbb{Z}_{M2} \dots \mathbb{Z}_{MM} \end{bmatrix} \quad (8)$$

where $\mathbb{Z}_{mn}$ the mutual impedance between elements m and n in the array and is defined in [5], [19], [20].

It can be seen from equations (7) and (8) that the mutual impedance matrix $\mathbb{Z}$ is not diagonal because of $\mathbb{Z}_{mn} \neq 0$ with $m \neq n$. Therefore, the effective input currents $\boldsymbol{I}$ are not essentially equal to the voltages $\boldsymbol{V}$. This causes some distortions on the array pattern including the nulls.

III. Proposal of the Null-Steering Beamformer

A. Block Diagram of the Proposed Beamformer

Based on amplitude-only control, the diagram of the proposed approach is presented in Fig. 2. In this diagram, the total number of array elements M is an even integer ($M = 2N$). In amplitude-only control system, the phase of the complex weight is a constant, which is chosen $\delta_n = 0$ in this study. When $a_{-n} = a_n$, the array factor in (2) can be rewritten as:

$$AF(\theta) = 2\sum_{n=1}^{N} a_n \cos\left(ndk sin(\theta)\right) \quad (9)$$

According to (9) and the configuration given in Fig. 2, the pattern is symmetrical around the main beam direction ($\theta = 0°$) and the computation time is halved.

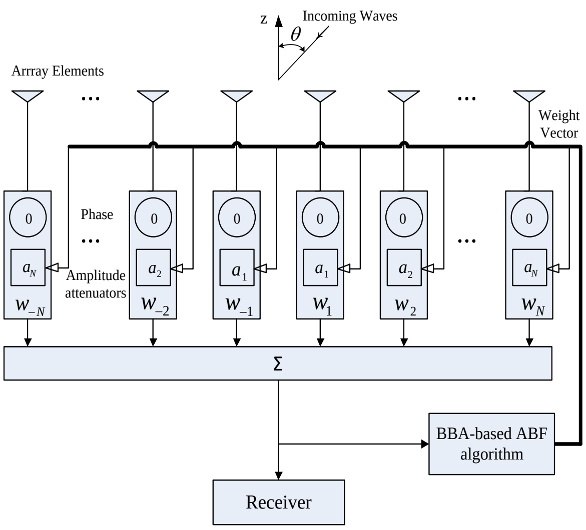

Fig. 2. Diagram of the proposed beamformer.

B. Fitness Function

Without loss of generality, the fitness function building in the case of the receiving end is presented as follows.

At the receiving arrays, the desired signal and interferences generally come simultaneously. Assuming that the direction of arrival of the desired signal and interferences are at the main lobe and in the sidelobes, respectively, the sub-total power of the desired signal will be nearly unchanged if the main lobe is maintained and the sidelobes are suppressed at a specific low level (this can be obtained by applying some popular classical techniques such as Dolph-Chebyshev or Taylor weighting). Therefore, the total output power of the array will be minimum only when the sub-total power of interference is minimized.

Equation (6) is applied to the NSNF by mapping variable vector $\boldsymbol{x}$ to the weight vector $\boldsymbol{w}$ of the array:

(i) The first term $f(\boldsymbol{w})$ in (6) has been built as (10) to have a desired pattern with a certain main lobe and a specific SLL:

$$f(\boldsymbol{w}) = \sum_{\theta=-\frac{1}{2}\theta_{FNBW}}^{\frac{1}{2}\theta_{FNBW}} |AF_o(\boldsymbol{w}) - AF_d|^2 \quad (10)$$

where: $AF_o(\boldsymbol{w})$ and AF_d are the optimization patterns obtained by using an optimization algorithm, which will be BBA in this study, and the desired pattern (a certain main lobe and a specific SLL), respectively; θ_{FNBW} is the elevation angle at the first null beamwidth (FNBW).

(ii) The second term in (6), which is chosen to place nulls at directions of interferences, is defined as the total output power of the array. This power is the total of all receiving signal powers including a desired signal (sig) and interferences (int). These signals are determined by incoming elevation angle θ_i and voltage $s_i(n)$ [23, 24].

$$P_e(\boldsymbol{w}) = \left|\frac{1}{\sum_{m=1}^{M} w_m} \sum_{i=1}^{N_{sig\_int}} s_i(n)P(\theta_i)\right|^2 \quad (11)$$

where: $P(\theta_i)$ is the pattern of the DULA at θ_i; M is the total number of elements ($M = 2N$); N_{sig_int} is the total number of incoming signals.

