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RESEARCH ARTICLE

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Flat top coverage pattern maintaining via boundary subarray elements thinning

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Abstract

This paper aims to study the effect of eliminating some elements from the original planar array (OPA) to generate a useful flat-top coverage pattern (FTCP) using a genetic algorithm. The study involves dividing the fully planar array (i.e., OPA) into two regions with an unequal number of elements. The first region includes the elements located in the core (center) of the array, and the remaining elements are the second region, and their location is within the boundary (side) of the array. Only the elements of the first region are included in the optimization process, while the elements of the second region are eliminated in the form of a specific geometric composition without affecting the FTCP generation. Comparing the OPA that $N{\times}M$ elements with the first region (active subarray) elements, it is noted that the number of elements has been reduced from $N{\times}M$ to $(N-2x)\times(M-2y)$ to reduce the complexity of the system as much as possible without affecting the performance in general. Different boundary subarray shapes are presented in this paper with different numbers of elements. The obtained results showed the effectiveness of the proposed method in generating FTCP close to its counterpart in the OPA.

KEYWORDS

boundary subarray elements, flat top pattern, GA, planar array, thinning method

1 | INTRODUCTION

In recent years, improving the coverage patterns of antenna arrays has become one of the important topics under the attention of researchers. Researchers deal with how to control array coverage pattern parameters, taking into account the practical and computational cost of correctly achieving the required coverage situation.[1–4] One of the most important types of coverage patterns required is the flat-top coverage pattern (FTCP). This type of pattern has many modern applications such as satellite and mobile communications. One of the applications of satellites is a Borne array antenna, where the main lobe is designed according to the shape of the area to be covered on the Earth's surface. In these systems, FTCP often suffers from ripples and high sidelobe-level values. In practice, constructing FTCP using planar arrays is considered preferable to linear arrays due to the ability of planar arrays to implement the formulation of coverage patterns on more than one plane (azimuth and elevation).

In the process of optimizing the FTCP with some restrictions (e.g., reducing side lobes, generating null steering,.... etc.), many coverage pattern design parameters can be preserved by choosing the optimization of the weights of all elements.[5–7] However, optimizing all elements in the array leads to a slow and difficult improvement process, in addition to the high complexity of the system in practice.[8–10] To overcome these obstacles, many analytical methods have been proposed by researchers.[11] One of these methods at present time is the use of evolutionary algorithms, which have proven to be powerful programming tools.[12–14]

To simplify the implementation of large planar arrays, some of the elements in the array can be removed (i.e., reducing many degrees of freedom) from the optimization process without affecting the overall array performance.[15] The removal process (i.e., thinning technique) gives many advantages, including faster process response, fewer RF components, and less vulnerability of elements to failure. Therefore, the planar antenna array that contains the smallest number of elements compared to the array with full elements has great research importance from a practical standpoint.

There are many challenges and difficulties in implementing the thinning technique to simplify the planar array system, including the change in the electromagnetic properties of the original array, as well as the change in the width of the main beam and the directivity, in addition to the distortion in the planes of the side lobes due to the elimination of many active elements.[15] Another difficult challenge is choosing the locations of the elements to be turned off within the array aperture. Thus, the aperture of the planar array can be divided into three stepped positions according to the weights of the elements, from the highest value (the center element weights) then the middle values (the middle element weights) to the lowest values (the boundary element weights). Turning off the center elements confuses the FTCP and is therefore excluded from the attenuation process. Turning off the middle elements may affect the FTCP, depending on the number of turning-off elements and the algorithm used. Choosing to turn off the elements located at the boundary is a better solution for preserving the FTCP, as it is not affected in most cases. Therefore, it is necessary to choose a method or a specific geometric shape for a group of canceled elements within the array aperture.

In this paper, an efficient scenario for optimizing standard FTCP is proposed. First, the elements of the basic square array (i.e., OPA) are completely divided into two unequal working areas that differ in the number of elements. These two regions are the inside subarrayed planar array (ISPA) and the boundary subarrayed planar array (BSPA). The elements of the BSPA that have the least influence on the formation of the FTCP are selected to be in an ineffective state, while the elements of the ISPA with the highest influence on the formation of the FTCP are selected in the active state to be involved in the optimization process. Then, the process of improving the complex feeding to the elements of the ISPA is carried out using GA.

