

Synthesis of new antenna arrays with arbitrary geometries based on the superformula

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ABSTRACT

The synthesis of antenna arrays with low sidelobe levels is needed to enhance the communication systems' efficiency. In this paper, new arbitrary geometries that improve the ability of the antenna arrays to minimize the sidelobe level, are proposed. We employ the well-known superformula equation in the antenna arrays field by implementing the equation in the general array factor equation. Three metaheuristic optimization algorithms are used to synthesize the antenna arrays and their geometries; antlion optimization (ALO) algorithm, grasshopper optimization algorithm (GOA), and a new hybrid algorithm based on ALO and GOA. All the proposed algorithms are high-performance computational methods, which proved their efficiency for solving different real-world optimization problems. 15 design examples are presented and compared to prove validity with the most general standard geometry: elliptical antenna array (EAA). It is observed that the proposed geometries outperform EAA geometries by 4.5 dB and 10.9 dB in the worst and best scenarios, respectively, which proves the advantage and superiority of our approach.

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1. INTRODUCTION

Several standard geometries like; line, circle, and ellipse, have been widely used in the synthesis of different antenna array designs in the literature, due to the availability and the ease of implementation of their parametric equations. These shapes have been implied in hundreds of articles to design antenna arrays, such as; linear antenna arrays (LAA) [1]–[6], circular antenna arrays (CAA) [7]–[12], and elliptical antenna arrays (EAA) [13]–[18], and to achieve different objectives like minimizing the maximum sidelobe level or increasing the directivity of the array. Results' variation of diverse geometries proves the significant role of the array's shape in determining the desired objective in the antenna arrays. Such observation is the main inspiration to think of creating new optimal geometries that will improve antenna array characteristics.

In 2003, Gielis [19] proposed a new geometrical equation, called the superformula. This geometrical approach has been used to model and understand numerous abstract, natural, and man-made shapes [19]. Superformula equation can describe different shapes in nature, which can be achieved by modifying the parameters of the equation that generate various natural polygons [19]. In the literature, the superformula equation has been implemented, before, in antenna designs [20]–[22].

In this paper, our goal is to minimize the sidelobe level in a new arbitrary antenna array radiation pattern using three optimization algorithms: antlion optimization (ALO) [23], grasshopper optimization

algorithm (GOA) [24], and a new hybrid optimization algorithm based on ALO and GOA [11]. The rest of the paper is organized. A brief overview of our new proposed hybrid algorithm is presented in section 2. The description of the superformula equation and its implementation in the array factor equation are discussed in section 3. The fitness function and numerical results are detailed in sections 4 and 5, respectively. Finally, section 6 presents the conclusions of the paper.

2. THE NEW PROPOSED HYBRID ALGORITHM

In study [11], authors proposed a new hybrid algorithm based on two evolutionary algorithms; ALO algorithm [23] and GOA [24]. The main inspiration behind proposing such hybridization is combining the characteristics and overcoming the drawbacks of ALO and GOA. The main characteristic of ALO is the robustness in exploiting the global optima, which has been verified in many articles in the literature [2], [13], [25], [26]. On the other hand, the social forces in the grasshopper's swarm show a strong ability to effectively explore the whole search space in GOA [27]–[29]. Thus, these features give the idea to combine ALO and GOA in a new hybrid algorithm, which makes a big improvement in their performance.

Moreover, the benefits of hybridization can be shown in overcoming the drawbacks of ALO and GOA. The usage of the roulette wheel selection method is the main drawback in ALO, since it may cause: early convergence, loss of diversity, and not enough pressure to select the fittest search agents among the same fitness search agents. While the disadvantage of GOA exists in the c parameter equation, which weakens the exploitation process in the algorithm.

Our proposed hybrid algorithm has the ability to efficiently explore and exploit the search space to reach the global optimum, due to merging the characteristics of both ALO and GOA. The hybrid algorithm has some factors that enhance the capability of exploration and exploitation processes like the population nature that reduces local optima stagnation, the repulsion and attraction forces in GOA algorithm, the random walks and roulette wheel selection method in ALO algorithm, choosing diverse samples of average and less fitness search agents from next position's matrix, and the modifications of c parameter in GOA algorithm. These factors and modifications lead to better diversity of the search agents all over the search space and a high probability for local optima stagnation avoidance. Moreover, the intensity of search agents in the proposed algorithm has been decreased rapidly compared with ALO and GOA, due to the modification of the c parameter and its combination with other shrinking factors. Therefore, the hybrid algorithm guarantees fast and mature convergence compared with ALO and GOA.

The equation (1) has been used in our proposed algorithms:

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

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 d^{th} dimension, respectively, and $s(r) = fe^{-\frac{r}{l}} - e^{-r}$ where f represents the intensity of attraction force and l indicates the attractive length scale.

$$\text{if } l \leq (L)/2$$

$$c = cmax - l \frac{cmax - cmin}{\frac{l}{2}} \quad (2)$$

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

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

Where $cmax$ and $cmin$ are the maximum and minimum values, respectively, L indicates the maximum number of iterations, and l is the current iteration [24].

$$c^t = \frac{c^t}{l} \quad (4)$$

$$d^t = \frac{d^t}{l} \quad (5)$$

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 [23].