The fitness function is then written as:

$$F(\boldsymbol{w}, \xi) = \frac{1}{\xi}\left[\begin{array}{c} \sum_{\theta=-\frac{1}{2}\theta_{FNBW}}^{\frac{1}{2}\theta_{FNBW}} |AF_o(\boldsymbol{w}) - AF_d|^2 \\ +\xi\left|\frac{1}{\sum_{m=1}^{M} w_m} \sum_{i=1}^{N_{sig\_int}} s_i(n)P(\theta_i)\right|^2 \end{array}\right] \quad (12)$$

where, the penalty parameter ξ, which affects the null depth level (NDL) of the placed nulls, is defined by simulations in Section IV-A.

It can be seen from equation (12) that the directions of interference are not required to be known. This characteristic is vital for the development of the proposed null-steering beamformer with unknown directions of interferences.

C. Proposed Algorithm

In this section, the proposed algorithm for null-steering beamformer is presented in Algorithm 1, in which *the termination condition* is chosen as the maximum number of iterations in all simulation scenarios except for calculating the computation time in Section IV-B.

Initialize *the parameters of arrays; termination condition; fitness function F in (12); bat population {frequency (f_i), velocity (v_i), pulse emission rate (r_i), loudness (A_i), and location/solution (x_i)}; Define the initial location vector ($\boldsymbol{x_i}$) based on the weight vector of Chebyshev array.*

While *(the termination condition is not satisfied)*
  Update positions.
  if $(\mathrm{rand} > \mathrm{r_i})$
    Select a solution (G_{best}) among the best solutions.
    Change some values of location vectors with those of G_{best}.
  end if
    Generate a new solution by flying randomly.
  if $\left(\mathrm{rand} < \mathrm{A_i} \ \& \ \mathrm{F}(\mathbf{x_i}) < \mathrm{F}(\mathrm{G_{best}})\right)$
    Accept the new solutions.
  end if
  Rank the bats and find the final G_{best}.
end while

Build *array element weights from the final G_{best} and conduct pattern nulling.*

Algorithm 1. Pseudocode of the proposed algorithm for null-steering beamformer.

IV. Numerical Results

In this section, the performance of the proposed BBA-based NSBF has been investigated by simulations in the case of half-wave dipole uniform linear arrays.

Firstly, all parameters for simulation processes have been defined. In the fitness function, AF_d is chosen as the array factor of Dolph-Chebyshev (Chebyshev) arrays. This choice is based on Dolph's method for obtaining weights for the optimal pattern of uniformly spaced linear arrays in view of a trade-off between the specified SLL and the minimum FNBW [25].

Specifically, AF_d is the array factor of a Chebyshev array with SLL of -30 dB, the total number of elements is 20, and the inter-element spacing is $\lambda/2$. Additionally, the parameters for the optimization algorithms are as follows

(i) BBA: Step size of random walk is 0.01; boundary frequency values: $f_{min} = 0$ and $f_{max} = 2$; and $A = 0.25$; $r = 0.1$ [17].
(ii) BPSO: $C_1 = C_2 = 2$; W is decreased linearly from 0.9 to 0.4; max velocity: 6 [18].
(iii) Velocity transfer function: V-shaped [17], [18].

Secondly, five scenarios have been conducted to investigate the capability and flexibility of the proposal for interference suppression. The first scenario (See Section IV-A) is necessary to determine the value of penalty constant ξ in the fitness function; the second one (See Section IV-B) is the initial state to investigate the computation speed of the proposal; the third scenario has been conducted to investigate and to compare the capability of null-steering of the proposed beamformer (See Sections IV-C) with that of BPSO-based one in no mutual coupling scenarios. Furthermore, the proposed beamformer has been evaluated with mutual coupling in the fourth scenario (See Section IV-D), and without interference in the fifth one (See Section IV-E). Simulation results of all scenarios are presented in Figs. 3-9, Tables I and III.

TABLE I: PARAMETERS FOR THREE CASES OF PATTERN NULLING

Case	Parameters
All	- *pop* = 100 and *ite* = 30; - The location vector of one bat in the population is initialized by the weight vector of Chebyshev array with SLL of -30 dB; - 100 Monte Carlo simulations.
Single null	A single null at the second sidelobe peak ($\theta = 14°$) (See Fig. 5)
Multiple nulls	Multiple nulls at 14°, 26°, 33° (See Fig. 6)
Broad null	A broad null from 20° to 40° (See Fig. 7)

TABLE II: NDL AND MAXIMUM SLL OF THE PATTERNS SHOWN IN FIGS. 5-7 AND IN SECTION IV-D (MC).

