The optimal synthesis of scanned linear antenna arrays

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Article Info	ABSTRACT
	In this paper, symmetric scanned linear antenna arrays are synthesized, in order to minimize the side lobe level of the radiation pattern. The feeding current amplitudes are considered as the optimization parameters. Newly proposed optimization algorithms are presented to achieve our target; Antlion Optimization (ALO) and a new hybrid algorithm. Three different examples are illustrated in this paper; 20, 26 and 30 elements scanned linear antenna array. The obtained results prove the effectiveness and the ability of the proposed algorithms to outperform and compete other algorithms like Symbiotic Organisms Search (SOS) and Firefly Algorithm (FA).

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1. INTRODUCTION

The process of finding the optimal solution(s) for a particular problem is generally referred to optimization [1]. The main characteristic of the metaheuristic (stochastic) optimization algorithms is the randomness [2, 3], which means that random operators are employed in each iteration to find solutions close to the exact global optimum during the searching process. Therefore, in this kind of optimization there is no assurance to find the global optimum [4]. The wide use of stochastic optimization algorithms in the last two decades occurred due to four main reasons: simplicity, flexibility, local optima avoidance, and the needlessness of calculating the gradient of a solution.

Antenna is defined as a key part that wirelessly transmits or receives electromagnetic energy in any electronic system. According to certain specifications, the radiation of the antenna can be enhanced when numerous antennas are working together, which is defined as antenna array. The main feature of the antenna array compared to single antenna, is the ability to steer the main beam to transmit and receive electromagnetic waves without any mechanical movement for the array itself [5]. Antenna arrays are widely used in radar, satellite and mobile applications [6]. Several types and geometries have been studied in the literature, such as; linear, circular, elliptical, planar, …, etc. The linear antenna array is the simplest and the most common type of antenna arrays [7].

In the literature, several stochastic optimization algorithms have been used for the synthesis of antenna arrays in order to get the desired radiation pattern, such as Firefly Algorithm (FA) [8], Particle Swarm Optimization (PSO) [9, 10], Ant Colony Optimization (ACO) [11], Taguchi Optimization [12], Invasive Weed Optimization (IWO) [13], Pattern Search optimization [14], Biogeography Based Optimization (BBO) [15], Antlion Optimization (ALO) algorithm [16] and Cat Swarm Optimization (CSO) [17]. In this work, two optimization algorithms are applied in the scanned antenna array problems;

Antlion Optimization (ALO) algorithm [18] and new proposed hybrid optimization algorithm based on Grasshopper Optimization Algorithm (GOA) [19] and ALO.

The rest of this paper is organized as follows: In section 2, the proposed hybrid algorithm is presented. In section 3, the geometry and problem formulation for the scanned antenna arrays is presented. Then, the fitness function and the results with their discussion are presented in section 4. Finally, the paper is concluded in section 5.

2.   THE PROPOSED HYBRID OPTIMIZATION ALGORITHM

2.1. The theory of the hybrid method

In [20-22], we proposed a new hybrid method that combines the features of two metaheuristic algorithms; Grasshopper Optimization Algorithm (GOA) [19] and Antlion Optimization (ALO) algorithm [18]. ALO is robust in exploitation process, which has been proved in many papers in the literature like [23, 24]. The social forces in grasshopper's swarm show the strong ability in exploration process all over the search space. So, these features give the chance to combine these two methods, GOA and ALO, in a novel hybrid method, to make a huge enhancement on the performance of these algorithms. The benefits of hybridization can be represented in overcoming the main disadvantages of GOA and ALO. The full dependence on roulette wheel selection method is the main disadvantage in ALO, since it may cause; loss of diversity, early convergence and not enough pressure to select the fittest search agents among same fitness search agents. Whereas the main drawback of GOA exists in c parameter equation, which weakens the exploitation process in the algorithm.

