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Comparative and comprehensive study of linear antenna arrays' synthesis

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ABSTRACT

In this paper, a comparative and comprehensive study of synthesizing linear antenna array (LAA) designs, is presented. Different desired objectives are considered in this paper; reducing the maximum sidelobe radiation pattern (i.e., pencil-beam pattern), controlling the first null beamwidth (FNBW), and imposing nulls at specific angles in some designs, which are accomplished by optimizing different array parameters (feed current amplitudes, feed current phase, and array elements positions). Three different optimization algorithms are proposed in order to achieve the wanted goals; grasshopper optimization algorithms (GOA), ant lion optimization (ALO), and a new hybrid optimization algorithm based on GOA and ALO. The obtained results show the effectiveness and robustness of the proposed algorithms to achieve the wanted targets. In most experiments, the proposed algorithms outperform other well-known optimization methods, such as; Biogeography based optimization (BBO), particle swarm optimization (PSO), firefly algorithm (FA), cuckoo search (CS) algorithm, genetic algorithm (GA), Taguchi method, self-adaptive differential evolution (SADE), modified spider monkey optimization (MSMO), symbiotic organisms search (SOS), enhanced firefly algorithm (EFA), bat flower pollination (BFP) and tabu search (TS) algorithm.

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1. INTRODUCTION

Antennas, in general, and antenna arrays, in specific, play significant roles in modern wireless applications like radars, radio, mobile, and satellite communications [1]. Antenna arrays are valuable in reducing the sidelobe level and power consumption, and effectively enhancing the signal-to-noise ratio. The main advantages of using antenna arrays, over single antennas, are their capabilities to control the radiation pattern, the main lobe, and the level of the side lobes, which can be accomplished by adjusting the antenna array's parameters (excitation currents, excitation phases, and positions) for each element [1]. Antenna arrays can be implemented using different geometries, such as; linear, circular, elliptical, rectangular, and hexagonal arrays. Linear antenna arrays (LAAs) are the simplest and the most common type among all other antenna arrays [2]. Elements in a LAA are placed along one axis, which allows the beam to steer in one dimension to provide omnidirectional radiation and permits directivity into a single plane.

Designing linear antenna arrays with desired radiation pattern has been a subject of very much interest in the literature. Numerous evolutionary optimization techniques have been applied in linear antenna array synthesis, such as Taguchi optimization [3], particle swarm optimization (PSO) [4], firefly algorithm (FA) [5], ant colony optimization (ACO) [6], pattern search optimization [7], cat swarm optimization (CSO) [8], biogeography based optimization (BBO) [2], self-adaptive differential evolution (SADE) [3] modified spider monkey optimization (MSMO) [9], symbiotic organisms search (SOS) [10], enhanced firefly algorithm (EFA) [11], bat flower pollinator (BFP) [12] and tabu search (TS) algorithm [13].

In this paper, a comparative and comprehensive study for synthesizing several linear antenna array designs is presented using three metaheuristic techniques; ant lion optimization (ALO) algorithm [14], grasshopper optimization algorithm (GOA) [15], and a new hybrid algorithm based on ALO and GOA methods. The obtained results prove the validity of our proposed algorithms as valuable optimization techniques compared to other already developed optimization methods. The main objective, in this paper, is to design LAA's with low sidelobe levels with specific nulls in certain directions. The optimized parameters will be the excitation amplitudes, the excitation phases, and the elements' positions.

The rest of this paper is organized as follows. The proposed hybrid algorithm is briefly presented in Section 2. The geometry of the linear antenna array and the fitness function are detailed in Section 3. Results and discussion are mentioned in Section 4. Finally, the conclusions of the paper are mentioned in Section 5. For more details of ALO and GOA methods, the reader may check [14] and [15], respectively.

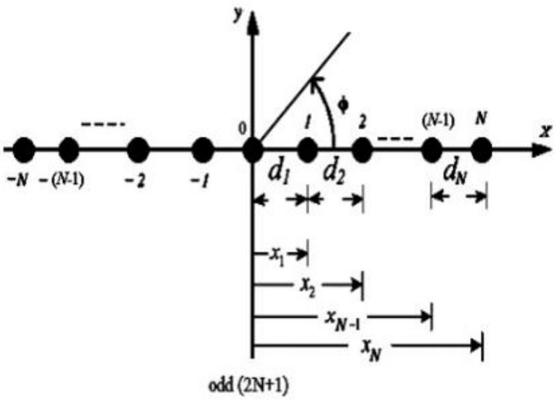
2. THE HYBRID OPTIMIZATION ALGORITHM

In this approach, two well-known metaheuristic methods; ALO and GOA, are combined in order to get a new hybrid optimization algorithm [16]. ALO and GOA have different features and characteristics that have been used to reach the optimal solutions in various problems. ALO, which is an evolutionary algorithm, has the capability to effectively exploit the search space to reach the global optimum, which was proved in the literature in different papers [17]–[24]. GOA is a swarm algorithm that is robust in exploring the whole search space efficiently, because of the social interactions between grasshoppers when they move. The characteristics' variety of these algorithms give the opportunity to hybridize them in one optimization algorithm that enhances the performance of both methods.

