(Received 22 December 2023, Accepted 5 January 2024, Scheduled 7 February 2024)

Unconventional Method for Antenna Array Synthesizing Based on Ascending Clustered Rings

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ABSTRACT: Recently, clustered antenna arrays have been proved as an efficient method in implementing the large planar arrays for massive MIMO wireless communications in 5G and beyond applications. However, obtaining optimum clustering configurations needs a high computational time, and it does not guarantee a total clustering coverage of the whole array aperture. In this paper, a new and unconventional array pattern synthesis method based on ascending/descending clustered subarray rings is presented. The method is equally applicable to the rectangular and circular planar arrays where they are first divided into multiple square or circular clustered rings starting from the largest ring at the array perimeter up to the last ring (the smallest one) at the array center. Then the amplitude distributions of these clustered rings are optimized to obtain the desired radiation characteristics subject to the user-defined constraint mask. Implementation of the proposed array at the clustered level instead of the conventional element level offers many advantages such as simplified feeding network, efficient taper efficiency, low side lobe level, and high directivity. Simulation results show the effectiveness of the proposed method for both square and circular planar array layouts.

1. INTRODUCTION

Large planar antenna arrays play a major role in improving the performances of the current and future 5G/6G wireless communication systems due to their high resolution and high radiation power. However, considering a large number of array elements results in a complex feeding network, high number of transmit/receive (T/R) modules, high cost, and complicated array feeding control devices.

Partitioning a large antenna array into a number of smaller regular or irregular planar subarrays is a common technique which overcomes the aforementioned problems by reducing the cost and maintaining the array performance. Usually irregular subarrays are more preferable than the regular counterparts due to their capabilities in avoiding the grating lobes [1]. In the literature, irregular subarrays have been implemented by several ways; overlapped subarrays [2], random subarrays [3], clustered subarrays [4], shaped and weights optimization [5].

Other methods such as thinned elements [6], compressed sensing [7], sharing elements [8], and partially optimized elements [9] have also been presented in the literature as effective approaches to significantly reduce the number of the active or adaptive array elements, and consequently reduce the implementation costs of the array feeding network. However, some of these approaches suffer from directivity degradation. When high gains and directivities are required, clustered antenna arrays are most promising solutions where each cluster contains a small number of the radiating elements arranged in a specific shape such as L-shape or T-shape or other shapes. Thus, the array feeding network is significantly simplified by connecting each group of elements in one cluster to a single T/R module [10–13]. In [10], a cluster-based phased arrays employing mixed antenna element factor was suggested to improve the scan range and many other radiation features, while in [11] a compressive sensing-based approach is proposed to detect the fault elements in the planar antenna arrays using a reduced set of phaseless far-field measurements. Generally, optimization algorithms are used to find the most proper irregular clustered shapes that may cover the whole array aperture. In [12], irregular polyomino or tiles were used to divide the whole array aperture into a set of arbitrary clusters. However, some small regions in the array aperture may be left uncovered by these tiles. To avoid this problem and to completely cover the entire array aperture, much simpler tiles like 2×1 or 1×2 rectangular tiles were suggested in [13]. This simple configuration comes at the cost of relatively increasing the required number of the T/R modules.

In [14], modular-based diamond tiling shapes were used to design the planar phased array antennas with hexagonal apertures presented. The tiling shapes and subarray coefficients were optimized to fit the user-defined power-mask constraints on the radiation pattern. In this paper, a new antenna array synthesis method based on the elegant clustered shapes in the form of square or circular rings is proposed. The idea comes from the visualization of the actual amplitude distributions of the non-uniformly excited planar array elements such as Dolph, Taylor, Gaussian, or any other distributions where their amplitude weights at the element level seem nearly like rings around the center of the array. Its normalized peak value located at the array center and reduces exponentially toward the perimeter of the array. This feature has been exploited to design a new amplitude distribution taper using clustered square or circular rings. The genetic algorithm is used to optimally find the

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best clustered subarray coefficients. Since the amplitudes of the clustered subarray coefficients are in a good approximation to their actual elemental amplitude counterpart, i.e., optimal amplitudes, the radiation performances of the corresponding clustered array are expected to be almost identical to the desired one with a small difference due to the quantized amplitude distributions. Moreover, the sidelobe level, directivity, and the taper efficiency of the resulting clustered array are almost identical to the optimal ones.

