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# Design of Phased Antenna Arrays using Evolutionary Optimization Techniques

Marco A. Panduro[1], David H. Covarrubias[2] and Aldo L. Mendez[1]
[1]*Reynosa-Rodhe Multidisciplinary Academic Center, Universidad Autónoma de Tamaulipas*
[2]*CICESE Research Center, Tijuana*
*México*

## 1. Introduction

Mobile and wireless communication systems have now arrived at the point where substancial advances in antenna technology have become a critical issue. The majority of these systems consist of an antenna array combined with an appropriate signal processing (Soni et al., 2002; Godara, 2002), i.e., the antenna elements are allowed to work in concert by means of array element phasing, which is accomplished with hardware or is performed digitally.

In these systems, the antenna array performance over a certain steering range is of primary concern. In this case, the antenna array design problem consists of finding weights that make the radiation pattern satisfy the desired characteristics (a maximum directivity, a minimum side lobe level, etc), so the direction of the main beam can be steered at will.

Generally, the design problem is formulated as an optimization problem. The design of antenna arrays has a nonlinear and non-convex dependence of elements parameters [Kurup et al. 2003], because of that, the interest has been focused on stochastic search techniques, such as simulated annealing (Murino et al., 1996), and mainly, genetic algorithms (GA's) (Ares-Pena et al., 1999; Haupt, 1994; Haupt, 1995; Panduro et al., 2005; Rahmat-Samii et al, 1999; Weile et al., 1997; Yan et al., 1997), widely used in electromagnetic problems, including the synthesis of phased antenna arrays (Mailloux, 2005; Hansen, 1998).

The antenna arrays optimization for improving performance represents an open line of research in the antenna design field. In the application of evolutionary optimization techniques for designing antenna arrays, it has been considered the design of different phased array structures, such as the linear arrays (Bray et al., 2002; Panduro, 2006) and the circular arrays (Panduro et al., 2006), among others. The design of planar arrays is dealt with in (Bae et al., 2005). In many design cases, it has been considered the optimization in the design of scannable arrays with non-uniform separation (Bray et al., 2002; Bae et al., 2004; Junker et al., 1998; Tian et al., 2005; Lommi et al., 2002).

In this chapter it is considered the case of designing scannable arrays with the optimization of the amplitude and phase excitations for maximum side lobe level reduction in a wide scanning range.

The purpose of this chapter is to investigate the behavior of the radiation pattern for the design of different phased array structures (linear and circular arrays) considering the



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optimization of the amplitude and phase excitation across the antenna elements, by using the well-known method of Genetic Algorithms. Due to the great variety of parameters involved, optimization techniques such as Genetic Algorithms are very appropriate tools to search for the best antenna array models.

The primary focus of this chapter is to present a study of the application of GA techniques to the design of scannable linear and circular arrays in a uniform geometry considering the optimization of the amplitude and phase excitation across the antenna elements. This study considers the design of scannable linear and circular arrays to be a problem optimizing a simple objective function. This objective function considers the synthesis of the radiation diagram with desired characteristics of the side lobe level and the directivity in a wide steering range. The contribution of this work is to present a model for the design of scannable linear and circular arrays that includes the synthesis of the radiation diagram using the method of genetic algorithms.

The remainder of this chapter is organized as follows. Section 2 states the design of phased linear arrays. A description of the objective function used by the genetic algorithm and the obtained results for this design problem are presented in this section. Following the same design philosophy, the design of phased circular arrays is presented in the section 3. Discussions and open problems are presented in the section 4. Finally, the summary and conclusions of this work are presented in the section 5.

## 2. Design of phased linear arrays

The design of scannable linear arrays has been dealt with in many papers. In these documents, the study has been focused mainly to design scannable linear arrays with non-uniform separation (Bray et al., 2002; Bae et al., 2004; Junker et al., 1998; Tian et al., 2005; Lommi et al., 2002; Panduro et al., 2005)., i.e, the performance of the array is improved, in the sense of the side lobe level, optimizing the spacing between antenna elements. In this case, it is presented the design of scannable linear arrays optimizing the amplitude and phase excitations across the antenna elements. It is believed by the authors that the performance of the array could be improved substantially, with respect to the linear array with the conventional progressive phase excitation, if the amplitude and phase excitations are set or optimized in an adequate way. Next, it is presented the theoretical model for the design of scannable linear arrays.

### 2.1 Theoretical model

Consider a scannable linear array with $N$ antenna elements uniformly spaced, as shown in figure 1. If the elements in the linear array are taken to be isotropic sources, the radiation pattern of this array can be described by its array factor (Stutzman, 1998). The array factor for a conventional linear array in the $x$-$y$ plane is given by (Balanis, 2005)

$$AF(\theta,\mathbf{I})=\sum_{n=1}^{N} I_n \exp\left\{j\left[kd_n\left(\cos\theta-\cos\theta_0\right)\right]\right\} \tag{1}$$

In this case, the array factor for a linear array with phase excitation is created by adding in the appropriate element phase perturbations, $\mathbf{P} = [\delta\beta_1, \delta\beta_2, ..., \delta\beta_N]$, $\delta\beta_i$ represents the phase perturbation of the $i$th element of the array, such that

$$AF(\theta, \mathbf{I}, \mathbf{P}) = \sum_{n=1}^{N} I_n \exp\left\{j\left[\psi_n + \delta\beta_n\right]\right\}. \quad (2)$$

In these equations, $\mathbf{I} = [I_1, I_2, ..., I_N]$, $I_i$ represents the amplitude excitation of the $i$th element of the array, $\psi_n = kd_n\cos\theta_0$, $\theta_0$ is the direction of maximum radiation, $k = 2\pi/\lambda$ is the phase constant and $\theta$ is the angle of incidence of a plane wave, $\lambda$ is the signal wavelength.