3. SUPERFORMULA AND ARRAY FACTOR EQUATIONS

The two-dimensional superformula representation in polar coordinates is given [19]:

$$\rho(\varphi) = \frac{1}{\left\{ \left[\left(\left| \frac{1}{a} \cos\left(\varphi \frac{m_1}{4}\right) \right| \right)^{n_2} + \left(\left| \frac{1}{b} \sin\left(\varphi \frac{m_2}{4}\right) \right| \right)^{n_3} \right]^{1/n_1} \right\}} \tag{6}$$

where n_1, n_2, n_3, m_1 and m_2 are real numbers. a and b are real numbers, excluding zero, that represent the major and minor axes, respectively. Variables m_1 and m_2 are responsible for increasing the rotational symmetry of the shape, while n_2 and n_3 determine whether the shape is inscribed or circumscribed within the unit circle [19].

The effect of adjusting superformula parameters is shown in Figure 1, which mentions 6 different shapes generated using the superformula equation with their specific parameters' values. Figure 1(a) represents generating an ellipse by tuning the values of $m_1, m_2, n_1, n_2, n_3, a$, and b into 4, 4, 2, 2, 2, 0.9, and 0.5, respectively, while the equality between a and b , with keeping all other parameters the same, would give a circle as shown in Figure 1(b). An equisetum stem and square shapes are shown in Figures 1(c) and 1(d) when the superformula parameters are changed into (7, 6, 6, 10, 0.9, 0.9), and (4, 100, 100, 100, 0.9, 0.9), respectively. Figure 1(e) represents a starfish with the following superformula parameters values (5, 1.7, 1.7, 0.1, 0.9, 0.9), and to achieve a rotational shape as Figure 1(f), the parameters must be tuned as (13/6, 0.3, 0.3, 0.3, 0.5, 0.5).

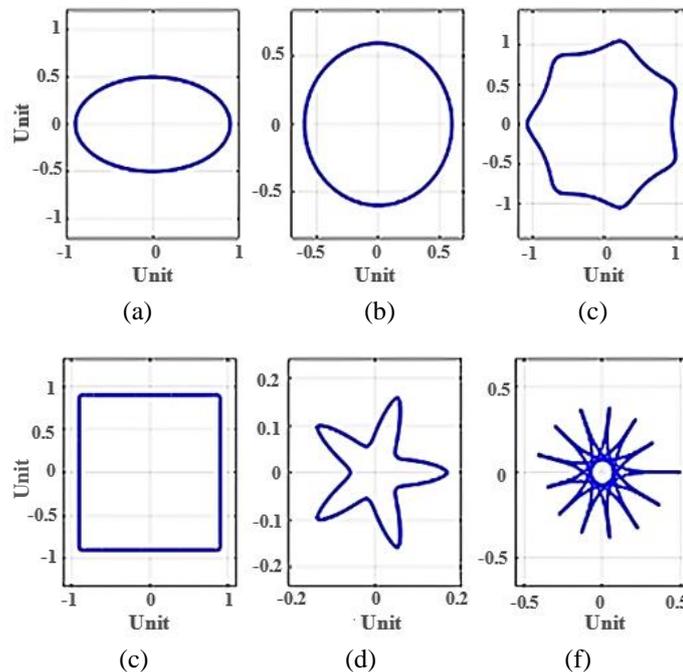


Figure 1. Shapes generated by superformula equation. The numbers inside the brackets refer to $(m (m_1=m_2), n_1, n_2, n_3, a, b)$. (a) ellipse (4, 2, 2, 2, 0.9, 0.5), (b) circle (4, 2, 2, 2, 0.6, 0.6), (c) equisetum stem (7, 6, 6, 10, 0.9, 0.9), (d) square (4, 100, 100, 100, 0.9, 0.9), (e) starfish (5, 1.7, 1.7, 0.1, 0.9, 0.9), and (f) rotational shape (13/6, 0.3, 0.3, 0.3, 0.5, 0.5)

Based on [30], the general array factor for any antenna array can be described as (7):

$$AF(\theta, \varphi) = \sum_{n=1}^N I_n e^{j(\alpha_n + K \bar{p}_n \cdot \hat{a}_r)} \tag{7}$$

where N represents the number of elements, which are assumed to lie on the XY-plane, I_n and α_n are the excitation current and phase for n^{th} element, respectively. The wavenumber $K = \frac{2\pi}{\lambda}$, where λ is the wavelength, $\bar{\rho}_n$ represents the position vector of the n^{th} element:

$$\bar{\rho}_n = x_n \hat{a}_x + y_n \hat{a}_y \quad (8)$$

and \hat{a}_r is the unit vector for the observation point, which can be written as (9).

$$\hat{a}_r = \sin \theta \cos \varphi \hat{a}_x + \sin \theta \sin \varphi \hat{a}_y + \cos \theta \hat{a}_z \quad (9)$$