2. THE PROPOSED CLUSTERED SUBARRAY RINGS

Consider a rectangular planar array composed of $N \times M$ total number of elements that are symmetrically distributed about the array center in both x and y axes with uniform inter-element spacing $d_x = d_y = 0.5\lambda$. Its array factor can be written as:

$$\mathrm{AF}\left(\theta,\emptyset\right) = \sum\nolimits_{n=1}^{N}\sum\nolimits_{m=1}^{M} a_{nm}e^{j\rho_{nm}}e^{j[(m-1)\psi_x]}e^{j[(n-1)\psi_y]} \quad (1)$$

where a_{nm} and ρ_{nm} are the amplitudes and phases of the array weights at the element level, $\psi_x = kd_x \sin\theta\cos\phi$, $\psi_y = kd_y \sin\theta\sin\phi$, $k = 2\pi/\lambda$, and λ is the wavelength in the free space. Conventionally, all the amplitudes and/or phases of the array elements are optimized to fit the user-defined power-mask constraints on the radiation pattern such as the main beamwidth and the side lobe level.

Here in this paper, the array elements are first grouped into clustered rings instead of the individual elements. That is, each group of elements that belong to a certain rectangular ring is considered as a single cluster that needs a single excitation weight. For the whole array plane, we will have multiple clusters in the form of rectangular rings starting from the perimeter of the array up to its center. Each cluster has a unique size and location as shown in Fig. 1. Thus, the problem of the grating lobes in the proposed array pattern cannot occur.

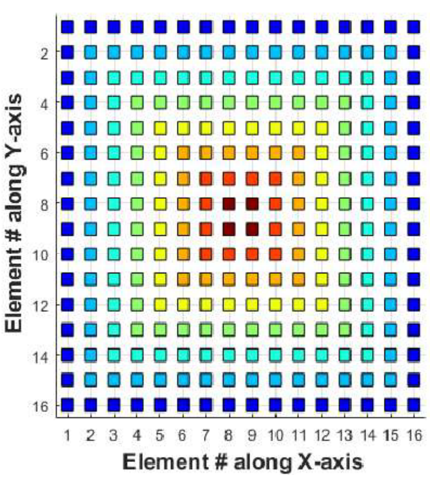

FIGURE 1. Proposed clustered square rings.

To start, let us assume a square array with $N \times N$ elements, thus, there is a total number of $N/2$ square rings. The number of the elements in the first ring located at the array perimeter is $Q_1 = 2\{(2\times1)(N-1)\}$, while the number of the elements in the second ring that is next to the perimeter is $Q_2 = 2\{(2\times2)(N-2)\} - 2\{(2\times1)(N-1)\}$. The number of elements in the third ring is $Q_3 = 2\{(2\times3)(N-3)\} - 2\{(2\times2)(N-2)\}$ and so on. In general, the number of elements in any square-ring can be written as

$$Q_r = 2\left\{(2\times r)\left(N-r\right)\right\} - 2\left\{(2\times(r-1))\left(N-r+1\right)\right\} \quad r = 1, 2, \ldots, N/2 \quad (2)$$

Next, let us assume amplitude-only control method where only the amplitude excitations of the clustered rings, A_r, are needed to be optimized while their phases are set to zeros. The resulting array factor of the clustered square rings can be written as:

$$\mathrm{AF}_{\mathrm{Cluster}}\left(\theta,\emptyset\right) = \sum\nolimits_{r=1}^{N/2}\sum\nolimits_{q=1}^{Q_r} A_{rq}e^{j[(q-1)\psi_x]}e^{j[(r-1)\psi_y]} \quad (3)$$

