Optimal Sidelobes Reduction and Synthesis of Circular Array Antennas Using Hybrid Adaptive Genetic Algorithms

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Abstract

In this article, a hybrid optimization method has been proposed consisting of Adaptive Genetic Algorithms (AGAs) and Constrained Nonlinear Programming (NLP) to solve the problems of performance optimization of circular array antenna consisting parallel center feeding short dipoles elements with two complex nonlinear optimization problems. In the first problem, the hybrid optimization algorithm is used to reduce the value of sidelobe level in the circular array radiation pattern by finding the optimal values of the excitation coefficients of each element in the circular array. In the second problem, a synthesis of circular array with different forms of the desired radiation pattern is considered. Several examples are considered here to verify the validity of this method. Comparisons were made between the results of this method and the results obtained by (SGA) Standard Genetic Algorithm, and it is clearly shown that this method is more efficient and flexible in solving the problems of performance optimization of circular array antenna.

أمثلية تقليل الفصوص الجانبية وتشكيل الأشعاع للهوائيات المصفوفية الدائرية بأستخدام طريقة الخوارزميات الجينية الهجينة

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الخلاصة:في هذا البحث، تم أقتراح طريقة أمثلة هجينة تتألف من كل من الخوارزمياتِ الجينية المُتكيفة [Adaptive Genetic Algorithms] (AGAs) وطريقة البرمجة غير الخطية المُقيدة (Constrained Nonlinear Programming)لغرض حل مسائل أمثلة الأداء الخاصة بالهوائيات المصفوفيه الدائرية المتألفة من مجموعة من هوائيات ثنائية القطب القصيرة مركزية التغذية. ولقد أُستُخدمت هذة الطريقة لحل مسألتين مُعقدتين في أداء الهوائيات المصفوفيه الدائرية. المسألة الأولى هي تصغير قيمة الفصوص الجانبية التي تظهر في نموذج الأشعاع عن طريق إيجاد القيم المُثلى لأثاراتِ كل عنصر من عناصر الهوائي المصفوفي الدائري. تمت مقارنة نتائج الطريقة المستخدمة في هذا البحث مع النتائج المستحصلة بأستخدام طريقة الخوارزميات الجينية القياسية [Standard Genetic Algorithm] SGAحيث أظهرت طريقة البحث تفوقاً ومرونةً في حل المشاكل المعقدة المتعلقة بأداء الهوائيات المصفوفية الدائرية وخصوصاً تقليل فصوص الأشعاع الجانبية، والحصول على التشكيل المرغوب من نموذج أشعاع الهوائي.

1. Introduction

The circular array antenna, in which elements are placed in a circular ring, as shown in Figure (1), is an array configuration of very practical interest. Its geometry facilitates *360* degree scanning. Its obvious applications are; direction finding in the HF-VHF-UHF bands, navigation systems, communications, and military electronic support systems [1]. With the development of radar and mobile communication systems, special shapes of antenna beams are needed [2], which demand more variables such as the general array layout, the excitation coefficients to control and form the array pattern. One of these applications is the smart antenna. A smart antenna array containing *M* identical elements that can steer a directional beam to maximize the signal from desired users, while nullifying the signals from other directions [3]. The array geometries that have been studied to increase the system capacity by reducing the co-channel interference, and increase the quality by reducing the fading effects include mainly uniform linear arrays, uniform rectangular, and circular arrays. A linear array has excellent directivity and it can form the narrowest main-lobe in a given direction, but it does not work equally well in all azimuthal directions. A major disadvantage of the uniform rectangular array is that an additional major lobe of the same intensity appears on the opposite side. Since a circular array does not have edge elements, directional patterns synthesized with a circular array can be electronically rotated in the plane of the array without a significant change of the beam shape [3].

The problems of the sidelobe level reduction and the synthesis of circular array antenna with a specific radiation pattern, are limited by several constraints, and considered as a nonlinear optimization problems. They can be solved by many known analytical optimization methods, but each of these methods has developed in response to a given class of problems, and treats the task subject to only one restriction. In more complex problem such as synthesis cases in which it desire to have a radiation pattern with various main beams and one or more nulls in (a) given direction(s)- the classical methods become inefficient, because they are vulnerable to local-minima-related difficulties. In these situations, there are too many possibilities to find the most fit solution. Exhaustive checking of all possible amplitude-phase excitations is very difficult, because these methods use deterministic rules, and they search from a single point. Such methods have many limitations such as the starting point in the optimization process should be chosen carefully, and there are restrictive requirements of the continuity and the existence of derivatives. Hence, such calculus-based methods must be rejected, because they are not robust. The other heuristic algorithms, such as genetic algorithms will be necessary. Genetic algorithms are robust and capable of solving complicated and nonlinear search problems. They are not limited by restrictive assumptions about the search space.

Genetic algorithms have many applications in general electromagnetic problems [4-7]. The methods of beam pattern synthesis generally based on controlling the complex weights (the amplitude and phase). Only the excitation amplitude, the phase, and the element position have been extensively considered in the literature [8-16]. The most important method is based on controlling the complex weights. This technique fully exploits the degrees of freedom for the solution space. Furthermore, the sidelobe level (*SLL*) and the main beam characteristics can be controlled. Recently, various versions of the GAs algorithm have been successfully used in linear and circular antenna array synthesis problems [17, 18]. Many of the attempts on antenna array synthesis assumed the elements of the array are represented by isotropic point sensors.