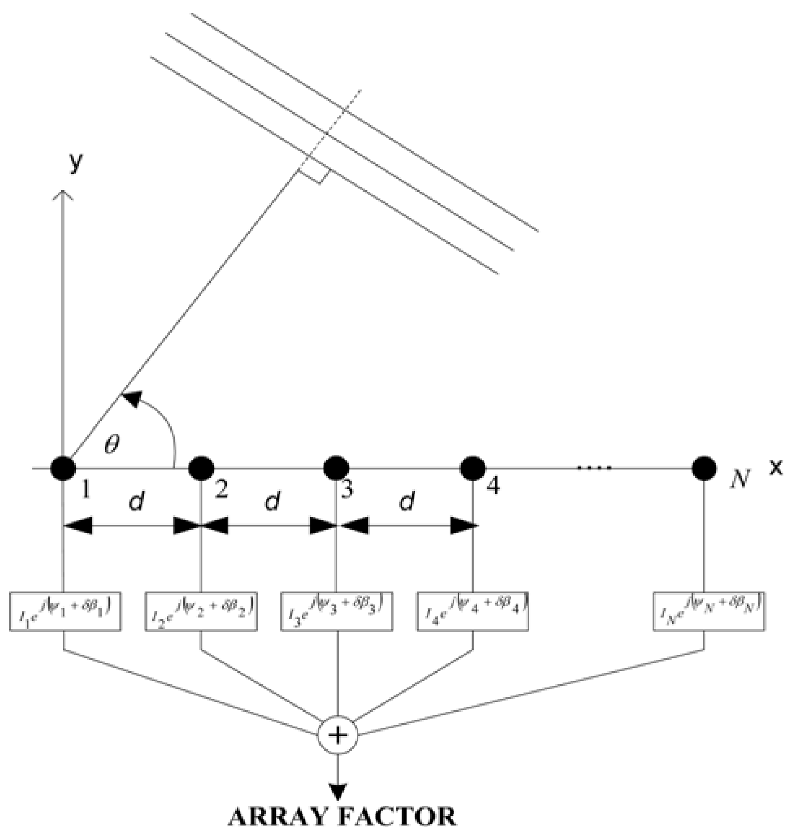



Figure 1. Steerable linear array with antenna elements uniformly spaced.

The idea of adding perturbations in the conventional array factor is that the optimization algorithm searches possible optimal phase excitations in angles near the direction of desired maximum gain. The optimization process developed in this paper for generating arrays that have radiation patterns with low side lobe level will be based on (2).
We now need to formulate the objective function we want to optimize.

### 2.2 Objective function used to optimize the design of linear arrays.

The objective function is the driving force behind the GA (Goldberg, 1989). It is called from the GA to determine the fitness of each solution string generated during the search. In this case, each solution string represents possible amplitude excitations and phase perturbations of antenna elements. As already being pointed out, the objective of the present study is to evaluate the radiation pattern of scannable linear arrays in a uniform geometry considering the optimization of the amplitude and phase excitation across the antenna elements. In this case, it is studied the behavior of the array factor for the scanning range of 50°≤$\theta_0$≤130° with an angular step of 10°. In order to calculate the objective function of an individual, the procedure described below is followed.

1. A set of 1000 points is used to specify a desired radiation pattern with direction of maximum gain in each angle of the scanning range. Each point represents the *i*th desired normalized radiation pattern value.
2. An individual is generated by the GA (amplitude excitations and phase perturbations of antenna elements). Each individual is in general represented by a vector of real numbers, i.e., $\mathbf{I} = [I_1, I_2, ..., I_N]$, and a vector of real numbers restrained on the range (0, 2$\pi$), i.e., $\mathbf{P} = [\delta\beta_1, \delta\beta_2, ..., \delta\beta_N]$.
3. The value of the objective function is calculated as

$$of = (|\mathrm{AF}(\theta_{MSL}, \mathbf{I}, \mathbf{P})| \ / \ max|\mathrm{AF}(\theta, \mathbf{I}, \mathbf{P})|) + (1/DIR(\theta, \mathbf{I}, \mathbf{P})) \tag{3}$$

where $\theta_{MSL}$ is the angle where the maximum side lobe is attained, and *DIR* the directivity for the radiation pattern. In this case, the design problem is formulated as minimize the objective function *of*.
4. A random population of individuals is generated and the genetic mechanisms of crossover, survival and mutation are used to obtain better and better individuals, until the GA converges to the best solution or the desired goals are achieved.

The results of using a GA for the design of scannable linear arrays are described in the next section.

### 2.3 Results obtained for the design of phased linear arrays

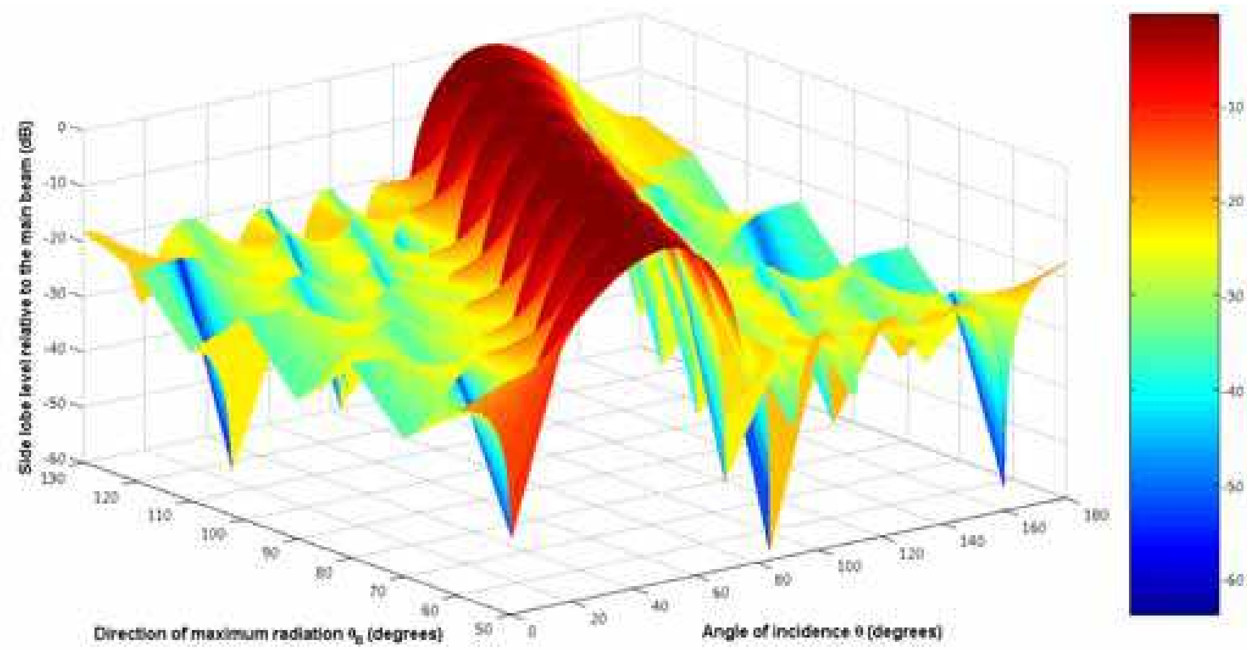
The method of Genetic Algorithms was implemented to study the behavior of the radiation pattern for scannable linear arrays. In this case, it is studied the behavior of the array factor for the scanning range of $50° \leq \theta_0 \leq 130°$. Several experiments were carried out with different number of antenna elements. In the experiments the algorithm parameters, after a trial and error procedure, were set as follows: maximum number of generations $rmax$ = 500, population size $gsize$ = 200, crossover probability $pc$ = 1.0 and mutation probability $pm$ = 0.1. A selection scheme combining Fitness Ranking and Elitist Selection (Goldberg, 1989) was implemented instead of a common weighted roulette wheel selection. The used genetic operators are standard: the well known two point crossover (Goldberg, 1989) along with a single mutation where a locus is randomly selected and the allele is replaced by a random number uniformly distributed in the feasible region. The obtained results are explained below.

