Array Pattern Reconfiguration Using Pixel Method

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***Abstract* ─** In this paper, the array elements are considered as pixels and their magnitude excitations are assigned to the values of 1 (i.e., active or turned ON) or 0 (i.e., inactive or turned OFF). Thus, each element either exists at its position in the considered array or not. The proposed pixel method can be applied to different planar array configurations such as square, rectangular, triangular, circular, or any other shape to achieve the required pattern reconfigurability. Moreover, by turning OFF some of the selected elements, the main beam of the array pattern can be switched to specify directions without using any phase shifters or any other RF components. Therefore, its practical implementation is simpler and cheaper than any other existing method. However, when comparing with arrays in which all their elements are turned ON, the gain of the considered arrays will be reduced when some selected elements are turned OFF. The array pattern reconfiguration using the pixel method has been designed and its parameters have been optimized using computer simulation Technology (CST-MWS), which uses the Finite Integration Technique (FIT). It's also verified by High-Frequency Surface Structure (HFSS) commercial software (based on the FEM method). Numerical results obtained under full-wave modeling CST environment demonstrate the effectiveness of the described method.

***Index Terms* ─** Beam steering, magnitude excitation, pattern configuration, pixel arrays, planar arrays.

I. INTRODUCTION

Currently, the array pattern reconfiguration becomes one of the important issues in the satellite and terrestrial communication systems, where the radiating parts of the transmitting and/or receiving devices in such systems need to be continuously reconfigured to assure reliable link over dynamic channels or environmental conditions. The design of the antenna arrays has been developed toward compact and simple architectures such as conventional beamforming [1], smart arrays [2-4], and re-configurable array patterns [5-11].

The array pattern configurability and beam steering capability of such types of antenna arrays are traditionally accomplished by using phase shifters, variable attenuators, and other RF components that connected to each element of the array in the feeding network which exhibits a complex circuitry. In addition, the use of phase shifters in such arrays exhibit scans loss and errors which lead to performance degradation [12].

Recently, the radiation characteristics of the reconfigurable arrays can be changed by using switches such as PIN diodes to connect the required elements and to achieve the desired radiation patterns [13].

Very recently, the array pattern configuration has been achieved by means of parasitic elements [14]. In such approaches, the need for phase shifters has been overcome. Therefore, the loss and error problems associated with the progressive phase shift between array elements are alleviated.

In this paper, the radiation characteristics such as beamwidth, gain, sidelobe level, and main beam direction of planar arrays can be controlled by turning ON/OFF a certain number of the array elements by selecting their magnitude excitations to be either 1 or 0. This type of array is known as Pixel Array. It can offer a great reduction in the cost and weight of the feeding network circuitry. Further, the method is capable to provide a narrow beamwidth that is approximately equal to that of the fully active array elements under the condition of keeping the same array size. Also, the elements that turned ON (active) with magnitude excitation selected to be 1, in an array is able to provide a lower sidelobe level with respect to that of the fully uniform array where all of its elements are active [15]. In this type of arrays, the directivity will depend directly on the number of turned on elements. The key feature of the proposed planar array is its ability to switch the main beam to some pre-specified directions in the azimuth plane without using any phase shifters or any other RF components.

Since the simplicity and versatility of the proposed pixel planar array are assured, thus, it can be recognized as a good candidate for 5G technologies in which the communication efficiency is of great importance [16].

Furthermore, the performance of the proposed array has been investigated and verified using (CST-MWS)

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software. The Time-Domain solver was used to obtain the required results [17]. Parametric studies and optimization using the built-in Trust Region Framework Algorithm which is a numerical optimization for solving nonlinear programming problems have been used. Section II describes the concept of designing the proposed array starting from a single patch, while section III presents the results. Section IV presents a numerical comparison of the results achieved by CST and HFSS [18]. Finally, the conclusions are listed in Section V.

II. THE PLANAR PIXEL ARRAY

In this work, the shape of the considered planar array is chosen to be triangular which is derived from an original square planar array with (NxN) elements. However, the proposed pixel method can be straight forwarded to any other planar shape. To illustrate the concept of the pixel elements, first the proposed planar array with assigned magnitude values is shown in Fig. 1. It consists of two sets of elements. The first set contains the active elements, while the second set contains only inactive elements. Here, each element in the considered array is chosen to be a small circular patch. Then an array of such patches is formed. The details of each part are shown in the next sections.