The inspiration behind doing this hybridization can be concluded in merging the main characteristics of ALO and GOA and excluding the main drawbacks of these methods. ALO may have a loss of diversity, early convergence, and disability to select the fittest among equally fit search agents, due to using the roulette wheel selection method in choosing the next positions. GOA's main drawback is giving more pressure to the exploration process at the expense of the exploitation process, and this point is clearly shown in c parameter equations.

3. PROBLEM FORMULATION AND FITNESS FUNCTION

Due to its simplicity and ease of implementation, LAA is widely used in different applications in the literature. Figure 1 shows the linear antenna array's geometry. Figure 1(a) shows a LAA with an odd number (2N+1) of elements that has an element at the origin, while Figure 1(b) shows an array with an even number (2N) of elements with no element at the origin.



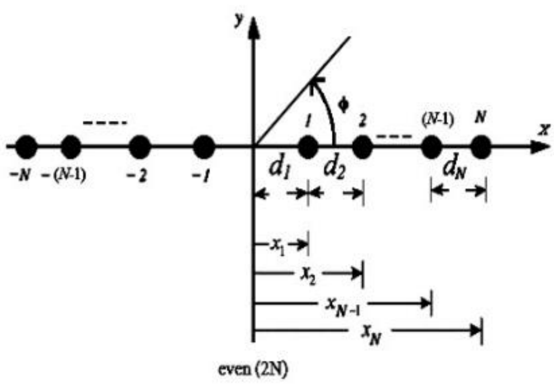


Figure 1. The geometry of symmetric linear antenna array, (a) with an odd number of elements and (b) with an even number of elements [2]

The array factor equations for such geometries can be written as (1), (2) [25]:

$$AF(\varphi) = I_o \exp(j\varphi_o) + \sum_{\substack{n=-N \\ n\neq 0}}^{N} I_n \exp(\, j \,[\, kx_n cos(\varphi) + \varphi_n] \,) \quad (1)$$

$$AF(\varphi) = \sum_{\substack{n=-N \\ n\neq 0}}^{N} I_n \exp(j[kx_n cos(\varphi) + \varphi_n]) \quad (2)$$

where, φ_n and I_n represent the excitation phase and amplitude of the feeding current for the n^{th} element, and x_n represents its position. $x_n = \sum_{i=1}^{n} d_i$, where d_i is the inter-element spacing. k is the wave number, such that; $k = \frac{2\pi}{\lambda}$. To simplify these equations, the following symmetry between the elements is assumed: φ_n=$-\varphi_{-n}$, $I_n = I_{-n}$, and $x_{-n} = -x_n$. Therefore, after some simplification, the array factor equations of symmetric linear antenna array become as (3), (4) [2]:

$$AF(\varphi) = I_o \exp(j\varphi_o) + \ 2\sum_{n=1}^{N} I_n \cos[kx_n cos(\varphi) + \varphi_n] \quad (3)$$

$$AF(\varphi) = 2\sum_{n=1}^{N} I_n \cos[kx_n cos(\varphi) + \varphi_n] \quad (4)$$

According to this equation, three variables (I_n, φ_n, and x_n) can be optimized using optimization techniques in order to achieve specific goals. In the following sections, our proposed methods; ALO, GOA, and the hybrid algorithm, will be used to optimize these parameters, with the purpose of suppressing the maximum side lobe level (SLL). With the aim of accomplishing this, the following fitness function is minimized [19]:

$$fitness = \max \left\{ 20\log_{10} \left| \frac{AF(\varphi)}{AF(\varphi_o)} \right| \right\}$$
$$\text{subject to } \varphi \in [0, \varphi_s] \quad (5)$$

where, $[0, \varphi_s]$ represents side lobes' region which depends on elements' number. For 16, 24 and 37-element linear antenna arrays, the region of the side lobes has been, respectively, chosen as [0, 80^o], [0, 83^o] and [0, 87^o]. φ_o is the angle in the direction of the major lobe, which has been chosen to be 90^o, i.e., broadside antenna array.

4. RESULTS AND DISCUSSION

This section is divided into three subsections; the first one discusses the optimization of the elements' amplitudes. The second and third sub-sections present elements' positions and excitation phases optimizations, respectively.

4.1. Optimizing the elements currents (In)

It has been assumed in this section, that the two variables φ_n and x_n are fixed to be the same as those of the uniform antenna array; such that; the excitation phase φ_n=0 and the distance between adjacent elements d=λ/2. Moreover, the range of the excitation currents amplitudes is chosen to be within [0, 1]. Hence, the array factor equations become as (6) and (7):

$$AF(\varphi) = I_o + 2\sum_{n=1}^{N} I_n \cos[n\,\pi\, cos(\varphi)] \quad (6)$$

$$AF(\varphi) = 2\sum_{n=1}^{N} I_n \cos[(n - 0.5)\,\pi\, cos(\varphi)] \quad (7)$$

16-element antenna array has been optimized using ALO, GOA, and the hybrid algorithm. Each technique was run for 20 independent runs on a PC with i7 CPU 3.5 GHz, in addition to 60 search agents used in each run. The best results of the mentioned algorithms are compared to those obtained by PSO, Taguchi, Cuckoo Search (CS), BBO, SADE, MSMO, SOS, EFA, BFP, and Chebyshev methods.