2 | MATHEMATICAL FORMULATION

2.1 | Original (fully filled) flat-top planar array coverage pattern optimization

A 2D square planar array of isotropic elements to construct FTCP illustrated in Figure 1 is considered. The original square planar array factor (OSPAF) of the FTCP can be written as[12]:

$$\mathrm{OSPAF}_{\mathrm{FTCP}}(\theta,\phi)=\sum_{n=1}^{N}\sum_{m=1}^{M}F_{nm}\exp\left(j\frac{2\pi d}{\lambda}[(n-1)u+(m-1)v]\right) \tag{1}$$

and in dB form, it can be written as:

$$\mathrm{OSPAF}_{\mathrm{FTCP_{dB}}}(\theta,\phi)=20\log_{10}|\mathrm{OSPAF}_{\mathrm{FTCP}}(\theta,\phi)|, \tag{2}$$

where $N=M$ and are represented the number of isotropic elements distributed about the x (nth) and y (mth) axes, u is the x-axis plane and is equal to $\sin\theta\cos\phi$, v is the y-axis plane and is equal to $\sin\theta\sin\phi$, F_{nm} is the complex feeding of the elements nth and mth, d is the interelement spacing ($d=dx=dy=0.5\lambda$), and λ is the wavelength. The values of F_{nm} are calculated using

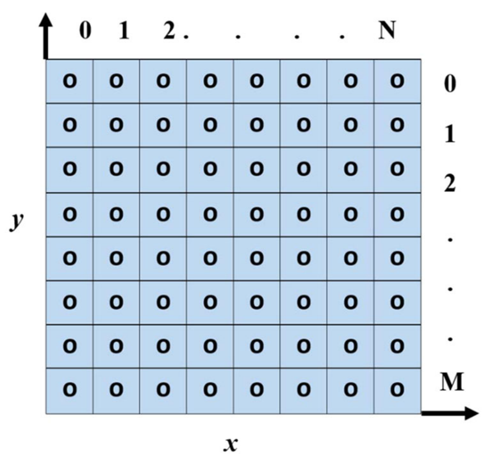

FIGURE 1 Structure of 2D original square planar array of isotropic elements.

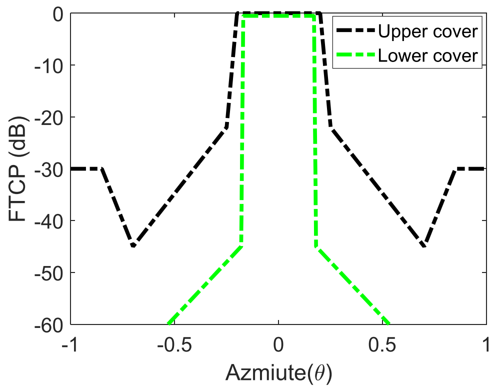

FIGURE 2 Proposed FTCP configuration. FTCP, flat-top coverage pattern.

the GA to reduce the SLL and ripples of the FTCP according to the proposed FTCP configuration shown in Figure 2 in coordination with the objective function defined as follows:

$$G(\Psi) = \sum |\mathrm{PSLL}_d - \underset{\mathrm{SLLregion}}{\theta \overset{\max}{\in} R}(\mathrm{OSPAF}_{\mathrm{FTCP}})|^2 + \sum \left| \underset{\text{main FTCP region}}{\mathrm{OSPAF}_{\mathrm{dB}}(\theta,\phi) - \mathrm{CRP}(\theta,\phi)} \right|, \quad (3)$$

where Ψ represents a set of unknown values through which the required FTCP are obtained and can be represented in the following manner:

$$\Psi = \{F_{nm}, 1 \le nm \le NM\}. \quad (4)$$

PSLL_d and R represent the required FTCP sidelobe levels and the area of the lobe on both sides of the pattern, respectively. $\mathrm{CRP}(\theta,\phi)$ is the required FTCP shown in Figure 2 and the range (θ,ϕ) is $(-0.25{:}0.25)$ rad. The objective function (i.e., Equation 3) is optimized by minimizing it and finding the feeding of the elements optimally through a GA.

2.2 | Boundary subarrayed planar array thinning

In this section, a group of elements located on the boundary of the square planar array are considered inactive and their complex feeding is not included in the optimization process, while the rest of the elements located inside are integrated in the optimization process. In this case, the OPA can be divided into two working regions: ISPA and BSPA. The elements of the two regions are selected by the designer and according to a specific geometric shape. Here, OSPAF will change and differ from Equation 1, so it can be written as:

