Progress In Electromagnetics Research, PIER 46, 105–126, 2004

DESIGN OF SWITCHED BEAM PLANAR ARRAYS USING THE METHOD OF GENETIC ALGORITHMS

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Abstract—A system consisting of a smart antenna and a processor can perform filtering in both the time and space domain, thus reducing the sensitivity of the receiver to interfering directional noise sources. Smart antennas can be used for further increase in the capacity of a communication system and for variable speed of transmission for multimedia information. Switched beam antenna arrays are a subset of smart antennas that cover either the x-y plane or a portion of it with multiple radiation patterns. A processor can decide which pattern to use for reception or transmission. In this paper the use of genetic algorithms (GAs) is examined in the design of switched beam antenna arrays. The antenna consists of five or six elements and the radiation patterns vary from 4 to 8, covering the x-y plane with the main beams of the radiation patterns pointing at 0°, 90°, 180°, 270° and 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° respectively. The positions of the antenna elements are either chosen exclusively by the GA or are assumed to form a circular array with one central element and the GA decides for the radius and the offset angle of the circle. Furthermore, the GA is asked to design an array covering the first 120° of the x-y plane with 4 radiation patterns pointing at 15°, 45°, 75° and 105°. Such a configuration can be used in sector antennas, which are widely used in 2G mobile communication systems.

1. INTRODUCTION

Wireless communication systems are limited in performance and capacity by various impairments. One of these is multipath fading which is very common in mobile communications. The signals arriving to the receiver from different paths may add with different phases resulting in received signal amplitude that exposes occasional deep fades thus making the communication with the transmitter very difficult and sometimes impossible. Another problem is delay spread which may result in significant intersymbol interference [1]. Also, even if the radio channel is a perfect one, the Shannon theorem limits the capacity of a communication system with an upper bound that used to be considered as the final frontier for over than five decades [2].

The demand for wireless mobile services is growing at an explosive rate making the existing communication systems inadequate. Recent research activities are moving to the third and fourth generation cellular systems. Antenna arrays have been suggested for these systems to satisfy the demand for increased data rates and the lack of unlimited channel bandwidth. It has been shown by many studies that when an array is properly used in a communications system, it helps in increasing channel capacity and spectrum efficiency. An array may also be useful to extend range coverage by tailoring beam shapes to cover near and far users. It also reduces multipath fading, cochannel interferences and Bit Error Rate (BER) [3]. Smart antennas allow a tighter reuse factor or offer a higher SNR level and therefore signal quality by keeping the same reuse factor, in FDMA and TDMA systems. In CDMA systems like UMTS, the Multiple Access Interference (MAI) reduction provided by smart antennas is translated into either more users in the system or higher data rates for the existing users [4]. Another possible application of smart antennas is for spatial separation of the signals arriving at the receiver resulting to a new multiple access scheme known as Space Division Multiple Access (SDMA). Smart antennas are considered to be the key to fulfilling the increased demand of channel requirement. Communication systems with smart antenna arrays on both the mobile units and the base stations, known as Multiple Input Multiple Output (MIMO) systems, are the main research field in mobile communications at the time with spectacular results [5]. Recent work on the field has delivered systems that can approach the 90% of the predicted capacity by the Shannon theorem [6–8] and arguments are presented that overcoming the Shannon limit is not inevitable [9].

On the other hand, genetic algorithms are used more and more for optimization in electromagnetic problems. Genetic algorithms were firstly announced as an idea in 1960's but only the last decade have they been used in a growing number of problems. Their success in searching non-linear spaces and their robustness has made them extremely popular among researchers. Genetic algorithms are inspired by the theory of natural selection and evolution. In genetic algorithms a population of possible solutions, referred to as individuals or chromosomes, is first generated. A number known as fitness is assigned to every individual. This number is produced by the objective function of the algorithm. The search of the solution space is performed through a simulated evolution. In general, the fittest individuals tend to be selected for mating and reproduction. There are various methods for selecting individuals (referred to as parents) such as the roulette method, the normalized geometrical, the tournament method and other [10]. The selected chromosomes are then mated by the crossover function. The new individuals are referred to as children and they are either added to the new generation of chromosomes or are mutated by a mutation function and then added to the new population. Finally, a new population is generated and the procedure restarts [11]. The criterion for stopping the algorithm may either be a maximum number of iterations or fulfilling the demands of the optimization.

In this paper a genetic algorithm is used to design antenna arrays that cover the x-y plane or a portion of it. The core of the genetic algorithm is the gaot toolbox that can be found in [12]. The designed arrays consist of 5 or 6 elements. All the arrays are designed to cover the x-y plane with either 4 or 8 radiation patterns. The radiation patterns point their main beam symmetrically, that is every 90° or every 45° respectively. The beamwidth is chosen to be 40° and the relative sidelobe level is asked to be 6 dB or higher for all cases. Two formations for the arrays are examined. In the first case the GA is left to choose the positions of the array elements thus resulting to arbitrary element positions. In the second case a circular array with one central element is used and the GA only decides the radius and the offset angle of the circle. We are to show that for symmetrical radiation patterns the circular array generally delivers better results than the arbitrary one but the second can still be used for switched beam array design. That is, the GA may be used to find not only the weights and the phases of all elements but also their positions. Furthermore, the technique that was developed is used to a non-symmetrical problem.

An array is designed with four radiation patterns covering the first 120° of the x-y plane. The beamwidth in this case is 30° and the minimum relative sidelobe level is set to 6 dB. For all cases mentioned above, the elements are $\lambda/2$ dipoles with 0.002λ radii and the method used for analysis purposes is the induced EMF method described below. The operating frequency is 2.4 GHz, suitable for 802.11 b WLAN applications.