However, in practice, the elements of antenna arrays have finite physical dimensions and specific radiation characteristics. Therefore, to evaluate accurately the resulting system performance of practical antenna arrays, the electromagnetic radiation characteristics of the elements must be carefully considered.

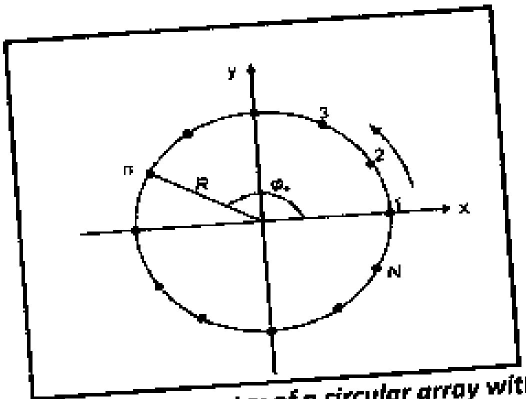


Figure (1): Geometry of a circular array with radius R and N elements

In this paper, a hybrid optimization method consists of the Adaptive Genetic Algorithms (*AGAs*) and the constrained nonlinear programming (*NLP*) is developed to solve the performance optimization problems of circular array antenna consisting of center-fed parallel short dipoles. The dipole is a practical radiator and used in many applications. The dipole elements are identical and oriented perpendicular to the plane of the array. The hybrid adaptive genetic algorithm (*HAGA*) is used to change the excitation coefficients of the dipole elements to reach the minimum sidelobe level, null placement control and also to obtain the desired radiation pattern.

A special type of genetic algorithms is used in this work which is called Adaptive Genetic Algorithm (*AGA*). *AGAs* are *GAs* whose parameters, such as the crossing over probability, or the mutation probability are varied while the genetic algorithm is running [19]. A simple variant could be the following: The mutation rate can be changed according to changes in the population; the longer the population does not improve, the higher the mutation rate is chosen. Vice versa, it is decreased again as soon as an improvement of the population occurs. The size of the population is chosen to be 100 individuals. For the selection operator, rank selection is used here and by which the population is ranked and every chromosome receives fitness from the ranking. Crossover consists of interchanging the genetic information between two individuals selected at random. Two types of crossover are used here: scattered and heuristic crossover [20]. Mutation, on the other hand, produces changes in the individuals. It permits the incorporation of new individuals, and avoids the possibility that all individuals might become equal. A uniform mutation is used here. Finally, Elitism was added to improve convergence quality since as the algorithm is very randomly, sometimes the next generation is not so good as the actual. So elitism compares parents and sons to choose the best ones. In this work, the two best individual are kept to the next generation.

The rest of the Paper is organized as follows. In the next section, an overview of the relationship between the GA and the circular array is introduced. The combination method between GA and NLP is provided in Section 3. The problem formulation and the design examples are demonstrated in sections 4 and 5, respectively. Finally the conclusion is given in section 6.

2. Genetic Algorithm and Circular Array Representation

A relationship between the *GA* and the circular array must be found firstly. A real adaptive genetic algorithm is used here where the parameters are represented by themselves in the chromosome structure without any coding and decoding processes and this will, of course, save the time and the memory required to solve the problem at hand.

Since each element of the circular array is characterized by its corresponding complex excitation; hence, each element is represented by its amplitude and phase as shown in Table (1). By using this representation, each element has two genes: one for the amplitude, and the other for the phase. Table (2) explains a genetic model for a population of M circular arrays each having N elements, where A_{CD} refers to the amplitude of the element (D) that belongs to array (C) and the symbol P_{CD} refers to the phase of the (D) element of array (C) .

3. Combination of GAs And Nonlinear Programming

Combining a *GA* with a local optimization algorithm is often referred to as hybrid *GA* and has a broad use [21]. The local optimizer attempts to improve a solution by moving to a neighboring solution of smaller residual. Whenever the neighboring solution is better than the current solution, it replaces the current solution. Genetic algorithms and local optimizer have complementary strengths and weakness. *GAs* are good at finding promising areas of the search space, but not so good at fine-tuning within those areas. Nonlinear programming, on the other hand, is good at fine-tuning but lacks a global perspective. Practice has shown that a hybrid algorithm, which combines *GAs* with the local optimizer often results in an algorithm that can outperform either one individually[19]. A Nonlinear Programming (*NLP*) is a problem that can be put into the form [22]:

$$\min_{x \in X} f(x)$$

subject to

$$ci(x) = 0 \;,\; i \in E,$$

$$ci(x) \leq 0 \;,\; i \in I, \qquad (1)$$

where

$$f : R^n \rightarrow R$$
$$X \subseteq R^n$$

here, $f(X)$ is objective function, X is a vector of x variables, where E and I are, respectively, the index set of equality constraints and inequality constraints, $c_i(x)$, ($i = 1,\ldots, m \in E \cup I$) are constraint functions. Nonlinear programming method attempts to find a constrained minimum of $f(X)$ of several variables starting at an initial estimate subject (perhaps) to one or more other such functions that serve to limit or define the values of these variables. This is generally referred to as constrained nonlinear optimization or nonlinear programming (*NLP*).

To create the hybrid algorithm, the genetic algorithm is run until it terminates where no improvement of the convergence value can be achieved or when the algorithm is executed to the maximal number of generations. The best solution found in the last population is then taken as the approximate global optimal solution. Then, nonlinear programming is applied to the final (the best) individual. In this case, the nonlinear programming algorithm starts with "good" solution found by the GA. Figure (2) shows the flowchart of the hybrid adaptive genetic algorithm.