The x and y coordinates of (6) are presented:

$$\begin{aligned} x_n &= \left\{ \left[\left(\left(\left| \frac{1}{a} \cos \left(\varphi_n \frac{m_1}{4} \right) \right| \right)^{n_2} + \left(\left| \frac{1}{b} \sin \left(\varphi_n \frac{m_2}{4} \right) \right| \right)^{n_3} \right]^{-1/n_1} \right\} \cos \varphi_n \\ y_n &= \left\{ \left[\left(\left(\left| \frac{1}{a} \cos \left(\varphi_n \frac{m_1}{4} \right) \right| \right)^{n_2} + \left(\left| \frac{1}{b} \sin \left(\varphi_n \frac{m_2}{4} \right) \right| \right)^{n_3} \right]^{-1/n_1} \right\} \sin \varphi_n \end{aligned} \quad (10)$$

where φ_n is the angular position of the antenna elements. For uniform array distribution, φ_n is given:

$$\varphi_n = 2\pi \frac{(n-1)}{N} \quad (11)$$

using (8)-(10), the array factor expression can be written:

$$\begin{aligned} AF(\theta, \varphi) &= \sum_{n=1}^N I_n \exp \left\{ j\alpha_n + jK \left(\left[\left(\left| \frac{1}{a} \cos \left(\varphi_n \frac{m_1}{4} \right) \right| \right)^{n_2} + \right. \right. \right. \\ &\left. \left. \left(\left| \frac{1}{b} \sin \left(\varphi_n \frac{m_2}{4} \right) \right| \right)^{n_3} \right]^{-1/n_1} \right\} \cos \varphi_n \sin \theta \cos \varphi + \left\{ \left[\left(\left| \frac{1}{a} \cos \left(\varphi_n \frac{m_1}{4} \right) \right| \right)^{n_2} + \right. \right. \\ &\left. \left. \left(\left| \frac{1}{b} \sin \left(\varphi_n \frac{m_2}{4} \right) \right| \right)^{n_3} \right]^{-1/n_1} \right\} \sin \varphi_n \sin \theta \sin \varphi \end{aligned} \quad (12)$$

where θ represents the elevation angle, which is measured from the positive z-axis. θ is assumed to equal 90° , since the array factor in the x-y plane will be of interest. It has been assumed, in this paper, that the main lobe is directed along the positive x-axis, such that; $\theta_o = 90^\circ$ and $\varphi_o = 0^\circ$. To achieve this, the excitation phase is assumed to be as (13).

$$\alpha_n = -K(x_n \sin \theta_o \cos \varphi_o + y_n \sin \theta_o \sin \varphi_o) \quad (13)$$

4. FITNESS FUNCTION

The main objective of this paper is to minimize the maximum sidelobe level in the array factor of the proposed antenna arrays. In order to accomplish this, the following fitness function is used [11]:

$$Fitness = (W_1 F_1 + W_2 F_2) / |AF_{max}|^2 \quad (14)$$

$$F_1 = |AF(\varphi_{nu1})|^2 + |AF(\varphi_{nu2})|^2 \quad (15)$$

$$F_2 = \max \{ |AF(\varphi_{ms1})|^2, |AF(\varphi_{ms2})|^2 \} \quad (16)$$

φ_{nu1} and φ_{nu2} represent the angles that define the first null beamwidth, $FNBW = \varphi_{nu2} - \varphi_{nu1} = 2\varphi_{nu2}$. Furthermore, φ_{ms1} and φ_{ms2} are the angles from -180° to φ_{nu1} , and from φ_{nu2} to 180° , respectively, in which the maximum side lobe level (SLL) is accomplished during the optimization process. The function F_1 minimizes the array factor at φ_{nu1} and φ_{nu2} to define the major lobe in the radiation pattern. F_2 minimizes the radiation pattern in the sidelobe region around the major lobe. AF_{max} is the maximum value of the array factor at (θ_o, φ_o) . W_1 and W_2 are weighting factors. The purpose of the optimization in this paper is to obtain new creative geometries for antenna arrays, toward achieving the lowest maximum SLL. Therefore, we are going to optimize the superformula parameters ($n_1, n_2, n_3, m_1, m_2, a, b$) to get the most suitable geometry for antenna elements distribution.

5. NUMERICAL RESULTS

In this section, three different subsections are discussed; 8-element, 12-element, and 20-element. Three different cases have been optimized using ALO, GOA, and the hybrid algorithm. The first case discusses creating new geometries by optimizing superformula parameters only ($m_1, m_2, n_1, n_2, n_3, a, b$), assuming that all elements have unity excitation currents and uniform angular position distribution depending on (11). So, all the obtained results, in this case, will be compared with uniform EAA results [13]. The second case discusses the optimization of array elements' excitation currents along with optimizing the superformula parameters. In this case, uniform distribution for the antenna elements' positions has been assumed depending on (11). The results for this case will be compared with the results of optimizing the excitation currents in EAA [13]. The third case presents the optimization of the elements' angular positions and superformula parameters, assuming unity amplitude currents for all elements. This case's results are compared with the corresponding angular positions optimization examples in EAA [13]. It is worth mentioning, that the EAA has been chosen for the comparison over the CAA due to the generality of the EAA.