2. THEORETICAL MODEL

2.1. Dipoles, Array Factor and EMF Method

In this paper all the arrays consist of dipoles with a length of $\lambda/2$ and a radius of 0.002λ. The radiation pattern of a dipole with length L is given by (1), where I_m is the rms value of the current on the dipole [13–15]. It is easy to see that for a constant θ angle the radiation pattern of such a dipole is constant for all ϕ angles.

$$U(\theta) = \frac{nI_m^2}{2\pi}\left[\frac{\cos\left(k_0\frac{L}{2}\cos\theta\right) - \cos\left(k_0\frac{L}{2}\right)}{\sin\theta}\right]^2 \tag{1}$$

For an array of identical elements the radiation pattern is given by (2).

$$U(\theta,\phi) = U_0(\theta,\phi)|AF(\theta,\phi)|^2 \tag{2}$$

where $U_0(\theta,\phi)$ is the radiation pattern of each element and $AF(\theta,\phi)$ is the array factor. Let O_m be a radiating element and P an observation point, as shown in Fig. 1. The array factor of an array consisting of M elements is given by (3).

$$AF(\theta,\phi) = \sum_{m=0}^{M-1} c_m \exp(jkr_m\cos\psi_m) \tag{3}$$

where $c_m = \frac{I_m}{I_0}$ are the relative excitation coefficients, I_0 is the excitation of zero element and $k = \frac{2\pi}{\lambda}$ where λ is the wavelength. Notice that c_m may be a complex number.

Since only the x-y plane is of interest and our array is a planar one the radiation pattern of the array becomes

$$U(\phi) = U_0\left|\sum_{m=0}^{M-1} c_m \exp(jkr_m\cos(\phi-\phi_m)\right|^2 \tag{4}$$

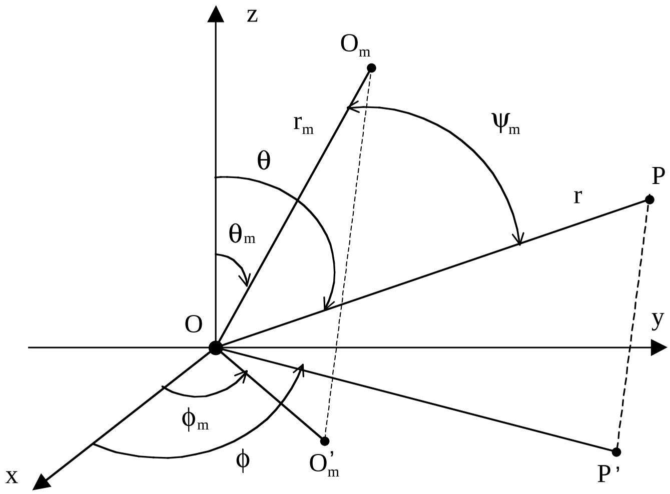

Figure 1. The Geometry Needed to Extract the Array Factor of an Arbitrary Array.

The excitation currents vector **I** is related to the excitation voltages vector **V** through the impedance matrix **Z** by (5).

$$V = Z \cdot I \tag{5}$$

Through (5) the terminal voltage of any one element can be expressed in terms of the currents flowing in the others. Also, the current flowing in any one element can be expressed in the terms of the voltages of the others and the matrix Z^{-1}.

The self-impedance of a dipole of length L is given by (6)

$$Z_i = -\frac{1}{I_i^2} \int_{-\frac{L}{2}}^{\frac{L}{2}} E_z(\rho = \alpha, z) I(z) dz \tag{6}$$

where $I(z) = I_m \sin[k(\frac{L}{2} - |z|)]$, E_z is the tangential electric field along the surface of the dipole and α is the dipole radius. The mutual impedance between two parallel dipoles at a distance d is given by (7).

$$Z_{21i} = \frac{V_{21}}{I_{1i}} = -\frac{1}{I_{1i} \cdot I_{2i}} \int_{-\frac{L_2}{2}}^{\frac{L_2}{2}} E_{z21}(z) I_2(z) dz \tag{7}$$

In equation (7), V_{21} is the voltage induced in dipole 2 because of the current flowing in dipole 1, E_{z21} is the E-field component along the surface of dipole 2 radiated by dipole 1, and I_2 is the current distribution along dipole 2.

2.2. The Objective Function of the Genetic Algorithm

The objective function is the core of the genetic algorithm. It evaluates each chromosome as a solution to the problem and is the main tool for the decision of selection and crossover. It is also referred to as evaluation function or fitness function. The GA has been extensively used in electromagnetic optimization and antenna array design. In [16] through [21] recent work on the field is presented. In this paper the goal is to design arrays with radiation patterns of a specific form. For each desired radiation pattern a vector of size three is given. The first element of the vector is the angle of the main beam, the second is the beamwidth and the third is the minimum relative sidelobe level. No further care for the shape of the main beam was taken since it is a result of the element positions and relative voltage and phase coefficients. The rest of the radiation pattern is sampled with a resolution of 5°. Then a comparison takes place between the n-th desired radiation pattern and the n-th calculated radiation pattern of the i-th chromosome and an error occurs using equation (8).

$$A_{i,n} = \frac{1}{N}\sum_{j=1}^{N} e_{i,n,j} \tag{8}$$

where

$$e_{i,n,j} = \left(\frac{U_{desired,i,n,j} - U_{calculated,i,n,j}}{U_{desired,i,n,j}}\right)^2, \quad \text{For the main beam} \tag{9a}$$

$$e_{i,n,j} = \left(\frac{U_{desired,i,n,j} - U_{calculated,i,n,j}}{U_{desired,i,n,j}}\right)^2, \quad \text{Otherwise if } U_{calculated} > U_{desired} \tag{9b}$$

$$e_{i,n,j} = 0, \quad \text{Otherwise if } U_{calculated} < U_{desired} \tag{9c}$$

The procedure is repeated for every radiation pattern of the chromosome (4 or 8 radiation pattern for the x-y plane and 4 radiation patterns for the first 120° of the x-y plane). Then, either the mean value ($A_i = m_{A_{i,n}}$) or the sum of the standard deviation and the mean value ($A_i = m_{A_{i,n}} + \sigma_{A_{i,n}}$) for all radiation patterns are calculated.