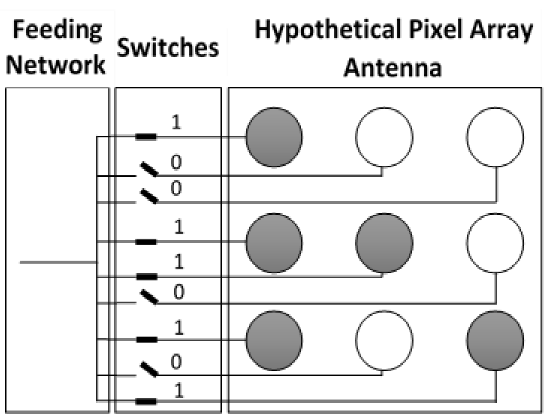


Fig. 1. Pixel array feeding network: gray (active elements) and white (inactive elements).

A. Single element circular patch antenna

The substrate of such a Patch element is chosen to be FR-4 with thickness h=1.6 mm, relative permittivity εr=4.3, and dielectric loss tangent of 0.025. The proposed antenna has been chosen to work at 2.4 GHz, which then designed, simulated and optimized. The structure of a single element circular patch antenna is shown in Fig. 2, where R represents the radius of the patch which is chosen to be 19 mm and F represents the feeding point. The procedure for designing the circular patch is illustrated below.

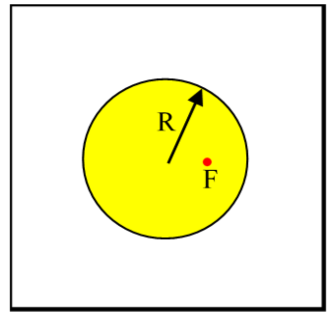


Fig. 2. Structure of the single element circular patch antenna.

The actual radius of the patch R at the resonant frequency f_0 can be calculated as in the following equations [19]:

$$f_0 = \frac{1.8412\times V}{2\pi R\sqrt{\varepsilon_r}}, \tag{1}$$

where V is the speed of light in the Freespace. The fringing effect does not take into account when calculating the f_0 in (1). Consequently, an effective radius R_e has been considered to replace the actual radius R as:

$$R_e = R\left\{1+\frac{2h}{\pi\varepsilon_r h}\left[ln\left(\frac{\pi R}{2h}\right)+1.7726\right]\right\}^{0.5}. \tag{2}$$

Therefore, and based on (2), the resonant frequency of (1) can be given as:

$$f_0 = \frac{1.8412\times V}{2\pi R_e\sqrt{\varepsilon_r}}. \tag{3}$$

Then, a first-order approximation to the solution of (2) for R is given by:

$$R = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[ln\left(\frac{\pi R}{2h}\right)+1.7726\right]\right\}^{0.5}}, \tag{4}$$

where F:

$$F = \frac{8.791\times 10^9}{f_0\sqrt{\varepsilon_r}}. \tag{5}$$

The excitation of the circular patch can be achieved by more than one technique such as a coaxial probe, a microstrip line, electromagnetic coupling or aperture coupling. A coaxial probe has been used as the feeding network of the antenna. The position of the feeding point with the patch must be equal to the characteristic impedance of the probe which is 50 Ω. The optimization tool of the CST-MWS has been used to specify the exact point which is matched the feeder characteristic impedance. It has been found that the feeding point that matches the characteristic impedance is F=7 mm from the circular patch center. The SMA connector has been mounted on the antenna back-side. Figure 2 shows the antenna feeding point. Figure 3 shows the Reflection Coefficient (S_{11}) of the designed circular patch antenna which is optimized to be < -10 dB. It is clear that the CST and HFSS simulators are giving almost the same results corresponding to the bandwidth, and deeper S_{11} for the CST at the operating frequency.

