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Two-Dimensional Array Coverage Pattern Recalculating under Faulty Elements

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ABSTRACT: Faulty elements (FEs) in a two-dimensional array (TDA) directly impact the performance and configuration of the coverage pattern due to the long operation of the antenna system. Therefore, the process of dealing with these failed elements, knowing their locations, and reducing their negative impact in practice is the main goal of designing a large TDA. In this article, three types of FE locations (faulty random elements, faulty clustered elements, and faulty subarray elements) are studied. Based on the genetic algorithm (GA), the damaged coverage pattern due to the presence of these failed elements is recalculated. The method relies on re-optimizing the amplitude-only weights of non-FE optimally while neglecting the the defective elements. Therefore, the entire TDA elements do not need to be redesigned again but rather rely on the working elements only. This gives great simplification for recalculating the coverage pattern. To further control the coverage pattern in terms of main beam width, directivity (D), first null to null beam width (FNBW), and sidelobe level (SLL), a fitness function is added to the optimization process under specific constraints. Simulation results for different scenarios are presented to demonstrate the validity and effectiveness of the proposed approach for dealing with FE.

1. INTRODUCTION

In general, in modern communications systems, TDAs play an important role in achieving spatial diversity in terms of forming a coverage pattern to provide appropriate services. The demand increases for large aperture arrays that have an optimal pattern with lower cost and operational complexity. However, due to the large size of these arrays and their long operation and other types of failure sources such as mutual coupling, temperature…, the possibility of failure of one or more radiating elements is possible, causing a defect in the performance of the associated practical circuits such as the power distributor or transmitter/receiver units. The presence of FE in the array leads to an undesirable distortion in the coverage pattern through a distortion in the main beam width and an increase in the SLL, which leads to the loss of energy in undesirable directions with a decrease in antenna gain and directivity, thus causing interference or failure of the whole system [1]. Here, it is necessary to recalculate the coverage pattern in the presence of these unavoidable damaged elements. However, FE cannot be replaced every time, and this represents a difficult challenge for designers to restore the original coverage pattern to maximize the signal-to-noise ratio [2].

In the literature, it has been observed that there are some analytical methods to deal with the problem of damaged elements. In [3], the array containing FE was completely redesigned by recalculating the weights of all elements to reconstruct the coverage pattern by using numerical methods. The process of recalculating the weights of all elements after deteriorating a group of them is called a completely compensating approach. Other researchers have used numerical analytical and global algorithms methods to deal with this type of problem. In [2], the particle swarm optimization (PSO) algorithm was used by a group of researchers to analyze and handle the compensation of failed elements in the array. In [4], a method for finding the minimum number of active radiating elements that can be improved in order to compensate for failed elements based on a GA is presented. The author of [5] dealt with the fast iterative Fourier transform to analyze and correct element failures by expanding the use of the Fourier transform. Another method was suggested by [6], in which replacing the feeding of defective elements was used, but the replacement method took a long time during the analysis, and this option is not desirable from a practical standpoint. A method to recalculate the weights of the failure-free elements based on the conjugate gradient method and the quadratic programming method was proposed in [7, 8], respectively, to control the SLL. The orthogonal method was also used to solve the same problem in [9]. Hybrid algorithms have also been proposed to deal with the same problem [10, 11]. In another approach, a neural network was used to correct the failed elements within the array [12]. In all of the above-mentioned literature, it was necessary to re-tune the excitation weights for all or most of the elements, which is practically difficult and takes a long time to reanalyze the problem. However, the problem of determining the locations of the FE remains important in order to know the ability to recalculate the coverage pattern. The locations of the elements in the TDA are divided into two parts according to the level of weights [13–15]. The elements located close to the core have high weights, and their failure, or some of them, leads to a major defect in the coverage pattern. The elements close to the border have low

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weights, and their failure does not cause a major defect in the pattern (i.e., the coverage pattern is under control).

In this article, an efficient method has been proposed to detect FE in TDAs based on a GA and then reduce their effect on the coverage pattern. Three types of failed elements are generally studied based on the composition of these elements. The first type is to study the effect of FE individually on the pattern and at random locations within the array aperture. The second type is the study of the FE in the form of a cluster, while the third type is the study of the effect of the damage of one or more subarrays within the main TDA composed of a group of subarrays. In all the studied methods, it is not necessary to re-improve all the elements as the case in other methods based on full compensation to solve the problem of faulty elements. Instead, only the non-corrupted elements (active elements) are optimized with a new taper distribution to recompute the damaged pattern. In order to reduce the complexity and operating load of the array system, amplitude-only weights are relied upon in the optimization process. A suitable fitness function has been formulated to fully control the recalculation or correction of the damaged coverage pattern, in coordination with the functions for detecting damaged elements.