Our proposed Hybrid method can efficiently explore and exploit the whole search space to reach the global optimal value, because of merging the features of GOA and ALO together. The hybrid method has some factors that improve the ability of exploitation and exploration processes like: the population nature that decreases local optima stagnation, the attraction and repulsion forces in GOA method, the roulette wheel selection method and random walks in ALO method, choosing different samples of less and average fitness search agents from next position's matrix, and the modifications of c parameter in GOA method. These factors and modifications lead to better diversity of the search agents all over the search space and high probability for local optima stagnation avoidance. Furthermore, the intensity of search agents in the proposed method has been reduced rapidly compared with ALO and GOA, due to the modification of c parameter and its combination with other shrinking factors. Thus, the hybrid method guarantees the mature and fast convergence compared with ALO and GOA [22].

The following equations have been used in our proposed algorithms [22]:

$$X_i^d = c \left(\sum_{\substack{j=1 \\ j \neq i}}^{N} c \frac{ub_d - lb_d}{2} s\left(\left|X_j^d - X_i^d\right|\right) \frac{X_j - X_i}{d_{ij}} \right) \qquad (1)$$

where X_i^d defines the next position for i^{th} grasshopper and d^{th} dimension, ub_d and lb_d are the upper and lower bounds in the dth dimension, respectively, and $s(r) = f e^{\frac{-r}{l}} - e^{-r}$ where f represents the intensity of attraction force and l indicates the attractive length scale [22].

$$if\ l \leq (L)/2$$

$$c = cmax - l \frac{cmax - cmin}{\left(\frac{L}{2}\right)} \qquad (2)$$

$$if\ l > \frac{L}{2}$$

$$c = (L - l + 1) \times \left(\frac{cmin}{L \times 10^l}\right) \qquad (3)$$

where $cmax$ and $cmin$ are the maximum and minimum values, respectively, L indicates the maximum number of iterations, and l is the current iteration [19].

$$c^t = \frac{c^t}{I} \qquad (4)$$

$$d^t = \frac{d^t}{I} \qquad (5)$$

where c^t and d^t indicate the minimum and maximum of all variables at t^{th} iteration, respectively, and I represents a ratio, such that $I = 10^w \frac{t}{T}$ where t represents the current iteration, T indicates the maximum number of iterations, and w is a constant that depends on the current iteration [18].

2.2. Flowchart of the hybrid algorithm [16]

In Figure 1 show the flowchart of the hybrid algorithm [16].
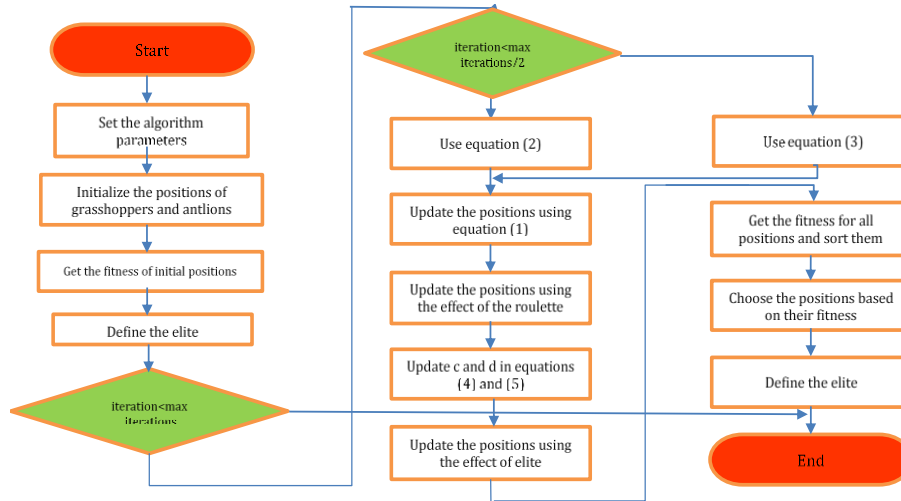

Figure 1. Flowchart of the hybrid algorithm

3. GEOMETRY AND PROBLEM FORMULATION

In scanned array antennas, the major lobe is steered to a specific direction, which can be applied in wide applications like mobile and cellular communications. To accomplish this, a progressive phase shift is added in the feeding currents [25]. Hence, the array factor equation for N-element scanned antenna array that lies along the x-axis, with λ/2 spacing between adjacent elements, can be written as follows [25]:

$$AF(\varphi) = \sum_{n=1}^{N} I_n \exp(j\pi(n-1)[\cos(\varphi) - \cos(\varphi_d)]) \tag{6}$$

where I_n represents the excitation amplitude of the nth element. φ_d is the angle at which the major lobe is steered. The geometry of such a scanned array with N elements is shown in Figure 2.
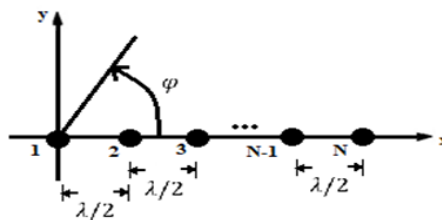