4. Problem Formulation

The radiation pattern $AF(a,\theta,\phi)$ of a uniform circular array of radius (a) located at the xy plane is given by [23]:

$$AF(a,\theta,\phi)=\sum_{n=1}^{N} I_n \exp\left\{j\frac{2\pi a}{\lambda}\sin\theta\cos(\Phi_n-\phi)\right\}F(\theta,\phi) \tag{2}$$

where

N = number of array elements

a = circle radius

λ = wavelength

I_n = excitation coefficients of nth element

Φ_n = $(2\pi/N)\ n$ = angular position of nth element on x-y plane

$F(\theta,\phi)$ = the element pattern.

When the array main beam is directed in the $(\theta o, \phi o)$, Eq. (2) can be rewritten as:

$$AF(a,\theta,\phi)=\sum_{n=1}^{N} I_n \exp\left\{j\frac{2\pi a}{\lambda}\left[\sin\theta\cos(\Phi_n-\phi)-\sin\theta_o\cos(\Phi_n-\phi_o)\right]\right\}F(\theta,\phi) \tag{3}$$

For the short dipole antenna, the element radiation pattern can be expressed as [24]:

$$F(\theta,\phi)=\sin\theta \tag{4}$$

To obtain the desired radiation pattern which has a maximum power located in the main beam direction, while power is minimized in other directions, the fitness function is taken to be the maximum SLL in numerous θ-cut plane $(\theta\in[0,\pi])$. The general form of the fitness function is then given by:

$$fitness=\max\left(\frac{|AF(\theta_c,\phi)|}{\max|(AF(\theta_c,\phi)|}\right) \tag{5}$$

where

θ_c is the elevation cut angle plane

$\max|(AF(\theta_c,\phi)| = |AF(\theta_c,\phi_o)|$

$\theta_c \in [0,\ \pi]$, $\quad 0<\phi<2\pi$,

On other hand, and in order to obtain a radiation pattern that it is similar to the desired one, the fitness can be written in the following form:

$$fitness=\max\left|\frac{AF_d(\theta_c,\phi)-AF_c(\theta_c,\phi)}{AF_d(\theta_c,\phi)}\right| \tag{6}$$

where

AF_d: the desired form of the radiation pattern

AF_c: the calculated radiation pattern

For generating a far-field pattern with a desired beam shape and has the ability to restrain the interference coming from the special directions, the fitness function is defined as follow:

$$fitness = A1\underbrace{\left[\max\left|\frac{AF_d(\theta_c,\phi)-AF_c(\theta_c,\phi)}{AF_d(\theta_c,\phi)}\right|\right]}_{\phi\in\phi_{mainbeam}} + A2\underbrace{\left[\sum_{n=1}^{N}\max\left|AF_c(\theta_c,\phi)-Null\right|\right]}_{\phi\in\phi_{Null}} \quad (7)$$

where

A_1, A_2: the weighting coefficients in the fitness function.

N: the desired number of nulls.

Null: the desired nulls depth.

The choices of the weighting coefficients values typically influence the rate of convergence, and they can be determined empirically by running several trial cases.

For the design process adopted in this work, only one dimension scan in azimuth direction is considered, and the objective functions are optimized in numerous θ-cut equal to 45^o.

5. Design Examples

The Hybrid *AGA* (*HAGA*) presented in the previous sections is applied to the *SLL* reduction and synthesis of equally spaced short dipoles placed on a circular ring of radius equal to one wavelength.

During the simulations, the following parameters are suggested:

- Population size of *AGA* =*100*;
- Initial crossover probability: $pc = 0.8$;
- Initial mutation probability: $pm = 0.09$;
- Maximum number of *AGA* generations= *500*.
- Maximum number of *SQP* iterations = *500*.

A) Sidelobes Reduction of circular array Radiation pattern:

An array of *25* equally spaced short dipoles placed on a circular ring of radius equal to one wavelength. The desired *SLL* suppression in the regions $[0^o, 40^o]$ and $[135^o, 360^o]$ is considered here. Figure (4) depicts the normalized optimal radiation pattern obtained by using *HAGA*. It is clear that the output power is maximized in the desired direction and minimized in the other directions. *SLL* of *-40dB* is achieved here. It can also be observed that all the sidelobes levels obtained by *HAGA* are *18 dB* lower than that obtained by *SGA*.

B) Synthesis Optimization of circular Array Antenna:

Five examples are considered here as follows:

i) An array with a wide flat- top beam, which is prefer in the radar applications, with radiation pattern extending from $\phi=150^o$ to $\phi=210^o$ with no sidelobes in the other scanning angles is synthesized. Figure (5) shows the normalized optimized pattern obtained by using *HAGA*. This Figure reflects the ability of *HAGA* as compared with *SGA* in forming the main beam region and also in controlling the sidelobes levels.

ii): The objective of the second design example is to have an array radiation pattern with two flat- top beams one extending from $\phi=100^o$ to $\phi=130^o$ and the other from $\phi=180^o$ to $\phi=210^o$. The sidelobes should be suppressed in the other scanning angles. The optimized pattern is shown in Figure (6) along with the elements excitation coefficients.