2. MATHEMATICAL THEORY

2.1. Faulty Random Elements and Faulty Clustered Elements

Let us consider a TDA with $N_x \times M_y$ elements evenly distributed along two axes x and y, assuming that the elements are placed on a plane $z = 0$. The general far-field (FF) coverage pattern of TDA can be estimated using the following mathematical formulation [16]:

$$FF_g(\theta,\phi)=\sum_{n_x}^{N_x}\sum_{m_y}^{M_y} ff_e(\theta,\phi) I_{n_x m_y} e^{ik(x_n \sin\theta \cos\phi + y_n \sin\theta \sin\phi)} \quad (1)$$

$$FF_g(\theta,\phi)=\sum_{n_x}^{N_x}\sum_{m_y}^{M_y} \delta_{n_x m_y}(\theta,\phi) \quad (2)$$

where $ff_e(\theta, \phi)$ is the element coverage pattern; $I_{n_x m_y}$ is the specific complex excitation of $N_x \times M_y$ elements located in the specific position $(x_n \times y_m)$; k is the wave number equal to $2\pi/\lambda$; λ is the free space wavelength; $\delta_{n_x m_y}(\theta, \phi)$ is the field of the directionally excited pattern for $N_x \times M_y$ elements according to the specific angle locations of the covering pattern. In order to simplify and reduce computational and practical complexity, the current sources (amplitude-only excitation) are set to $I_{n_x m_y} = |I_{n_x m_y}|$ in Eq. (1). It will be assumed what is called "active-passive" or "faulty-nonfaulty" elements, i.e., the failed elements have zero specific amplitude excitation ($I_{faulty} = 0$). The elements can fault in random locations or cluster locations within the array aperture. Therefore, a TDA that has f faulty elements leads to an unsatisfactory deterioration in the coverage pattern, so $FF_f(\theta, \phi)$ (the faulty element's far-field coverage pattern) can be known through the following:

$$FF_f(\theta,\phi) = FF_g(\theta,\phi) - \underbrace{\sum\sum \delta_{n_x m_y}(\theta,\phi)}_{n_x m_y \notin f} \quad (3)$$

After that, it is assumed that the coverage patterns of $N_x \times M_y$ elements radiated $FF_{nm}(\theta,\phi)_{n_x m_y=1}^{N_x M_y}$ by the array when a set of elements is a failure are known. Then, the radiated coverage pattern by a faulty array can be calculated through the free-faulty elements coverage pattern and faulty patterns $FF_{nm}(\theta,\phi)_{n_x m_y \in f}$ as in the following expression:

$$FF_f(\theta,\phi) = FF_g(\theta,\phi) - \underbrace{\sum\sum \left[FF_g(\theta,\phi) - FF_{n_x m_y}(\theta,\phi)\right]}_{n_x m_y \in f} \quad (4)$$

where $\delta_{n_x m_y}(\theta,\phi) = FF_g(\theta,\phi) - FF_{n_x m_y}(\theta,\phi)$.

It is worth noting that if there are FEs, the distances between the working elements will change and may be irregular according to the number of failed elements. This case is investigated if the original TDA consists of $N_x \times M_y$ independently excited elements, but if the array is composed of subarrays, it will be explained in the next section.

2.2. Faulty Subarray Elements

The TDA is divided into several subarrays $(S_x \times S_y)$. When one or more subarrays fail, the intersubarray space will be irregular according to the number of faulty subarrays. In the case that the original TDA contains defective elements, for the purpose of mathematical analysis, Equations (1)–(4) will change according to the implementation of the principle of dividing the array into subarrays and based on the following general subarrayed array equation [16]:

$$FF_g(\theta,\phi)_{subarray} = \sum_{s_x}^{S_x}\sum_{s_y}^{S_y} FF_{subarray}(\theta,\phi) \left|I_{s_x s_y}\right| \sum_{n_x}^{N_x}\sum_{m_y}^{M_y} FF_e(\theta,\phi) \left|I_{n_x m_y}\right| \quad (5)$$

where $|I_{s_x s_y}|$ is the amplitude-only excitation of a set of elements within a specific subarray. After the mathematical analysis of the TDA containing the faulty subarrays is completed, the indexes and number of defective subarrays are determined as well as how to calculate the faulty, free-faulty, and original coverage patterns. The coverage pattern recovery (recalculating) depends on the far field in coordination with the proposed fitness function.