Figure 2 shows the behavior of the radiation pattern for a scannable linear array with the amplitude and phase excitation optimized by the GA. The separation between antenna elements is set as $d$=0.5$\lambda$. In this case, we illustrate the examples for a) $N$=6, b) $N$=8, c) $N$=12.

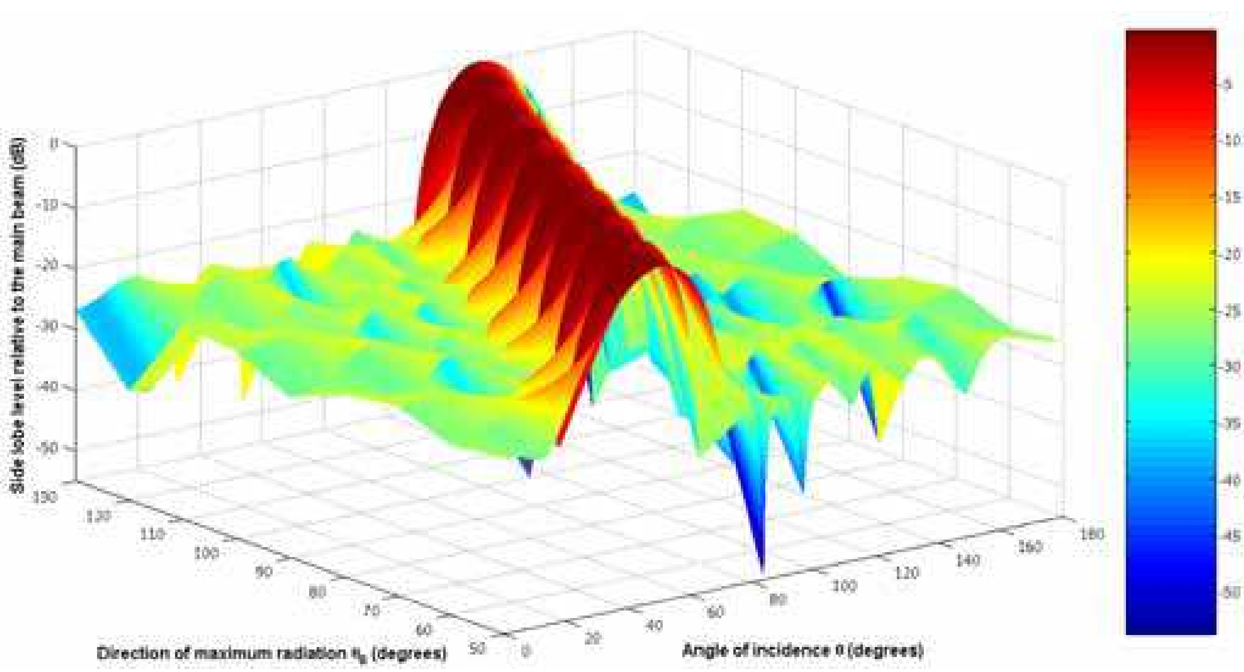
As shown in the examples of the Figure 2, the Genetic Algorithm generates a set of amplitude and phase excitations in each angle of the scanning range to provide a normalized array factor with a side lobe level < -20 dB in the steering range. The optimization of the array can maintain a low side lobe level without pattern distortion during beam steering.

Numerical values of the side lobe level, directivity, amplitude and phase perturbation distributions for the array factor illustrated in Figure 2 are presented in the Table 1.

Table 1 illustrates that the design case with the amplitude and phase optimized by the GA could provide a better performance in the side lobe level with respect to the conventional case. These low values of the side lobe level for the optimized design case could be achieved with very similar values of directivity and the same aperture in both design cases.

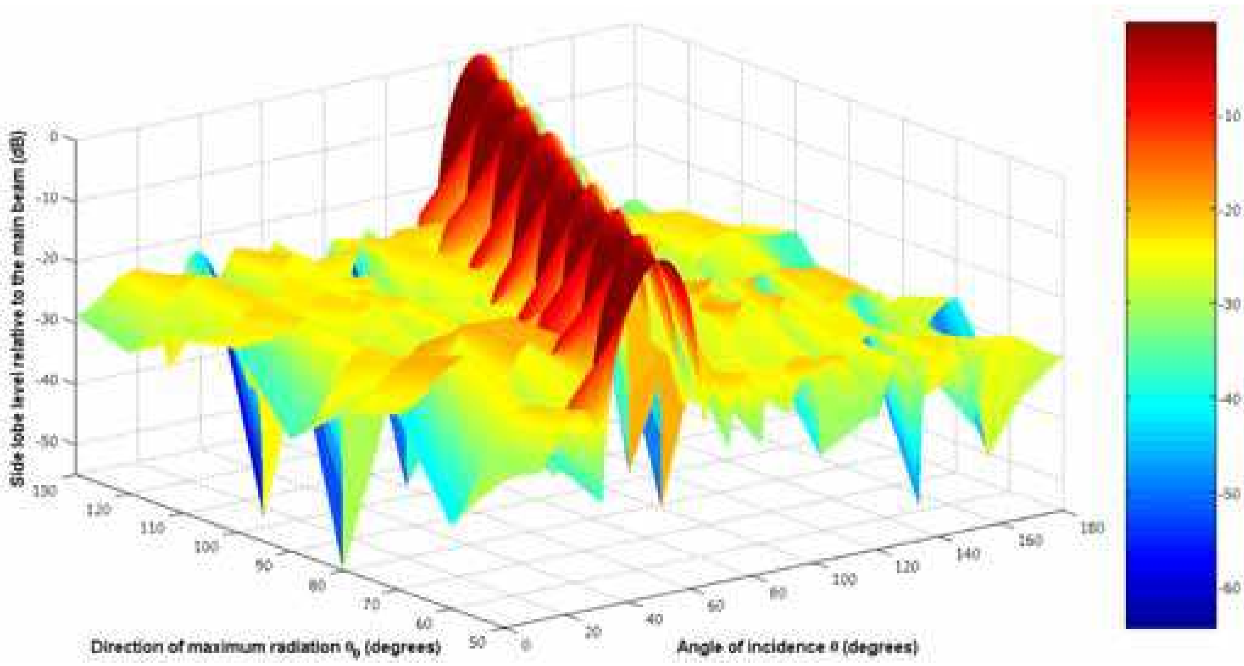



(a)




(b)

Figure 2. Behavior of the radiation pattern for a scannable linear array in a steering range of 50°≤$\theta_0$≤130° with the amplitude and phase excitation optimized by the GA, a) $N$=6, b) $N$=8, c) $N$=12.