Comparing between (1) which is in the form of element level and (3) which is in the clustered level, it is clear that the amplitude levels of the array weights have been reduced from N to only $N/2$ while keeping a good approximation of the original amplitude excitations. Surely, this reduces the cost and feeding network complexity and maintains a good performance. To maintain the radiation pattern of the proposed clustered array as close as possible to the desired one, the following constraint mask is applied:

$$\text{Constraint Mask}\left(\theta\right) = \begin{cases} \text{SLL}, & -90^\circ \leq \theta \leq -\text{FNBW},\ \text{FNBW} \leq \theta \leq 90^\circ \\ 0, & -\text{FNBW} \leq \theta \leq \text{FNBW} \end{cases} \quad (4)$$

where FNBW represents the first-null-to-null beamwidth in the array pattern, and SLL is the desired side lobe level. To maintain the main beam of the clustered array undistorted, its normalized magnitude is assumed to be 0 dB within the range from $-$FNBW to FNBW. To meet the best match between the clustered array pattern and the desired one at the elemental level, the following cost function is used to optimize the amplitude excitations of the clustered rings, A_r,

$$\text{Cost} = \sum\nolimits_{p=1}^{P}\left|\mathrm{AF}_{\mathrm{cluster}}\left(\theta_p\right) - \text{Constraint Mask}\left(\theta_p\right)\right|^2 \quad (5)$$

where $p = 1, 2, \ldots, P$ are the taken sample points between the two patterns. The cost function will minimize any excess magnitudes of the $\mathrm{AP}_{\mathrm{cluster}}(\theta_p)$ located outside the desired constraint mask.

Moreover, the technique can be further extended to multiple ascending/descending clustered rings as shown in Figs. 2(a) and (b) for an array of 16×16 elements. In Fig. 2(a), the ascending clustered technique starts with a single ring at the array perimeter, and then the second cluster contains the elements of both the 2nd and 3rd rings, while the third cluster contains the elements of 4th, 5th, and 6th rings and so on. Fig. 2(b) shows the descending clustered case. In general, the multiple clustered rings have less number of subarrays and, thus, less number of

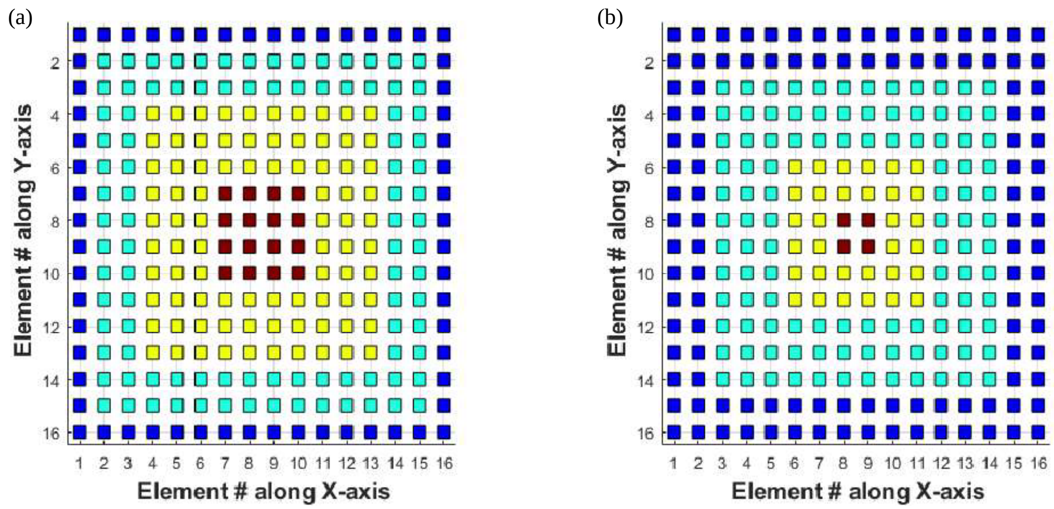

FIGURE 2. Clustered multiple square rings. (a) Ascending case. (b) Descending case.

degrees of freedom than the single-ring clustered array. Although, this helps to further simplify the feeding network complexity, it comes at the cost of lower radiation performance.

Finally, the technique can be equally applied to the planar circular arrays as shown in Fig. 3 for an array of 256 total elements distributed on different circular clusters. Again, this elegant clustered configuration is capable to provide the desired array patterns.