- Example 1: 16-element LAA

A 16-element LAA is optimized using the hybrid method, GOA, and ALO, in this example. The best optimum amplitude results are listed in Table 1. The best SLL found using GOA, the hybrid method and ALO are -33.35 dB, -33.36 dB, and -33.36 dB, respectively. These values are slightly better than the values found using PSO, Taguchi, SADE, MSMO, TS, and Chebyshev methods, and almost equal to those resulted using BBO, SOS, EFA, and BFP algorithms. The radiation patterns for the best values of GOA, the hybrid method, and ALO compared to the other algorithms, are shown in Figure 2(a). The convergence curves of the proposed methods over 1000 iterations and the box-and-whisker plots over 20 independent runs are resented in Figures 2(b) and 2(c), respectively. It can be shown that these algorithms start converging to the global optima in less than 200 iterations, in which GOA has the fastest convergence compared with ALO and the hybrid method. Furthermore, it can be concluded that ALO and the hybrid algorithm have a better performance than GOA.

Table 1. Optimum amplitude values of 16-element LAA

	$[I_1, I_2, I_3, I_4, I_5, I_6, I_7, I_8]$	Max. SLL (dB)	FNBW (degree)
GOA [19]	[1.0000, 0.9466, 0.8475, 0.7136, 0.5625, 0.4093, 0.2699, 0.2088]	-33.35	23.2
ALO [19]	[1.0000, 0.9466, 0.8475, 0.7136, 0.5624, 0.4093, 0.2698, 0.2088]	-33.36	23.2
Hybrid	[1.0000, 0.9468, 0.8474, 0.7139, 0.5623, 0.4093, 0.2699, 0.2087]	-33.36	23.2
BBO [2]	[1.0000, 0.9402, 0.8487, 0.7104, 0.5596, 0.4115, 0.2697, 0.2035]	-33.06	23.2
PSO [26]	[1.0000, 0.9521, 0.8605, 0.7372, 0.5940, 0.4465, 0.3079, 0.2724]	-30.63	22
Taguchi [3]	[1.0000, 0.9500, 0.8575, 0.7317, 0.5861, 0.4381, 0.2988, 0.2552]	-31.2	22.2
SADE [3]	[1.0000, 0.9515, 0.8586, 0.7333, 0.5889, 0.4404, 0.3020, 0.2616]	-31.01	22
MSMO [9]	[1.0000, 0.9613, 0.7249, 0.8346, 0.5556, 0.3977, 0.2842, 0.1844]	-25.94	22.4
SOS [10]	[1.0000, 0.9466, 0.8475, 0.7137, 0.5624, 0.4094, 0.2697, 0.2088]	-33.33	23.2
EFA [11]	[1.0000, 0.9464, 0.8460, 0.7118, 0.5593, 0.4061, 0.2667, 0.2038]	-33.62	23.6
BFP [12]	[1.0000, 0.9464, 0.8459, 0.7119, 0.5594, 0.4060, 0.2667, 0.2037]	-33.62	23.6
TS [13]	[1.0000, 0.9627, 0.8766, 0.7560, 0.6105, 0.4833, 0.2957, 0.3426]	-26.18	21
Cheby [27]	[1.0000, 0.9515, 0.8602, 0.7364, 0.5933, 0.4457, 0.3069, 0.2713]	-30.70	21.8