All the results in this paper have been optimized through 20 independent runs using 1,000 iterations and 50 search agents. Three parameters, four parameters, five parameters, and seven parameters of the superformula equation are optimized for most of the examples. In three parameters optimization, the parameters: m, n_2 and n_3 are optimized, assuming that $m_1=m_2$ and $n_1=2$ (since the ellipse has these assumptions). While in four parameters optimization; the parameters: m_1, n_1, n_2 and n_3 are optimized, with $m_1=m_2$. In five parameters optimization, all superformula parameters are optimized except a and b . While in seven parameters optimization, all superformula parameters are optimized. Note that, the major and minor axes (a and b) have been assumed to equal 0.5 and 0.433 for 8-element antenna array examples, 1.15 and 0.9959 for 12-element examples, and 1.6 and 1.3856 for 20-element examples. Moreover, the range of optimized parameters is assumed as $[1, 50]$ for m_1, m_2 and n_1 , and $[-50, 50]$ for n_2 and n_3 . It is worth mentioning that all distances are in terms of λ .

5.1. Optimizing 8 elements

5.1.1. Optimizing superformula parameters

In this example, an 8-element antenna array with unity amplitudes and uniform angular positions is optimized to suppress the maximum SLL of the array factor. This can be achieved by optimizing different parameters in the superformula equation. So, the aim here is to optimize the geometry of the 8-element array, to get a better maximum SLL compared with standard geometries like EAA. Table 1 shows the optimum values of superformula parameters and their corresponding maximum SLL, compared with uniform EAA. According to the obtained results, optimizing 4-parameters, the algorithms ALO, GOA, and the hybrid outperform the uniform EAA shape by almost 11 dB. In other words, without any change in the excitation currents or the angular positions, the maximum SLL is improved significantly. Figure 2(a) shows the radiation patterns for optimizing three and four superformula (S.F.) parameters based on ALO, the hybrid and GOA algorithms compared with uniform EAA. Figure 2(b) presents the convergence curves for the proposed methods, which shows that they reach the global optima with a small number of iterations. Box-and-whisker plot is represented in Figure 2(c), which proves the stability of the hybrid method and ALO over 20 independent runs. Figure 3 represents elements distributions along three-parameter optimized superformula shape based on ALO, three-parameter optimized based on the hybrid method, four-parameter optimized based on ALO, four-parameter optimized based on GOA, and four-parameter optimized based on the hybrid method.

5.1.2. Optimizing elements amplitudes and superformula parameters

The optimization of excitation currents and superformula parameters is discussed in this example. The optimal values of 8 elements currents and three, four, and seven superformula parameters, based on the hybrid method, compared with 8-element EAA results are tabulated in Table 2. Figure 4(a) illustrates the array factors depending on the results in Table 2. It can be noticed that generating new creative shapes gives maximum SLL less than the best results of the optimized EAA by almost 6 dB, which confirms the significance of generating new geometries of antenna arrays. Figure 4(b) shows the distribution of the 8 elements along the optimized superformula shapes.

Table 1. Optimum values of superformula parameters for 8-element optimization

Method and optimized parameters $\varphi_{mz} = 51^\circ$	$[m_1, n_2, m_2, n_3, n_1, a, b]$	Max. SLL (dB)
Three-parameter (ALO)	[24.0052, 2.82534, 24.0052, 1.59748, 2, 0.5, 0.4330]	-15.25
Three-parameter (Hybrid)	[24.0099, 1.17679, 24.0099, 3.85461, 2, 0.5, 0.4330]	-16.66
Four-parameter (ALO)	[36, 44.071, 36, 41.702, 30.3222, 0.5, 0.4330]	-17.95
Four-parameter (Hybrid)	[12, 18.4426, 12, 17.555, 12.8075, 0.5, 0.4330]	-17.94
Four-parameter (GOA)	[44.0000, 39.1136, 44.0000, 36.4979, 26.7506, 2, 0.5, 0.4330]	-17.66
EAA (Uniform)	[4, 2, 4, 2, 2, 0.5, 0.4330]	-7.76