iii): The ability of circular array to avoid the interference signals by placing nulls in the direction of interference signals is adopted in this design example. Four signals S_1, S_2, S_3, and S_4 are assumed to arrive the antenna in the same plane in the direction of 90^o, 30^o, 180^o, 270^o, respectively. In this assumption S1 is the desired signal while S_2, S_3, S_4 are the interference signals. A1, A2 in Equation (7) are given values of *0.45, 0.55* in the optimization process, respectively. Figure (7) shows the optimized pattern with triple imposed nulls at 30^o, 180^o, and 270^o. The levels of the first two nulls are as deep as *-90 dB*, and about *-77 dB* for the third null. The deeper null level that can be obtained by using *SGA* is only *-35 dB*.

iv): It is well known that the broad nulls are needed when the direction of arrival of the unwanted interference may vary slightly with time or may not be known exactly, and where a comparatively sharp null would require continuous steering for obtaining a reasonable value for the signal-to-noise ratio. To illustrate the broad-band interference suppression capability of the *HAGA*, a pattern with a main beam directed in 90^o and having a broad null located at 195^o with $\Delta\phi i = 30^o$ is formed using a circular array of *25* short dipole elements. Figure (8) shows that a null with *30* degree width at depth level of *-70dB* is obtained by *HAGA* compared with *16* degree width null at depth level of *-40dB* obtained by using *SGA* method.

v): In this design example, two broad nulls around the main beam located at 35^o and 145^o can be obtained by *HAGA* as shown in Figure (9). The width of each null is equal to 10^o with low level of *-50 dB*. Five degree wide at *-40 dB* level for the first null can be achieved by using *SGA*.

6. Conclusion

This paper illustrated the use of the hybrid adaptive genetic algorithm optimization method in the SLL reduction and pattern synthesis of circular conformal array antenna for the purpose of suppressed sidelobe in certain regions and null placement in prescribed directions and shaping the main beam region. The hybrid genetic algorithm was successfully used to optimize the excitation coefficients of short dipoles center fed antennas to realize the array pattern with desired sidelobe level down to *-40 dB*. A wide null of *30* degree was successively imposed in the desired direction of the radiation pattern. A radiation pattern with wide flat main with width of *60* degree beam is achieved also in this work. The obtained results explain the ability of the hybrid algorithm by hybridizing the *AGA* with *NLP* compared with *SGA*.

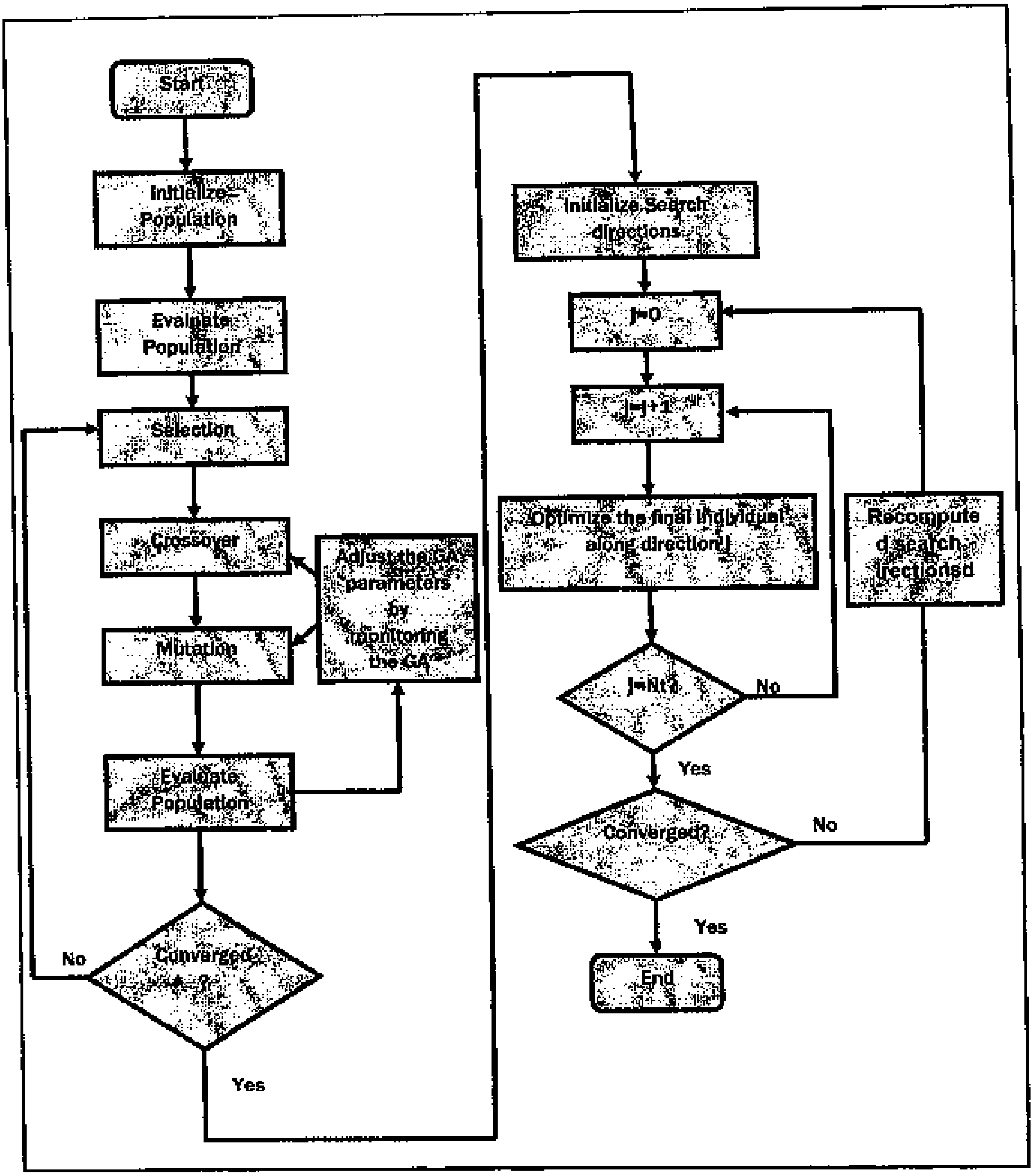


Figure (2): Flowchart of the hybrid adaptive genetic algorithm.