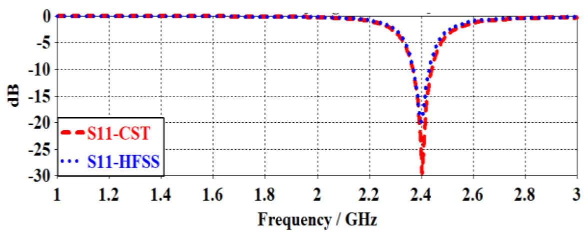


Fig. 3. S_{11} for the designed single element circular patch antenna.

B. Design of the triangular planar array

The geometry of the proposed planar array is shown in Fig. 4, the design consists of a number of single circular patch elements arranged in a right-angle triangle shaped planar array.

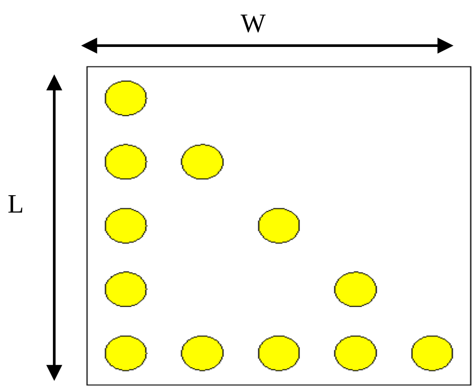


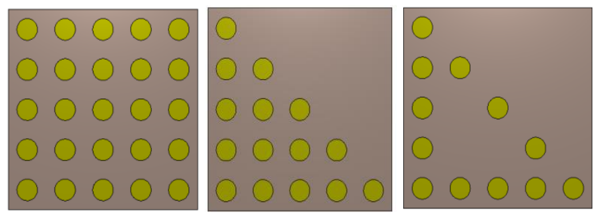
Fig. 4. Proposed planar antenna array, *W=L=312 mm*.

The design procedure of such a planar array has been divided into three steps as follows; in the first step, a single element circular patch antenna has been designed. In order to obtain the best performance, the patch has been optimized using CST built-in Trust Region Framework Algorithm. In the second step, a planar array or 5 × 5 elements are designed. Then, the active elements of the designed array have been reduced. Finally, to measure the performance, a comparison between the fully active array elements and the proposed array is presented.

C. Array configurations

A planar array of 5 × 5 circular patch antennas has been formed as shown in Fig. 5 (I). In order to keep the mutual coupling between the elements as small as possible, the spacing between any successive elements in the considered planar array is set to be as $\lambda_e/2$ in both *X* and *Y* direction, then it is optimized to have the best performance.

The main idea of this paper is to minimize the number of active elements and simplify the feeding network circuitry. Also, the performance of the designed array should be kept as close as possible to that of the fully active arrays. Thus, the removal of the active elements from the planar array has been applied in two steps. The first one is by removing the upper right six elements as in Fig. 5 (II). Then, removing another three elements from the center of the triangle as in Fig. 5 (III). The structure that is shown in Fig. 5 (III) has many important features where it consists of three sides (vertical, horizontal, and diagonal (sloped by 45 degrees)). These three sides can be used to generate different radiation patterns with different main beam direction as can be seen in the next section.



(I) (II) (III)

Fig. 5. Array configuration: (I) fully 5 × 5 array antenna, (II) array after removing the upper right six elements, and (III) the proposed planar antenna array.

III. SIMULATION RESULTS

Each side of the right-angle triangle shaped planar array can be considered as separate linear sub-array elements. Their corresponding radiation patterns can be configured in different directions with different polarization. The main beam directions can be switched toward any of the following three cases. In all these cases, it is worthy to mention that the directivity of the original fully active array elements (i.e., all of 25 elements in 5 × 5 array are set to be on and active) is (19.8 dB). Certainly, this value of the directivity cannot be maintained when switching OFF some of the array elements as can be seen in the following cases. The three cases have been simulated using CST then the results have been further verified using HFSS, the results show great similarities. For simplicity, the CST has been chosen to present the remaining results.

A. Case1

In this case, the lower (or horizontal) side elements of the triangle array are chosen to be active (i.e., their magnitudes are set to 1) while all other remaining elements are switched OFF as shown in Fig. 6 (see Type 3). This figure also shows two other types as shown in the second and third columns of Fig. 6. Type 1 represents an original 5 × 5 square planar array with only lower side elements were selected to be active. This type is considered here for only comparison purposes. Figure 7 shows the 2D radiation patterns of the three types.