Fig.	Parameters	BPSO (dB)	BBA (dB)	
		Ideal	Ideal	**MC**
5	NDL at: $\pm 14°$	-45.66	-80.23	$\mathbf{-61.96}$
	Maximum SLL	-26.74	-26.38	$\mathbf{-25.40}$
6	NDL at: $\pm 14°$	-41.92	-66.87	$\mathbf{-60.83}$
	$\pm 26°$	-40.63	-66.13	$\mathbf{-62.11}$
	$\pm 33°$	-41.19	-67.45	$\mathbf{-53.85}$
	Maximum SLL	-24.02	-23.59	$\mathbf{-22.99}$
7	Maximum NDL	-50.41	-59.99	$\mathbf{-53.54}$
	Minimum NDL	-36.00	-40.85	$\mathbf{-38.08}$
	Maximum SLL	-25.32	-24.28	$\mathbf{-23.91}$

TABLE III: NDL, MAXIMUM SLL AND HPBW WITH DIFFERENT ξ.

$\boldsymbol{\xi}$	SIR $= 0$			SIR $= -1$			SIR $= -10$			SIR $= -20$			SIR $= -30$		
	NDL (14°)	Max SLL	HPBW	NDL (14°)	Max SLL	HPBW	NDL (14°)	Max SLL	HPBW	NDL (14°)	Max SLL	HPBW	NDL (14°)	Max SLL	HPBW
$1e0$	-30.466	-29.605	6.395	-30.485	-29.634	6.395	-30.654	-29.518	6.396	-33.835	-27.691	6.403	-46.855	-25.383	6.418
$\mathbf{1e1}$	-30.688	-29.479	6.395	-30.774	-29.417	6.396	-33.778	-27.690	6.403	-48.184	-25.529	6.417	**-70.898**	**-23.220**	**6.420**
$\mathbf{1e2}$	-33.697	-27.922	6.403	-35.048	-27.216	6.404	-45.936	-25.640	6.417	**-69.705**	**-23.534**	**6.422**	-79.224	-21.140	6.424
$\mathbf{1e3}$	-47.681	-25.236	6.417	-48.686	-25.283	6.418	**-70.168**	**-23.021**	**6.421**	-79.429	-20.158	6.421	-79.875	-15.350	6.315
$\mathbf{1e4}$	**-71.447**	**-23.149**	**6.421**	**-72.814**	**-22.869**	**6.422**	-80.707	-20.004	6.425	-81.010	-16.026	6.358	-84.263	-14.878	6.212
$1e5$	-80.568	-20.071	6.417	-80.872	-19.660	6.418	-81.846	-15.991	6.347	-85.896	-15.191	6.240	-88.018	-13.568	5.918
$1e6$	-82.197	-16.262	6.362	-82.059	-15.958	6.347	-82.846	-15.044	6.233	-87.577	-13.682	5.952	-92.757	-12.226	5.709
$1e7$	-85.739	-14.800	6.183	-85.225	-14.943	6.182	-87.620	-13.532	5.950	-94.642	-11.666	5.623	-97.258	-10.327	5.456
$1e8$	-86.967	-13.987	5.993	-86.616	-13.553	5.961	-91.248	-11.807	5.630	-97.746	-10.648	5.481	-100.810	-10.025	5.346

A. Penalty Parameter ξ in the Fitness Function

In the first scenario, it is necessary to define all related parameters in the fitness function (12), of which penalty parameter ξ is the only unknown parameter and is chosen by simulations in this study. In order to do that, the effect of ξ on the optimization results has been explored.

So as to investigate the suitable value of ξ, NSBF has been used to adaptively place a single null at the second sidelobe peak ($\theta = 14°$) of -30 dB Dolph-Chebyshev array pattern with different values of ξ in the range of $[1e0, 1e8]$ and $SIR = 0$ dB, -1 dB, -10 dB, -20 dB, -30 dB, respectively. Consequently, the null depth levels (NDLs) of this null, maximum sidelobe levels (SLLs), and HPBW, which are averaged valued of 100 Monte Carlo simulations, in which pop is 500, and ite is 5, are shown in Table I.

It can be seen from Table I that the value of ξ should be chosen as one, which is the trade-off choice considering NDL, maximum SLL, and HPBW. For example, with SIR $= 0$ dB, ξ should be $1e4$ because the trade-off performance is achieved with NDL $= -71.447$ dB, maximum SLL $= -23.149$ dB, and HPBW $= 6.421^{\circ}$, while $\xi = 1e1$ in the case SIR $= -30$ dB. For demonstration purposes, $\xi = 1e1$ in the case SIR $= -30$ dB is chosen for all following simulations.