Figure 2. Geometry of N-element linear array

The main objective in this paper is to minimize the maximum side lobe level (SLL) with respect to the main lobe. With the purpose of accomplishing this goal, the following fitness function is minimized [24]:

$$fitness = \max \left\{ 20 \log_{10} \left| \frac{AF(\varphi)}{AF(\varphi_d)} \right| \right\} \tag{7}$$

subject to $\varphi \in [0, \varphi_s]$ \hfill (8)

where φ_d is the angle in the direction of the major beam. $[0, \varphi_s]$ represents the side lobes region that depends on the total number of the elements.

4.   RESULTS AND ANALYSIS

In this paper, three different examples are considered; 20-element LAA with $\varphi_d = 30°$, 26-element LAA with $\varphi_d = 45°$ and 30-element LAA with $\varphi_d = 60°$. In all the examples, the excitation currents are optimized to minimize the side lobe level using ALO and the proposed hybrid algorithm compared to Symbiotic Organisms Search (SOS) algorithm [25] and Firefly Algorithm (FA) [8] results. 40 search agents and 1000 iterations are used in all examples.

4.1. Example 1: Optimization of 20-Element LAA ($\varphi_d = 30°$)

In this example, the excitation currents for 20-element LAA with $\varphi_d = 30°$ have been optimized. Table 1 shows the optimal values for the feeding current amplitudes and the maximum SLL for ALO, the hybrid method, Symbiotic Organisms Search (SOS) [25] and Firefly Algorithm (FA) [8]. The maximum SLL values in (dB) are -15.45, -15.66, -15.64 and -15.59, respectively, for ALO, the hybrid method, SOS and FA techniques. Furthermore, the FNBW values are 29.56°, 29.44°, 29.44° and 30.08° for ALO, the hybrid, SOS and FA, respectively, and these are almost equal. The obtained radiation patterns and convergence curves for the proposed algorithms are displayed in Figure 3 and Figure 4. The statistical results for ALO and the hybrid method are tabulated in Table 2. It can be noticed that the standard deviation (STD) for both methods outperforms the STD for SOS and FA [25], which proves the stability and robustness of the proposed methods.

Table 1. Optimum currents for 30° scanned LAA with 20 elements using ALO
and the hybrid algorithm compared to other optimization techniques

$\varphi_d = 30°$, N=20	Feeding current amplitudes (I_1 ... I_{20})	Max. SLL (dB)	FNBW (degree)
ALO	[1.0000, 0.48938, 0.583, 0.43543, 0.25664, 0.8691, 0.48552, 0.80474, 0.3192, 0.69249, 0.5965, 0.81911, 0.7401, 0.46723, 0.25881, 0.79585, 0.5334, 0.23493, 0.57805, 0.99917]	-15.45	29.56
Hybrid	[0.86058, 0.39071, 0.31623, 0.47141, 0.36107, 0.42318, 0.59255, 0.52504, 0.43337, 0.39471, 0.64721, 0.61082, 0.49428, 0.40356, 0.45944, 0.47877, 0.3173, 0.41312, 0.22736, 1.0000]	-15.66	29.44
SOS [25]	[1.0000, 0.2762, 0.4499, 0.3040, 0.3787, 0.6113, 0.5305, 0.5042, 0.5554, 0.6113, 0.4950, 0.4909, 0.5940, 0.4393, 0.3429, 0.5587, 0.4266, 0.3142, 0.4099, 0.9092]	−15.64	29.44
FA [8]	[0.98041, 0.76626, 0.36907, 0.55297, 0.90715, 0.20192, 0.51964, 0.84496, 0.50948, 0.98057, 0.51426, 0.53871, 0.80273, 0.55406, 0.88082, 0.40378, 0.33214, 0.46556, 0.50348, 0.94604]	−15.59	30.08