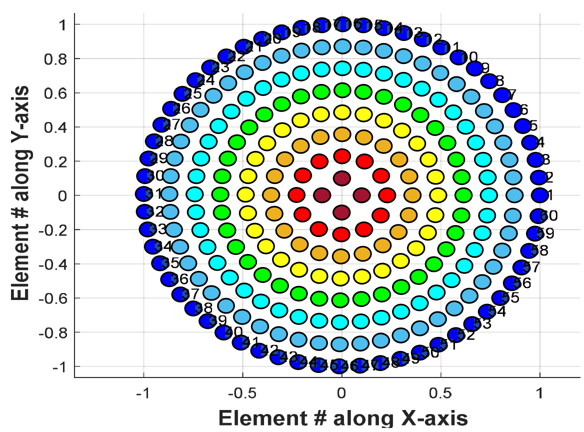

FIGURE 3. Proposed clustered circular rings.

3. SIMULATION RESULTS

To verify the idea, a planar square array with 16×16 elements is illustrated. Nevertheless, it can be applied to any other array size. The amplitude distributions of the array weights at the element level and at the clustered level are assumed to be symmetric around the array center. Consequently, the resulting radiation patterns are symmetric in all four quadrants. The optimization parameters of the used genetic algorithm were set; an initial population size is set to 50; number of iterations is set to 1000; selection is roulette; number of crossovers is 2; mutation probability is 0.04; and mating pool is chosen to be 4. Referring to (4), the desired limit of the side lobe level was set to $\text{SLL} = -30\,\text{dB}$ and the width of the main beam $2 \times \text{FNBW} = 11.4°$. Fig. 4 shows two-dimensional amplitude distributions of the conventional fully optimized array antenna at element level, i.e., reference one, and the proposed clustered array antenna. It can be seen from Fig. 4(a) that the shape of the optimized amplitude distributions at the element level of the reference array appears almost like rings around the array center. Its normalized peak value located at the array center and decreases exponentially toward the edges of the array. Thus, they can be quantized well to get optimal squared rings as shown in Fig. 4(b).

Figure 5 shows the three-dimensional amplitude distributions of the array weights at the element level and the corresponding radiation pattern of the conventional fully optimized array elements without clusters, while Fig. 6 shows the three-dimensional radiation patterns of these two tested arrays. It can be seen that the magnitudes of the clustered rings take almost the same shape as that of the optimized reference ones.

On the other hand, the radiation patterns of these two arrays are exactly same at the azimuth and elevation planes, and there is a little difference at $45°$ plane. To highlight this observation, the two-dimensional radiations patterns of the two tested arrays at the elevation plane are shown in Fig. 7 in which the superiority of the proposed clustered array pattern is clearer. The difference between the two tested patterns in the $45°$ plane is due to the discretization in the amplitude distributions of the proposed clustered rings array. Nevertheless, the radiation characteristics of the proposed clustered array are very promising as shown in Table 1.

To further assess the performance of the proposed clustered array, it is also compared with other arrays such as standard Dolph and the uniform arrays as shown in the Table 1. The simplicity of the feeding network in terms of the needed number of the variable attenuators or amplifiers in the T/R modules is also included in Table 1. Clearly, the proposed clustered array needs the lowest radio frequency (RF) components to realize it.