B. Convergence Characteristics

Without loss of generality, in the second scenario, the convergence ability of the proposed BBA-based NSBF, which is used to set a single null at the second sidelobe peak (14°) in Chebyshev array pattern, has been investigated and compared with BPSO-based one in the case of no interference. To do that, at the initial step, all bats have been generated randomly in the population; pop is 100; ite is 100. The simulation results of the fitness function are shown in Fig. 3. The computation time of two NSBFs has been examined in the situation of getting the same value of the fitness function ($F \leq 1.1$). The simulation results on MATLAB show that the BBA-based NSBF and BPSO-based NSBF take **0.336** seconds and **5.784** seconds, respectively on Desktop PC (CPU i7 8700,8 GB RAM). Therefore, it is clear that BBA-based NSBF operates faster than the BPSO-based one. Additionally, the fitness function of BBA-based NSBF has been investigated with various pop and is shown in Fig. 4. The fitness function takes 90 iterations, 30 iterations, and 10 iterations to converge corresponding to $pop = 10, 30,$ and 100, respectively.

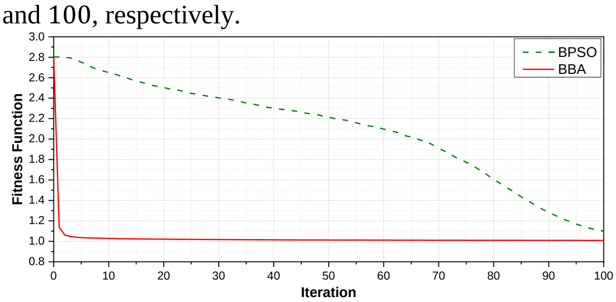

Fig. 3. Fitness function comparisons of NSBF based on BBA and BPSO.

To demonstrate the null-steering ability following scenarios have investigated with these parameters: pop is 100 and ite is 30.

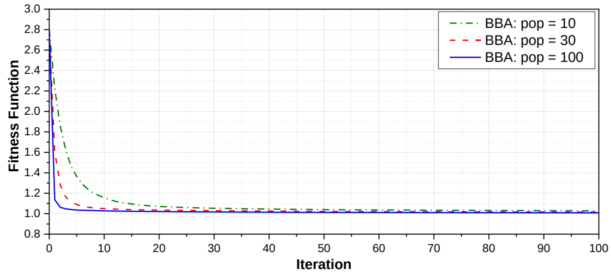

Fig. 4. Fitness function of BBA-based NSBF with various population sizes (pop).

C. Null-Steering Ability

The third scenario has been conducted to demonstrate the null-steering ability of the proposed beamformer. In particular, the optimized DULA pattern with imposed nulls, which can be a single null, multiple nulls, or a broad null, has been investigated. The parameters for three cases in this scenario are given in Table II.

Fig. 5 demonstrates the simulation results for the optimized pattern with a single null, which can be set arbitrarily on sidelobes. In this test case, this null is set at the second sidelobe peak (14°).

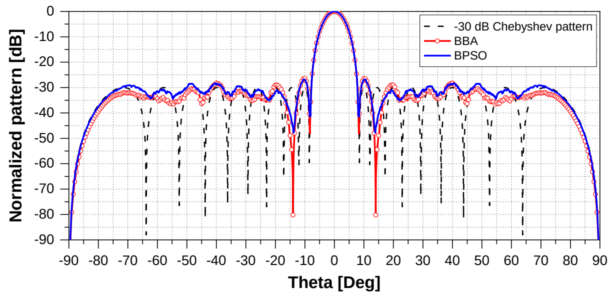

Fig. 5. Optimized patterns with a single null at 14°.

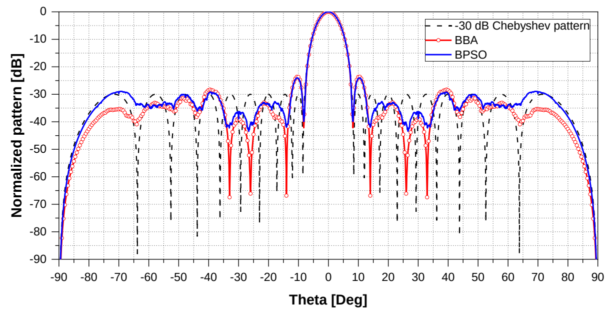

Fig. 6. Optimized patterns with three nulls at 14°, 26°, and 33°.