Table 2. Performance of ALO and the hybrid algorithm for 20 independent runs

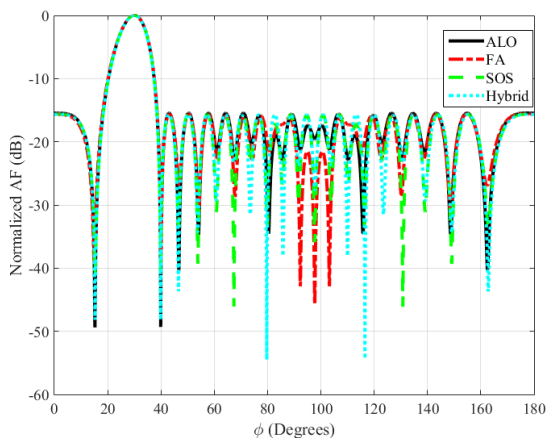|	ALO	Hybrid
Min value (dB)	-15.4466	-15.6623
Max value (dB)	-15.1441	-15.4003
Median (dB)	-15.3217	-15.5586
Mean (dB)	-15.3087	-15.5624
STD (dB)	0.0859	0.0674

Figure 3. Radiation patterns of ALO and the hybrid technique for 20-element scanned LAA
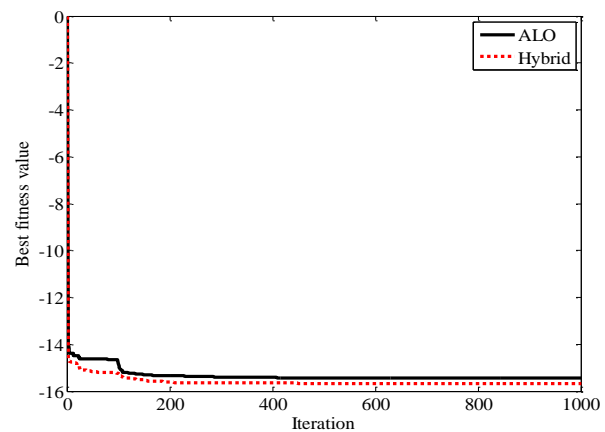

Figure 4. Convergence curves for the best result of scanned LAA using ALO and the hybrid algorithm

4.2. Example 2: Optimization of 26-Element LAA ($\varphi_d = 45°$)

The optimum currents values and maximum SLL for 26-element $45°$ scanned array antenna are tabulated in Table 3, while Table 4 shows the statistical properties for ALO and the hybrid method in 20 independent runs. Figure 5 and Figure 6 demonstrate the radiation patterns and convergence curves, respectively. It is obvious that the maximum SLL value obtained using the hybrid algorithm is slightly better than the ALO, SOS and FA techniques. For all methods, the FNBW=12.62.

Table 3. Optimum currents for 45° scanned LAA with 26-element array using ALO
and the hybrid method compared to other optimization techniques

$\varphi_d = 45°$, N=26	Feeding current amplitudes ($I_1 \dots I_{26}$)	Max. SLL (dB)
ALO	[0.9845, 0.92464, 0.010525, 0.6751, 0.62702, 0.063028, 0.65201, 0.54108, 0.5882, 0.75892, 0.49313, 0.69067, 0.82217, 0.44326, 0.56542, 0.62967, 0.65334, 0.53038, 0.4111, 0.7564, 0.37021, 0.74546, 0.0055742, 0.74332, 0.36553, 1.0000]	-16.05
Hybrid	[0.9777, 0.34246, 0.54211, 0.084948, 0.283, 0.52902, 0.52469, 0.40156, 0.45987, 0.58482, 0.35575, 0.5388, 0.53935, 0.58524, 0.38648, 0.63499, 0.47567, 0.50461, 0.36721, 0.45082, 0.35472, 0.3458, 0.5698, 0.23679, 0.28481, 1.0000]	-16.32
SOS [25]	[1.0000, 0.2314, 0.4243, 0.4349, 0.3933, 0.4423, 0.4890, 0.3892, 0.5260, 0.5470, 0.3889, 0.8891, 0.4148, 0.5557, 0.4317, 0.7241, 0.4748, 0.3302, 0.7278, 0.5896, 0.2174, 0.5061, 0.1908, 0.4341, 0.6199, 0.9584]	−16.18
FA [8]	[1, 0.72429, 0.55905, 0.44837, 0.71979, 0.31947, 0.70758, 0.62037, 0.53995, 0.86304, 0.67322, 0.71588, 0.83498, 0.77957, 0.42717, 0.79538, 0.71365, 0.63019, 0.62672, 0.6301, 0.74732, 0.060126, 0.73871, 0.59844, 0.77826, 0.9975]	−15.61