The objective function of the chromosome is given by (10).

$$f_i = \frac{1}{1 + \sqrt{A_i}} \tag{10}$$

The genetic algorithm was ran several times with different size of population, different parameters for mutation, selection and crossover and with both the $A_i = m_{A_{i,n}}$ and $A_i = m_{A_{i,n}} + \sigma_{A_{i,n}}$ formulas for calculating A_i. Solution with overlapping dipoles are rejected while solutions with nearby dipoles are treated by the induced EMF method. The best results were obtained and are presented in the next paragraph.

3. NUMERICAL RESULTS

In this paper we present the design of antenna arrays with 4 and 8 different radiation patterns. The main beam lobes of the arrays must be as narrow as possible covering the whole 360° azimuth and the relative side lobe levels must be as greater as possible. Arrays consisted of 5 and 6 elements are examined and the positions of the elements are either chosen exclusively by the GA or form a circle with one central element and the GA chooses the radius and the offset angle of the circle. All radiation patterns are normalized per 100, the angles and phases are given in degrees or otherwise mentioned and the R.S.L.L. is in dB. A chromosome vector is used where the relative voltage and phase coefficients for every radiation pattern are stored together with the radii and angles of the elements on the x-y plane. The relative current coefficients are derived from equation (5) and the radiation pattern is calculated using equation (4). Then the objective function of each chromosome is calculated using the procedure described in paragraph 2.2.

Various measures are used in order to compare the designs with each other. These are the mean beamwidth value, the mean relative sidelobe level (R.S.L.L.) and the objective function of the GA. As expected, the main beams do not target exactly on the desired directions. Thus, the "mean main beam error" (M.M.B.E.) is introduced in order to measure this characteristic. The "mean main beam error" (M.M.B.E.) is defined as the mean value of the deviation from the desired main beam direction over all radiation patterns.

At first an effort was made to meet the requirements of the design with a 5-element array. A 5-element array with arbitrary element positions can cover the x-y plane with 4 different radiation patterns. Such an array can achieve a mean beamwidth value of 52.475° and a mean R.S.L.L. value of 9.861 dB while the M.M.B.E. is 2° (see Table

Table 1. Results for the 5-element array with arbitrary element positions covering the x-y plane with four radiation patterns.

	5 elements, 4 diagrams, Arbitrary Positions			
# Pattern	1	2	3	4
ϕ_{max}	-2	88	177	271
ϕ_{-}	-28.7	63.0	150.5	245.9
ϕ_{+}	26.4	113.1	206.0002	295.2
$\Delta\phi_{3dB}$	55.1	50	55.5	49.3
Max R.S.L.L.	9.679	10.173	9.713	9.901
Objective Function	0.8554			

Table 2. Results for the 5-element circular array covering the x-y plane with four radiation patterns.

	5 elements, 4 diagrams, Circular Formation			
# Pattern	1	2	3	4
ϕ_{max}	0	90	180	270
ϕ_{-}	-15.3	74.6	164.5	254.5
ϕ_{+}	15.3	105.5	195.5	285.15
$\Delta\phi_{3dB}$	30.7	30.9	31	30.9
Max R.S.L.L.	8.451	8.415	8.650	8.343
Objective Function	0.8801			

1). If the array is a circular one then the mean beamwidth is 30.875° and the mean R.S.L.L. is 8.465 dB while the M.M.B.E. is 0° (see Table 2). One can see that the circular array offers perfect M.M.B.E. and a 21.6° reduction on the mean beamwidth with a cost of only 1.396 dB on the R.S.L.L. The R.S.L.L. reduction can be justified by the fact that the mean beamwidth is greatly decreased and the available power must be transmitted through the side lobes. The objective function for the circular array (0.8801) is greater than the one for the arbitrary-positions array (0.8554) as expected. Tables 1 and 2 show the best results for the 5-element arrays with arbitrary element positions or circular formation, radiating at four different directions.

The 5-element array was also used in order to derive 8 different radiation patterns covering the x-y plane. The 5-element array with arbitrary element positions can achieve a mean beamwidth value of 53.513° and a mean R.S.L.L. value of 8.733 dB while the objective function is 0.7809 and the M.M.B.E. is 6.375° (see Table 3). The 5-element circular array can achieve a mean beamwidth value of 62.25°

Table 3. Results for the 5-element array with arbitrary element positions covering the x-y plane with eight radiation patterns.

	5 elements, 8 diagrams, Arbitrary Positions							
# Pattern	1	2	3	4	5	6	7	8
ϕ_{max}	0	49	87	119	192	225	269	300
ϕ_{-}	-36.6	24.5	65.3	95.6	151.5	200.2	246.9	276.3
ϕ_{+}	32.2	72.5	110.3	147.4	220.6	247.8	291.6	330.1
$\Delta\phi_{3dB}$	68.8	47.9	45.1	51.2	69.1	47.6	44.7	53.7
Max R.S.L.L.	7.801	8.570	11.311	6.806	7.574	9.106	10.831	7.865
Objective Function	0.7809							

Table 4. Results for the 5-element circular array covering the x-y plane with eight radiation patterns.

	5 elements, 8 diagrams, Circular Formation							
# Pattern	1	2	3	4	5	6	7	8
ϕ_{max}	359°	41°	89°	131°	179°	221°	269°	311°
ϕ_{-}	327°	9.5°	57°	99.5°	147°	189.5°	237°	279.5°
ϕ_{+}	30°	71°	120°	161°	210°	251°	300°	341°
$\Delta\phi_{3dB}$	63°	61.5°	63°	61.5°	63°	61.5°	63°	61.5°
Max R.S.L.L.	9.66 dB	10.35 dB	9.66 dB	10.35 dB	9.66 dB	10.35 dB	9.66 dB	10.35 dB
Objective Function	0.7972							

and a mean R.S.L.L. value of 10.005 dB while the objective function is 0.7972 and the M.M.B.E. is 2.5°. We can see that there is an increase on the R.S.L.L. for the circular array with a cost at the mean beamwidth. There is also a better M.M.B.E. and a slightly increased objective function. Tables 3 and 4 contain the best results for the 5-element arrays with arbitrary element positions or circular formation, radiating at eight different directions.