It can be seen from Fig. 5 that the optimized patterns preserve most characteristics of Chebyshev pattern such as approximately half-power beamwidth (HPBW = 6.4°) and SLL (-30 dB) except for the placed null point. The maximum SLL is -26.38 dB and NDL at 14° is -80.23 dB. Additionally, Fig. 5 indicates that the pattern with a single null optimized by the BBA-based NSBF is better than that of the BPSO-based NSBF in terms of NDL at the desired direction. It is noted that a symmetric null is also set at $\theta = -14°$ because of the symmetry of the array factor in (2).

Simulation results for the last two cases including multiple nulls and a broad null have been presented in Fig. 6 and Fig. 7, respectively. These optimized patterns show the similar results to the single null case where all required nulls are exactly placed at directions of interferences and the BBA-based NSBF outperforms BPSO-based one in terms of the context of NDL. Detailed results for NDL and SLL are summarized in Table III.

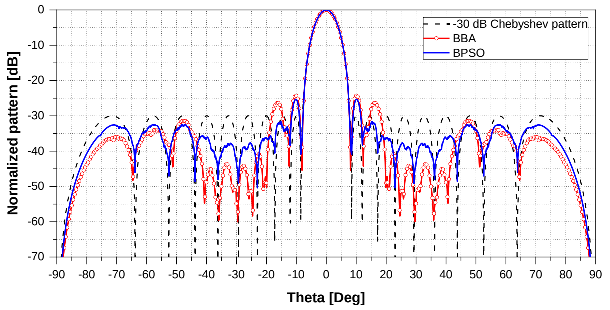

Fig. 7. Optimized patterns with a broad null from 20° to 40°.

D. *Optimized Patterns in the Presence of Mutual Coupling Effect*

The fourth scenario has been conducted to investigate the effectiveness of the proposed beamformer in the case of Mutual Coupling (MC). The mutual coupling effect has been calculated based on equations (7). To do that, the proposal has been applied for the pattern nulling with the same situation presented in Section IV-C. Specifically, Fig. 8 presents the simulation results in the case of multiple nulls, while the others have been shown in Table III. The results demonstrate that nulls have been successfully placed at desired locations but with shallower NDLs.

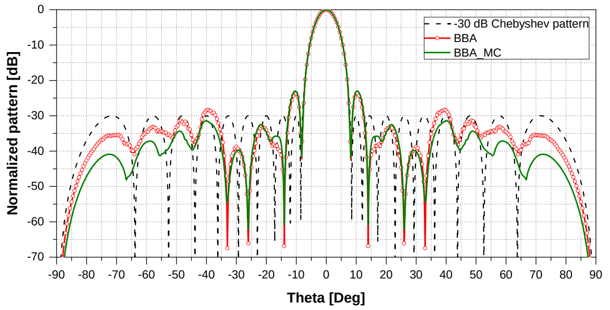

Fig. 8. Optimized patterns (nulls: 14°, 26°, and 33°) with mutual coupling.

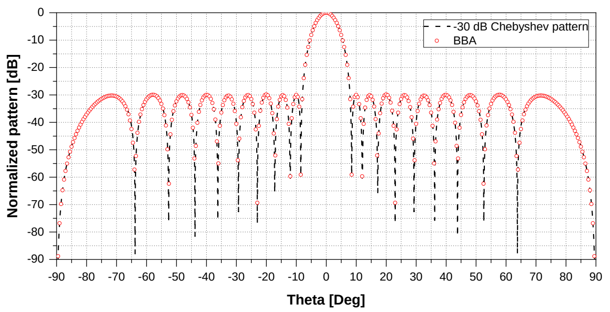

Fig. 9. Optimized pattern in case of none interferences.

E. *Optimized Patterns without Interference*

In the fifth scenario, the proposed beamformer has been evaluated without any interference. Simulation results in Fig. 9 show that the optimized patterns are the same as the default −30 dB Dolph-Chebyshev array pattern. It means that the proposal still maintains the desired signal at the main lobe while suppressing the sidelobes at −30 dB when no interference presents.