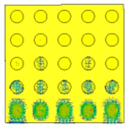
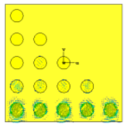
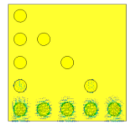
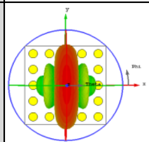
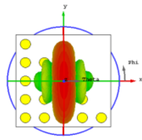
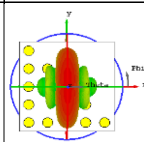
	Type 1	Type 2	Type 3
Surface Current			
Farfield Pattern			
Directivity (dBi)	12.8	12.8	12.9
HPBW (Deg)	19.6	19.7	20
Efficiency (%)	92	90	89

Fig. 6. Results of Case1.

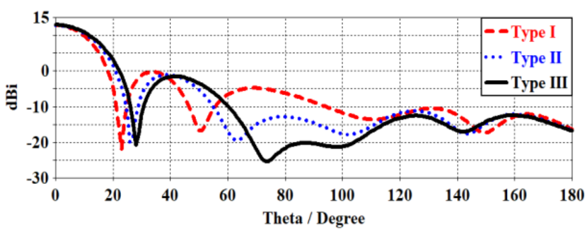


Fig. 7. The corresponding 2D radiation patterns.

From Fig. 6 and Fig. 7, it's clear that the radiation pattern of the array in type 3 is almost the same as those in type 2 and type 3. Indeed, the directivity of the three types is around 12.8 dBi and the HPBW is around 19.7˚. From this result, it can be seen that the Type 3 configuration, represents the most efficient configuration in terms of a smaller number of overall elements while maintaining the same performance. Indeed, the efficiency is perfect for the proposed array 89%, compared with the other two array types.

B. Case2

In this case, the vertical side elements of the triangle array are chosen to be active while all other remaining elements are switched OFF as shown in Fig. 8. This figure shows the various configuration and their corresponding array patterns. Again, the result of the array in Type 3 represents the cheaper design in terms of containing the smaller number of elements while achieving the same performance. In this case, the main beam direction is pointed toward 90˚. Figure 9 shows the 2D radiation patterns of the three types. The directivity of the three types is around 12.2 dBi and the HPBW is almost the same 20.1˚. Indeed, the efficiency is perfect for the proposed array 89.5%, compared with the other two array types.

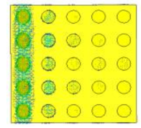
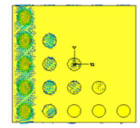
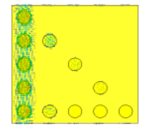
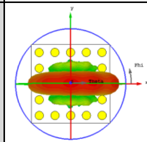
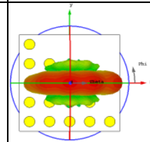
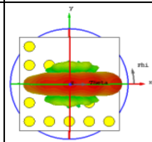
	Type 1	Type 2	Type 3
Surface Current			
Farfield Pattern			
Directivity (dBi)	12.3	12.2	12.2
HPBW (Deg)	20	20.1	20.1
Efficiency (%)	93	91	89.5

Fig. 8. Results of Case2.

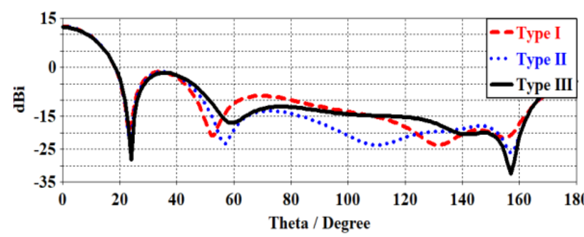


Fig. 9. The 2D radiation patterns for Case2.

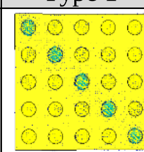
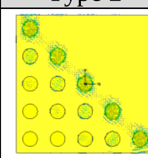
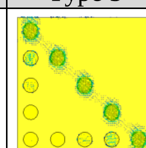
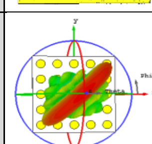
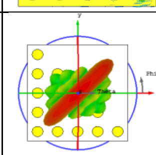
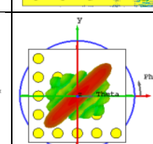
	Type 1	Type 2	Type 3
Surface Current			
Farfield Pattern			
Directivity (dBi)	13.5	13.6	13.6
HPBW (Deg)	19.9	19.9	20
Efficiency (%)	90	89	88

Fig. 10. Results of Case3.