$$\mathrm{OSPAF}_{\mathrm{FTCP}}(\theta,\phi) = \underbrace{\sum_{n=1}^{N-2x}\sum_{m=1}^{M-2y} F_{nm_I}\exp\left(j\frac{2\pi d}{\lambda}[(n-1)u+(m-1)v]\right)}_{\mathrm{ISPA}} + \underbrace{\sum_{n=N-2x+1}^{N}\sum_{m=M-2y+1}^{M} F_{nm_B}\exp\left(j\frac{2\pi d}{\lambda}[(n-1)u + (m-1)v]\right)}_{\mathrm{BSPA}} \quad (5)$$

where $F_{nm_I} = (N-2x) + (M-2y)$ and $F_{nm_B} = 2x(N-x) + 2y(M-y)$ are complex feeding elements matrix of the ISPA and BSPA respectively. The F_{nm_B} values in the BSPA matrix are inactive in the optimization process (i.e., they are not taken into account in the optimization process), while the F_{nm_I} is in the active state and is used to produce the required FTCP according to the proposed configuration shown in Figure 2. After the OPA was divided into two main submatrices, its array factor was written. Equation 5 is coupled with the objective function Equation 3. The objective function here will only deal with optimized feeding weights which are specified between (0,1 and $-\pi/2$, $\pi/2$). Next, a set of proposed boundary sub-decorative shapes must be damped in the optimization process (see Figure 3). The shapes shown in Figure 3 were created based on patterns that exist in nature, or that can be created through fractal shapes. These shapes were chosen finally based on prior experiments to identify the elements within the limits that have the least influence on forming the desired FTCP during the optimization process.

3 | NUMERICAL RESULTS AND DISCUSSION

To explain the effectiveness of the proposed idea, several planar array configurations with a thinned boundary subarray have been examined. In all tests, the specifications of the GA in terms of the population size, selection, mutation rate, and crossover were 50, roulette, 0.155, and single point respectively. Complex feeding is used to find improved weights for feeding the ISPA elements (inner radiating subarray elements). Where the feeding of the amplitude and phase of the ISPA elements are equipped in the improvement process as (0,1) and $(-\pi/2, \pi/2)$, respectively. Also, in all calculations, the improvement planar array was considered square in dimensions of

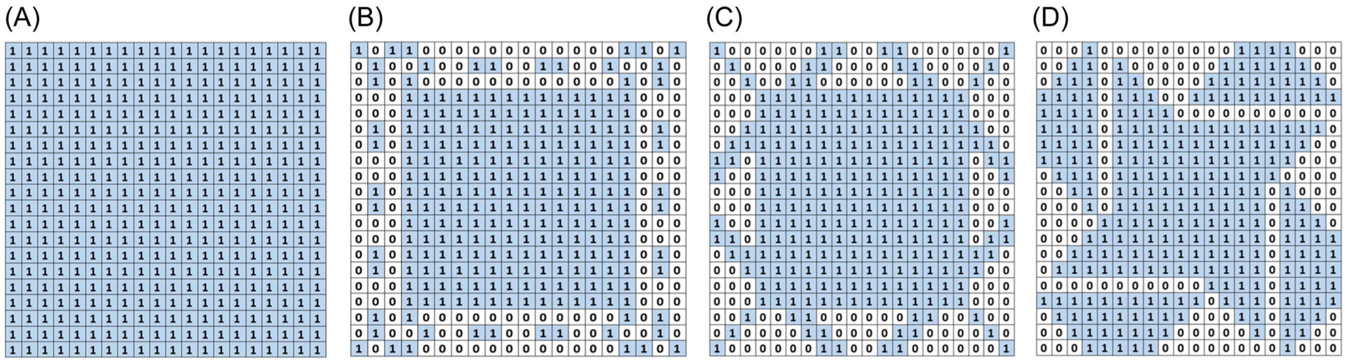

FIGURE 3 Set of proposed planar arrays with boundary sub-decorative shapes thinning set of proposed boundary sub-decorative shapes. (A) OPA. (B) 1st boundary sub-decorative array. (C) 2nd boundary sub-decorative array. (D) 3rd boundary sub-decorative array. FTCP, flat-top coverage pattern; OPA, original planar array.

NXM (i.e., $N = M$), and different dimension arrays can also be used by making $N \neq M$.

For the purpose of simulating tests, the MATLAB program was used. FTCP is analyzed before and after the thinning of the boundary radiating subarrays within the OPA. More details about the experimental preparation and analysis of the results obtained from the examinations are mentioned below. To install and compare the FTCP in the two cases (original and optimized planar array), the feeding ISPA elements of Equation 5 are improved only. Here, two advantages are obtained, reducing the complexity of the system and reducing the time of the implementation of the algorithm.