(c)

Figure 2. (continued).

| Design case with the amplitude and phase excitation optimized by the GA (*N*=6) | | | | | Conventional case | |
|---|---|---|---|---|---|---|
| $\theta_0$ | ***SLL* (dB)** | ***DIR* (dB)** | **Normalised amplitude distribution** | **Phase perturbation distribution (deg)** | ***SLL* (dB)** | ***DIR* (dB)** |
| 50° | -20.57 | 5.95 | 5.2812 8.3264 11.1717 10.071 7.8738 5.0515 | 93.46, 103.56, 100.2, 102.06, 103.95, 94.22 | -12.42 | 6.41 |
| 60° | -22.97 | 6.54 | 4.6352 8.5603 11.8683 11.6959 9.0046 5.0082 | 87.23, 92.48, 89.33, 90.30, 89.66, 89.65 | -12.42 | 6.73 |
| 70° | -21.95 | 7.01 | 4.861 8.0166 11.481 11.6839 9.3365 5.5832 | 52.80, 58.69, 60.12, 60.05, 56.70, 53.96 | -12.42 | 7.32 |
| 80° | -23.01 | 7.09 | 4.2881 8.753 11.427 11.4502 8.1468 4.6648 | 81.17, 73.84, 70.18, 71.08, 69.03, 83.96 | -12.42 | 7.39 |
| 90° | -24.08 | 7.15 | 4.4101 8.6824 11.8247 11.9992 9.0169 4.3549 | 108.1, 114.48, 115.7, 114.46, 117.9, 107.2 | -12.42 | 7.60 |
| 100° | -23.13 | 7.16 | 4.2918 7.6439 10.8717 11.7129 9.058 5.2613 | 90.28, 91.94, 95.46, 95.45, 93.59, 94.37 | -12.42 | 7.39 |
| 110° | -23.49 | 6.86 | 4.1223 7.0177 10.4515 11.5757 9.0148 4.8233 | 75.35, 64.63, 60.83, 61.18, 64.72, 74.03 | -12.42 | 7.32 |
| 120° | -21.13 | 6.60 | 4.5337 7.1531 9.9966 10.2654 7.6541 4.8863 | 83.29, 87.44, 94.70, 94.38, 87.42, 83.89 | -12.42 | 6.73 |
| 130° | -20.14 | 6.03 | 5.3514 8.16 10.6545 10.117 7.8955 5.3136 | 89.32, 84.89, 89.40, 87.97, 84.96, 87.70 | -12.42 | 6.41 |

(a)

Table 1. Numerical values of the side lobe level (*SLL*), directivity (*DIR*), amplitude and phase perturbation distribution for the array factor illustrated in Fig. 2, a) *N*=6, b) *N*=8, c) *N*=12.

| Design case with the amplitude and phase excitation optimized by the GA (*N*=8) | | | | | Conventional case | |
|---|---|---|---|---|---|---|
| $\theta_0$ | *SLL* (dB) | *DIR* (dB) | Normalised Amplitude distribution | Phase perturbation distribution (deg) | *SLL* (dB) | *DIR* (dB) |
| 50° | -23.37 | 7.22 | 4.087 4.9365 8.5532 10.2015 10.799 9.7949 7.5327 4.0191 | 100.41, 97.92, 103.90, 98.9, 101.2, 105.25, 101.56, 105.16 | -12.79 | 7.48 |
| 60° | -21.34 | 7.90 | 4.2851 8.0845 9.094 11.5372 11.8051 10.633 7.121 5.8245 | 107.84, 95.16, 102.25, 105.2, 100.63, 105.05, 92.13, 105.7 | -12.79 | 8.25 |
| 70° | -23.12 | 8.22 | 4.5748 6.4426 9.221 11.8394 11.792 10.3245 7.1393 4.827 | 66.60, 60.46, 59.03, 62.87, 63.14, 62.06, 62.34, 65.21 | -12.79 | 8.51 |
| 80° | -22.20 | 8.43 | 4.5666 7.6476 9.81 11.5279 10.9044 9.513 6.7872 4.23 | 102.55, 104.3, 115.14, 103.7, 106.7, 109.5, 104, 94.6 | -12.79 | 8.76 |
| 90° | -22.36 | 8.54 | 4.4301 7.6973 9.0958 10.86 10.8595 9.2315 5.927 4.6922 | 114.10, 102.9, 104.58, 99.58, 98.06, 104.4, 99, 111.62 | -12.79 | 8.89 |
| 100° | -21.71 | 8.41 | 4.6048 6.5117 9.263 11.1713 11.982 9.9245 8.7118 4.8284 | 52.6, 76.44, 68.51, 77.12, 72.34, 73.01, 73.56, 57.24 | -12.79 | 8.76 |
| 110° | -22.32 | 8.18 | 4.6991 7.3316 10.1467 11.8 11.00 9.1493 5.9517 4.2841 | 56.36, 53.19, 59.30, 47.77, 43.77, 54.19, 46.66, 53.58 | -12.79 | 8.51 |
| 120° | -20.79 | 7.89 | 4.57 6.0843 9.1019 10.2557 9.7068 7.6138 6.6535 4.0621 | 105.23, 92.6, 104.36, 90.73, 95.37, 103.52, 92.73, 109.056 | -12.79 | 8.25 |
| 130° | -23.37 | 7.25 | 4.141 6.4183 8.7271 11.4705 11.2 9.9689 7.0337 4.3883 | 101.21, 99.28, 102.08, 97.16, 97.26, 97.17, 98.01, 98.06 | -12.79 | 7.48 |

(b)

