Optimum design of shaped beam cylindrical array antenna with electronically scan radiation pattern

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Abstract
In this paper, the shaped beam cylindrical array is presented to obtain full angular scanning in the plane of the array. This array antenna is designed such that it produces sum and difference radiation patterns simultaneously. The array elements are wideband printed dipole antennas which operate in L- frequency band. To design of the array antenna at first step, certain numbers of the elements (16 elements) in a sector of the cylindrical array (active area) are used to synthesize by the Particle Swarm Optimization (PSO) method. In the second step to rotate the optimum radiation pattern extracted from the first step, appropriate feeding network is suggested to rotate the active area around the cylindrical array axis. Therefore the radiation patterns of the array antenna remain completely constant in all scan angles.

Keywords: Array Antennas, Particle Swarm Optimization

1 Introduction
Circular array antennas have been popular because of their capability to scan the radiation beam in all angles of the plane of array without any change in their radiation patterns. Moreover, compared to linear and rectangular arrays they are less sensitive to mutual coupling between their elements [1], [2]. The cylindrical array antennas combine the advantage of linear and circular arrays [3]. This is due to the fact that a cylindrical array antenna behaves such as a circular array in the azimuth plane (plane of the array) and a linear array in the elevation plane. Furthermore, in these array antennas by producing the active sector and rotating it the electronically scan radiation pattern is implemented [4], [5]. The key aspects in design of the cylindrical array antenna are to set the elements excitations including phase and amplitude and also the position of elements to reach the specific radiation pattern [6]. Conventional methods are not capable to design of the array antennas with complex arrangement. Therefore it is necessary to use more...
accurate methods to synthesize such array antennas. To date various optimization methods such as Genetic Algorithms (GA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Simulated Annealing (SA) and the bees algorithm have been used to synthesize different types of the array antennas [7], [8].

This paper presents the design of a cylindrical array antenna with electronically scan radiation patterns suitable for Identification Friend or Foe (IFF) radar systems. To this purpose, the 64 wideband printed dipole antennas are placed around the cylindrical ground plane. Then 16 elements are activated to create sum and difference radiation patterns to cover desired area in the azimuth plane. Electronic scanning can be achieved by moving the active region by suitable feeding network. The PSO is used to synthesize the radiation patterns in the active region to obtain the desired radiation patterns. This synthesis method is powerful, simple and computationally efficient. Also this method is capable to consider the mutual coupling between the array elements and compensate it in the design procedure. The array antenna and their elements are simulated by full wave EM software HFSS [9] based on the FEM. Section 2 of this paper presents the array configuration and the wideband printed dipole as the array element. Also, the suitable feeding network to produce the electronically scan radiation pattern is presented in this section. In section 3, the PSO is implemented to synthesize the cylindrical array antenna. In section 4 to verify the optimization results, the full wave simulations with investigating the mutual coupling compensation are presented which show good agreement between them.

2 Configuration of Array Antenna

The cylindrical array antenna consists of 64 elements of wideband printed dipole antennas that operate at L- frequency band. The configuration of this array antenna is shown in Fig.1. The inter-element spacing is 0.4λ at f=1GHZ. The dipole antennas are located along the z-axis and the optimization is carried out by 16 elements of the active region in H-plane (θ = 90°).

![Figure 1: Configuration of the cylindrical array with 64 printed dipole antenna](image)

2.1. Wideband printed dipole antenna

The printed dipole antenna is shown in Fig. 2. In this antenna the balun carried out by the printed transmission line which can be integrated with the antenna. The printed dipole with the integrated balun provides broadband performance that makes it suitable for wireless communication and array antennas [10], [11]. To obtain a wideband impedance matching with 50Ω, instead of using a ¼ stub, the feed point of the integrated balun is adjusted as described in [12]. The input reflection coefficient of the antenna for different values of feed point (H3) is shown in Fig.2.
Based on the proposed feeding network in the next sections, it is necessary to have two printed dipole antennas as transmitting and receiving antennas simultaneously. The input reflection coefficient of each antenna and their mutual coupling are shown in Fig 3. The antenna is designed on the Rogers RO4003 PCB board with $\varepsilon_r=3.38$ and a thickness of 32mil.