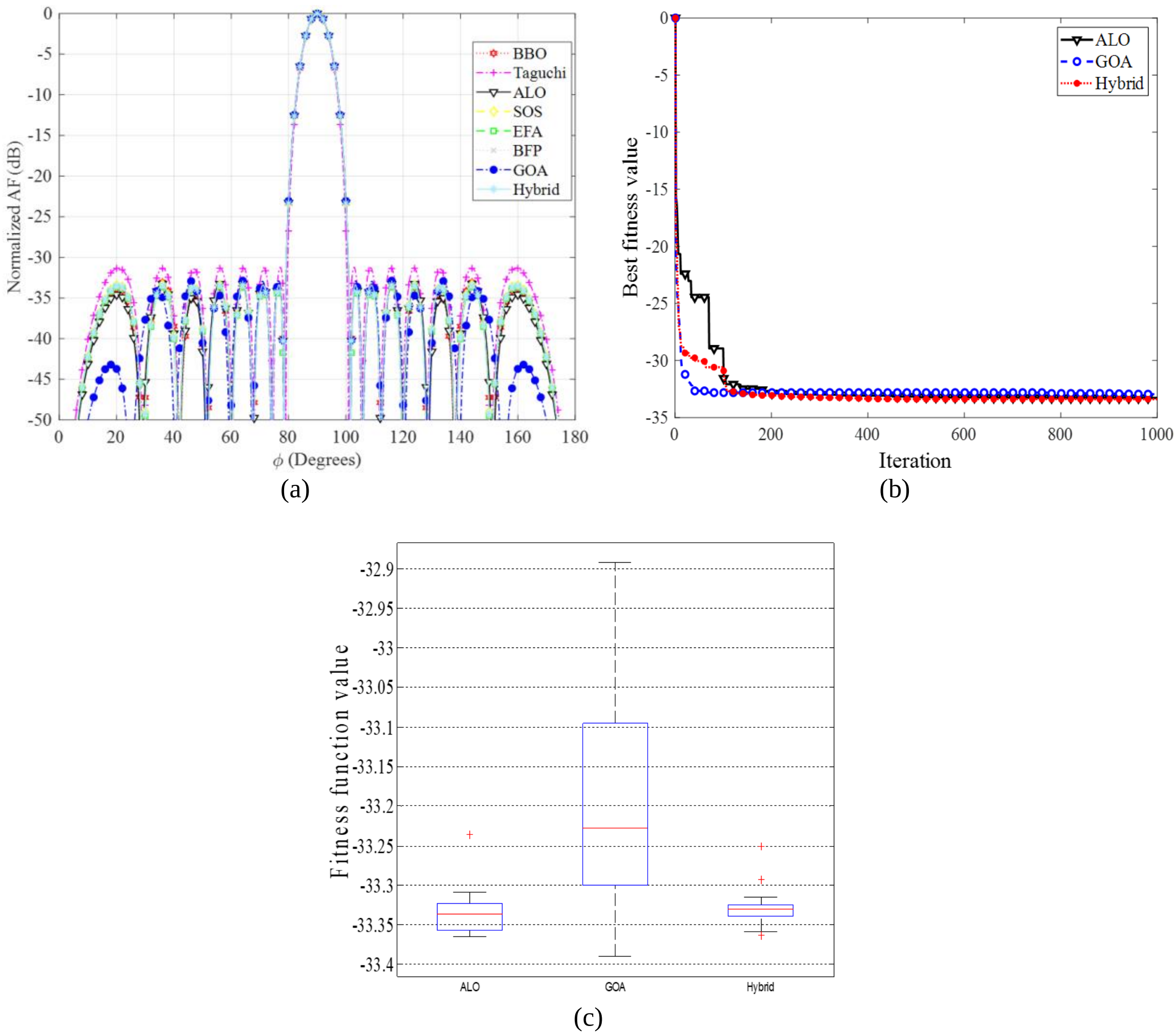


Figure 2. Results for the 16 elements array (a) radiation patterns of 16-element LAA, (b) convergence curves of 16-element LAA, and (c) box-and-whisker plot of 16-element LAA in 20 runs

4.2. Optimizing the elements positions (x_n)

With the aim of optimizing the elements' positions in the LAA, the elements amplitudes and phases have been fixed as I_n=1 and φ_n=0. So, the array factor turns into:

$$AF(\varphi) = 1 + 2\sum_{n=1}^{N} \cos[kx_n cos(\varphi)] \quad (8)$$

$$AF(\varphi) = 2\sum_{n=1}^{N} \cos[kx_n cos(\varphi)] \quad (9)$$

- Optimizing 37-Element LAA

A 37-element LAA has been optimized using GOA, ALO, and the hybrid algorithm, in this example. Multiple constraints have been considered, such that; the distance between elements must be larger or equal 0.5λ and an aperture size of 21.996λ. Therefore, the positions of the outermost elements ($x_{\pm 18}$) are fixed at ±10.998λ, and the other 17 elements positions are optimized. So, the array factor will be as (10):

$$AF(\varphi) = 1 + 2\left\{\sum_{1}^{17} cos[kx_n\, cos(\varphi)] + cos[\,21.996\,\pi\, cos(\varphi)]\,\right\} \quad (10)$$

1,000 iterations and 65 search agents were used in this example. The inter-element spacing obtained using the ALO, GOA, and the hybrid method are mentioned in Table 2. The maximum SLL found by ALO, GOA, the hybrid method, BBO, modified genetic algorithm (MGA) [28] and analytical approach (AA) [29] techniques, are -20.81 dB, -19.07 dB, -20.89 dB, -20.81 dB, -20.49 dB and -19.37 dB, respectively. It can be noticed that the best technique in this problem is the hybrid method, which outperforms ALO and BBO by little difference.

Therefore, the hybrid and ALO performance are very good in this example as they give a maximum SLL that is equivalent to that obtained using other powerful techniques. Figure 3(a) shows the radiation pattern for the proposed results, while Figures 3(b) and 3(c) represent the convergence curves and box-and-whisker plots for the three algorithms, respectively.