The goal of this paper is to install FTCP with a beam width of 0.5 rad and a maximum ripple in the flat area of 0.1 dB, according to the configuration (mask) proposed in Figure 2, with a limited number of radiating subarray elements. It is also desirable for the flat pattern to have a sharp transition on either side of the main flat beam. The width of the flat pattern is defined as the angular difference between the two points within the proposed configuration coverage pattern, where the maximum energy is concentrated within these two points with less energy in the sidelobes regions.

In all tests, the number of OPA elements of $N \times M = 20 \times 20$ is considered. Figure 4 shows a set of tests that were tried on the OPA. It can be seen from these subfigures that the same FTCP was achieved for the OPA and within the specifications described above. These figures also include the amplitude and phase distribution for each case. It can be observed from these distributions that the amplitude-only distribution took the form of a composition of the active and non-active elements, and this is evidence of the sensory thinning process of the proposed configuration pattern. As for the phase distribution, it differs from the proposed distribution structure as a result of the difference in phase values between positive, negative, and zeros. The difference in phase distribution in this case is due to several reasons, including the range of phase optimization being −pi/2 to pi/2 and not as in the amplitude (0–1). Also, the element carrying phase zero does not mean that it is turned off, so turning off the elements depends on making the amplitude element zero, and this gives us a difference in the distribution of complex weights.

Also, to demonstrate the robustness of the proposed method in constructing a thinned planar array with the required FTCPs, Table 1 shows a comparison of a set of parameters between the OPA and the proposed planar array in terms of the flat top width, PSLL, the shape of the FTCP, complexity% and the execution time of the algorithm. It is worth noting that the complexity% of the proposed arrays was calculated through:

$$\text{Complexity\%} = \frac{\text{number of boundary nonactive elements}}{\text{total number of OPA elements } (N \times M)}. \tag{6}$$

The extent of conformity with the results can be observed in this table, and this confirms the validity of the proposed method in achieving the desired FTCP.

Next, to better demonstrate the efficacy of the proposed method, Table 2 provides a comparison between the proposed approach in this paper with the methods presented by some other researchers in terms of the type of algorithm used, the shape and size of the array, the use of the thinning technique or not, complete control of the desired coverage pattern and the PSLL. It can be seen from this table that the clear superiority of the proposed method by evident.

Finally, these proposed methods can be used to reduce the size of a large array while maintaining work efficiency in practice, as new array shapes can be