After this first trial, another element was added to the array in order to increase the directivity of the array factor, decrease the beamwidth and increase the relative sidelobe level. The 6-element array with arbitrary element positions effectively covers the x-y plane with 4 different radiation patterns. The mean value of the beamwidth for these patterns is 38.875°, the mean value of the R.S.L.L. is 11.368 dB, the relative objective function is 0.9738 and the M.M.B.E. is 2.5° (see Table 5). The 6-element circular array on the other hand

Table 5. Results for the 6-element array with arbitrary element positions covering the x-y plane with four radiation patterns.

	6 elements, 4 diagrams, Arbitrary Positions			
# Pattern	1	2	3	4
ϕ_{max}	358°	94°	180°	274°
ϕ_-	340.5°	74°	161°	254°
ϕ_+	17°	114.5°	198.5°	295°
$\Delta\phi_{3dB}$	36.5°	40.5°	37.5°	41°
Max R.S.L.L.	11.79 dB	11.25 dB	11.14 dB	11.29 dB
Objective Function	0.9738			

Table 6. Results for the 6-element circular array covering the x-y plane with four radiation patterns.

	6 elements, 4 diagrams, Circular Formation			
# Pattern	1	2	3	4
ϕ_{max}	358°	92°	179°	261°
ϕ_-	329.5°	63°	152°	241°
ϕ_+	28°	119.5°	210°	299°
$\Delta\phi_{3dB}$	58.5°	56.5°	58°	58°
Max R.S.L.L.	9.56 dB	9.36 dB	9.23 dB	8.9 dB
Objective Function	0.8006			

can offer a mean beamwidth of 57.75° and a mean R.S.L.L. of 9.263 dB while the objective function is 0.8006 and the M.M.B.E. is 3.5° (see Table 6). One can see that the 5-element circular array is more effective than the 5-element arbitrary-positions array but the same is not true for the 6-element arrays. One possible reason for that is that the 5-element circular array is inherently symmetrical with the 4 radiation patterns covering the x-y plane, which is not true for the 6-element circular array. As we will see later though, when it comes to the 8 radiation patterns, the 6-element circular array is better than the 6-element arbitrary-positions array. Tables 5 and 6 contain the best results for the 6-element arrays with arbitrary element positions or circular formation, radiating at four different directions.

The same procedure was followed in order to derive 8 radiation patterns covering the x-y plane from a 6-element array. The 6-element array with arbitrary element positions can cover the x-y plane with 8 radiation patterns. The mean value of the beamwidth is 46.313°, the

Table 7. Results and relative voltage and phase coefficients for the 6-element array with arbitrary element positions covering the x-y plane with eight radiation patterns.

	6 elements, 8 diagrams, Arbitrary Positions							
# Pattern	1	2	3	4	5	6	7	8
ϕ_{max}	-11°	60°	95°	135°	176°	241°	277°	314°
ϕ_-	-33°	36.5°	76.5°	115°	149°	221°	259.5°	296.5°
ϕ_+	21	79.5°	116°	156.5°	210.5°	277.5°	296°	334.5°
$\Delta\phi_{3dB}$	54°	43°	39.5°	41.5°	61.5°	56.5°	36.5°	38°
Max R.S.L.L.	7.44 dB	5.33 dB	10.29 dB	8.78 dB	10.28 dB	6.95 dB	10.81 dB	8.64 dB
w_1	0.5500	0.8377	0.3678	0.8831	0.4033	0.2290	0.5717	0.0643
w_2	0.6686	0.1911	0.1595	0.0048	0.4923	1.0000	1.0000	0.2384
w_3	0.1358	0	0.8374	1.0000	1.0000	0.4612	0.4274	0.0778
w_4	0.5555	0.4733	0.3362	0.0998	0.4203	0.6000	0.7431	0.4247
w_5	0.6376	0.3893	0.0557	0.4280	0.1290	0.4475	0.1526	0.0995
w_6	0.9824	1.0000	1.0000	1.0000	1.0000	0.8046	0.7996	0.5314
ϕ_1	2.4141	4.2887	1.7463	3.3783	5.2772	4.9268	0.0018	0.5476
ϕ_2	6.2832	5.0383	0	1.0081	1.6613	0	3.6014	1.7011
ϕ_3	2.4627	5.7354	3.1725	1.4067	0.7773	0.0492	6.2831	3.7411
ϕ_4	3.0941	1.0569	4.5042	1.6800	4.9497	2.0395	3.9770	5.6860
ϕ_5	4.7641	2.0191	3.9395	0.5975	3.4197	6.2832	6.2227	2.8923
ϕ_6	6.2832	1.0221	3.2287	3.7762	3.6575	4.1013	1.5175	2.1799
Objective Function	0.7383							

mean value of the R.S.L.L. is 8.565 dB, the relative objective function is 0.7383 and the M.M.B.E. is 7.375° (see Table 7). The 6-element circular array also covers the x-y plane with 8 radiation patterns and the respective mean values are 59° and 9.114 dB while the objective function is 0.8114 and the M.M.B.E. is 2.25° (see Table 8). We can see that there is a better R.S.L.L. for the circular array but also a worse mean beamwidth. A possible reason is that the 6-element circular array is not inherently symmetrical with coverage of the x-y plane by 8-radiation patterns. The objective function is much greater for the circular array and also the standard deviation of the beamwidth is significantly lower for the circular array meaning that the radiation patterns are much more similar to each other than in the arbitrary-positions case. This is a very desirable characteristic in switched beam antenna arrays. In Tables 7 and 8 one can see the best results for the 6-element arrays with arbitrary element positions or circular formation,

Table 8. Results and relative voltage and phase coefficients for the 6-element circular array covering the x-y plane with eight radiation patterns.