Table 2. Optimum inter-element spacing values (d_i) (in terms of wavelength) found by ALO, GOA, and the hybrid method for the 37-element LAA in comparison with other optimization techniques

	$[d_1, d_2, \dots, d_{18}]$	Max. SLL (dB)
ALO	[0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.54876, 0.62649, 0.5447, 0.71101, 0.7273, 0.92492, 0.97626, 0.87637, 0.5622] ⇒∑=10.998	-20.81
GOA	[0.5, 0.5, 0.5, 0.5, 0.5, 0.56489, 0.5, 0.52946, 0.5147, 0.60667, 0.72208, 0.57931, 0.87251, 0.73559, 0.79982, 0.64432, 0.57027, 0.85837] ⇒∑=10.998	-19.07
Hybrid	[0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.50086, 0.5, 0.55536, 0.75934, 0.73307, 0.85924, 0.99999, 0.99875, 0.5914] ⇒∑=10.998	-20.89
BBO [2]	[0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.50386, 0.5, 0.59865, 0.5, 0.5, 0.7686, 0.79479, 0.9, 0.9, 0.97342, 0.5587] ⇒∑=10.998	-20.81
MGA [28]	[0.5024, 0.5, 0.5, 0.5008, 0.5003, 0.5001, 0.5045, 0.5703, 0.5369, 0.5194, 0.5868, 0.5765, 0.7737, 0.7045, 1.0065, 0.8806, 0.8293, 0.5054] ⇒∑=10.998	-20.49
AA [29]	[0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.589, 0.633, 0.664, 0.687, 0.707, 0.722, 0.735, 0.746, 0.754, 0.761] ⇒∑=10.998	-19.37

4.3. Optimizing the elements phases (φ_n)

In this section, the excitation phases for the elements of the linear antenna array have been optimized using ALO, GOA, and the hybrid technique. Similar to previous sections, some parameters must be assumed as uniform antenna array parameters, such that; the spacing between adjacent elements is set to 0.5 λ and the currents to be unity. The elements' phases are assumed to be symmetric, such that;

$$\varphi_n = \varphi_{-n}\,, n = 1, 2, 3 \dots, N,$$

where, φ_n is the phase of the n^{th} element. Thus, the array factor can be written as (11), (12):

$$AF(\varphi) = exp(j\varphi_o) + 2\sum_{n=1}^{N} exp(j\varphi_n)\, cos[n\,\pi\, cos(\varphi)] \quad (11)$$

$$AF(\varphi) = 2\sum_{n=1}^{N} exp(j\varphi_n)\, cos[(n - 0.5)\,\pi\, cos(\varphi)] \quad (12)$$