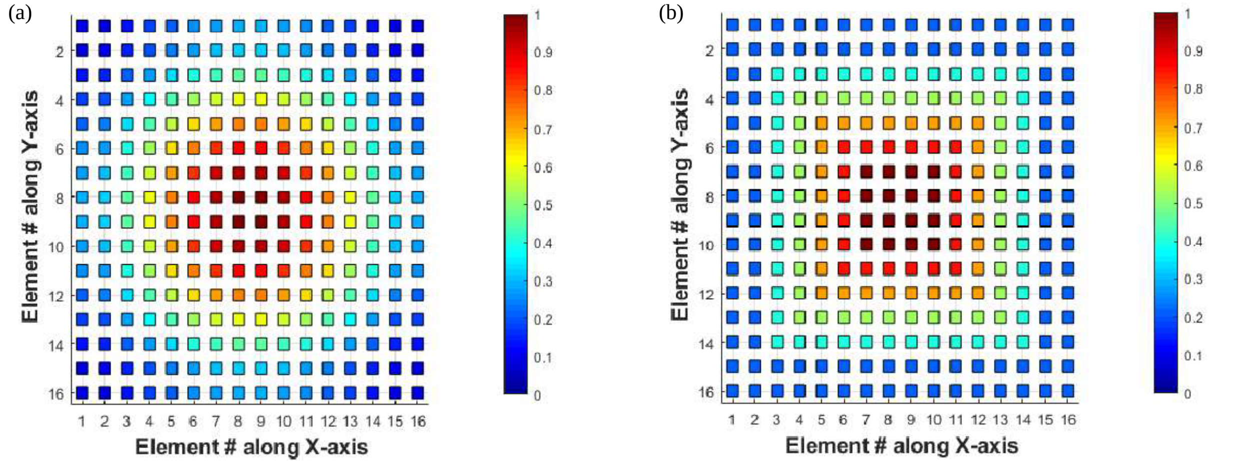

FIGURE 4. Layout of the amplitude distributions of (a) the conventional fully optimized array elements and (b) the clustered square-rings array.

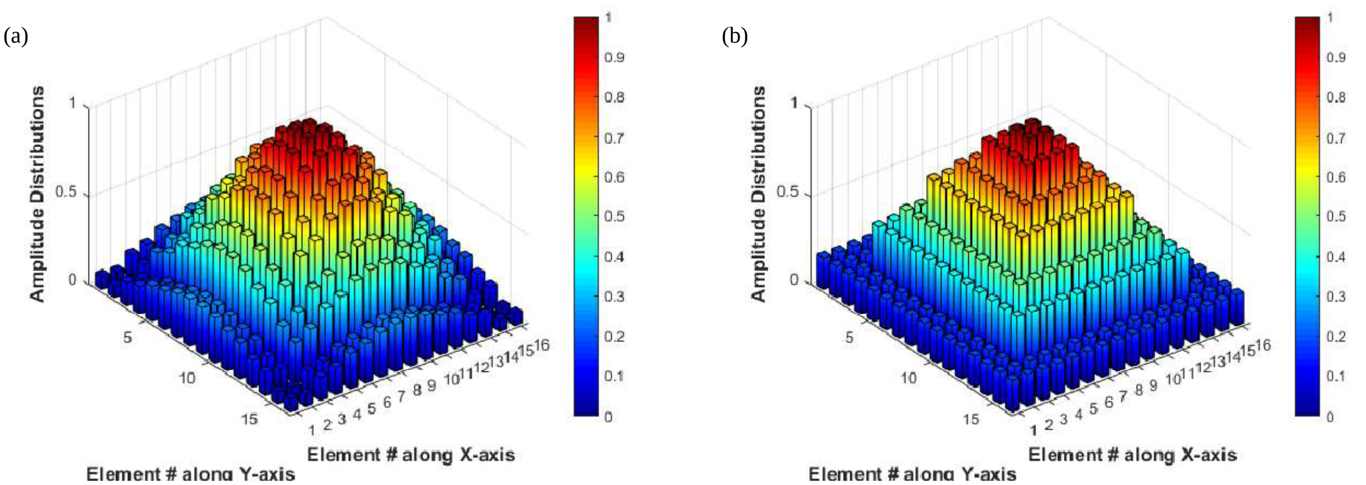

FIGURE 5. Three-dimensional amplitude distributions of (a) the conventional fully optimized array elements and (b) the clustered square-rings array.

