Unconventional and Irregular Clustered Arrays

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Abstract. In this paper, two different structures based on fully and partially irregular clustered elements are presented to optimize the radiation patterns of the large arrays. In the Fully Irregular Clustered Elements (FICE) structure, all the elements of an ordinarily large linear array are divided into multiple irregular and unequal-size clusters, while in the Partially Irregular Clustered Elements (PICE) structure, only the elements those located at the edges of the ordinarily linear array are grouped into unequal-size clusters. In this structure, the central elements are left without clustering (i.e., excited individually). The PICE structure has several advantages over the FICE structure. Since the quantized amplitudes (i.e., discrete distribution) are used with the proposed clustered structures, the corresponding clustered array patterns are usually associated with the undesirable high periodic sidelobes. In order to overcome this problem, the elements in the clusters are distributed periodically. Simulation results demonstrate the ability of the proposed two structures, FICE and PICE, to significantly reduce the high periodic sidelobe level to -35dB and -40dB respectively for an array with a number of elements N=100 and unequal-size clusters.

1. Introduction

Designing a large antenna arrays for modern communication systems such as 5G, radar and satellites is one of the most difficult challenges in the practice. Thus, techniques must be used to simplify the design process. Subarray techniques were widely used to simplify the practical implementation of the large arrays, in which a number of elements are connected to a common subarray to reduce the number of control points in the excitation network [1-9]. This reduction in the architecture's complexity allows a significant and reasonable simplification in array fabrication, and consequently lower cost. This simplification requires an unconventional design in a corporate feeding network, so, the calibration processes must be simplified theoretically, but it is still difficult to identify and correct the random errors that may affect the excitation of the elements during feeding [10]. The techniques that described in [11-13] aim to evaluate the effects of random errors in terms of amplitudes, phases and element locations on the array radiation pattern.

The concept of the subarray’s technique involves dividing the radiating elements N in the large arrays into small groups called clusters, each cluster with M radiating elements, so that M<<N. Here, each cluster has only a common controller for specifying the amplitude or the phase (time delays) or both [14-15]. Although high directivity and half power beam width (HPBW) are still warranted, such a conventional architectural solution makes a minor contribution in terms of limited operating bandwidth and low reconfiguration potential due to the quantized distribution of amplitude or phase weights or both across the array aperture [15-21]. If the array aperture is divided into clusters with equal-sized, then the radiation patterns with undesired grating lobes are noticed (i.e., high periodic
sidelobes) and they found to be more noticeable for increasing bandwidth. Thus, this structure with equal-sized clusters fails to provide a good solution. The authors in [5] suggested to place the clusters periodically through the array aperture. It uses certain types of irregular cluster shapes (i.e., polyomino shaped) that are rotated in specific directions to fill the array aperture so that the periodicity of the arrangement of clusters is eliminated. However, this method needs a rather complex corporate feeding network.

Several optimization strategies [22-26] have been suggested in the literature to get an optimum architecture for the array clusters that meets the desired radiation pattern. In this paper, the desired array pattern under the required constraints is obtained by using several irregular arrangements of the clustered elements. The first structure composes a number of clusters with each one having unequal number of array elements. This will be referred to as Fully Irregular Clustered Elements (FICE). In the second structure, the elements that located only on both ends of the linear array are divided into irregular clusters while the central elements are let without grouping into clusters. This will be referred to as Partially Irregular Clustered Elements (PICE). This structure provides more degrees of freedom than the first structure, FICE. Thus, the performance of the second structure may be better than that of the first structure. Also, more constraints may be flexibly applied with the second structure.

2. The Proposed Structure

In this section, the fully and partially irregular clustered structures are introduced. The array factors and the cost functions of these two structures are given. The genetic optimization is used to get the desired array patterns. Its specifications were: the number of populations is 50; rate of mutation is 0.15; and a single point crossover.