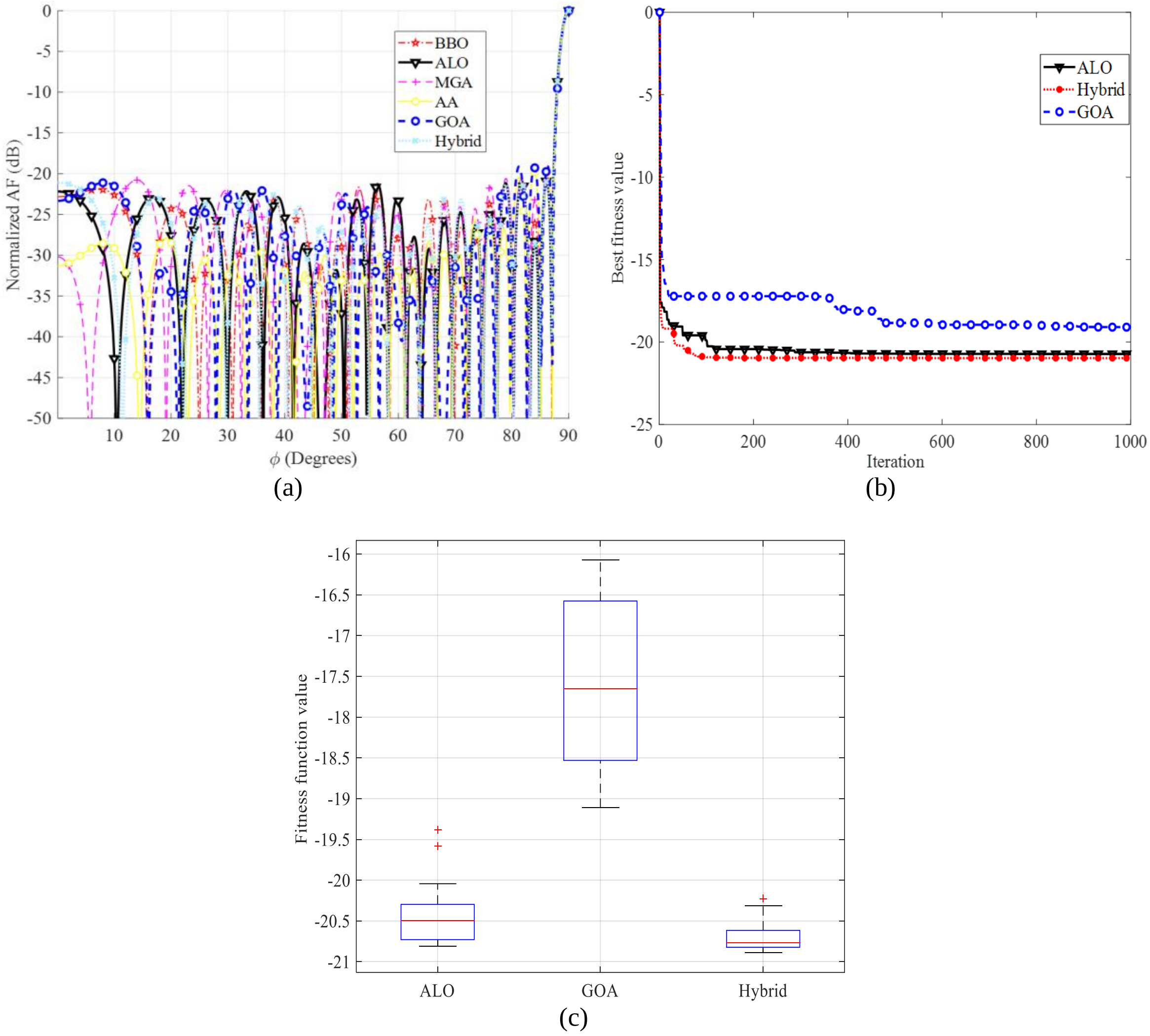


Figure 3. Results for the 37 elements array (a) radiation patterns for optimizing the position of 37-element LAA, (b) convergence curves for optimizing the position of 37-element LAA, (c) Box-and-whisker plot for optimizing the position of 37-element LAA in 20 runs

4.3.1. Minimizing the side lobe level

- 40-element LAA

In this example, the optimization of the excitation phase for a 40-element linear antenna array has been studied. Table 3 shows the optimum phases, the FNBW values, and the max SLL values found by ALO, GOA, and the hybrid algorithm for optimizing 40-element LAA compared to other optimization techniques. We observe that the hybrid algorithm and ALO obtained slightly better results than CS, BBO, GOA, SOS, and GA. Figure 4 illustrate the radiation patterns for the optimization process of ALO, GOA, and the hybrid technique. It has been assumed that the range of φ_n=[0, π]. Moreover, 40 search agents and 1000 iterations were used in this example.

4.3.2. Minimizing sidelobe level and null steering

In this section, in addition to the reduction of the maximum SLL of LAA by optimizing the excitation phases of the elements, nulls at specific angles are going to be imposed. So, the fitness function is going to be as (13), (14) [2]:

$$fitness = w_1 f_{SL}(\varphi) + w_2 f_{NS}(\varphi) \tag{13}$$

Such that:

$$f_{SL}(\varphi) = max\left\{20\,log_{10}\left|\frac{AF(\varphi)}{AF(\varphi_o)}\right|\right\}$$
$$f_{NS}(\varphi) = \sum_k \left\{20\,log_{10}\left|\frac{AF(\varphi_{\,k-null})}{AF(\varphi_o)}\right|\right\} \quad (14)$$

where, w_1 and w_2 represent weighting factors; w_1 is chosen to be 1 while w_2 depends on the problem of each example individually. $f_{SL}(\varphi)$ represents the fitness function in the region of the side lobes, while $f_{NS}(\varphi)$ is the fitness function at the desired nulls. In the next examples, we are going to optimize the elements' phases and getting nulls at specific angles. It has been assumed that the excitation phases range is assumed to be within [-π, π]. In this section, two examples; 40 and 20-element arrays, have been optimized using ALO, GOA, and the hybrid technique, to get nulls at different angles.

- Example 1: 40-element LAA with null at 81°

The optimum values for the excitation phases are presented in Table 4. It can be noticed that the null values of ALO, GOA, and the hybrid technique outperform BBO, SADE, and Taguchi. The values of the maximum SLL for ALO, GOA, the hybrid method, BBO, Taguchi and SADE are -15.32 dB, -15.42 dB, -16.08 dB, -16.51 dB, -16.26 dB and -15.23 dB, respectively. The radiation patterns obtained by ALO, GOA, and hybrid methods compared to BBO, SADE, and Taguchi are shown in Figure 5. In this example, w_2=2, 700 iterations are implemented for all algorithms, 200 search agents are used for ALO, and 100 search agents for the hybrid and GOA are applied.