	6 elements, 8 diagrams, Circular Formation							
# Pattern	1	2	3	4	5	6	7	8
ϕ_{max}	357°	38°	90°	135°	180°	222°	274°	314°
ϕ_-	328.5	9.5°	59.5°	107°	151°	193°	245°	284.5°
ϕ_+	26.5	72°	118.5°	164°	210°	253.5°	303°	345.5°
$\Delta\phi_{3dB}$	57	61.5°	59°	57°	59°	60.5°	58°	60°
Max R.S.L.L.	8.85 dB	9.45 dB	9.03 dB	8.91 dB	8.56 dB	10.01 dB	9.01 dB	9.09 dB
w_1	0.3148	0.5096	0	1.0000	0.6188	0.2618	0.9932	0.7642
w_2	1.0000	0.7903	0.5303	0.6765	0.1477	0.0622	0.3933	0.6664
w_3	0.3828	0.3969	1.0000	0.8150	0.2853	0.1354	0.4111	0
w_4	0.4691	0	0.4695	0.9024	1.0000	0.1442	0.5116	0
w_5	0.4481	0.3407	0.1394	0.5452	0.3934	0.3116	1.0000	0.6104
w_6	0.7234	0.3662	0.1731	0.1917	0.4955	0.1838	0.7640	1.0000
ϕ_1	5.8527	4.1510	5.1669	3.9242	3.3294	5.2817	1.6961	4.2503
ϕ_2	4.5582	5.4478	3.8472	4.9209	4.3252	2.2429	2.9749	4.7802
ϕ_3	0.8769	6.2831	2.4823	1.8810	1.6638	0.2230	0.0001	0.4777
ϕ_4	4.4251	4.1482	4.3595	1.7784	5.5141	4.1866	2.9336	0.9445
ϕ_5	1.5757	4.9131	2.1990	4.6319	0.2025	3.1812	6.2831	4.9260
ϕ_6	5.0444	1.6381	0.4297	1.8732	3.3009	5.5678	6.2832	3.2645
Objective Function	0.8114							

radiating at eight different directions. Also, the relative voltage and phase coefficients of the array elements are shown. In Table 9 one can see the radii and angles of the elements on the x-y plane for both cases. The two arrays are shown in Figs. 2 and 3. The radiation patterns of the 6-element array with arbitrary positions are shown in Fig. 4 through 11 and the radiation patterns for the 6-element circular array are shown in Fig. 12 through 19.

Finally, the GA is used in order to derive 4 radiation patterns covering the first 120° of the x-y plane. The main beams must point at 15°, 45°, 75° and 105° and the beamwidth must be 30°. Such an antenna may be used as a subsystem in sector antennas that are widely used in 2G mobile communications. Arrays consisted of 5 and 6 elements have been used. The 5-element array with arbitrary element positions presents a mean beamwidth value of 48.2° and a mean R.S.L.L. of 9.237 dB while the objective function is 0.7535 and

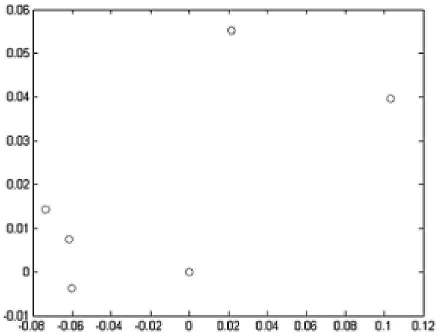

Figure 2. The 6-element array with arbitrary positions of elements radiating at 8 different directions.

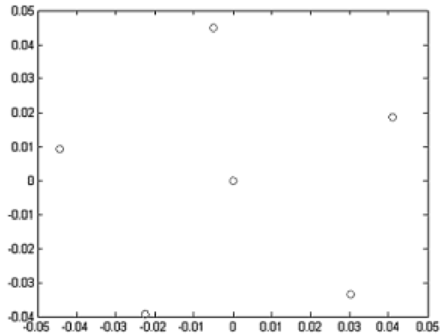

Figure 3. The 6-element circular array radiating at 8 different directions.

Table 9. Element positions for the 6-element arrays (circular and arbitrary element positions) covering the x-y plane with eight radiation patterns.

	6-element Array for x-y Plane Coverage with 8 diagrams, Arbitrary Positions of Elements					
# Element	1	2	3	4	5	6
Radius (m)	0.0593	0.0603	0.0752	0.0001	0.1104	0.0622
Angle (rad)	1.1955	3.2025	2.9515	3.8206	0.3680	3.0221
	6-element Circular Array for x-y Plane Coverage with 8 diagrams					
# Element	1	2	3	4	5	6
Radius (m)	0	0.0452	0.0452	0.0452	0.0452	0.0452
Angle (rad)	0	0.4231	1.6797	2.9364	4.1930	5.4496

the M.M.B.E. is 2.5° (see Table 10). For the 6-element array with arbitrary element positions the mean beamwidth is 42.6°, the mean R.S.L.L. is 9.728 dB, the objective function is 0.8027, and the M.M.B.E. is 3.5° (see Table 11). We can see a slight improvement in the mean beamwidth, the mean R.S.L.L. and the objective function of the 6-element array compared to the 5-element array. In Tables 10 and 11 the best results for the 5- and 6-element arrays covering the first 120° of the x-y plane are shown while in Tables 11 and 12 the relative voltage and phase coefficients as well as the element positions for the 6-element array are shown. The radiation patterns of the 6-element array with arbitrary element positions covering the first 120° of the x-y plane are shown in Fig. 20 through 23.