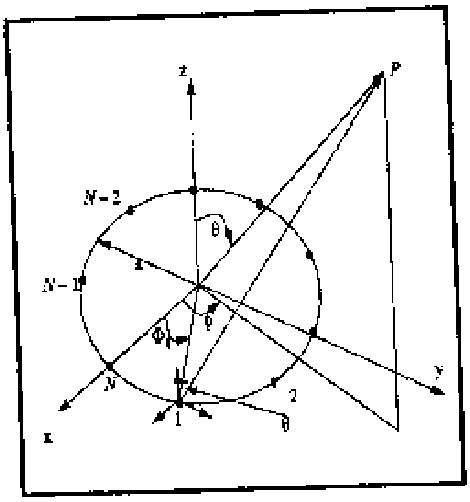


Figure (3): Geometry for a circular array antenna

Table 1: The relationship between elements of GAs and circular arrays

Genetic Parameter	Circular Array Antenna
Gene	Amplitude, Phase
Chromosome	One element of array
Individual	One array
Population	Several arrays

Table 2: A genetic model for a population of M circular array with N elements each.

	Element $_1$		Element $_2$		.....	Element $_N$		Fitness
	Gene$_1$	Gene$_2$	Gene$_3$	Gene$_4$	.....	Gene$_{(2N-1)}$	Gene$_{(2N)}$	
Array$_1$	A_{11}	P_{11}	A_{12}	P_{12}	.....	A_{1N}	P_{1N}	0.834
Array$_2$	A_{21}	P_{21}	A_{22}	P_{22}	.....	A_{2N}	P_{2N}	0.521
:	:	:	:	:	:	:	:	:
Array$_M$	A_{M1}	P_{M1}	A_{M2}	P_{M2}	.....	A_{MN}	P_{MN}	0.002

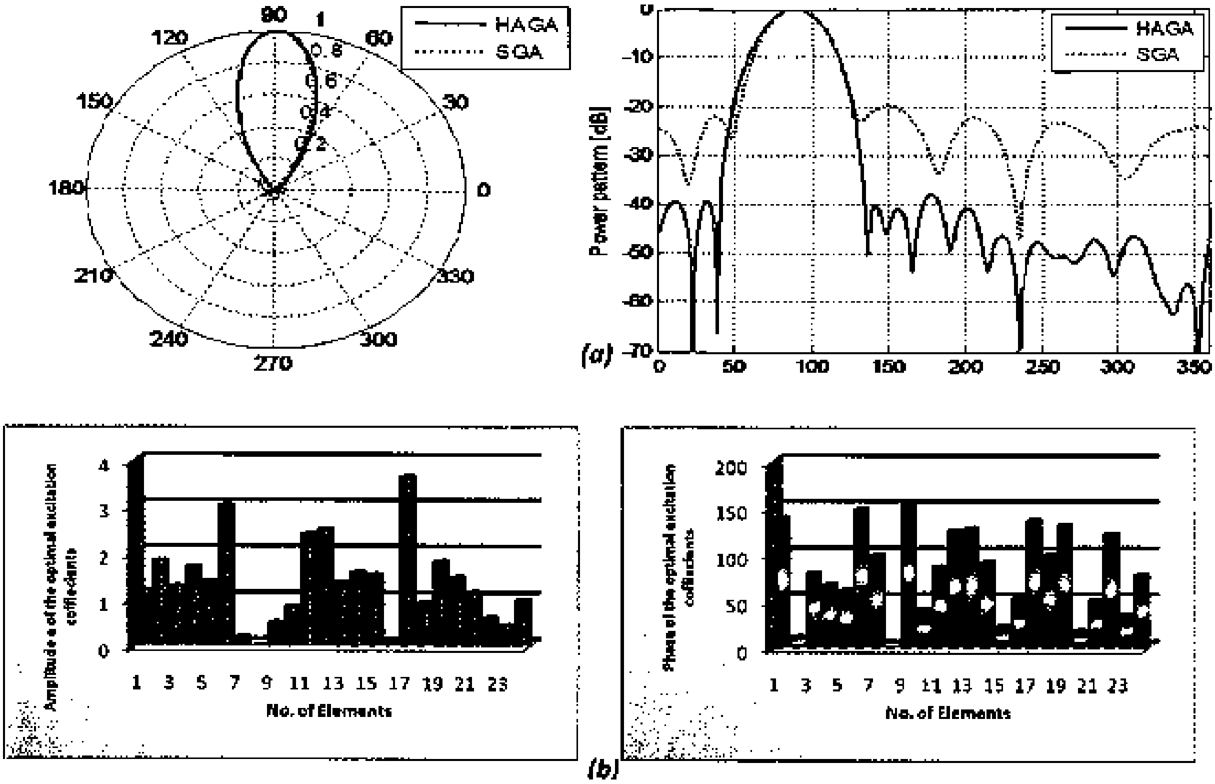


Figure 4: (a) plots of the optimized radiation patterns; (b) plots of elements' excitation coefficients of the optimized circular array antenna with 25 elements