2.1 Fully Irregular Clustered Elements

This section includes two types of fully clusters, i.e., fully regular clustered elements (FRCE) and the fully irregular clustered elements (FICE). It should be mentioned that the FRCE was already presented in [14]. It will be shown that better results can be obtained by using FICE instead of the FRCE. Thus, this paper mainly focuses on the FICE. Suppose a linear array with an even number of elements N. The elements are arranged symmetrically around the centre, which means that only half of the elements are optimized. Thus, the number of the RF (attenuators and phase shifters) components is also halved. In the FICE structure, all the array elements, N, will be subdivided into multiple clusters, say Q, and each cluster, q, contains different Mq elements. Q is calculated by dividing N by Mq on the condition that the remainder of the division is zero, meaning that the c must be integer number. Figure 1 shows the structure of the FICE structure. From this figure, it can be seen that each cluster contains a number of elements equal to 2, 3, 4, and so on. By choosing different size clusters, the problem of appearing quantized high sidelobes can be overcome.

The array factor of this structure can be written as

\[ AF(u) = 2 \sum_{q=1}^{Q/2} A_q \sum_{n=1}^{N/2} \delta_{cna} w_n \cos \left\{ \frac{(2n-1)}{2} k d u \right\} \]

where \( \delta_{cna} = \begin{cases} 1 & \text{if the nth element belong to the mth cluster} \\ 0 & \end{cases} \)
To further simplify the feeding network, amplitude only excitation is used and the phase is considered to be zero. Thus, equation (1) is simplified to:

\[
AF(u) = 2 \sum_{q=1}^{Q/2} A_q \sum_{n=1}^{N/2} \delta_{cnq} a_n \cos \left\{ \frac{(2n-1) \pi}{2} kdu \right\}
\]  

This equation is used in the optimizing process in order to obtain the optimum weights of the clusters. In this equation, \(A_q\) is calculated based on the values of \(a_n\), where at the beginning the optimized values of \(a_n\) are calculated to obtain the desired pattern with required sidelobes, then the average values of the amplitudes of the optimized elements \(a_1, a_2, a_m, \ldots, a_M\) within each cluster, \(Q\), are computed. As a result, the excitation of the amplitudes of the \(a_1, a_2, a_m, \ldots, a_M\) for each cluster will be quantized to the value of \(A_q\). To control the level of the sidelobes and prevent them to be higher than the required sidelobe level, an additional condition is added to the cost function which draws a specified line to control the sidelobes. Any point above the line contributes a value to the cost function equal to the power difference between the clustered array pattern and the desired pattern of the uniform linear array. Thus, the cost function can be written as follows:

\[
Cost\ Function = \sum [AF - Constraints (Mask\ limit)]^2
\]  

As the inputs for this function include the array factor with its \(A_q\) and \(a_n\), the desired array pattern, as well as the specified mask constraints. The constraints of this function can be identified as follows:

\[
Constraints_{FICE} = \begin{cases} 
uppermasklimit = -35\ dB & \text{Exempt Main Beam} 
lowermasklimit = -60\ dB 
\end{cases}
\]  

2.2 Partially Irregular Clustered Elements

Another new structure presented in this paper is based on the partially irregular clustered elements. Here in this structure, the elements that located at the ends of the array are grouped into different-size clusters followed by the common weights \(A_q\) as shown in Figure 2. Whereas, the elements that located in the centre of the array are left without clustering (i.e., excited individually).

![Figure 1. Structure of the FICE.](image)
The main benefit of this structure is its ability to provide more degrees of freedom than the previous one. Thus, the constraints have more flexibility on the peak sidelobe level. The array factor of this structure can be written as

$$AF(u) = 2 \sum_{n=1}^{L/2} b_n \cos \left(\frac{(2n-1)}{2} kdu\right) + 2 \sum_{q=1}^{Q/2} A_q \sum_{n=(N-1)/2}^{N/2} a_n \cos \left(\frac{(2n-1)}{2} kdu\right)$$

(5)

The mask constraints are

$$Constraints_{PICE} = \begin{cases} 
\text{uppermasklimit} = -40 \text{dBExemptMainBeam} \\
\text{lowermasklimit} = -60 \text{dB} 
\end{cases}$$

(6)

3. Simulation Results

In order to verify the effectiveness of the proposed structures (i.e., FICE and PICE), several examples are illustrated for each structure. In all examples, the element phases are made zero (i.e., element amplitudes are only used). The number of the elements in each side of the linear array is chosen to be 50 (the total number of the array elements is 100). The number of the elements in each cluster Mq may be chosen as 2, or 3, or any other value (when Mq=1 it represents a non-clustering state). Since a symmetrical linear array has been used in all examples, then, only a one side of the element amplitudes is displayed.