| Design case with the amplitude and phase excitation optimized by the GA (*N*=12) | | | | | Conventional case | |
|---|---|---|---|---|---|---|
| $\theta_0$ | *SLL* (dB) | *DIR* (dB) | Normalised Amplitude distribution | Phase perturbation distribution (deg) | *SLL* (dB) | *DIR* (dB) |
| 50° | -21.43 | 9.20 | 5.834 5.819 7.759 8.9656 11.427 11.96 11.109 11.0136 10.232 7.295 6.952 4.6 | 97.6, 105.9, 101.5, 110, 90.5, 102.12, 95.96, 100.8, 102.54, 102, 103.1, 101.34 | -13.05 | 9.48 |
| 60° | -23.56 | 9.58 | 4.001 6.1168 8.7636 10.192 11.69 11.563 11.6994 11.0176 8.62 6.31 4.908 4.13 | 88.59, 84.56, 86.26, 96.48, 87.56, 90.73, 86.58, 85.11, 102.20, 83.35, 94.8, 83.9 | -13.05 | 10.05 |
| 70° | -19.08 | 10.01 | 5.971 7.8776 7.052 11.7027 10.658 10.886 11.539 10.817 10.136 8.486 6.636 6.371 | 67.94, 88.3, 85.7, 105.95, 98.62, 87.08, 92.3, 103.06, 99.9, 88.22, 96.42, 64.1 | -13.05 | 10.41 |
| 80° | -19.11 | 10.23 | 7.3289 6.4067 9.1657 9.121 9.5598 11.419 11.164 9.1777 8.9068 6.812 6.353 4.022 | 17.87, 23.62, 11.35, 38.56, 19.02, 10.57, 17.68, 33.39, 19.07, 21.61, 32.24, 359.9 | -13.05 | 10.62 |
| 90° | -23.77 | 10.18 | 4.3008 4.705 7.9 9.1098 11.2055 11.325 10.077 9.723 7.3412 5.32 4.784 4.0317 | 86.99, 94.23, 92.56, 93.22, 98.9, 101.5, 106.6, 103.37, 96.13, 92.3, 89.9, 86.84 | -13.05 | 10.69 |
| 100° | -22.33 | 10.13 | 4.683 5.0336 8.207 10.2406 11.407 11.664 11.9685 10.84 8.61 6.992 5.307 5.076 | 95.2, 99.54, 104.57, 92.94, 104.3, 89.63, 87.54, 99.45, 89.9, 103.15, 97.5, 100.9 | -13.05 | 10.62 |
| 110° | -22.38 | 10.01 | 4.748 6.2578 7.7439 8.9026 10.5646 11.617 11.78 10.328 10.562 6.653 6.363 4.356 | 84.30, 94.71, 79.67, 86.31, 73.17, 92.29, 82.51, 78.79, 84.01, 81.04, 87.27, 90.22 | -13.05 | 10.41 |
| 120° | -21.25 | 9.67 | 4.5847 6.208 7.4537 9.5612 11.112 11.413 10.195 10.736 9.0616 7.4537 4.866 4.806 | 86.35, 70.13, 70.10, 71.82, 74.06, 81.96, 68.87, 82.64, 72.91, 66.77, 70.65, 88.11 | -13.05 | 10.05 |
| 130° | -22.59 | 9.15 | 4.9722 5.9917 6.805 9.83 11.2548 11.3448 11.99 10.71 9.3777 7.7632 5.5745 4.92 | 91.46, 106.02, 94.3, 100.5, 101.1, 103.9, 100.8, 104.9, 99.45, 95.6, 99.57, 95.76 | -13.05 | 9.48 |

(c)

Table 1. (continued)

From the results shown previously, it is illustrated a perspective of designing scannable linear arrays in a uniform structure with amplitude and phase optimization using genetic algorithms. The genetic algorithm efficiently computes a set of antenna element amplitude and phase excitations in each angle of the steering range in order to provide a radiation pattern with maximum side lobe level reduction in all scanning range. The optimized design case provides a considerable side lobe level reduction with respect to the conventional phased array, with very similar values of directivity and maintaining the same aperture.
The design case for phased circular arrays is presented in the next section.

## 3. Design of phased circular arrays

Among antenna array configurations, the phased linear array is the most common form employed in cellular and personal communication systems (PCS) (Song et al., 2001). However, 360° scanning of the radiation beam can be obtained by combining a few linear arrays whose sector scans add to give the desired 360° scan. This could result in objectionably high costs, i.e., the array cost, the control complexity, and the data processing load are increased. Furthermore, the radiation pattern varies with the scan angle, i.e., the gain of a linear array degrades in its end-fire directions giving way to interference coming from other directions (Durrani et al., 2002). Unlike the linear array, the performance of the circular arrays (Du, 2004; Goto et al., 1977; Tsai et al., 2001; Tsai et al., 2004; Vescovo, 1995; Watanabe, 1980) has not been extensively studied. Therefore, in this section it is presented the design of scannable circular arrays optimizing the amplitude and phase excitations across the antenna elements. It is believed by the authors that an evaluation of the array factor for scannable circular arrays optimized by GA's considering a scanning range in all azimuth plane (360°) has not been presented previously. Depending on the performance improvement that we could get (in terms of the side lobe level and the directivity) with respect to the circular array with the conventional progressive phase excitation, this information could be interesting for antenna designers. Next, it is presented the theoretical model for this design case.

### 3.1 Theoretical model

Consider a circular antenna array of $N$ antenna elements uniformly spaced on a circle of radius $a$ in the $x$-$y$ plane. The array factor for the circular array shown in Figure 1, considering the center of the circle as the phase reference, is given by

$$AF(\phi,\mathbf{I}) = \sum_{n=1}^{N} I_n \exp\left[jka\left(\cos(\phi-\Delta\phi_n) - \cos\left(\phi_0-\Delta\phi_n\right)\right)\right] \tag{4}$$

where $\Delta\phi_n=2\pi(n-1)/N$ for $n$=1,2, …, $N$ is the angular position of the $n$th element on the $x$-$y$ plane, $ka=Nd$, i.e., $a=Nd\lambda/2\pi$, $\mathbf{I} = [I_1, I_2, ..., I_N]$, $I_n$ represents the amplitude excitation of the $n$th element of the array, $\phi_0$ is the direction of maximum radiation and $\phi$ is the angle of incidence of the plane wave.
As it was established for the linear array case, the array factor with phase excitation is created by adding in the appropriate element phase perturbations, $\mathbf{P} = [\delta\beta_1, \delta\beta_2, ..., \delta\beta_N]$, $\delta\beta_i$ represents the phase perturbation of the $i$th element of the array, such that

$$\varphi_n = ka[\cos(\phi-\Delta\phi_n) - \cos(\phi_0-\Delta\phi_n)] \quad (5)$$

where $\varphi_n=ka[\cos(\phi-\Delta\phi_n)-\cos(\phi_0-\Delta\phi_n)]$.

It is important to mention that as the center of the circle is taken as the phase reference in the array factor, it is considered a symmetrical excitation for the optimization process, i.e, the phase perturbation would be given in the next way $I_1\exp(j\delta\beta_1)$, …, $I_{N/2}\exp(j\delta\beta_{N/2})$, $I_{N/2+1}\exp(j\delta\beta_{N/2+1})=I_1\exp(-j\delta\beta_1)$, …, $I_N\delta\beta_N=I_{N/2}\exp(-j\delta\beta_{N/2})$. Note that we will have $N/2$ amplitude and phase excitations in the optimization process.