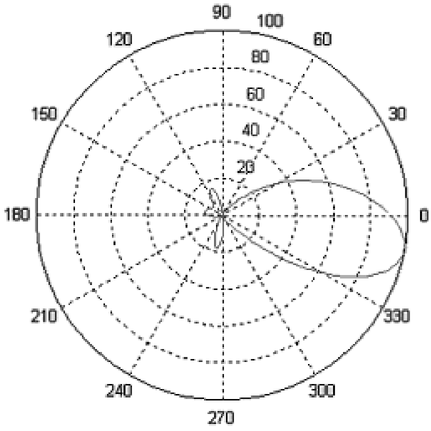

Figure 4. Radiation pattern at 0° for a 6-element array with arbitrary positions of elements.

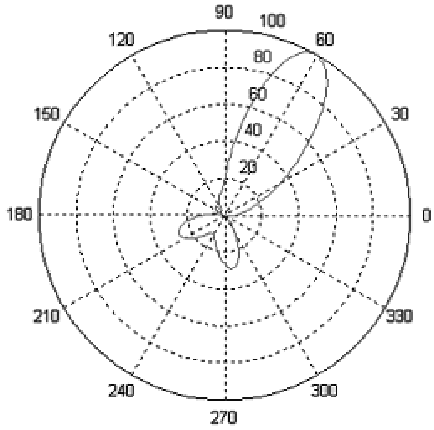

Figure 5. Radiation pattern at 45° for a 6-element array with arbitrary positions of elements.

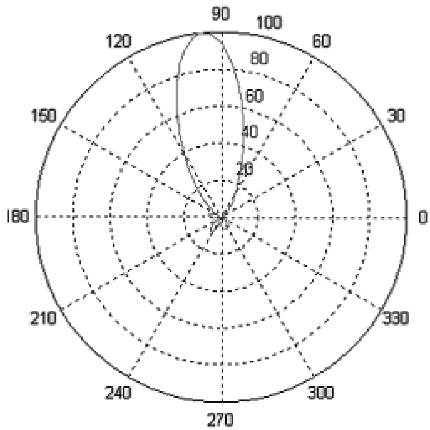

Figure 6. Radiation pattern at 90° for a 6-element array with arbitrary positions of elements.

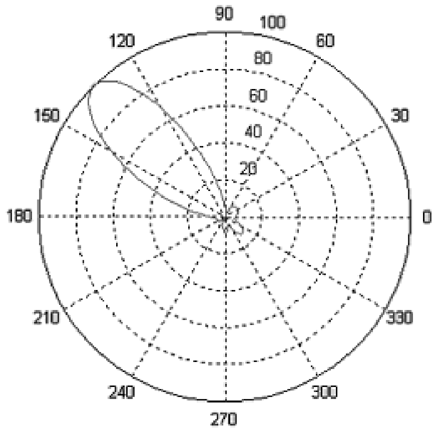

Figure 7. Radiation pattern at 135° for a 6-element array with arbitrary positions of elements.

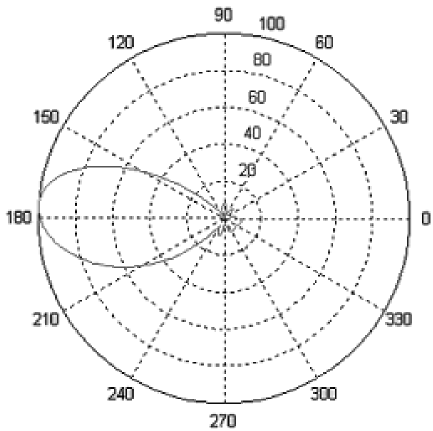

Figure 8. Radiation pattern at 180° for a 6-element array with arbitrary positions of elements.

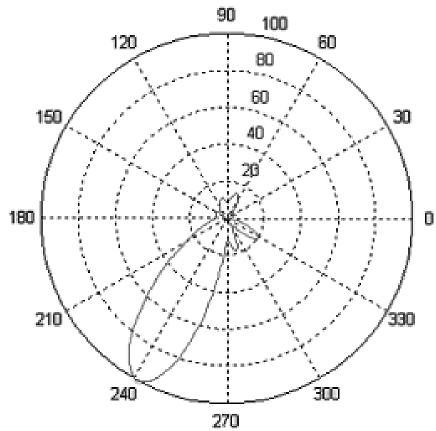

Figure 9. Radiation pattern at 225° for a 6-element array with arbitrary positions of elements.

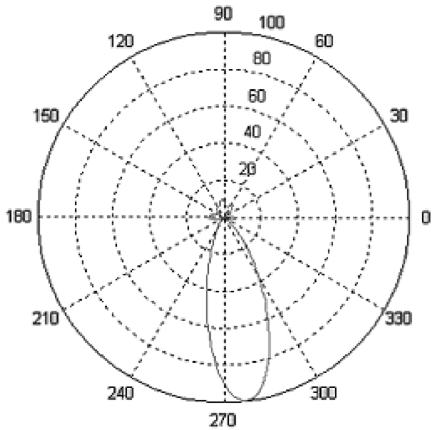

Figure 10. Radiation pattern at 270° for a 6-element array with arbitrary positions of elements.

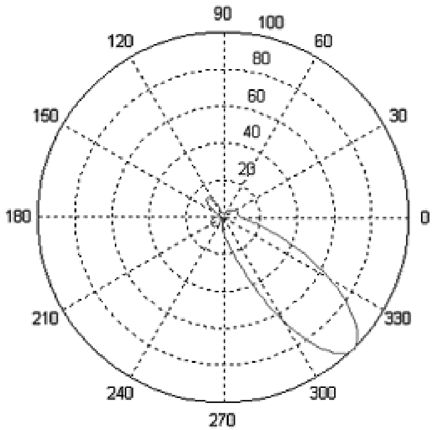

Figure 11. Radiation pattern at 315° for a 6-element array with arbitrary positions of elements.