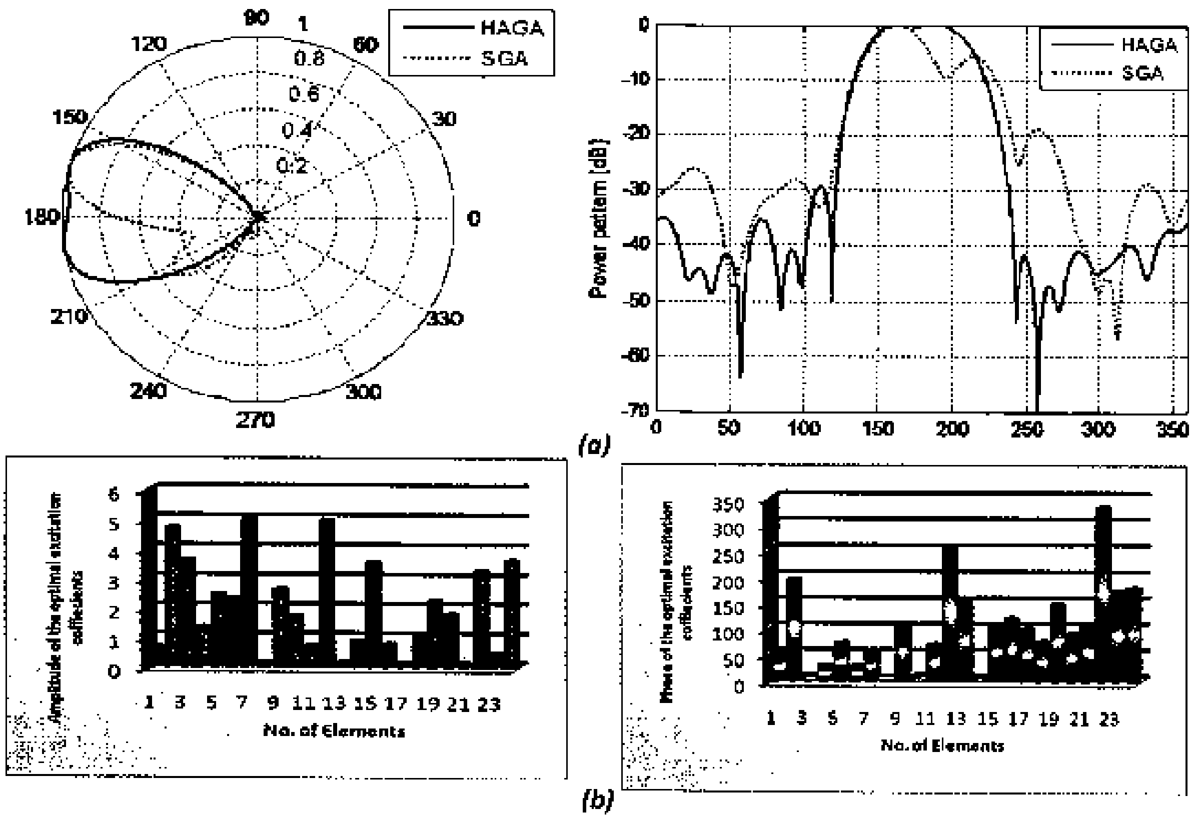
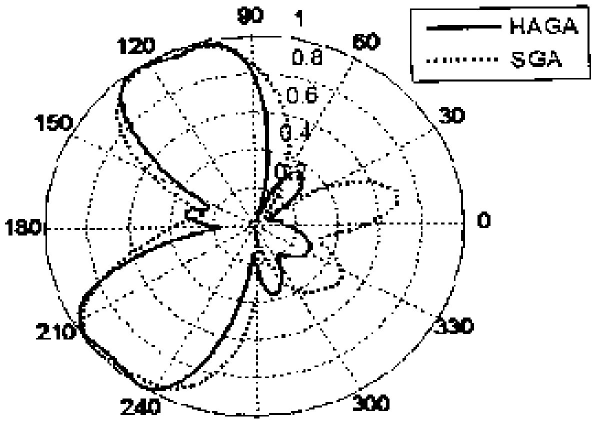
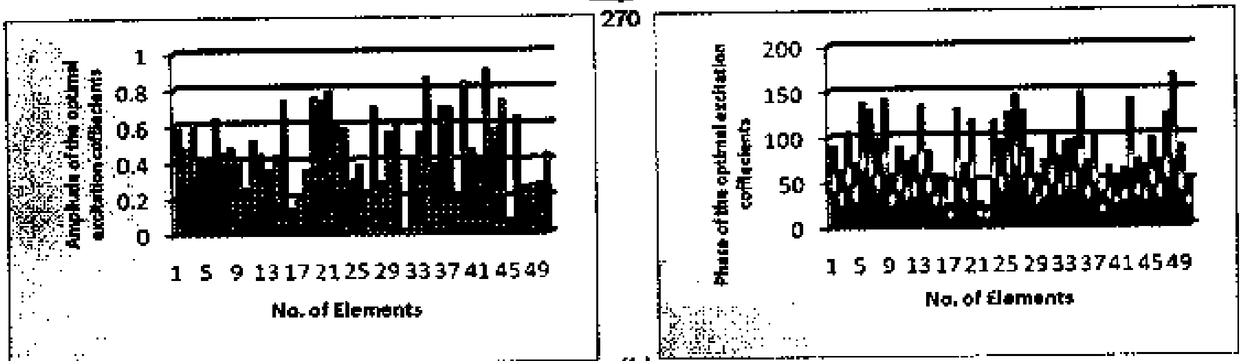