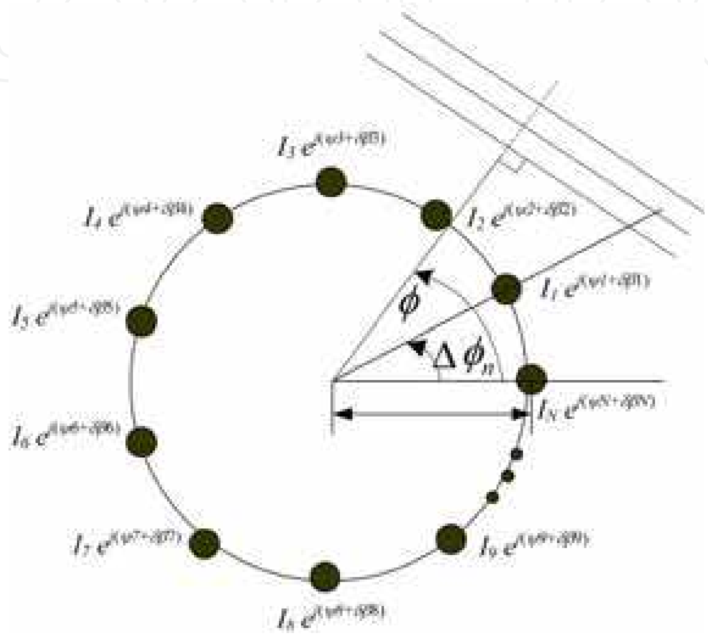


Figure 3. Array geometry for an $N$ element uniform circular array with inter-element spacing $d$.

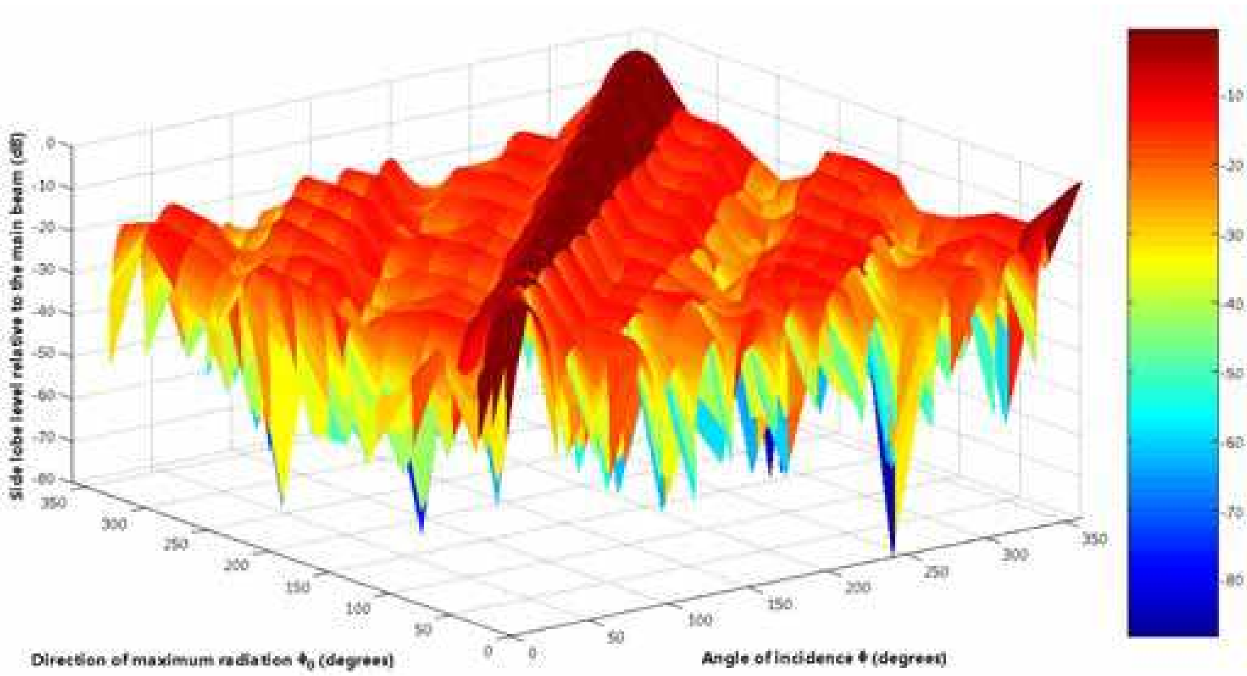
As already being pointed out, the objective of this section is to present an evaluation of the array factor for scannable circular arrays in a uniform geometry considering the optimization of the amplitude and phase excitation across the antenna elements. In this case, it is studied the behavior of the array factor for the scanning range of $0° \leq \phi_0 \leq 360°$ with an angular step of 30°. In this case, the objective function and the optimization process are set as they were presented for the linear array case, with the considerations of the scanning range and the symmetrical excitation aforementioned.

The results of using the GA for the design of scannable circular arrays are described in the next section.

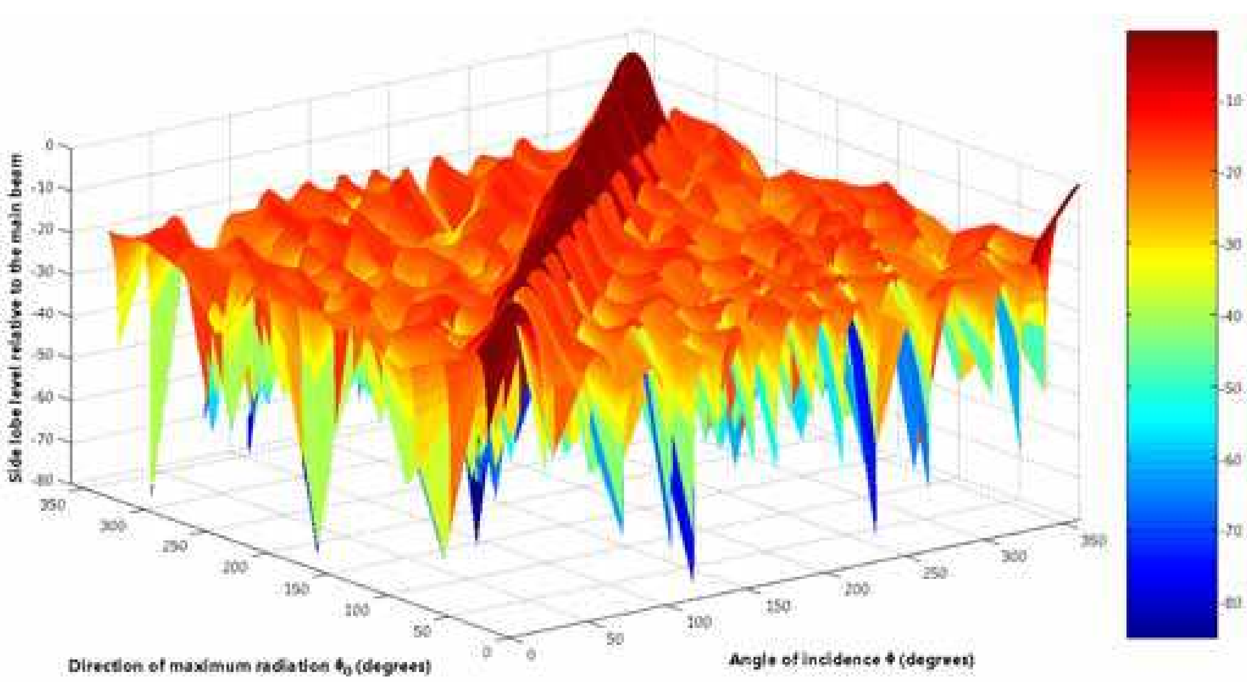
### 3.3 Results obtained for the design of phased circular arrays

The application of a phased circular array has sense when it is used to have a scanning range in all azimuth plane (360°). Therefore, the method of GA's was implemented to evaluate the behavior of the array factor for the scanning range of $0° \leq \phi_0 \leq 360°$ with an angular step of 30°. Next, some examples of the obtained results for the design of scannable circular arrays are explained.