Table 4. Performance of ALO and the hybrid algorithm for 20 independent runs

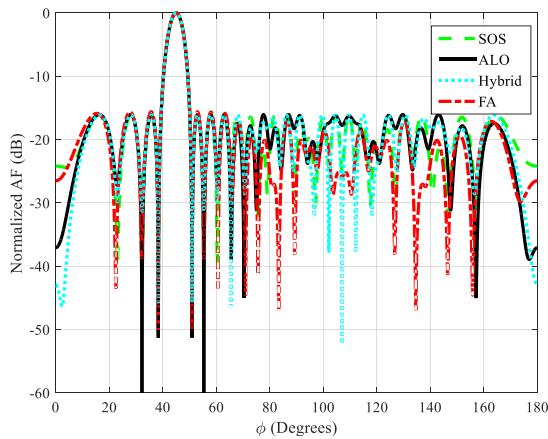|	ALO	Hybrid
Min value (dB)	-16.0487	-16.3188
Max value (dB)	-15.7675	-16.1154
Median (dB)	-15.8969	-16.2159
Mean (dB)	-15.9033	-16.2146
STD (dB)	0.0943	0.0911

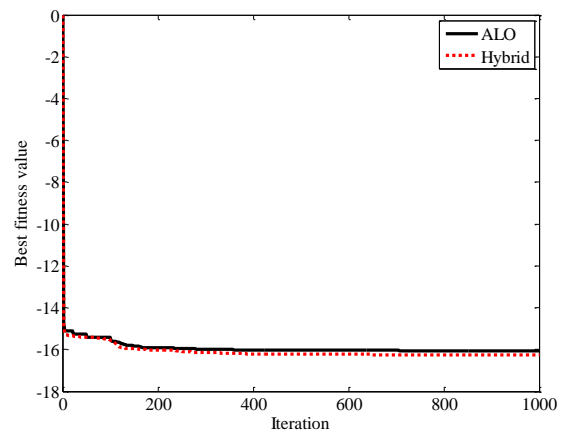Figure 5. Radiation patterns of ALO and the hybrid technique for 26 elements scanned LAA

Figure 6. Convergence curves for the best result of scanned LAA using ALO and the hybrid algorithm

4.3. Example 3: Optimization of 30-Element LAA ($\varphi_d = 60°$)

The excitation currents for 30 elements in $60°$ scanned antenna array have been investigated in this example. Table 5 shows the best value of the maximum SLL and FNBW values for ALO, the hybrid method, SOS and FA techniques. According to this table, it can be concluded that the hybrid algorithm somewhat beats other techniques. Table 6 mentions the consistency for ALO and the hybrid algorithm. The radiation patterns and convergence curves are illustrated in Figure 7 and Figure 8, respectively.

Table 5. Optimum currents for 60° scanned LAA with 30-element array using ALO
and the hybrid method compared to other optimization techniques