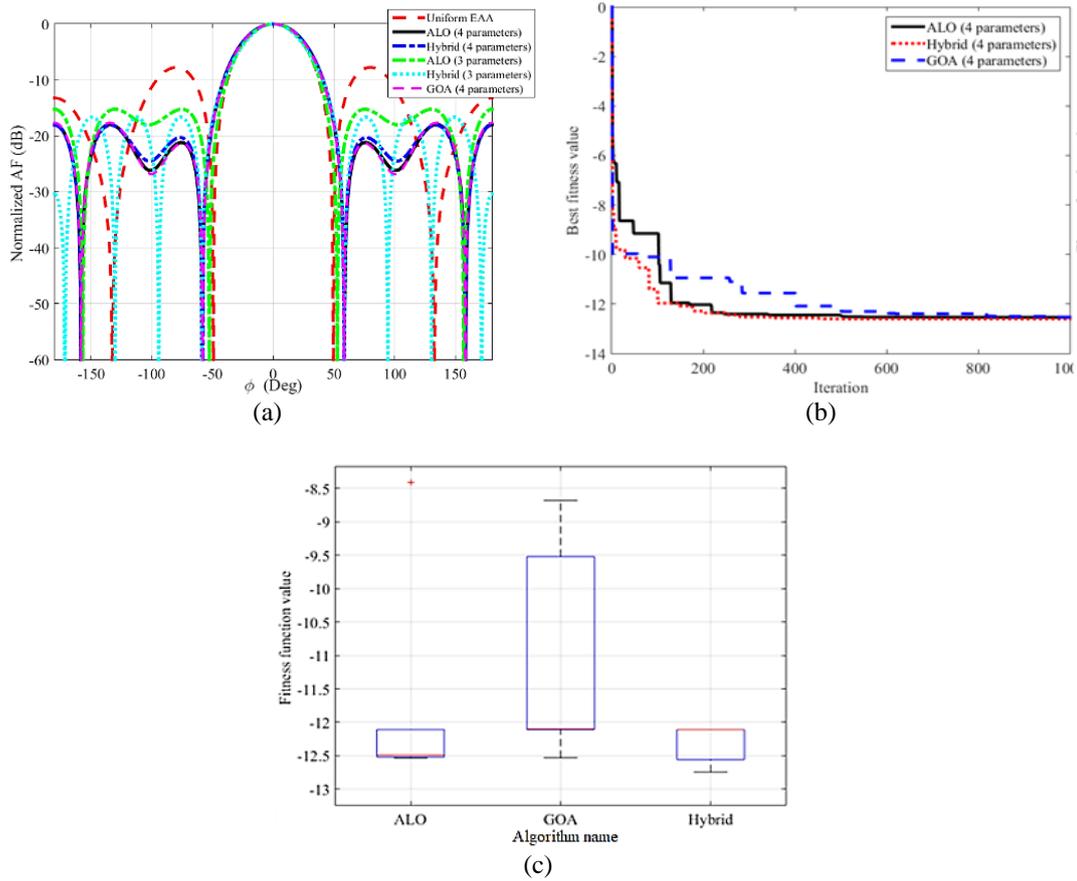


Figure 2. Results for optimizing superformula parameters for 8-element antenna array (a) radiation patterns for 8-element optimization, (b) convergence curves for 8-element optimization, and (c) box-and-whisker plots for 8-element optimization in 20 runs

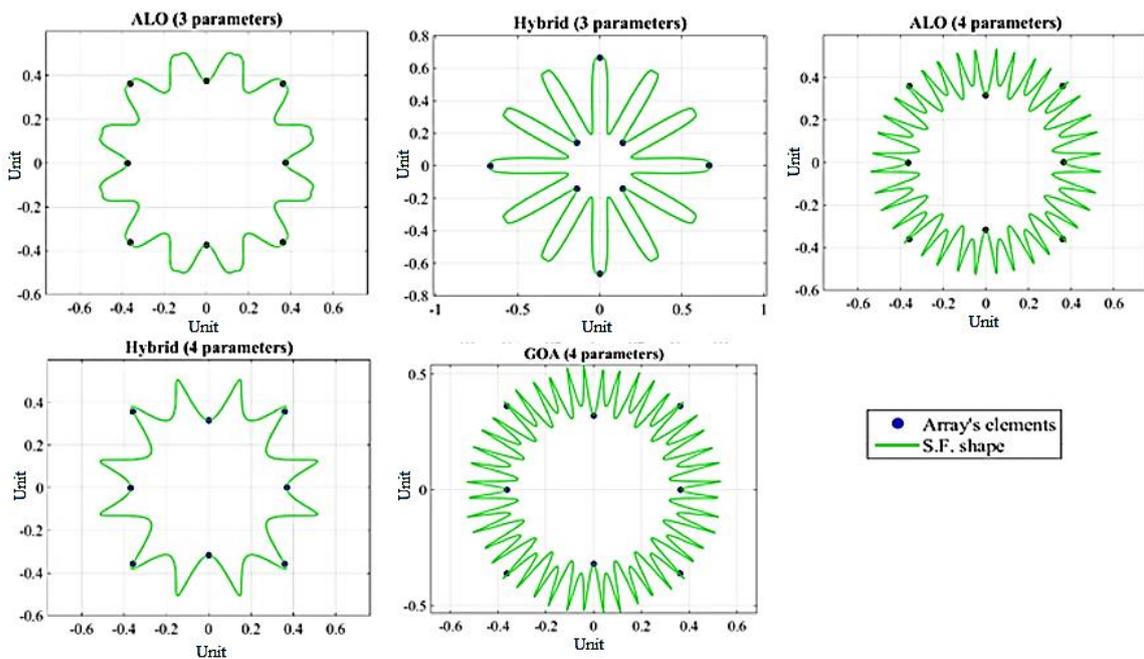


Figure 3. Distribution of 8-element array over optimized shapes based on ALO, GOA, and the hybrid method

Table 2. Optimum values of excitation currents and superformula parameters for 8-element optimization

$N=8$ $\varphi_{nu2} = 51^\circ$	$[m_1, n_2, m_2, n_3, n_1, a, b]$ $[I_1, I_2, I_3, \dots, I_8]$	Max. SLL (dB)
Three-parameter (Hybrid)	[7.8031, 2.6905, 7.8031, 1.558, 2, 0.5, 0.4330] [0.6223, 0.9365, 0.2873, 1.000, 0.6537, 0.9806, 0.2981, 0.9183]	-19.10
Four-parameter (Hybrid)	[15.9703, 24.8769, 15.9703, -1.98988, 21.2323, 0.5, 0.4330] [1.000, 0.7896, 0.7519, 0.8200, 0.0060, 0.8380, 0.7196, 0.8077]	-20.71
Seven-parameter (Hybrid)	[15.9746, 15.8241, 20.0043, -5.17621, 20.5931, 0.35375, 0.564119] [1.000, 0.7004, 0.6741, 0.8938, 0.0903, 0.8358, 0.7965, 0.6413]	-20.93
EAA (ALO)	[4, 2, 4, 2, 2, 0.5, 0.4330] [0.5379, 0.9011, 0.0667, 0.9246, 0.5856, 1.0000, 0.0249, 0.9764]	-14.64
EAA (Hybrid)	[4, 2, 4, 2, 2, 0.5, 0.4330] [0.5666, 1.0000, 0.0516, 0.9700, 0.5609, 0.9586, 0.0690, 0.9887]	-14.60