Figure 4 shows the behavior of the array factor for a scannable circular array with the amplitude and phase excitation optimized by the GA. In this case, the separation between antenna elements is set as $d$=0.5λ, and it is illustrated the examples for a) $N$=12 and b) $N$=18. The numerical values of the side lobe level, directivity, amplitude and phase perturbation distributions for the array factor shown in Figure 4 are presented in the Table 2.




(a)




(b)

Figure 4. Behavior of the radiation pattern for a scannable circular array in a steering range of $0° \leq \phi_0 \leq 360°$ with the amplitude and phase excitation optimized by the GA, a) $N$=12, b) $N$=18.

As illustrated in the Figure 4 and the Table 2, the results of the side lobe level and the directivity for the optimized design are surprising. Observing the results, the conventional case of progressive phase excitation provides a *SLL*= -7.16 dB, and *DIR*=10.6 dB for a) *N*=12, and a *SLL*= -7.9 dB, *DIR*=12 dB for b) *N*=18. For the case of the optimized design, it is obtained a $SLL_{min}$= -12.17 dB, $SLL_{max}$= -13.68 dB and $DIR_{min}$=11.35 dB, $DIR_{max}$=11.56 dB for a) *N*=12, and a $SLL_{min}$= -13.50 dB, $SLL_{max}$= -16.74 dB and $DIR_{min}$=12.96 dB, $DIR_{max}$=13.23 dB for b) *N*=18.

These values mean a substantial improvement in the performance of the array for the design optimized by the GA with respect to the conventional case, i.,e, it is obtained a substantial improvement in the sense of the side lobe level and an improvement of about 1 dB in the directivity, maintaining the same scanning range and the same aperture.

| Design case with the amplitude and phase excitation optimized by the GA (*N*=12) | | | | | Conventional case | |
|---|---|---|---|---|---|---|
| $\theta_0$ | *SLL* (dB) | *DIR* (dB) | Normalised Amplitude distribution | Phase perturbation distribution (deg) | *SLL* (dB) | *DIR* (dB) |
| 0° | -13.26 | 11.50 | 8.9861, 7.0281, 6.0653, 7.1273, 8.6156, 13.6634 | 165.62, -109.48, 179.99, 108.64, -161.28, 149.09 | -7.167 | 10.62 |
| 30° | -12.17 | 11.35 | 13.9516, 12.0757, 6.3265, 6.0282, 6.4862, 10.6097 | 18.52, -6.39, 39.77, -10.41, -26.71, 9.63 | -7.165 | 10.65 |
| 60° | -12.78 | 11.53 | 10.444, 13.9698, 10.5989, 6.9121, 6.5014, 6.8659 | -17.52, 25.97, -13.76, 57.97, -2.92, -59.70 | -7.164 | 10.66 |
| 90° | -13.01 | 11.54 | 6.5076, 10.5052, 13.9753, 10.7816, 6.2717, 6.1824 | 65.56, -20.46, 26.50, -15.54, 57.09, 1.70 | -7.165 | 10.66 |
| 120° | -13.42 | 11.50 | 6.0569, 6.8042, 10.9555, 13.8561, 8.9444, 6.1517 | -17.08, 76.07, -11.95, 26.74, -30.83, 66.82 | -7.167 | 10.66 |
| 150° | -13.18 | 11.56 | 6.2821, 6.0246, 7.0327, 9.669, 13.7562, 8.3516 | 114.21, 169.51, -114.93, 168.12, -151.91, 160.20 | -7.165 | 10.65 |
| 180° | -12.48 | 11.50 | 9.1939, 6.015, 6.3482, 6.2204, 11.0839, 13.9433 | 14.83, -52.36, -5.56, 59.88, -11.88, 24.69 | -7.164 | 10.65 |
| 210° | -13.24 | 11.47 | 13.7931, 9.391, 6.2871, 6.0677, 6.8493, 10.4153 | -24.87, 19.04, -51.57, -19.56, 70.88, -12.32 | -7.165 | 10.65 |
| 240° | -13.36 | 11.51 | 9.0782, 13.9387, 9.9896, 6.0713, 6.0022, 6.6342 | -157.31, 155.52, -168.26 114.07, -176.6, -107.67 | -7.167 | 10.66 |
| 270° | -12.74 | 11.50 | 7.3426, 11.2421, 13.9757, 11.0413, 7.2521, 6.0368 | -52.84, 14.82, -26.20, 14.92, -51.18, -1.47 | -7.165 | 10.66 |
| 300° | -12.51 | 11.48 | 6.0446, 7.609, 11.5202, 13.7836, 11.3168, 7.6133 | -176.94, 125.17, -161.71 153.62, -165.07, 130.3 | -7.164 | 10.66 |
| 330° | -13.68 | 11.54 | 6.0884, 6.0135, 6.2152, 9.2554, 13.9733, 10.1944 | -113.97, -178.77, 110.13 -160.49, 152.53, -165.7 | -7.165 | 10.66 |

(a)

Table 2. Numerical values of the side lobe level (*SLL*), directivity (*DIR*), amplitude and phase perturbation distribution for the array factor illustrated in Fig. 4, a) *N*=12, b) *N*=18.