V. Conclusion

This study has proposed a BBA-based null-steering beamformer for DULA which utilizes amplitude-only control of array excitation weights. The proposed beamformer is able to suppress interferences with unknown directions in sidelobes. Several scenarios have been conducted to investigate the performance of the proposal in terms of operation speed and null-steering ability with a single, multiple, and broad nulls. The simulation results show that above-mentioned nulls can be imposed accurately to directions of interferences while maintaining the main lobe and the low SLL either with or without the effect of mutual coupling. Additionally, compared with BPSO-based NSBF, the proposed beamformer performs better in terms of computation time and NDL in pattern nulling. Furthermore, the proposal has been proven to be a potential null-steering solution for smart antennas in various applications such as wireless communications, Radar, or wireless sensor networks. For future works, the various array geometries such as planar, simultaneously multiple main lobes for multiple users, the amplitude change effect and the resolution of digital attenuators, and the directions of interference at the main lobe should be considered.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Luyen Tong, Kha Hoang and Cuong Nguyen conducted the research; Linh Trung and Giang Truong analyzed the data; Luyen Tong wrote the paper. All authors had approved the final version.

Acknowledgement

This research is supported by Hanoi University of Industry (HaUI) under science research grant in 2022.

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Luyen Van Tong (Luyen V. T.) was born in Hai Duong, Vietnam, in 1979. He has been a lecturer at Faculty of Electronic Engineering, Hanoi University of Industry since 2002. He received the B.S. and M.S. degree from the Hanoi University of Science and Technology, in 2002 and 2004, respectively, and Ph.D. degree from VNU University of Engineering and Technology in 2019. He has been a postdoctal researcher at Advanced Institute of Engineering and Technology (AVITECH) - VNU University of Engineering and Technology since April 2020. His research interests are in Beamforming and Beamsteering for antenna arrays, Smart Antennas, Optimum Array Processing, Nature-inspired Optimization Algorithms, and Artificial Intelligence.

Kha Manh Hoang (Kha M. H.) was born in Bac Giang, Vietnam, in 1979. He received the B.E and M.E degree in Electronics and Telecommunications Engineering both from Hanoi University of Science and Technology, in 2002 and 2004, respectively. He obtained his Dr.-Eng. (PhD) degree in Communications Engineering from the University of Paderborn, Germany, in 2016 with specialization in parameter estimation of missing data and application to indoor positioning. He is now working as a dean of Faculty of Electronics, Hanoi University of Industry. He has served as the CoTPC Chairs of RICE (2019), TPC member of ATC (2018, 2019), reviewer of REV-ECIT, ATC, Journal of Science and Technology (ISSN 1859-3585). His research interests include digital signal processing, wireless communication, positioning engineering, machine learning and pattern classification, and nature-inspired algorithm application.

Cuong Van Nguyen (Cuong V. N.) received the B.E. degree from Hanoi University of Industry, in 2020, where he is currently pursuing the M.E. degree in electronic engineering. His research interests include beamforming for antenna arrays, smart antennas, nature-inspired optimization algorithms, and deep learning.

Trung Linh Nguyen (Trung L. N.) obtained his B.Eng. and Ph.D. degrees, both in electrical engineering, from Queensland University of Technology, Brisbane, Australia, in 1998 and 2005. Since 2006, he has been on the faculty of VNU University of Engineering and Technology (VNU-UET), a member university of Vietnam National University, Hanoi (VNU), where he is currently an Associate Professor of electronic engineering in the Faculty of Electronics and Telecommunications and Director of the Advanced Institute of Engineering and Technology of VNU-UET. Also, since 2016, he has been an Adjunct Professor in the School of Electrical and Data Engineering, University of Technology Sydney. He is interested in signal processing methods, including time-frequency signal analysis, blind source separation, compressive sampling, tensor-based signal analysis, graph signal processing, and apply them to wireless communication and networking, biomedical engineering, with a current focus on large-scale processing.

Giang Bang Vu Truong (Giang B. T. V.) was born in Hanoi, Vietnam, in 1973. He received the BS and MS degrees from the VNU-University of Sciences, in 1994 and 1997, respectively, and the Dr.- Ing. (Ph.D.) degree in Electrical Engineering from the Hamburg-Harburg University of Technology, Hamburg, Germany, in 2006. He is currently the Vice President of Radio Electronics Association of Vietnam; Member of IEEEMTTs and APS. He has served as the Steering Committee (Co-Chair), Organizing Committee (Chair and Co-Chairs) or Technical Committee of ATC, REV-ECIT, VJMW, VJISAP conferences in Vietnam; Scientific and Technical Committee, International Transaction Journal of Engineering, Management and Applied Sciences and Technologies (Thailand); Editorial Board, VNU Journal of Science: Computer Science and Communication Engineering (JCSCE).