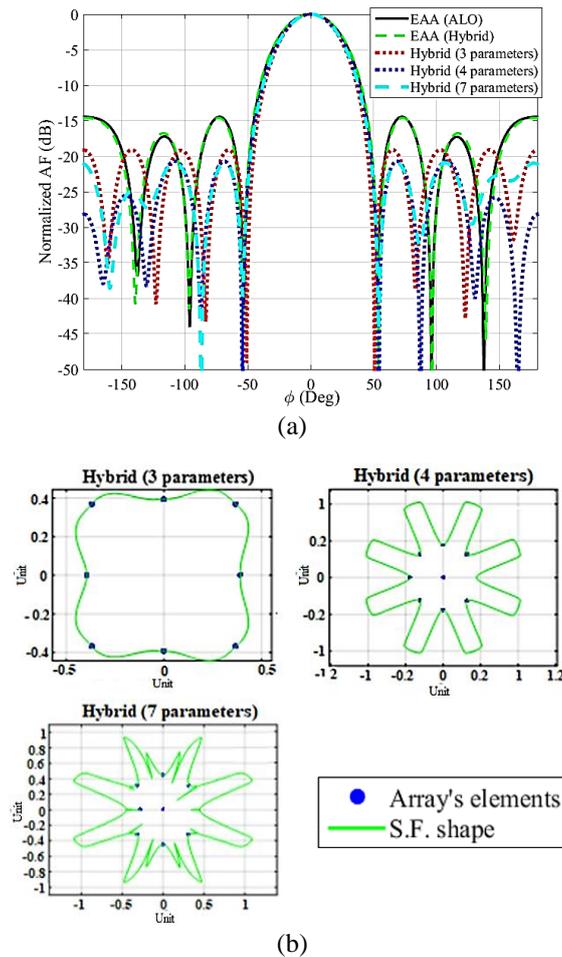


Figure 4. Results for optimizing excitation amplitudes and superformula parameters for 8-element antenna array (a) radiation patterns for 8-element array and (b) distribution of 8-element array over S.F. optimized shapes based on the hybrid method

5.2. Optimizing 12 elements

5.2.1. Optimizing angular positions and superformula parameters

S.F. parameters and the angular positions for 12-element antenna array are going to be optimized in this example. Five and seven parameters of the SF equation are optimized with 12 elements angular positions based on the hybrid algorithm as mentioned in Table 3. The maximum SLL value obtained by optimizing the seven-parameter is -16.12 dB, and -15.44 dB for optimizing the five-parameter. It is obvious that using the SF enhances the maximum SLL by almost 6 dB compared with EAA results. Figure 5(a) shows the radiation patterns for optimizing five-parameter, seven-parameter, and EAAs based on ALO, GOA, and the hybrid method. Figure 5(b) represents 12 elements distributions for optimizing five-parameter and seven-parameter SF.

Table 3. Optimum values of angular positions and S.F. parameters for 12-element optimization

$N=12$ $\varphi_{nu} = 22^\circ$	$[m_1, n_2, m_2, n_3, n_1, a, b]$ $[\theta_1, \theta_2, \theta_3, \dots, \theta_{12}]$ in degrees	Max. SLL (dB)
Five-parameter (Hybrid)	[4.11638, 23.5199, 4.63125, 24.5776, 24.7026, 1.15, 0.9959] [1.8360, 29.2719, 73.0149, 132.5429, 152.8216, 175.9628, 195.9229, 254.4374, 281.2805, 316.2005, 325.4463, 345.7353]	-15.44
Seven-parameter (Hybrid)	[9.25799, -4.91652, 10.0473, -9.52872, 12.3331, 0.356268, 0.66011] [7.0744, 86.9813, 100.8709, 115.5467, 136.2431, 169.4018, 202.4140, 209.2568, 227.7020, 234.5620, 248.9834, 254.8533]	-16.12
EAA (ALO)	[4, 2, 4, 2, 2, 1.15, 0.9959] [13.5053, 39.4896, 85.4927, 95.4538, 141.8509, 167.4591, 188.0407, 210.0000, 240.0111, 299.8681, 330.0000, 351.8085]	-9.52
EAA (GOA)	[4, 2, 4, 2, 2, 1.15, 0.9959] [9.2464, 43.3007, 60.0002, 93.9722, 139.9140, 164.3480, 189.0621, 210.0000, 269.7800, 299.1580, 330.0000, 356.2058]	-9.27
EAA (Hybrid)	[4, 2, 4, 2, 2, 1.15, 0.9959] [7.2016, 42.3489, 60.1202, 92.8993, 140.9393, 166.8977, 191.8173, 210.0000, 268.6000, 300.0000, 330.0000, 355.1231]	-9.42