| Design case with the amplitude and phase excitation optimized by the GA ($N$=18) | | | | | Conventional case | |
|---|---|---|---|---|---|---|
| $\theta_0$ | *SLL* (dB) | *DIR* (dB) | Normalised Amplitude distribution | Phase perturbation distribution (deg) | *SLL* (dB) | *DIR* (dB) |
| 0° | -16.74 | 12.98 | 9.606, 10.0796, 8.7306, 7.4423, 6.0729, 13.1574, 10.1184, 12.7586, 13.948 | 151, 137.36, -175.89, -3.65, 18.19, -175.31, -119.92, 176.34, -147.15 | -7.9 | 11.91 |
| 30° | -14.59 | 13.15 | 13.8924, 13.4948, 12.384, 6.1859, 9.089, 7.2624, 8.7293, 6.1218, 10.978 | -19.84, -9.665, -2.166, 27.55, -85.76, -19.785, 75.877, 25.36, 1.656 | -7.9 | 12.0 |
| 60° | -14.85 | 13.05 | 7.7885, 10.2233, 13.7296, 10.4833, 8.1398, 10.8737, 6.5203, 6.1301, 9.315 | 140.02, 172.19, 156.37, 172.09, 139.6, -178.963, -40.93, 70.3, -170.776 | -7.9 | 11.96 |
| 90° | -14.20 | 13.23 | 9.5658, 6.1554, 13.1213, 13.7249, 13.4988, 11.421, 6.0703, 8.8405, 7.243 | 101.49, -172.8, 175.48 166.3, 159.385, 177.2, 172.646, 105.8, -170.73 | -7.9 | 12.0 |
| 120° | -14.08 | 12.96 | 6.8649, 6.1881, 10.5908, 7.0292, 11.4631, 13.7734, 9.398, 8.1573,10.8491 | -137.484, 99.2, -9.642, -43.582, 1.26, -17.302, -10.043, -23.553, -9.312 | -7.9 | 11.96 |
| 150° | -14.16 | 13.12 | 6.2198, 8.1045, 7.2332, 8.8087, 6.0134, 11.5031, 13.8558, 13.7171, 11.9379 | -3.078, 76.838, 0.51, -77.027, 14.863, 2.441, -12.856, -10.865, 2.579 | -7.9 | 12.0 |
| 180° | -16.21 | 13.17 | 11.2931, 6.9325, 9.8873, 6.0995, 7.026, 6.1086, 11.0604, 12.6843, 13.1782 | -7.805, 28.515, 9.038, -102.785, -178.52, 8.36, -62.315, -27.75, -29.808 | -7.9 | 11.95 |
| 210° | -14.85 | 13.18 | 13.4792, 13.806, 13.7676, 6.2475, 10.5248, 6.23, 8.2037, 6.1015, 9.0618 | -144.58, -178.87, -165.5, 110.127, -112.7, -137.6, 111.07, 144.61, 176.76 | -7.9 | 12.0 |
| 240° | -14.74 | 13.00 | 8.1184, 9.5482, 13.75, 11.8184, 7.7963, 12.1036, 6.0628, 6.5981, 8.9808 | -149, -171.964, -159.465 176.53, -141.74, 178.43, 42.03, -50.722, 171.964 | -7.9 | 11.96 |
| 270° | -14.07 | 13.15 | 8.649, 6.4937, 12.5178, 13.9531, 13.1291, 9.6387, 6.0478, 6.2315, 7.3053 | 76.656, -29.518, 4.1517, 6.344, 23.728, 7.36, 27.052, 71.543, -18.029 | -7.9 | 12.0 |
| 300° | -13.50 | 13.00 | 6.6366, 6.4168, 10.2879, 7.7545, 9.5766, 13.9128, 11.4554, 7.9931, 11.7014 | -68.05, 65.273, -169.852 -144.74, -179.74, -161.4, -176.4, -155.88, -165.66 | -7.9 | 11.96 |
| 330° | -14.80 | 13.17 | 6.2548, 9.9819, 7.4138, 8.7991, 6.002, 10.5322, 13.7914, 13.7537, 13.7233 | -116.06, 98.633, 136.89, -120.18, -126.33, -166.8 -152.76, -167, -165.53 | -7.9 | 12.0 |

(b)

Table 2. (continued).

Now, if the results of the side lobe level and the directivity for the scannable circular array optimized by the GA (for $N$=12, shown in the Table 2a) are compared with the linear array case with conventional phase excitation (for $N$=12, shown in the Table 1c), we observe that the values of the *SLL* and *DIR* are a little better for the circular array case with the great advantage of having a scanning range several times bigger than the linear array case.

## 4. Discussions and open problems

The main objective of this chapter is to illustrate the application of an evolutionary optimization technique in the problem of designing scannable antenna arrays with geometry lineal and circular. A genetic algorithm is applied to evaluate the performance of scannable linear and circular arrays optimizing the amplitude and phase excitations across the antenna elements. The results obtained for the design of scannable linear and circular arrays reveal that the performance of the phased array could be improved substantially, with respect to the conventional case of progressive phase excitation, if the amplitude and phase excitations are optimized in an adequate way by an evolutionary algorithm.

There are many remaining open problems. In this case, we propose the following questions:

- Which is the best evolutionary algorithm for the problem in terms of solution quality and in terms of computation time?
- Given the algorithm, what is the best representation and the best genetic operators to use?
- Is there a better way to model or represent the problem in such a way to avoid the evaluation of the *SLL* and the *DIR* for each angle in the scanning range?
- What are the limits of performance for non-uniformly spaced phased arrays? How do these limits compare with the ones obtained by uniformly spaced phased arrays?

## 5. Conclusions

This chapter illustrates how to model the design of phased linear and circular arrays with the optimization of the amplitude and phase excitations for improving the performance of the array in the sense of the side lobe level and the directivity.

In the case of the scannable linear arrays, the experimental results illustrated that the design of scannable linear arrays with the amplitude and phase optimized with the use of genetic algorithms could provide a lower side lobe level (<-20 dB), with respect to a conventional phased linear array. In this case, these values of the side lobe level for the optimized design case are achieved with very similar values of directivity and the same aperture in both design cases.

For the case of the scannable circular arrays, the obtained results illustrated that the optimization of the array could provide a substantial improvement in the side lobe level and an improvement of about 1 dB in the directivity, with respect to the conventional case of progressive phase excitation. These improvements in the performance of the array are achieved maintaining the same scanning range, i.e., in all azimuth plane (360°), and the same aperture.

Future research will be aimed at considering the application and performance evaluation of new evolutionary algorithms in the design of different array geometries to understand which algorithm fits best a given problem. Also, the answer for the proposed set of questions will be investigated. Furthermore, it will be investigated the application of evolutionary techniques in the optimization of different phased arrays considering the feeding network in order to simplify the beam-forming network.

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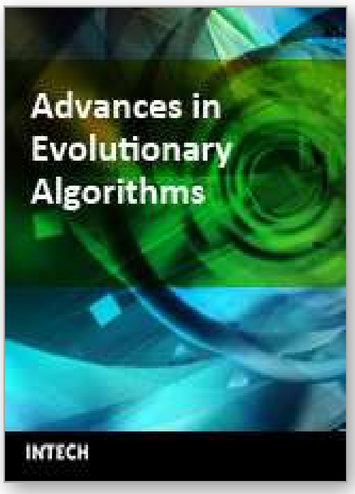


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