C. Case3

In this case, the elements located on the main diagonal of the triangle array are chosen to be active while all other remaining elements are switched OFF as shown in Fig. 10. Figure 11 shows the 2D radiation patterns of the three types. Again, the result of the array in Type 3 represents the cheaper design in terms of containing the smaller number of elements while achieving the same performance as compared to the other two types. In this case, the main beam direction is pointed toward 45°. The directivity of all the types is around 13.6 dBi which is lower than that of the fully active array elements 19.1 dBi and the HPBW is almost the same 19.9°. However, this reduction comes at a profit of many advantages including a lower number of active elements and a simplified feeding network. Again, the efficiency is perfect for the proposed array 88%, compared with the other two array types.

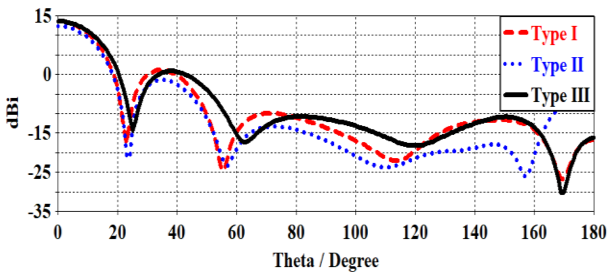


Fig. 11. The 2D radiation patterns for Case3.

From the above-mentioned three cases, it has been found that the antenna bandwidth is almost the same for the proposed antenna (Type 3) as can be seen in Fig. 12.

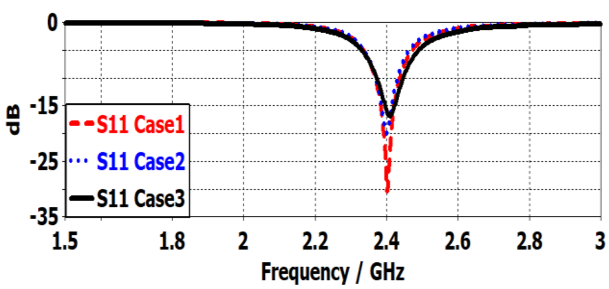


Fig. 12. S_{11} for the proposed antenna for the three cases.

Table 1: Comparison between CST and HFSS results

	Case1		Case2		Case3	
	CST	HFSS	CST	HFSS	CST	HFSS
Directivity (dBi)	12.9	12.7	12.2	12.1	13.6	13.5
HPBW (Deg)	20	20.5	20.1	20	20	19
Efficiency (%)	89	88	89.5	88	88	89

IV. DESIGN VERIFICATION WITH HFSS

To verify the proposed antenna array, the HFSS simulation program has been used. The results show great matching between the two programs in terms of Directivity, HPBW, and Efficiency. Table 1 shows the obtained values for the proposed array (Type 3) in the previous three cases using both CST and HFSS.

V. CONCLUSION

This work showed that the elements in the planar arrays could be considered as pixels, where their magnitude excitations were assigned to the values of either 1 or 0, depending on which elements need to exist at its position in the array. The pixel method can be applied to the different array configuration such as square, rectangular, triangular, or any other shape. To switch the main beam direction, only the magnitude of the selected elements can be altered from 1 to 0 or vice versa. Thus, the proposed approach needs only switches rather than phase shifters or attenuators to achieve the main beam scanning capability. Moreover, the polarization can be also easily altered from vertical to horizontal or vice versa without any mechanical movement of the array. Therefore, the proposed pixel array is simpler and cheaper to implement. Simulation results showed that the directivity and the efficiency of the proposed pixel array are almost the same as those of the fully planar array. Nevertheless, the proposed array enjoys many advantages such as a smaller number of active elements.

In the future work, the method may be further extended by using an optimization algorithm such as a genetic algorithm to optimally choose which elements should be switched OFF such that the array pattern reaches the desired configuration.

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