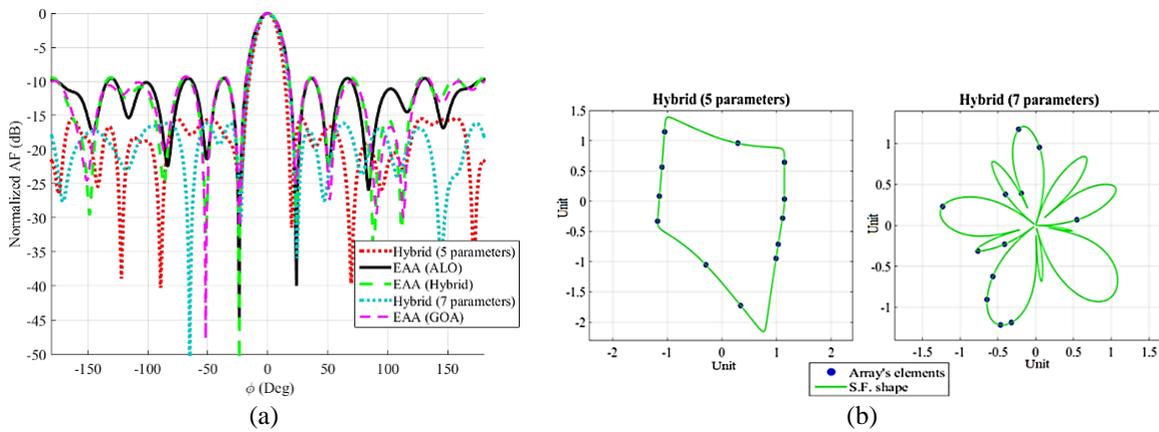


Figure 5. Results of optimizing angular positions and S.F. parameters for 12-element antenna array (a) radiation patterns for 12-element arrays and (b) distribution of 12-element array over S.F. optimized shapes

5.3. Optimizing 20 elements

5.3.1. Optimizing superformula parameters

In this example, the number of array elements is increased to 20. So, the SF parameters are optimized to generate the optimal geometry of a 20-element array that has minimum suppression for SLL. Table 4 shows the optimum values for four and seven parameters using our proposed hybrid method, ALO, and GOA. The best maximum SLL is obtained by optimizing the seven-parameter using the hybrid method, with max SLL=-16.01 dB, which is 10 dB less than the results of uniform EAA.

Figure 6(a) shows the radiation patterns of the 20-element array for different SF parameters optimization. Figures 6(b) and 6(c) show convergence curves and box and whisker plots for ALO, GOA, and the hybrid method, respectively. The uniform distribution of the obtained shapes for optimizing: four-parameter based on ALO, four-parameter based on the hybrid method, seven-parameter based on ALO, seven-parameter based on GOA, and seven-parameter based on the hybrid algorithm, are illustrated in Figure 7. These results, again, prove that optimizing array shapes will significantly improve the max SLL without changing the excitation currents or angular positions.

Table 4. Optimum values of S.F. parameters for 20-element optimization

$\varphi_{nu2} = 16^\circ$	$[m_1, n_2, m_2, n_3, n_1, a, b]$	Max. SLL (dB)
Four-parameter (ALO)	[44, 5.63766, 44, 46.3647, 14.9658, 1.6, 1.3856]	-14.49
Four-parameter (Hybrid)	[36, 5.8958, 36, 49.1193, 15.6256, 1.6, 1.3856]	-14.58
Seven-parameter (ALO)	[24.0644, 13.1663, 18.3572, 21.9164, 21.0494, 0.931817, 1.76903]	-15.78
Seven-parameter (GOA)	[21.3997, 8.5576, 2.6021, 11.1608, 24.2988, 1.5287, 1.2400]	-12.78
Seven-parameter (Hybrid)	[20.0259, 10.76, 1.99925, -8.7371, 14.3647, 1.29043, 0.233034]	-16.01
EAA (Uniform)	[4, 2, 4, 2, 2, 1.6, 1.3856]	-6.88