Figure 5: (a) plot of the optimized radiation pattern with wide flat main beam extends from $\phi=150^0$ to $\phi=210^0$; (b) the plots of elements' excitation coefficients of the optimized circular

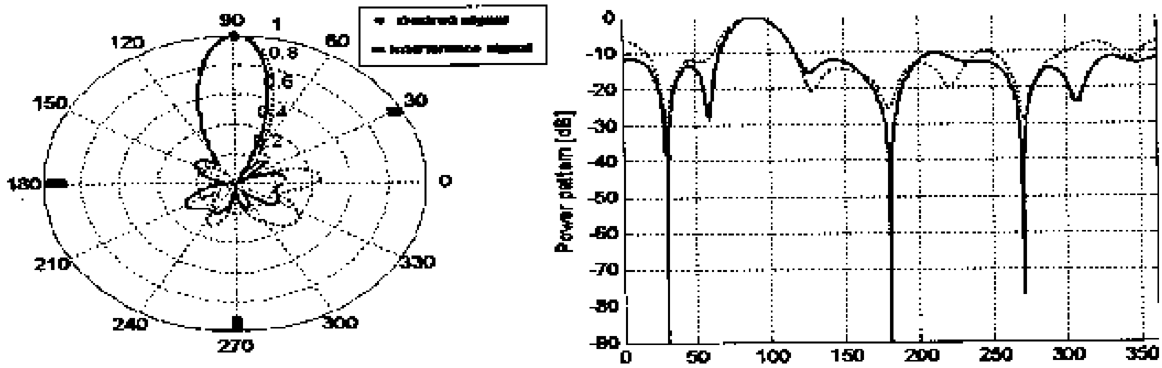
(a)



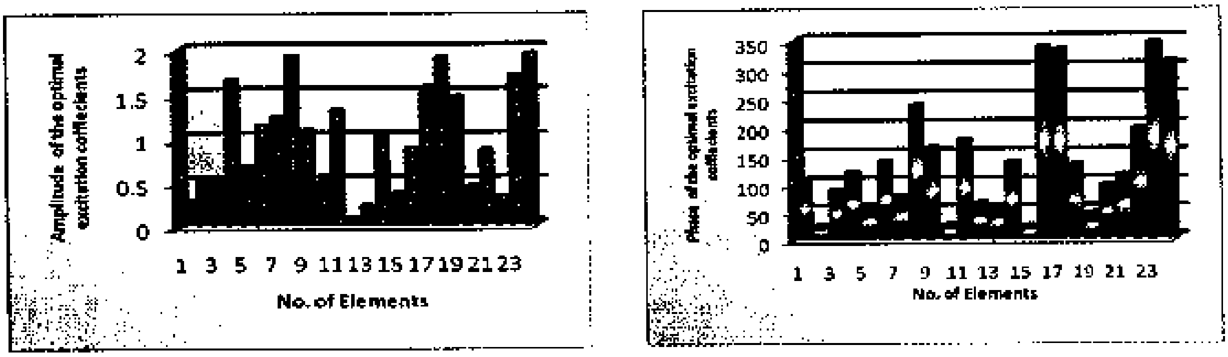


(b)

Figure 6: (a) Plot of the optimized radiation pattern with two flat beams ;(b) plots of elements' excitation coefficients of the optimized circular array antenna with 50 elements



(a)



(b)

Figure 7: (a) Plots of the optimized pattern with triple imposed nulls at 30°, 180°, and 270°; (b) the plots of elements' excitation coefficients of the optimized circular array antenna with 25 elements