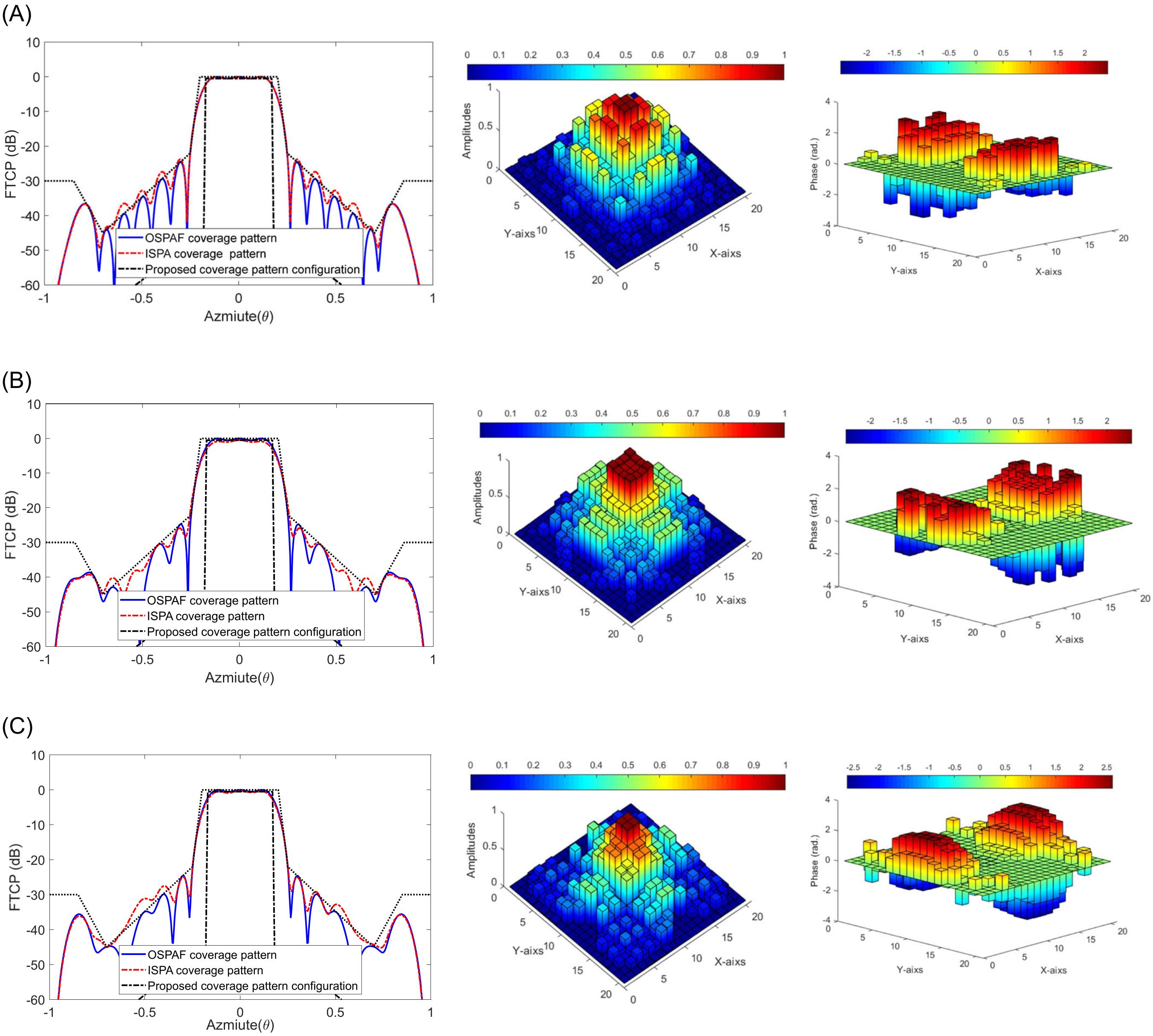

FIGURE 4 Desired and obtained flat-top coverage pattern (FTCP) configuration with proposed boundary sub-decorative shapes thinning. (A) First tested FTCP configuration with corresponding amplitude and phase distributions. (B) Second tested FTCP configuration with corresponding amplitude and phase distributions. (C) Third tested FTCP configuration with corresponding amplitude and phase distributions.

TABLE 1 A comparison of a set of parameters between the OPA and the proposed planar array.

Parameter	FTW (rad.)	PSLL (dB)	Shape of FTCP	Complexity %	Execution time (sec.)
OPA	0.5	−26	Verified	100	2
First tested array	0.5	−26	Verified	61.5	1.2
Second tested array	0.5	−26	Verified	64	1.3
Third tested array	0.5	−26	Verified	57	1

Abbreviations: FTCP, flat-top coverage pattern; OPA, original planar array.

TABLE 2 A comparison between the proposed approach with other methods.

Ref.	Algorithm	Type of array and size	Using thinning technique?	Coverage pattern-shaped control	PSLL (dB)
[16]	Differential evolution (DE)/GA	Concentric ring array, 30 elements	No	Not exact	−18
[17]	GA	Planar, 10*10 elements	No	Exact	−15
[18]	iterative FFT	Square grid with a circular boundary, 208 elements	No	Exact	−20
[18]	Elliott–Stern method	Square grid with a circular boundary, 50*50 elements	No	Exact	−20
This paper	GA	Square planar, 20*20 elements	Yes	Exact	−26

produced such as a diamond, a circle, conformal, or any other geometric shapes. This provides a simplified method through which square arrays can be converted into other arrays with new shapes, for which it is easy to design the feeding network simply and efficiently with a small number of elements. It is also possible to design three-dimensional arrays (cubic arrays) in which each face consists of a specific geometric shape derived from a single reference array structure that can be used appropriately in satellite applications.

4 | CONCLUSION

The procedures used in this paper, in terms of the optimization process, changes in design, and implementation, have shown that the OPA can be greatly simplified through the proposed approach while maintaining the same performance as the OPA system. The proposed approach was implemented on the OPA consisting of $N \times M$ to be isolated into two different working areas: the BSPA (passive area) and the ISPA (active area). After turning off the BSPA area in the form of different geometric shapes, the computational complexity was significantly reduced without affecting the performance of the standard array system. In addition, the parameters of the proposed array system in terms of the width of FTCP, PSLL, FTCP shape, and complexity% were found to be very close to their values in the OPA, with a reduction in the execution time of the algorithm. It is also possible to use the proposed method to convert square arrays into other forms such as rhombus, circle, conformal, and other forms. by choosing to eliminate appropriate locations for the boundary elements. It is also possible to build three-dimensional arrays such as a cube array to be suitable for satellite communications applications.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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