3. GA APPROACH

In order to restore the damaged beam pattern, the amplitude-only excitation of free-faulty elements or clusters is perturbed. A GA is used to find out the locations of free-faulty elements or clusters and excite them to compensate the coverage pattern. The chromosomes in the algorithm contain data about the location and excitation of the potential compensatory element or cluster to compensate the desired pattern. Assuming that the TDA will contain faulty elements or clusters, the chromosome will consist of $(N_x \times M_y) - (n \times m) + 1$ genes. The first gene always encodes all free-faulty elements or clusters in a specific order according to the shape of the planar array. After the array is exposed to influential factors that make some elements or clusters faulty, the genes will consist of ones and zeros bits. Bit 0 means that the element or cluster is not used in the process of recalculating the damaged pattern, while bit 1 means that the element or cluster is recalculating its excitation, and so on with the rest of the genes, according to the number of bits specified for each gene in the chromosome by the designer.

As mentioned previously, the process of recalculating the coverage pattern depends on the amplitude-only weights of the active elements, while the FE will have zero weights. Here, the process of dealing with faulty arrays is similar to applying the thinning principle to reduce the number of radiating elements in large arrays. Then, GA is used to calculate the excitation of the active elements so that the coverage pattern obtained from the optimization process is close to the original pattern. Recalculating the pattern (as before the failure) is done by restoring the level of the original side lobes, preserving the directivity, as well as preserving the FNBW while relying on a small number of radiating elements or clusters. To implement this task, an efficient fitness function shown in Eq. (6) is proposed and combined with an optimization process to control the new coverage pattern.

$$fitness = \frac{1}{P}\sum |[FF_{active\_elements}(\theta,\phi)] - SLL_r(\theta,\phi)|^2$$

$$+|D(\theta,\phi)-D(\theta,\phi)_r|^2+|FNBW(\theta,\phi)-FNBW(\theta,\phi)_r|^2 \quad (6)$$

where P is the total number of points taken in the process of calculating the new coverage pattern; $SLL_r(\theta,\phi)$ is the required sidelobe levels; $D_r(\theta,\phi)$ is the required directivity; $FNBW_r(\theta,\phi)$ is the width of the main beam as it is in the pattern before the elements or clusters fail. According to Eq. (6), samples are taken from the main lobe width area, and the level of the desired sidelobes of the coverage pattern is obtained equally at points P. At each point, the algorithm calculates the difference between the obtained and desired sidelobe levels while maintaining the main lobe width. If the absolute value obtained $SLL_r(\theta,\phi)$ is higher than the required limit, then the excitations of the active elements must be updated frequently to control the required limit levels. This scenario contributes to reducing the cost, which represents the result of the error difference between the obtained and required coverage pattern points.

3.1. Faulty Elements and Faulty Subarrays Diagnosis

The process of determining the locations of FE (or faulty clustered elements or faulty subarrayed elements) begins by relying on measuring the degraded coverage pattern $FF_d(\theta,\phi)$ (i.e., the coverage emanating from the TDA that presents one or more defective elements or subarrays). Next, the proposed approach compares the coverage pattern measured in the presence of a set of samples (the array containing active elements or subarrays only) with the corresponding coverage pattern of the array in the presence of faulty/non-faulty elements. This is implemented by finding the set of f faulty elements or subarrays, which minimizes the squared distance between the faulty coverage pattern $FF_f(\theta,\phi)$ and the degraded coverage pattern $FF_d(\theta,\phi)$ as follows [17]:

$$dc = \sum |FF_d(\theta,\phi) - FF_f(\theta,\phi)|^2 \quad (7)$$

GA is used to deal with f. Chromosomes' genes will carry a binary coding of array elements that describes the status of each element or subarray (faulty/non-faulty) in the main TDA.

4. SIMULATION RESULTS

The idea of this paper can be applied to various types of TDAs such as square, rectangular, circular, concentric, and random ... ones. For simplicity, a square TDA with isotopic radiating elements $N_x = M_y$ distributed around two axes xy and spaced equally at 0.5λ is considered. The parameters of the GA in terms of the number of iterations, population size, crossover, selection, mutation rate, mating pool, and amplitude excitation were 100, 60, single point, roulette, 0.155, 4, and (0-1), respectively. Also, according to the square TDA, the v-cut pattern equals the u-cut pattern. All results were implemented using MATLAB version 2022b.

