Obtaining Performance Similar to Rectangular Planar Antenna Using Crossed Arrays with Smaller Number of Elements

Abdulrazaq Abdulhaq Khmees and Jafar Ramadhan Mohammed

1College of Electronic Engineering, Ninevah University, Mosul-41002, Iraq

*E-mail: abdulrazaq.khmees2019@stu.uoninevah.edu.iq

Abstract. Conventional rectangular planar arrays with fully filled elements are practically very complicated especially for large arrays. They usually occupy a large space. Thus, any reduction in the space and the number of the array elements is highly desirable in many applications. In this paper, the authors present a novel technique for obtaining a performance similar to that of the conventional rectangular planar antenna using two orthogonal crossed arrays with a smaller number of elements. The proposed technique consists of redesigning the amplitude element excitations of only two crossed arrays using either deterministic or optimization algorithms. Simulation results are shown to prove the proposed idea.

1. Introduction

In certain applications such as massive MIMO wireless communication and the satellite systems, the weight of the used antenna array is need to be as small as possible and takes a small space. Thus, designing of such arrays with a fewer number of elements while maintaining a good radiation characteristic is highly desirable. Other advantages of such antennas with a fewer number of array elements include lower cost and great simplification in the array feeding network. Uniformly excited rectangular planar arrays are commonly used to generate pencil beam patterns with good directivity which can be made electronically steerable by properly controlling the progressive phases of the array elements [1]. The authors in[2], present a method for reducing the number of array elements based on the matrix pencil method (MPM). The method was applied to the non-uniform linear arrays to synthesize a pre-specified radiation patterns with limited number of elements. In[3], the authors present a narrowband MIMO imaging radar with two orthogonal linear T/R arrays where they were able to get an image resolution with a small number of array elements that is close enough to that of the conventional two-dimensional planar array that uses all of the array elements. In [4], the authors designed a MIMO cross array with azimuth-elevation combination beamforming capability by the use of DBF systems. They greatly reduced the number of the designed arrays with compared to the conventional two-dimensional rectangular array of one-way and two-way beamforming. Their proposed configuration were able to reduce the size of the designed array from (M x N) to only (M+N+4) elements. In[5], the authors analyzed the performance of the square planar arrays in term of their radiation patterns with that of the Mills cross array. They found that, although the square planar arrays have better efficiency, the Mills array was able to provide good directivity for the applications of a 5G mobile handset at 28 GHz.

In[6], the authors suggested to use the Bayesian compressive sensing to minimize the number of the array elements. They were able to achieve the required radiation patterns of both linear and planar arrays with minimum number of array elements. In [7], the authors use convex optimization to design the crossed array with minimum number of the array elements to achieve the required radiation
pattern. However, in general, reducing the number of the array elements is associated with the losses in the directivity which is undesirable in many of the aforementioned applications. Thus, instead of reducing or minimizing the number of the array elements, it is possible to select a certain number of the array elements to be controllable with required RF components such as variable attenuators, variable phase shifters, and other hardware to control the array radiation patterns according to the required goals. In[8–12], the authors suggested different optimization methods and configurations to control only the amplitude and the phase excitations of a number of the selected elements instead of all of the array elements. Thus, a great reduction in the array weight, cost, and feeding complexity was obtained without any loss in the directivity. The inverse fast Fourier transform (FFT) method has been also suggested, in [13]to synthesize antenna array patterns with controlled sidelobes and improved directivity.

In this paper, the authors demonstrate that by a simple configuration of two crossed arrays along with a proper choice of the element weightings, the radiation pattern of the crossed array which has a very small number of elements can be made equal to that of the conventional rectangular array with fully grid large number of elements. The element weightings of the proposed crossed array can be computed either deterministically through the use of triangular, Dolph, Taylor distributions or numerically through the use of genetic algorithm.

2. Principles of The Proposed Cross Array

Consider a fully filled conventional rectangular planar array with odd number of isotropic elements equal to $(2N + 1) \times (2M + 1)$ as shown in Figure 1. The array elements are assumed to be located in the x-y plane and the coordinate system’s origin is set to be the array’s geometric center. The array factor of this antenna can be expressed as[1]

$$AF(\theta, \phi) = \sum_{n=1}^{2N+1} \sum_{m=1}^{2M+1} w_{nm} e^{j[(m-1)kd_x \sin \theta \cos \phi] + j[(n-1)kd_y \sin \theta \sin \phi]}$$

(1)

where $w_{nm}$ is the coefficients of the amplitude element excitation, $d_x$ is the spacing between elements along the x-axis and $d_y$ is the spacing between elements along the y-axis, $k = 2\pi/\lambda$ and $\lambda$ is the wavelength in free space.