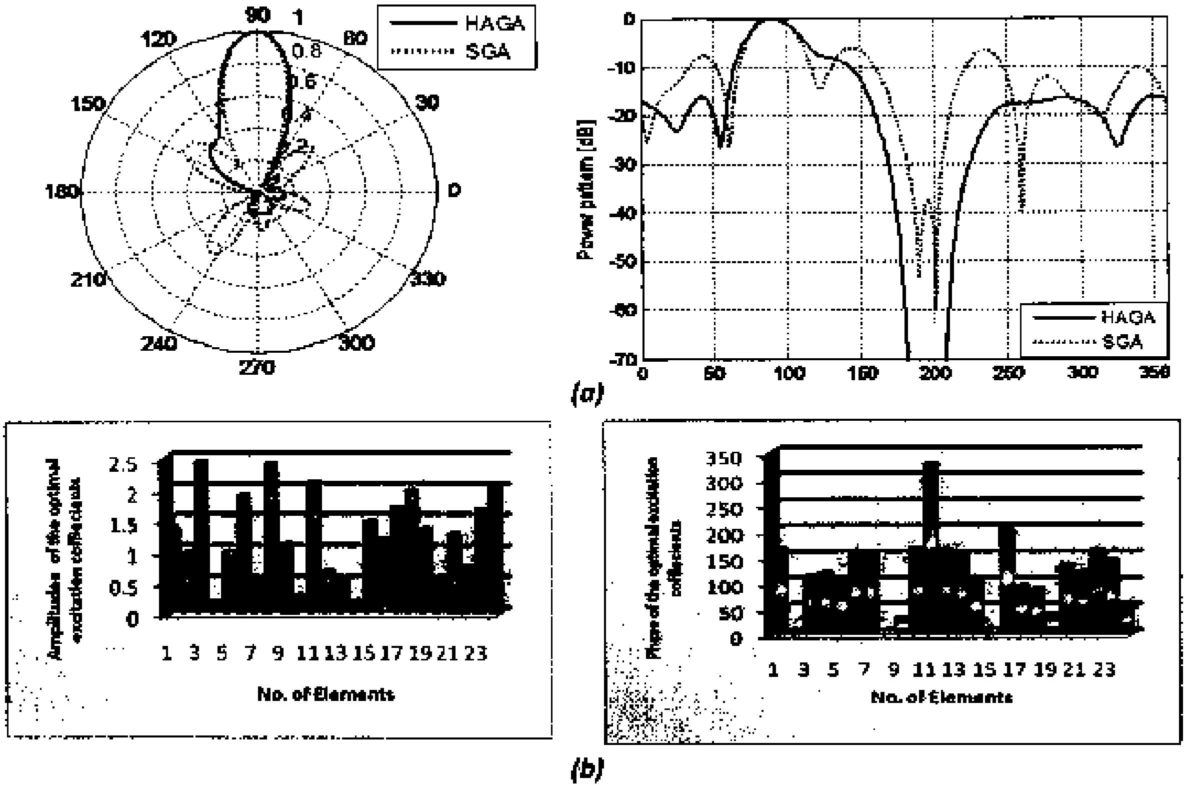


Figure 8:(a) Plots of the optimized radiation patterns with imposed broad null centered at 185°, with $\Delta\phi i = 30°$ (b) plots of elements' excitation coefficients of the optimized circular

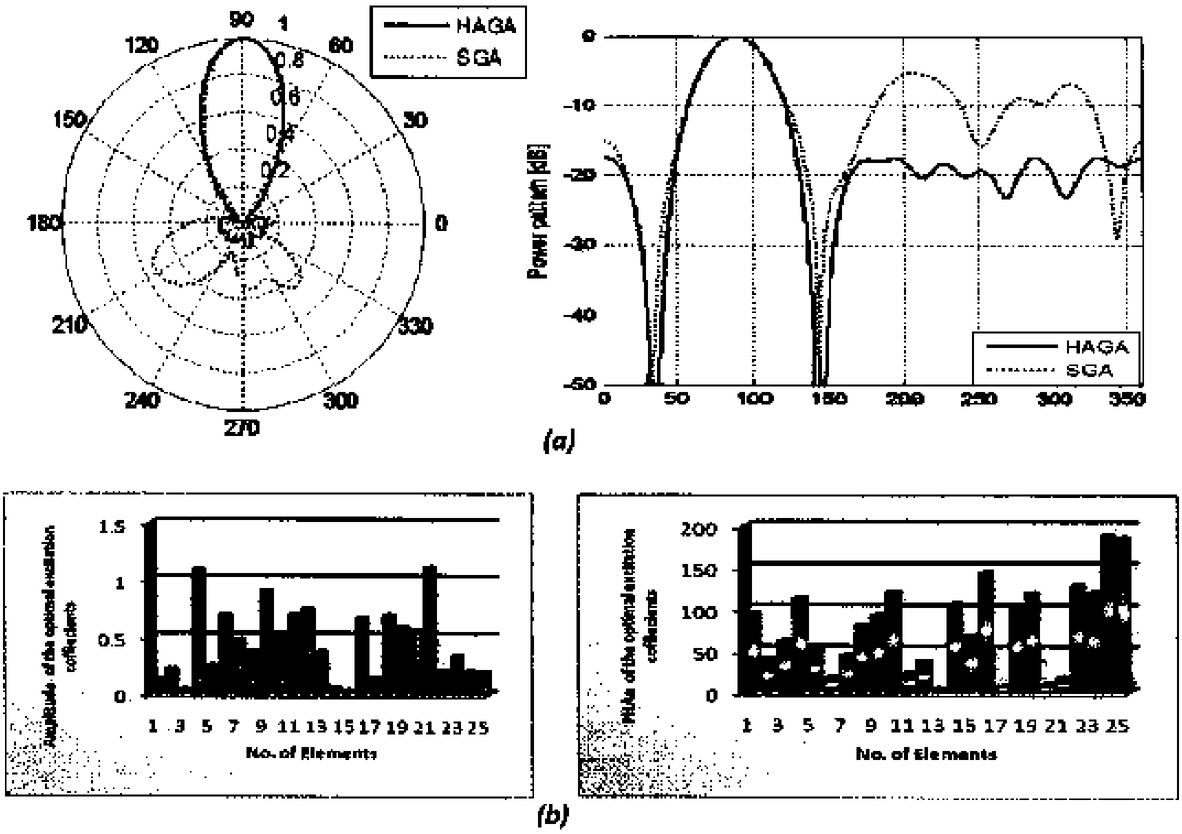


Figure 9: (a) Plots of the optimized Radiation patterns with two imposed broad nulls centered at 35°, 145° with $\Delta\phi i = 10°$;(b) plots of elements' excitation coefficients

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