### 2.2. Active area in the cylindrical array

The cylindrical array with axial symmetry can produce scan-invariant radiation pattern around its axis. This is done by producing active area and rotating it around the axis of the cylindrical array. The main advantage of this method is that its radiation pattern remains constant at all scan angles. The elements of the cylindrical array antenna only are excited in the active area therefore by rotating the active area its radiation pattern rotates around the axis of the cylindrical array. Unlike the conventional array antennas, in this method to rotate the radiation pattern of the array antenna it is not necessary to vary the phase difference between the adjacent elements. Therefore, the radiation pattern keeps its original shape in all scan angles. In this paper, the active area is selected as 90° sector with 16 elements and the optimization process is carried out to this area to obtain the desired radiation pattern.

### 2.3. The feeding network configuration

Schematic of the proposed feeding network is shown in Fig. 4. This Network is designed for the IFF radar application with electronically scan ability. To this application it is necessary to have two sum and difference radiation patterns simultaneously. Thus, in the feeding network, two separate paths are carried out to create sum and difference radiation patterns. This feeding network operates as a transceiver system in which the signals at $f=1030\text{MHz}$ and $f=1090\text{MHz}$ are transmitted and received respectively. There is a
power divider 1:64 in each path. The 64 outputs of the power divider are connected to the 64 antenna elements of the cylindrical array. To excite the array antenna elements in the active region and also to rotate this area, 64 two state switches are embedded in all paths where only the 16 switches allow the signals transmitted to the antennas or received by the power dividers. By suitable control of switches the active region and therefore the radiation pattern of cylindrical array can rotate around the axis of cylindrical array. Also, the desired sum and difference radiation patterns can be produced in the active area using the digital phase shifters and attenuators. To this end the PSO optimization algorithm will be used in the next section to determine the optimum amplitudes and phases of the antenna excitations in the active region. In the final stage of feeding network the signals at $f=1030\,\text{MHz}$ and $f=1090\,\text{MHz}$ are separated by suitable filters to transmit and receive respectively. As is seen in this feeding network, the rotation of the radiation pattern of the antenna carried out by switching and displacement of the active region. Therefore, the radiation pattern remains invariant in all scan angles.

Figure 4: Proposed feeding network

3 Synthesis of the cylindrical array

As mentioned in the previous section the radiation pattern of cylindrical array antenna is rotated by rotating the active region as is shown in the Fig. 5. To obtain the desired radiation pattern only it is sufficient to determine the excitation coefficients of the antenna elements in the active region. To synthesize the cylindrical array antenna in the active region according to the IFF radar application we use the particle swarm optimization (PSO) procedure. To this purpose the desired radiation pattern for cylindrical array antenna in its active region is defined according to Fig. 6. The desired radiation pattern is divided into different parts with different weights depending on the importance and necessary resolution of each part. In the synthesis procedure, the array factor of the cylindrical array must be matched with desired radiation pattern using the PSO algorithm.
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The array factor for circular array of isotropic elements is:

\[ F(\theta) = E(\theta, \phi) = \sum_{n=1}^{N} I_n e^{j\beta r (\sin \theta \cos(\phi - \phi_n) - \sin \theta_0 \cos(\phi_0 - \phi_n))} \]  

(1)

Generally, the amplitudes and phases of excitation currents \( I_n = |I_n| e^{j\phi_n} \) of the array elements, control the shape of the radiation pattern of the array antenna. In (1), all elements are considered to have the same radiation pattern which does not happen in practice because of the mutual coupling effect between the elements. To consider the effect of the mutual coupling, it is necessary to consider the amplitude and phase of the radiated field of each element in presence of the other elements of the array. This radiation field \( E_n(\theta, \phi) \) is called the active radiation pattern for each element. \( E_n(\theta, \phi) \) for each element is multiplied by \( A_n e^{j\phi_n} \) and form the array factor as:

\[ F(\theta, \phi) = \sum_{n=1}^{N} A_n e^{j\phi} E_n(\theta, \phi) \]  

(2)

The normalized radiation pattern of the cylindrical array antenna which is used as the fitness function in the optimization procedure is:

\[ F_N = 10 \log_{10} \frac{F^2}{\max(|F|^2)} \]  