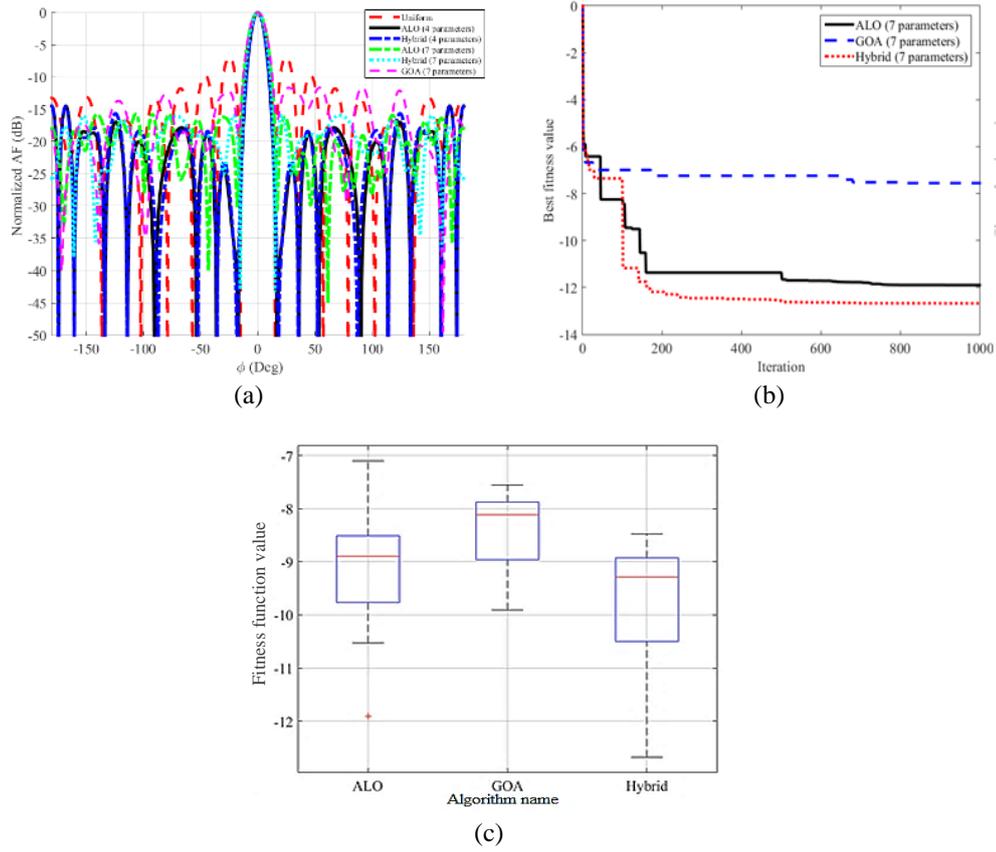


Figure 6. Results of optimizing S.F. parameters for 20-element antenna array (a) radiation patterns of optimizing 20-element array, (b) convergence curves for 20-element optimization, and (c) box and whisker plot for 20-element optimization

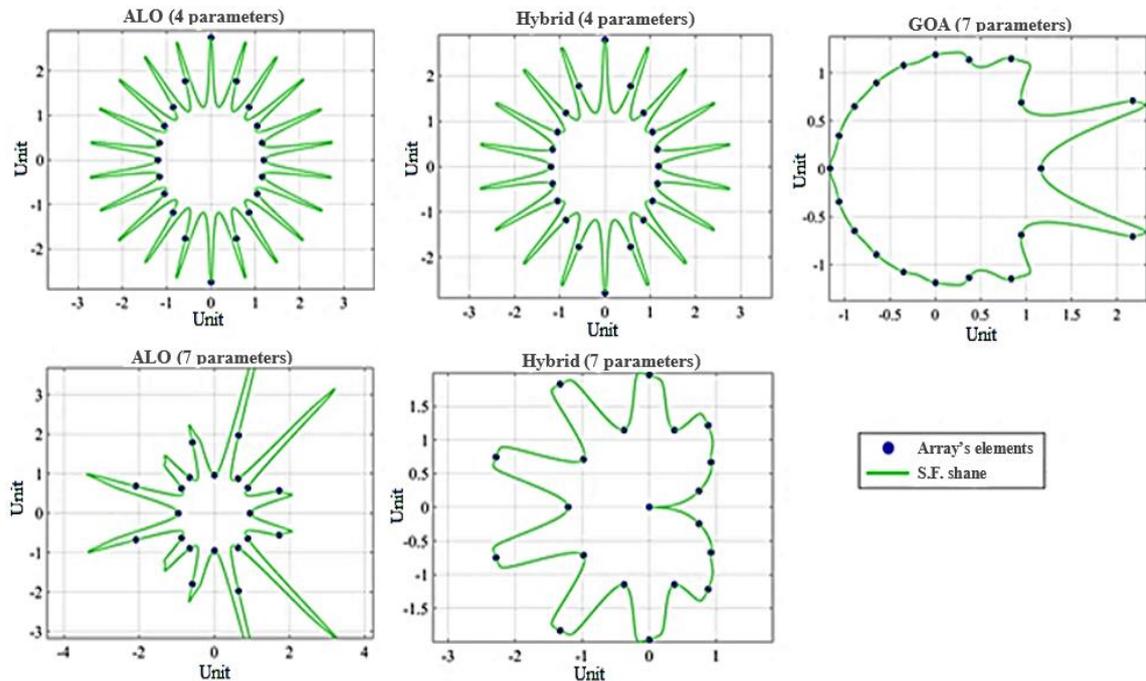


Figure 7. Distribution of 20-element array over S.F. optimized shapes based on ALO, GOA, and the hybrid method

6. CONCLUSION

In this paper, new arbitrary geometries for antenna arrays were proposed. Three evolutionary algorithms, ALO, GOA, and the hybrid algorithm based on ALO and GOA, were used in the synthesis of the arbitrary antenna arrays. The objective function was to reduce the maximum sidelobe level with the constraint of a fixed major lobe beamwidth. Three cases were investigated in this paper; 8-element, 12-element, and 20-element antenna array geometries. Additionally, three different examples were illustrated; optimizing only the superformula parameters, optimizing superformula parameters and excitation currents of the antenna array, and optimizing superformula parameters with the angular position of the antenna array. The results of all cases and examples prove the capability of our geometries to outperform the standard geometries with a huge difference.

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