Table 3. Optimum phase values (degrees) of the 40-element LAA

	$\varphi_1, \varphi_2, \ldots, \varphi_{20}$ (degrees)	Max. SLL (dB)	FNBW (°)
ALO	[60.0746, 55.8605, 58.4875, 54.6739, 56.8609, 57.2482, 57.9490, 54.6063, 54.358, 36.5020, 51.6103, 26.9319, 68.9555, 34.2846, 175.6230, 51.2270, 9.0310, 88.5907, 92.7619, 95.3574]	-18.10	6.6
GOA	[105.6362, 107.2348, 106.4326, 101.5969, 107.9281, 100.1702, 97.7409, 101.4766, 100.9151, 83.6805, 88.9460, 88.8314, 139.1371, 98.2565, 0.0000, 146.9178, 111.7726, 168.8965, 104.6278, 109.4980]	-17.97	6.4
Hybrid	[106.5988, 110.7814, 114.6718, 114.3223, 110.5064, 116.5855, 113.5545, 103.7111, 132.0439, 133.3674, 110.5350, 143.3884, 120.7910, 2.9539, 115.2218, 94.4693, 175.0673, 76.4669, 81.1480, 101.7688]	-18.13	6.4
CS [30]	[45.9692, 39.7155, 39.6464, 36.8069, 41.0828, 42.4519, 50.2623, 32.5464, 36.8147, 34.4894, 30.8162, 16.1212, 81.8888, 20.4923, 41.963, 177.6511, 30.7085, 53.6503, 35.3756, 87.3351]	-17.59	6.4
BBO [2]	[90.4185, 90.5331, 97.2825, 90.2466, 88.384, 97.1507, 90.0002, 90.3497, 97.2596, 85.9950, 75.0002, 115.5026, 71.8604, 0.3610, 122.9166, 97.0247, 178.8087, 83.3081, 83.9670, 79.2057]	-17.96	6.4
GA [2]	[69.7175, 68.4570, 72.3187, 63.5582, 53.3699, 51.9283, 66.1537, 36.5971, 50.4650, 38.3526, 75.1950, 15.6011, 91.3810, 39.8412, 83.9670, 171.8873, 32.3028, 28.6863, 57.2958, 73.1724]	-17.39	6.1
SOS [10]	[28.3636, 25.0046, 22.2290, 31.1901, 23.7626, 17.3337, 15.5147, 39.0199, 18.1678, 7.8822, 1.8298, 60.0022, 0, 0.0146, 0.0161, 148.3908, 45.0096, 56.1693, 61.9867, 2.1350]	-18.02	6.6

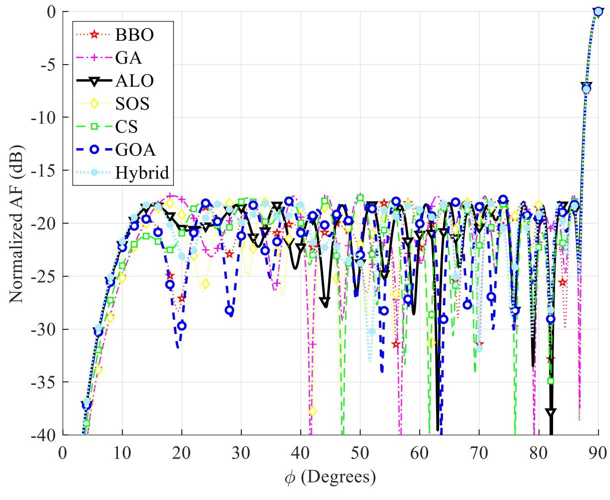


Figure 4. Radiation patterns of 40-element LAA

Table 4. Optimum phase values (degrees) of 40-element LAA with null at 81°

	$\varphi_1, \varphi_2, \dots, \varphi_{20}$ (deg.)	Null value (dB)	Max. SLL (dB)
ALO	[92.7674, 64.3466, 62.4028, 56.2745, 89.9629, 62.4957, 100.5601, 100.8682, 91.2946, 84.2592, 73.9212, 72.1928, 68.4046, 68.7634, 70.0995, -51.8900, 70.0716, 96.1744, -4.7488, 39.0293]	-141.54	-15.32
GOA	[22.6259, 19.4652, 30.8647, 25.3484, 33.7761, 37.9812, 37.2569, 19.3399, 11.4242, 22.2950, 23.9312, 44.0379, 17.5836, 44.2360, 8.1484, 80.4283, -16.6852, -42.4096, 86.6102, 26.2374]	-151.05	-15.42
Hybrid	[48.8304, 60.2302, 51.9549, 53.8298, 52.2468, 39.8218, 82.2317, 31.0986, 45.4317, 73.2459, 50.2129, 62.3092, 49.1348, 42.0506, 43.5561, 58.1491, -101.5410, 51.6264, 77.2473, 30.6827]	-144.69	-16.08
BBO [2]	[-151.36, -151.26, -150.26, -144.46, -152.46, -180.00, -174.27, -171.88, -150.04, -180.00, -142.17, -138.05, -168.70, -148.72, 171.90, -142.74, 0, -170.48, -135.85, -112.30]	-99.70	-16.51
Taguchi [3]	[63.935, 52.596, 62.808, 55.933, 73.719, 81.473, 86.684, 55.439, 19.538, 23.263, 59.938, 77.89, 62.579, 56.510, 66.814,112.846, -30.596, 118.459, 60.524, 40.272]	-98.95	-16.26
SADE [3]	[-2.152, -4.772, -1.000, 6.145, -1.000, -1.000, -9.465, -1.000, -1.000, -5.280, 0.000, 0.000, -1.000, -1.000, 12.082, 20.134, 131.145, 55.280, 0.000, -27.990]	103.1	-15.23