(3)
3.1. The PSO algorithm procedure for array synthesis

In 1995, Eberhart and Kenedy introduced particle swarm optimization algorithm which was an imitation of swarms of fish, bees and birds when exploring the space to find the maximum amount of food. The importance of this algorithm is due to its fast and accurate convergence, simple calculation steps, and easy implementation which are the result of the Newtonian law of motion as the base of this algorithm [13]. The PSO was introduced in electromagnetic by Robinson and Rahmat Samii [14]. Different applications such as synthesis of array antennas, optimization of reflector antennas, design of the patch antennas, design of frequency selective surfaces and microwave absorbers are the examples in electromagnetic where the PSO is implemented recently [15]. In this paper we use the PSO to synthesize the cylindrical array in its active region. The following steps are implemented to this purpose:

Step 1: Generating the random particles. In this research the two sets of particles are the amplitudes and phases of the elements. The random amplitudes of the excitations are defined as:

\[ X = \{ x_1, x_2, x_3, \ldots, x_{N-1}, x_N \} \]

The random phases of the excitations are defined as:

\[ Y = \{ y_1, y_2, y_3, \ldots, y_{N-1}, y_N \} \]

And, the random initial velocities are defined as:

\[ V = \{ v_1, v_2, v_3, \ldots, v_{N-1}, v_N \} \]

Step 2: In this step the new values of the amplitudes and phases of the excitations are obtained as follows:

\[ x_k = x_{(t-1)} + v_k^x \]  \hspace{1cm} (4)

\[ y_k = y_{(t-1)} + v_k^y \]  \hspace{1cm} (5)

\[ v_k^x = \omega_k v_{(t-1)}^x + r_1 c_1 (p_{(t-1)}^x - x_{(t-1)}) + r_2 c_1 (g_{(t-1)}^x - x_{(t-1)}) \]  \hspace{1cm} (6)

\[ v_k^y = \omega_k v_{(t-1)}^y + r_1 c_1 (p_{(t-1)}^y - y_{(t-1)}) + r_2 c_1 (g_{(t-1)}^y - y_{(t-1)}) \]  \hspace{1cm} (7)

\[ \omega_k = \omega_{max} - \frac{(\omega_{max} - \omega_{min})(k-1)}{k_{max}} \]  \hspace{1cm} (8)

\( v_k^i \) is the velocity of the ith particle in the kth iteration, \( x_k^i \) is the position of the ith particle in the kth iteration. \( r_1 \) and \( r_2 \) are random matrices, and \( c_1 = c_2 = 2 \) are called the acceleration coefficients. \( p^i \) is the best position of the particle in the kth iteration during its exploration and \( g \) is the global best of the whole group. The weighting coefficient, \( w \), is set to change linearly based on the equation (8) while \( w_{min} = 0.2 \) is the minimum value of the weighting factor, and \( w_{max} = 0.9 \) is its maximum value. \( k \) is the iteration number with the maximum value of \( k_{max} = 150 \).

Step 3: Defining the error function as:

\[ Error = \omega_1 \sum_{d=1}^{a_1} |F_d - F_N| + \omega_2 \sum_{d=a_1+1}^{a_2-1} |F_d - F_N| + \omega_3 \sum_{d=a_2}^{b_1} |F_d - F_N| + \omega_4 \sum_{d=b_1+1}^{b_2-1} |F_d - F_N| + \omega_1 \sum_{d=b_2}^{b_3} |F_d - F_N| \]  \hspace{1cm} (9)
F_d is the desired radiation pattern and F_N is the normalized calculated array factor (2) which is calculated in each iteration using the amplitudes and phases delivered by the PSO algorithm. The 2\textsuperscript{nd} step is continued until we obtain the acceptable error.

4 Simulation procedure

4.1. Cylindrical array synthesis in the active region with an Investigation of the Mutual coupling

The array configuration is shown in Fig. 1. In this configuration because of the presence of far field mutual coupling between the elements, the radiation pattern of each element differs from the other elements. To consider this effect, the complex active element patterns are used in the optimization procedure. To this end, the active patterns of the array elements are created using the HFSS based on the FEM method [16]. The typical active radiation patterns of elements 1, 4, 8, 12 and 16 for both amplitude and phase are shown in Fig. 7(a) and Fig. 7(b) respectively.