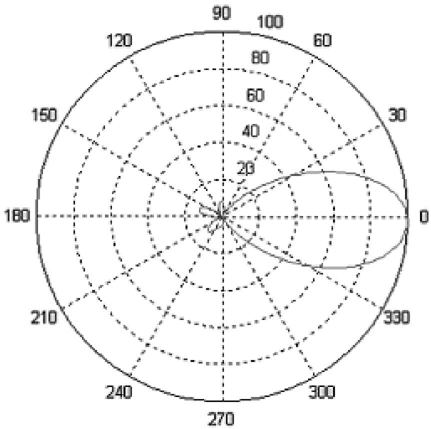

Figure 12. Radiation pattern at 0° for a 6-element circular array.

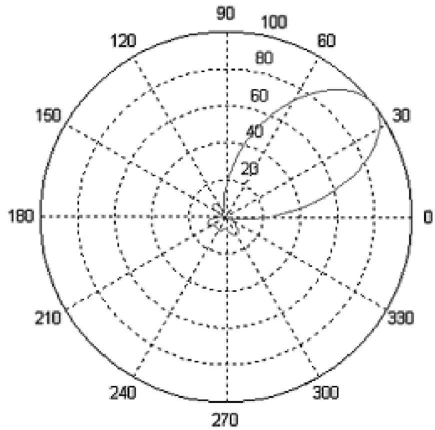

Figure 13. Radiation pattern at 45° for a 6-element circular array.

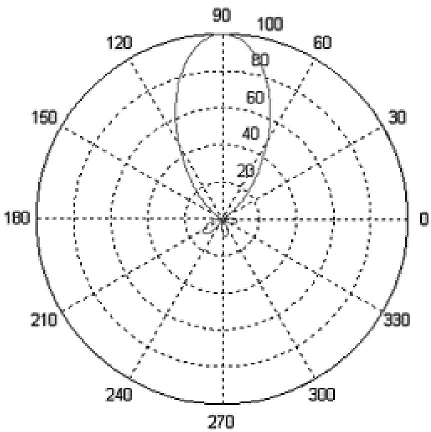

Figure 14. Radiation pattern at 90° for a 6-element circular array.

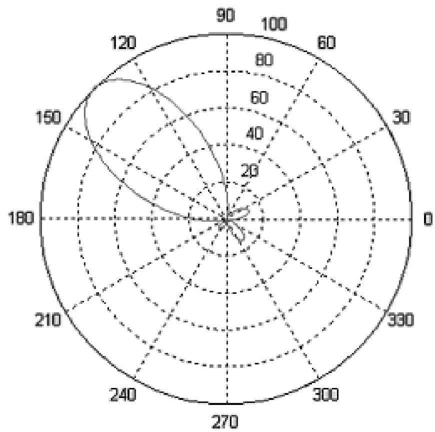

Figure 15. Radiation pattern at 135° for a 6-element circular array.

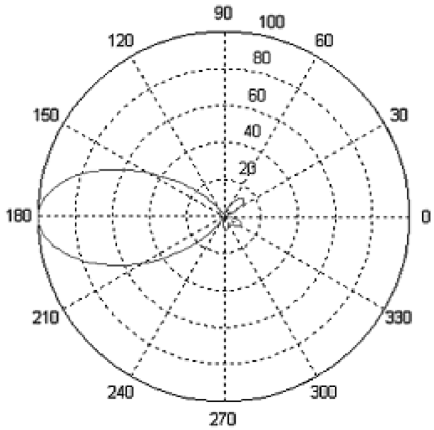

Figure 16. Radiation pattern at 180° for a 6-element circular array.

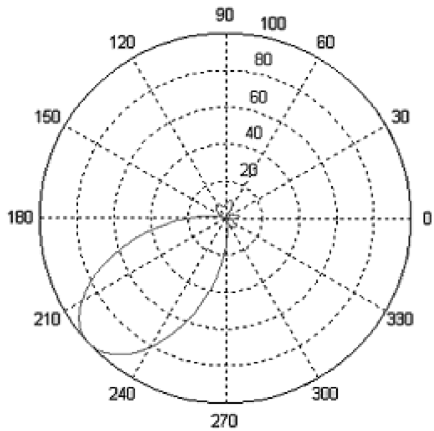

Figure 17. Radiation pattern at 225° for a 6-element circular array.

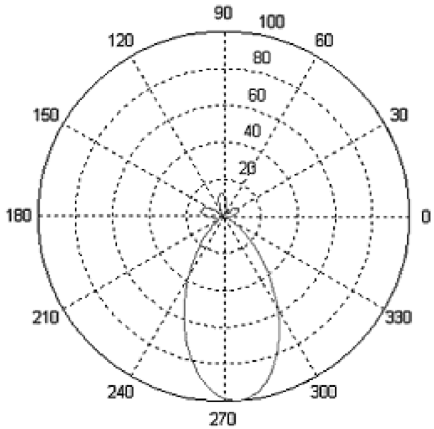

Figure 18. Radiation pattern at 270° for a 6-element circular array.

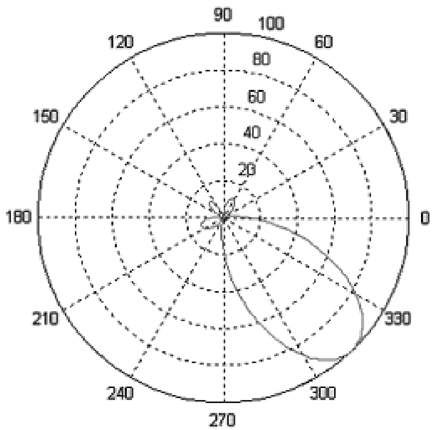

Figure 19. Radiation pattern at 315° for a 6-element circular array.

Table 10. Results for the 5-element array with arbitrary element positions covering the first 120° of the x-y plane with four radiation patterns.