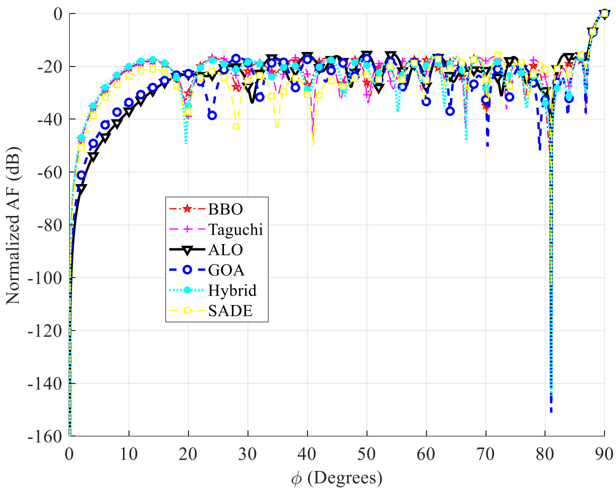


Figure 5. Radiation patterns of 40-element LAA with null at 81°

- Example 2: 20-element LAA with nulls at 50° and 56.5°

In this example, the nulls are placed at two angles; 50° and 56.5°. The optimum phases with their corresponding SLL and nulls' values are shown in Table 5. According to this table, the proposed algorithms achieve very competitive nulls' and SLL values compared to the other techniques. Figure 6 shows the radiation patterns for ALO, GOA, and the hybrid method compared with CS, BBO, and Taguchi. w_1=10 and w_2=1.

Table 5. Optimum phase values (degrees) of 20-element LAA with nulls at 50° and 56.5°

	$\varphi_1, \varphi_2, \dots, \varphi_{10}$ (deg.)	Max. SLL (dB)	1st null value (dB) (50°)	2nd null value (dB) (56.5°)
ALO	[-9.5781, -18.0688, -37.9063, -27.3759, -2.4190, -63.0884, -38.6918, -15.8864, -9.4200, 43.2188]	-13.86	-99.82	-98.20
GOA	[-21.7495, -32.5589, -39.5685, -30.9873, 12.6309, -50.0742, -34.6857, -13.9601, -23.6924, 53.6214]	-13.89	-100.32	-100.13
Hybrid	[84.9868, 95.8387, 77.0342, 93.2088, 102.8975, 44.1453, 65.4261, 90.2409 87.9318, 150.7165]	-13.92	-100.37	-101.10
CS [30]	[180.0000, -180.0000, 179.9883, 180.0000, 151.4641, -140.0311, -153.7865, -180.0000, -167.4428, 112.7044]	-13.9	-91.84	-111.5
BBO [2]	[114.5916, 114.5916, 97.9128, 114.5916, 135.6821, 84.4654, 110.5866, 135.9400, 139.8590, -171.8873]	-13.62	-89.26	-99.87
Taguchi [3]	[55.7474, 59.2978, 69.5063, 56.3685, 29.6016, 90.8367, 71.5181, 46.7219, 44.3011, -14.4442]	-14.29	-77.82	-79.51

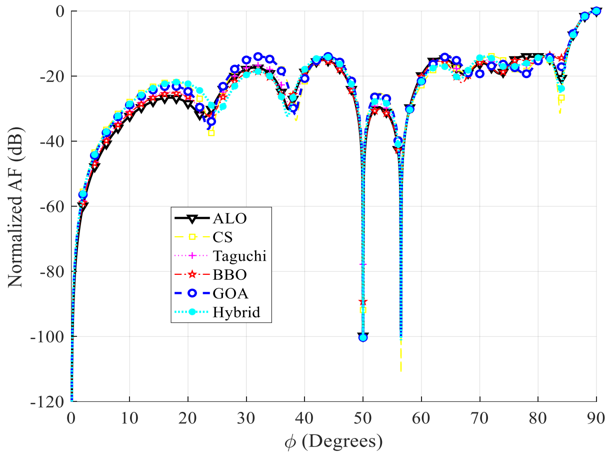


Figure 6. Radiation patterns of 20-element LAA with nulls at 50° and 56.5°

5. CONCLUSION

In this paper, we mainly ALO algorithm, GOA, and their new hybrid optimization method to the design of linear antenna array in order to achieve the carefully-formulated fitness function. Three cases with different elements' number of linear antenna arrays were studied; amplitudes optimization positions optimization and phases optimization. It was found that the proposed algorithms are robust, fast converging algorithms, and their results are very competitive, better in some examples, compared to those obtained using other optimization methods.

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