![Figure 7](image-url)

(a) The Normalized amplitude of E-Field of elements 1, 4, 8, 12 and 16 in the array (b) The phase of E-Field of elements 1, 4, 8, 12 and 16

4.2. Simulation and Optimization result

The optimization is performed twice. At first, the desired pattern is obtained with isolated element and without considering the mutual coupling in the optimization process. As seen in Fig. 8 due to the effect of mutual coupling the HFSS simulation result is different from the optimization result.

![Figure 8](image-url)

Figure 8: Normalized E-Field radiation pattern of 16 printed dipole antennas in active area without considering Far-Field mutual coupling

In order to compensate the mutual coupling effect, the active radiation patterns of the elements shown in Fig. 7(a) and Fig. 7(b) are used in the optimization algorithm. The optimization and simulation results are
depicted in the Fig. 9 where show a good agreement between them. The radiation pattern converges to the desired radiation pattern after 50 iterations.

![Normalized E-Field radiation pattern of 16 printed dipole antennas in active area with consideration the Far-Field mutual coupling](image)

Figure 9: Normalized E-Field radiation pattern of 16 printed dipole antennas in active area with consideration the Far-Field mutual coupling

To construct the difference radiation pattern, we use the optimum amplitudes of the sum radiation pattern. The optimum phase coefficients are divided into two sets and 180 degrees are added to half of them. The constructed difference radiation pattern using this procedure is shown in Fig. 10 which presents the acceptable difference radiation pattern for IFF application.

![Normalized sum and difference E-Field radiation patterns for the IFF radar application](image)

Figure 10: Normalized sum and difference E-Field radiation patterns for the IFF radar application

As was mentioned in the section II.3, the optimum amplitudes and phases are implemented using digital attenuators and phase shifters respectively. Therefore it is necessary to quantize the optimum amplitudes and phases obtained from the PSO to acceptable values for digital attenuators and phase shifters. The quantized values of the amplitudes and phases for 8 bite digital attenuators and phase shifters are depicted in Table 1.
Table 1: Amplitude and phases of elements excitations

<table>
<thead>
<tr>
<th>PSO Amplitude</th>
<th>Quantized Amplitude</th>
<th>PSO Phase(Deg)</th>
<th>Quantized Phase(Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1186</td>
<td>0.1250</td>
<td>117.504</td>
<td>118.125</td>
</tr>
<tr>
<td>0.1015</td>
<td>0.1094</td>
<td>338.3834</td>
<td>337.5</td>
</tr>
<tr>
<td>0.2338</td>
<td>0.2344</td>
<td>283.9936</td>
<td>281.125</td>
</tr>
<tr>
<td>0.4064</td>
<td>0.4063</td>
<td>130.5519</td>
<td>129.3750</td>
</tr>
<tr>
<td>0.5683</td>
<td>0.5625</td>
<td>52.5027</td>
<td>50.625</td>
</tr>
<tr>
<td>0.8919</td>
<td>0.8906</td>
<td>5.4957</td>
<td>5.625</td>
</tr>
<tr>
<td>0.6656</td>
<td>0.6563</td>
<td>315.3834</td>
<td>315</td>
</tr>
<tr>
<td>0.8720</td>
<td>0.8750</td>
<td>280.5226</td>
<td>281.25</td>
</tr>
</tbody>
</table>

The quantized radiation pattern derived from the quantized amplitudes and phases is shown in Fig. 11. As is seen in this figure the quantized radiation pattern has an acceptable agreement with the non-quantized optimum radiation pattern. To obtain the more accurate radiation pattern it is necessary to use the digital attenuators and phases shifters with more bits.

Figure 11: The PSO synthesis result and HFSS simulation result for quantized amplitudes and phases

5 Conclusion

In this paper, the cylindrical array antenna with the ability of the electronically scanning to full coverage in the azimuth plane was presented. This array antenna was designed to use in the IFF radar application. The PSO was implemented to synthesize the array in its active region with including the effect of mutual coupling between the array elements. The optimum sum and difference radiation patterns were obtained by this algorithm. The designed cylindrical array consist of the 64 printed dipole antennas with spacing d=0.4λ operating at L- frequency band. The suitable feeding network for this system was presented so that it can rotate the active region and therefore the radiation pattern of the antenna.

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