Figure. 1 Conventional rectangular array

For simplicity, we will assume a symmetric square planar array with total number of elements equal to $(2N + 1) \times (2N + 1)$. From equation (1), it can be seen that the synthesis of the fully filled rectangular array is complex and computationally intensive, especially when the number of elements is large. To simplify this complicated array, the authors suggest replacing this square planar array to only two orthogonal linear crossed arrays as shown in Figure 2. The total number of the elements in the
The crossed array is made to be \(4(2N) + 1\). The patterns of the two crossed linear arrays with a total number of elements \(4(2N) + 1\) have been combined to produce an effective pattern that is equivalent to that of the fully filled square planar with a total number of elements \((2N + 1)^2\). To achieve such matching between the radiation patterns of these two antenna arrays, the amplitude element excitation of the crossed arrays needs to be properly computed.

The array factor of the symmetric two orthogonal linear arrays can be written as:

\[
AF(\theta, \phi) = 2 \times w_n + 2 \sum_{n=1}^{2N} w_n \left[ \cos(n(kd_x \sin \theta \cos \phi)) + \cos(n(kd_y \sin \theta \sin \phi)) \right]
\]  

(2)

If the element weightings \(w_n\) are all uniformly excited, then the resultant radiation pattern will have usually high sidelobe level[14]. Figure 3, show the radiation patterns in three-dimension at \(N=2\) for both conventional planar array with size \((2N + 1) \times (2N + 1)\) and the proposed cross array with size \(4(2N) + 1\) and uniform excitations, i.e., \(w_n = 1\) for all elements (This design is referred to as Design 1).

It can be seen from that the radiation pattern of the crossed array with uniform excitation has a relatively high sidelobe level. Thus, we need to redesign or recalculating the amplitude element excitations of the crossed array such that the sidelobes can be reduced.
One of the simplest techniques that can be used to reduce the side lobe level is by selecting the amplitude element excitations of the crossed array according to a specific taper, i.e., triangular taper (this design is referred to as Design 2) as given by the following equation:

\[ w_n = 2N + 1 - |n|, \quad \text{for} \quad 0 \leq |n| \leq 2N \]  

(3)

Where the weights of the elements at each arm from center to edge of crossed array having a tapered linear slope. Further, the above equation represents a straight line with a slope equal to 1. Moreover, it is also possible to apply other tapering such as Dolph (this design is referred to as Design 3) or Taylor (this design is referred to as Design 4) as will be shown in the next section. More important, the amplitude element excitations of the proposed cross array can be optimized using genetic algorithm to obtain lower sidelobe level (this design is referred to as Design 5).

3. Simulation Results

To demonstrate the usefulness of the proposed two orthogonal linear cross array, different examples are illustrated. In the first example, a small size arrays are considered where the amplitude element excitations of all the five designs of the proposed cross arrays and their corresponding radiation patterns are computed and compared. In the second example, a large size arrays are considered. In these two examples, antennas of an equally spaced linear arrays \( d_x = d_y = \lambda / 2 \) is considered, in addition, the amplitude-only control method is used to synthesis the excitation coefficients of the tested arrays. Thus, the phase element excitations are assumed to be zero.

For example 1, we assume a small square planar array with size equal to \( (2N + 1) \times (2N + 1) = 5 \times 5 \) and the coefficient weights of the element excitation are assumed to be uniform. The proposed cross array has a size equal to \( 4(2N + 1) = 17 \). The coefficient weights of this array are also assumed to be uniform (design 1). The coefficient weights of the element excitation are then redesigned using triangular taper (design 2), Dolph with required SLL=-20 dB (design 3), Taylor with SLL=-20 dB and \( nbar = 4 \) (design 4), and the genetic algorithm (design 5). Figure 4 and table I show the results of these five designs.

Furthermore, the dilution factor has been defined as the percentage ratio of the total number of elements in the proposed design, to the total number of the elements in the conventional square planar array. Thus, a smaller value of the dilution factor represents the better design.

\[
\text{Dilution factor} = \frac{\text{Total element number in the proposed design}}{\text{Total element number in conventional square array}} \times 100\% 
\]

(4)

Accordingly, the Dilution factor of the proposed cross array under this case is \( 17/25 = 68\% \).
Figure 4. Results of the tested arrays for square array with size \((2N + 1) \times (2N + 1) = 5 \times 5\) and crossed array with size \(4(2N + 1) = 17\). (a) Radiation patterns of the designed arrays, (b) Amplitude excitations of the planar array, (c) Triangular taper (design 2), (d) GA (design 5).