φ_d= 60°, N=30	Feeding current amplitudes ($I_1 ... I_{30}$)	Max. SLL (dB)	FNBW (degree)
ALO	[0.9380, 0.5472, 0.4980, 0.4647, 0.4777, 0.0382, 0.4824, 0.7979, 0.3462, 0.4455, 0.6926, 0.3170, 0.6597, 0.6022, 0.7500, 0.1379, 0.8532, 0.5132, 0.7009, 0.1911, 0.7336, 0.7231, 0.0303, 0.6409, 0.5290, 0.3575, 0.3012, 0.2129, 0.7843, 1.0000]	-15.94	9
Hybrid	[0.76681, 0.31841, 0.2907, 0.33733, 0.20298, 0.30963, 0.25103, 0.4666, 0.33325, 0.28434, 0.2275, 0.55575, 0.41659, 0.41468, 0.35724, 0.48412, 0.41547, 0.27134, 0.29311, 0.47269, 0.52282, 0.29816, 0.28305, 0.35377, 0.32292, 0.23532, 0.34489, 0.14076, 0.23816, 1.0000]	-16.20	8.96
SOS [25]	[1.0000 0.9219 0.4011 0.1512 0.6258 0.0149 0.7433 0.5357 0.4412 0.8182 0.3055 0.5388 0.8813 0.5962 0.4734 0.8110 0.3965 0.6665 0.3149 0.7865 0.6591 0.4047 0.3755 0.5224 0.5257 0.5935 0.2734 0.3698 0.6766 0.9982]	−15.93	9
FA [8]	[0.99575, 0.68442, 0.62997, 0.049937, 0.17937, 0.73457, 0.48525, 0.61814, 0.33365, 0.63189, 0.63643, 0.39343, 0.49183, 0.77247, 0.64547, 0.48407, 0.73964, 0.74411, 0.52797, 0.45014, 0.82218, 0.52901, 0.45825, 0.41905, 0.48686, 0.24166, 0.86684, 0.63618, 0.29691, 0.99934]	−15.97	9.08

Table 6. Performance of ALO and the hybrid algorithm for 20 independent runs

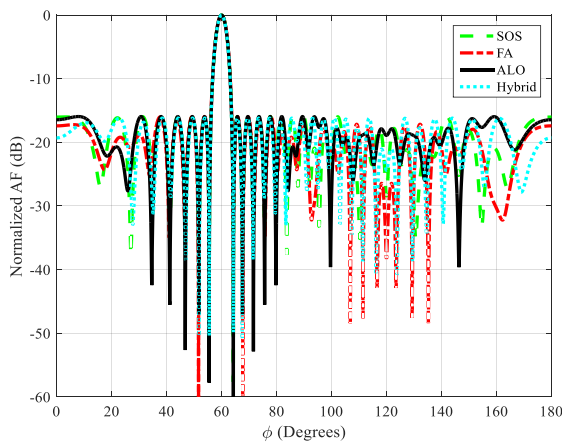|	ALO	Hybrid
Min value (dB)	-15.9449	-16.1959
Max value (dB)	-15.6637	-15.9615
Median value (dB)	-15.8149	-16.0773
Mean value (dB)	-15.8074	-16.0822
STD (dB)	0.0865	0.0501

Figure 7. Radiation patterns of ALO and the hybrid technique for 30-element array scanned LAA
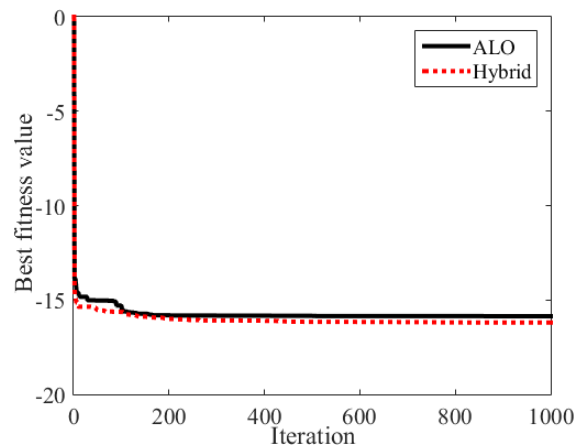

Figure 8. Convergence curves for the best result of scanned LAA using ALO and the hybrid algorith

5.   CONCLUSION

In this paper, optimal design of scanned linear antenna arrays was performed using two metaheuristic algorithms; Antlion optimization (ALO) algorithm and our new proposed hybrid algorithm based on Grasshopper Optimization algorithm (GOA) and ALO. Our objective function in this paper was to reduce the side lobe level with the constraint of a fixed major lobe beamwidth. In this paper, three examples were discussed; 20-element, 26-element and 30-element scanned antenna array. The results show that the proposed hybrid algorithm is very competitive in reducing the SLL compared to other methods like; SOS and FA. In all experiments, a population size of 40 and 200 iterations only were enough to reach to the solution.

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