4.1. Faulty-Free Coverage Pattern Optimization

With no failed elements or subarrays in the array, the radiating elements are excited to emit in the $(\theta, \phi = 0)$ plane as a 2D v-cut coverage pattern (main beam width of 1.5 rad and SLL of -30 dB). The coverage patterns shown in Fig. 1 were formed by perturbing the amplitude-only of all elements (fully faulty-free elements), which produces the maximum radiation efficiency in the main lobe area while controlling the SLL to a great extent. To study the effect of FE, the focus is on preserving the coverage pattern shown in Fig. 1 by recalculating it based on the active elements only.

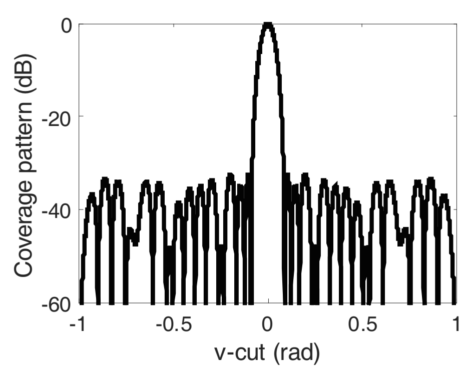

FIGURE 1. The Original coverage pattern.

4.2. FE Scenario

First, 230 elements are chosen to be faulty out of 24×24 elements (40% damaged elements) and not able to radiate; therefore, the coverage pattern will be destroyed, leading to an undesirable increase in the sidelobes, knowing that the locations of these FEs are important from a practical standpoint and contributes accurately to applying correct methods to recalculate the coverage pattern with the possibility of restoring the original pattern. If the locations of the FE are close to the edges (or

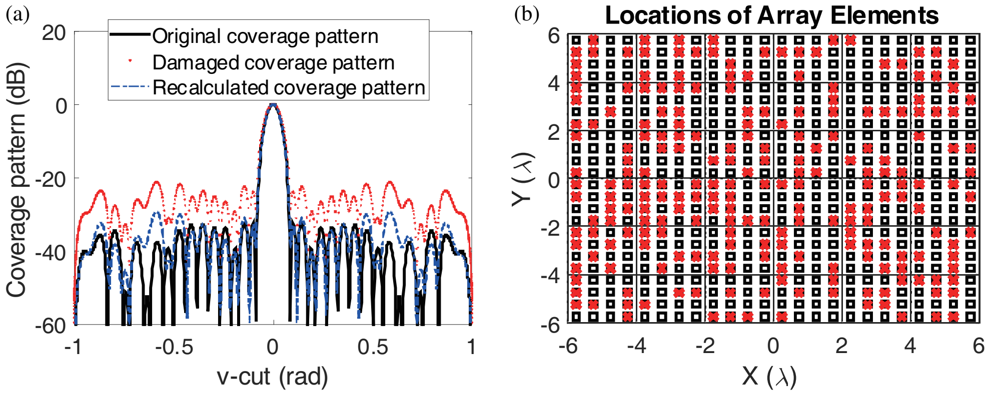

FIGURE 2. (a) The original, damaged and the recalculated coverage patterns with (b) 40% randomly FEs highlighted in red color.

boundary) of the square TDA, it is easy to recalculate the pattern from the remaining active elements close to the center. On the other hand, if the locations of the FEs are close to the center, then it is difficult to recalculate the pattern. The reason for the difference in the effect of locations on pattern recalculation is that the elements located on the edges have low amplitude weights, while the elements near the center have high weights. The amplitude weights attributing to the locations of the elements are through the taper distribution, by either polynomials (such as Dolph or Taylor) or algorithms (such as GA or others). To overcome the problem of determining the locations of faulty elements in terms of the element's weight value, it is assumed that the FEs were distributed randomly or clustered within the array aperture.

Figure 2(a) shows the distribution of elements in the square TDA, including the locations of the FE (where the * red color indicates FE, and the black color indicates active elements). Fig. 2(b) shows a 2D v-cut pattern comparison among the fault-free coverage pattern, damaged pattern, and recalculated pattern through the GA based on the excitations of working elements only in coordination with the proposed fitness function. It can be seen from this figure that the recalculated coverage pattern is close to the fault-free pattern, which is the goal. It is also possible to recalculate a phased coverage pattern in the presence of FE (see Fig. 3). Maintaining the phased pattern is important from a practical point of view because it has the property of beam steering.