	5-element Array, 4 diagrams, Arbitrary Positions			
# Pattern	1	2	3	4
ϕ_{max}	15°	50°	71°	106°
ϕ_-	-13.2°	27.0°	48.5°	83,0°
ϕ_+	40.4°	71.7°	95,7°	130,4°
$\Delta\phi_{3dB}$	53.7°	44.6°	47.2°	47.4°
Max R.S.L.L.	9.011 dB	8.975 dB	9.523 dB	9.440 dB
Objective Function	0.7535			

Table 11. Results and relative voltage and phase coefficients for the 6-element array with arbitrary element positions covering the first 120° of the x-y plane with four radiation patterns

	6-element Array, 4 diagrams, Arbitrary Positions			
# Pattern	1	2	3	4
ϕ_{max}	15°	45°	69°	97°
ϕ_-	23°	57°	85.5°	112°
ϕ_+	73°	100°	122°	153°
$\Delta\phi_{3dB}$	50°	43°	36.5°	41°
Max R.S.L.L.	8.36 dB	10.32 dB	10.68 dB	9.55 dB
w_1	0.4400	0.6607	0.4152	1.0000
w_2	0.7938	0.7734	0.9559	0.7739
w_3	0.4226	0.1644	0.4267	0.2218
w_4	0.3131	0.3172	0.0725	0.2663
w_5	1.0000	0.4604	0.4630	1.0000
w_6	0.8137	0.9695	1.0000	0.8337
ϕ_1	4.4882	2.6625	4.3878	6.2827
ϕ_2	2.4198	0.0003	0.0001	2.1558
ϕ_3	4.4217	6.2832	3.1827	1.3701
ϕ_4	0.4957	4.9165	6.2829	3.7335
ϕ_5	5.3958	1.0599	0.5716	2.4954
ϕ_6	1.7848	3.3625	0.9921	0.5338
Objective Function	0.8027			

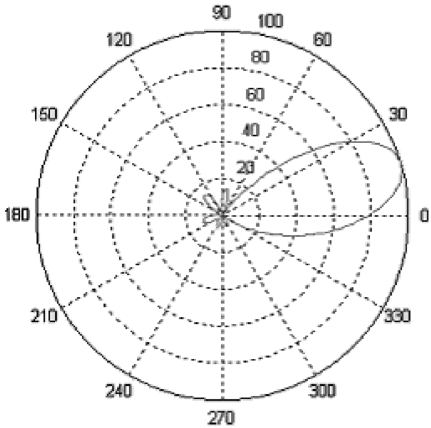

Figure 20. Radiation pattern at 15° for a 6-element array with arbitrary positions of elements.

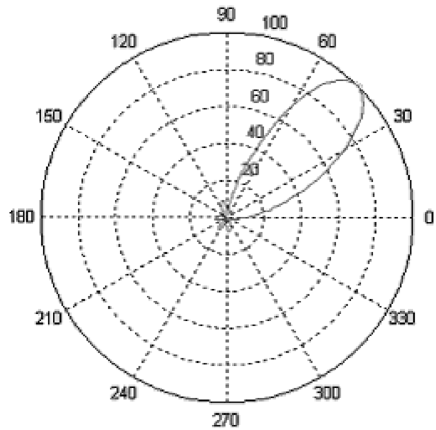

Figure 21. Radiation pattern at 45° for a 6-element array with arbitrary positions of elements.

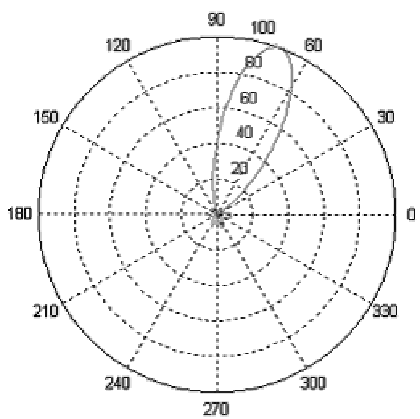

Figure 22. Radiation pattern at 75° for a 6-element array with arbitrary positions of elements.

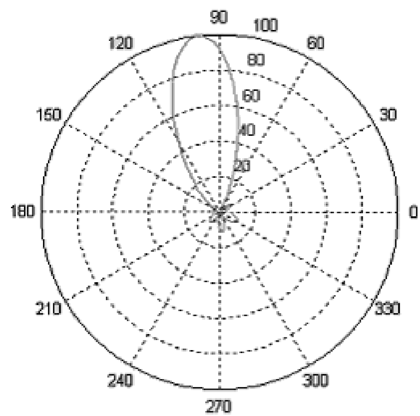

Figure 23. Radiation pattern at 105° for a 6-element array with arbitrary positions of elements.

Table 12. Element positions for the 6-element array covering the first 120° of the x-y plane with four radiation patterns.

	6-element Array for 120° Coverage with Arbitrary Positions of Elements					
# Element	1	2	3	4	5	6
Radius	0.0525	0.0618	0.0606	0.0119	0.0125	0.0548
Angle	0.8792	0.9282	3.3659	5.2509	1.1495	3.1552

4. CONCLUSIONS

A GA has been successfully used to design antenna arrays that cover symmetrically the x-y plane with 4 or 8 radiation patterns. The positions of the array elements are either exclusively chosen by the GA or form a circle and the GA chooses the radius and offset angle of this circle. Arrays with 5 and 6 elements are designed. Adding one more element in the array generally results in better radiation characteristics, as expected. Clearly the 6-element array can cover the x-y plane more effectively than the 5-element one. Also, one can exploit the symmetry of the radiation pattern and use symmetrical formations for the array. This results in arrays that are easier for the GA to design due to the reduction in the elements of the chromosome vector. The circular array offers better results except for the 6-element, 4-radiation patterns case. When symmetry does not exist the GA can be used to design arrays that cover a portion of the x-y plane effectively with non-symmetric element positions. Arrays of 5 and 6 elements are designed that cover the first 120° of the x-y plane with 4 radiation patterns. Again, the 6-element array is superior to the 5-element one.

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