In the first example, the advantages of using the proposed FICE with compared to the previous structures such as fully regular clustered elements (FRCE) that were presented in [14] is addressed. Figure 3 shows the results of the FRCE and the proposed FICE. For the FRCE structure, the number of the clusters is Q=5, the number of the elements in each cluster is Mq =10. For the FICE structure, we used different sizes of Q, and different number of elements in each cluster Mq as can be seen in Figure 3. From the results of the FRCE structure, it can be seen that a periodic high sidelobes can be clearly noticed. This undesirable effect was found to be proportionally increased with the increased size of the clusters. As can be seen from the results of FICE (see Figure 3(c)), the problem of appearing a periodic high sidelobes is completely eliminated with the use of FICE structure.
In the second example, the idea of PICE is illustrated. To highlight its performance, it is compared to the partially regular clustered elements (PRCE) that were presented in [14]. Among these four structures (i.e., FRCE, FICE, PRCE, and PICE), we found that the new two structures (i.e., FICE and PICE) give best results in terms of lower sidelobes.

Figure 4 shows the results for PRCE with $2N=100$, $M=6$, the number of elements that are excited individually $L=20$, and for PICE with different sizes of clusters as shown in figure. From this figure, it is observed that the peak sidelobe level can be reduced to more than $-34$ dB in the case of PRCE, and to more than $-40$ dB for the structure of PICE.

**Figure 3.** Results of FRCE and FICE Structures.

a. Fully optimized amplitude distribution  

b. The FRCE amplitude distribution

c. Radiation patterns  

d. The FICE amplitude distribution
Figures 5 and 6 show the variations of the cost functions according to (3), (4) and (5) versus the number of iterations during the optimization process for the FRCE, FICE, PRCE, and PICE structures. It is clear from these two figures that the two fully clustered structures need less number of iterations to converge with compared to that of the partially clustered structures. This is mainly due to the lesser number of degrees of freedom in the fully clustered structures.

To further highlight the effectiveness of the proposed structures with compared to some existing methods such as the I-CPE, M-CPE structures in [27]. Figure 7 show the results of all tested structures. The PICE structure provides lower sidelobes.

Figure 4. Results of PRCE and PICE Structures.
Figure 5. Comparisons between FRCE and FICE

Figure 6. Comparisons between PRCE and PICE
Furthermore, some numerical results are also shown with compared to the structures that were presented in [14] as shown in Table 1.

| Clustered Method | Clustered Type | Size of Large Array, Clusters and Individually Elements | Level of Peak Sidelobe (dB) |
|------------------|----------------|--------------------------------------------------------|-----------------------------|
| FRCE [14]        | Regular        | 2N=100, Q=5(M=10) and L=0                             | ≤ -30                       |
| FICE (this paper)| Irregular      | 2N=100, Q=2,3,4,5, and 10, and L=0                    | ≤ -35                       |
| PRCE [14]        | Regular        | 2N=100, Q=5(M=6) and L=20                             | ≤ -32                       |
| PICE (this paper)| Irregular      | 2N=100, Q=2,3,4,5, and 10, and L=20                    | ≤ -40                       |

4. Conclusion
It is clear from the current investigation that the desired array patterns with required constraints can be obtained by using both the fully and partially irregular clustered element structures. The use of
irregular clustered helps to eliminate the undesirable periodic high sidelobes that were unavoidable with the regular clustered. Other advantages include a significant reduction in the array complexity of the feeding network.

5. References
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