| The Method                     | Directivity [dB] | Peak SLL [dB] | FNBW [Deg.] | HPBW [Deg.] |
|--------------------------------|------------------|---------------|-------------|-------------|
| uniformly Excited square array | 15.5             | -13.1         | 47          | 20.5        |
| Uniformly Excited array design1| 14.5             | -9.9          | 24.6        | 12          |
| Triangular taper array design2 | 15.1             | -11.7         | 31.8        | 15.6        |
| Dolph taper array design3      | 14.0             | -11           | 27.3        | 13          |
| Taylor taper array design4     | 14.07            | -11           | 27.3        | 13          |
| GA array design5               | 13.3             | -11.3         | 31.3        | 16          |
From figure 4 and the table 1, it can be seen that the level of the peak side lobe in the crossed array pattern has been slightly reduced. This reduction can be significantly reduced with larger array sizes as can be seen in the next example. Thus, the proposed crossed array method is found to be more suitable for the applications that require large array sizes such as massive MIMO.

For example 2, we assume a large square planar array with size equal to $(2N + 1) \times (2N + 1) = 31 \times 31$ and the coefficient weights of the element excitation are assumed to be uniform as previous. The proposed cross array has a size equal to $4(2N) + 1 = 121$. The coefficient weights of proposed cross array are found using the five design methods as previous. Figure 5 and table II show the results of this case of large arrays. The dilution factor of this case is $\frac{121}{961} = 12.59\%$

![Figure 5](image-url)
From Figure 5 and table II, it can be seen that the results of the method that use the genetic algorithm are the best one among all other methods.

4. Conclusions

It has been shown from the presented results that the designed cross array with a total number of elements equal to $4(2N) + 1$ and adjusted amplitude excitations can be an alternative to the conventional rectangular planar array with a total number of elements equal to $(2N + 1) \times (2N + 1)$. For a small size array, for example $N=2$ (the total number of elements is 17), the Dilution factor was found to be 68%. This factor has been significantly reduced for a large array size, for example $N=15$, to only 12.59%. Thus, the number of the elements in the crossed arrays has been greatly reduced with compared to that of the conventional planar array. This reduction is come at the cost of relatively lower directivity. Nevertheless, the peak sidelobe level of the designed pattern of the crossed array is much lower than that of the conventional rectangular planar array which is another key advantage for the proposed array.

5. References

[1] Balanis C A 2016 *Antenna theory analysis and design* (Hoboken, New Jersey)
[2] Liu Y, Nie Z and Liu Q H 2008 Reducing the number of elements in a linear antenna array by the matrix pencil method *IEEE Trans. Antennas Propag.* **56** 2955–62
[3] Wang H and Su Y 2008 Narrowband MIMO radar imaging with two orthogonal linear T/R arrays *Int. Conf. Signal Process. Proceedings, ICSP* 2513–6
[4] Lu Y and Tang Y 2014 A study of cross array with MIMO DBF *IEEE Antennas Propag. Soc. AP-S Int. Symp.* 482–3
[5] M. J. Martínez Silva M S R P 2017 Radiation Pattern Analysis of Mills Cross Array of Patch Antennas for 5G Mobile Handset Applications *Int. J. Res. Electron. Electr. Eng.* **3** 1–6
[6] Zhang W, Li L and Li F 2011 Reducing the number of elements in linear and planar antenna arrays with sparseness constrained optimization *IEEE Trans. Antennas Propag.* **59** 3106–11
[7] Gu B, Chen Y, Jiang R and Liu X 2020 Optimization of sparse cross array synthesis via
perturbed convex optimization *Sensors (Switzerland)* **20** 1–17
[8] Mohammed J R and Sayidmarie K H 2014 Sidelobe cancellation for uniformly excited planar array antennas by controlling the side elements *IEEE Antennas Wirel. Propag. Lett.* **13** 987–90
[9] Mohammed J R 2018 A new antenna array pattern synthesis method with sidelobe control *J. Telecommun. Electron. Comput. Eng.* **10** 31–6
[10] Mohammed J R 2018 Element Selection for Optimized Multiwide Nulls in Almost Uniformly Excited Arrays *IEEE Antennas Wirel. Propag. Lett.* **17** 629–32
[11] Mohammed J R 2020 Phased Sub-arrays Pattern Synthesis Method with Deep Sidelobe Reduction and Narrow Beam Width Jafar
[12] Mohammed J R 2020 Simplified rectangular planar array with circular boundary for side lobe suppression *Prog. Electromagn. Res.* **M97** 57–68
[13] Mohammed J R 2021 Rectangular Grid Antennas with Various Boundary Square-Rings Array 10
[14] Bracewell R and Roberts J 1954 Aerial Smoothing in Radio Astronomy *Aust. J. Phys.* **7** 615