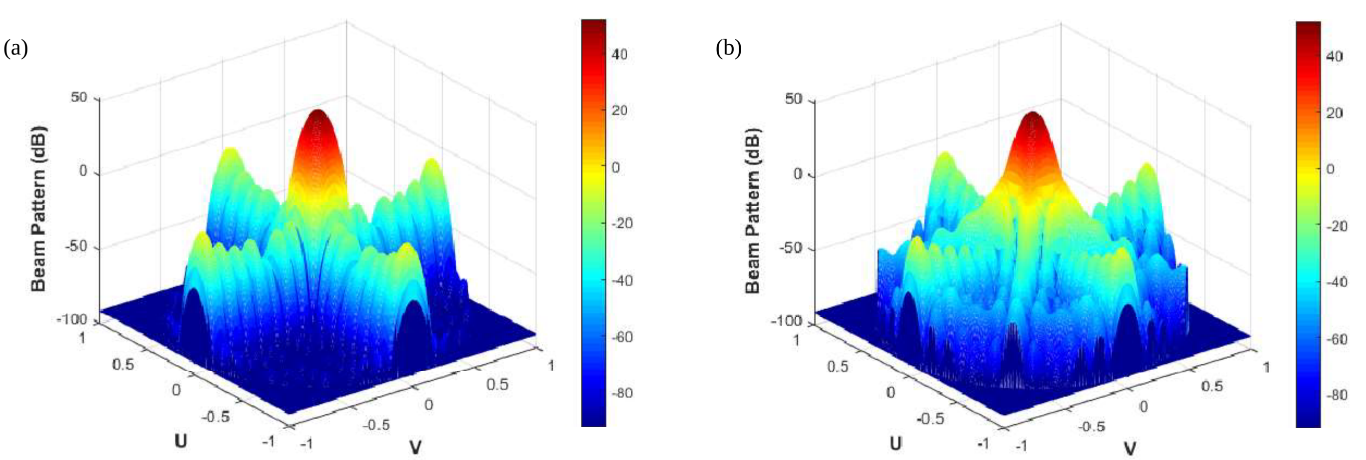

FIGURE 6. Radiation patterns of (a) the conventional fully optimized array elements and (b) the clustered square-rings array.

TABLE 1. Performance comparison of the tested arrays for 16×16 elements.

The Method	Taper efficiency	Directivity [dB]	Peak SLL [dB]	Average SLL* [dB]	RF components #
Uniform amplitude array	1	20.3893	−13.23	−12.0766	0
Dolph array	0.86163	18.9407	−30	−16.1377	256
Fully optimized array	0.8457	18.7939	−30	−16.2918	256
Proposed clustered array	0.80146	18.1547	−32	−16.7898	8

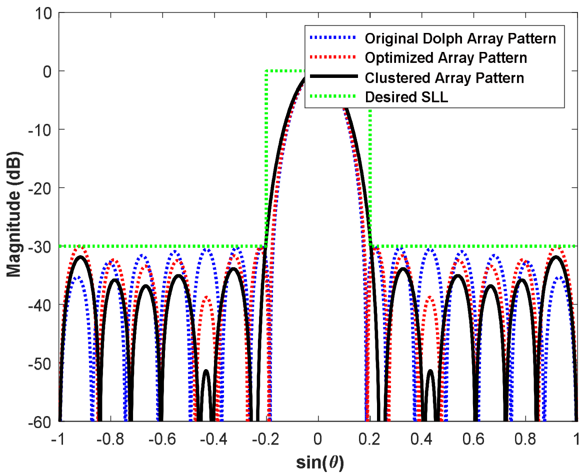

FIGURE 7. Two-dimension radiation patterns of the standard Dolph array, conventional fully optimized array, and the proposed clustered array at the elevation plane.

These results verify the superiority of the proposed clustered array.

4. CONCLUSIONS

It is demonstrated that the amplitude excitations of the array weights at the element level can be well approximated by a number of clustered rings. An optimization algorithm was used to find the optimal values of the clustered amplitudes that best fit the user-defined power-mask constraints on the radiation pattern. Results reveal that it can generate radiation patterns with the clustered rings that best match the desired one in terms of peak side lobe level, main beam width, directivity, and taper efficiency.

Moreover, comparing the performance of the proposed array with other standard nonuniform amplitude arrays such as Dolph array and the conventional fully optimized array elements, it is found that the difference in the directivity was less than 0.5 dB, and the taper efficiency was less than 6% while the feeding network complexity was greatly reduced. These results prove the effectiveness of the proposed array.

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