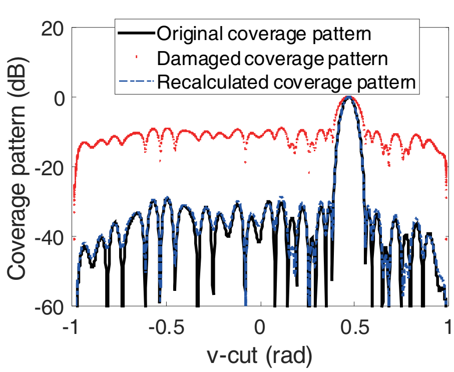

FIGURE 3. The original, damaged and the recalculated phased coverage patterns with 40% randomly FEs.

Next, the effect of faulty cluster elements with dimensions 6×12 inside the square TDA aperture is considered. The important thing to take into consideration is to avoid considering the center elements of the array as defective, as mentioned previously. Fig. 4 shows the results of the 2D v-cut coverage pattern in the failure of a cluster of elements. It can be seen from this figure that the faulty cluster is far from the center to avoid the difficulty of restoring the original pattern. It is also possible to deal with different dimensions of faulty clusters, provided that the dimensions do not exceed a quarter ($\frac{N_x}{4} \times \frac{M_y}{4}$) of the array, i.e., the dimensions of the defective cluster do not exceed one of the four quarters of the array, considering that the main array consists of four quarters.

4.3. Faulty Subarrays Scenario

The other check is the presence of faulty subarrays and their effect on the square TDA system. Here, it is assumed that the main array is divided into a set of subarrays, and then it is assumed that some of these subarrays become defective. In this case, the deviation of these subarrays from the radiation causes major problems in the coverage pattern because the subarrayed array depends on the radiation of the subarrays and not the radiation of each element individually. Therefore, the corruption of any subarray leads to a significant reduction in the degrees of freedom in the optimization process, which makes retrieving the coverage pattern somewhat difficult.

To clarify this case, let us assume that 16 subarrays out of 36 subarrays (the main array consists of 36 sub-arrays) are faulty (44% damaged subarrays). Fig. 5 shows the 2D v-cut coverage pattern in the faulty free pattern and faulty subarrayed pattern cases, indicating the locations of the faulty subarrays. The process of controlling the SLL in this case is difficult due to the reliance on a small number of active subarrays in recalculating the coverage pattern. As can be seen from Fig. 1, the assumed SLL constraint is -22 dB. However, using the proposed approach in this paper, the coverage pattern was recalculated with preserving all the characteristics of the original free defective pattern.

In all previous tests, the main beamwidth and directivity of the pattern were almost unchanged in the presence of different types of defects (see Fig. 6). This is because the square TDA

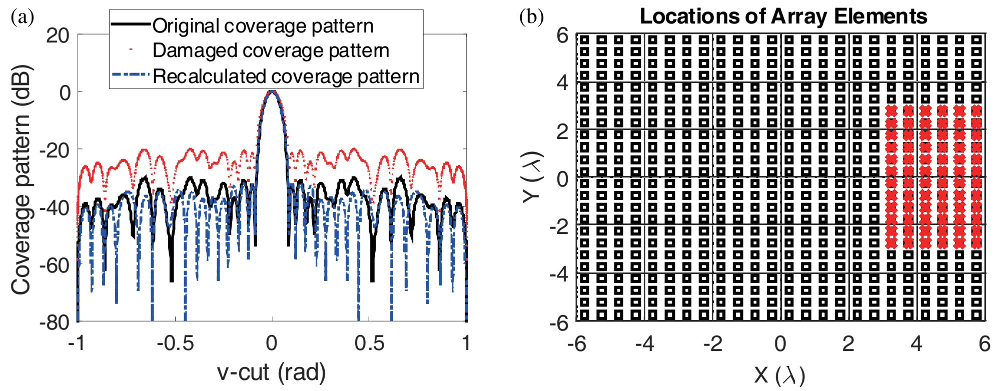

FIGURE 4. (a) The original, damaged and the recalculated coverage patterns with (b) 6 × 12 faulty cluster highlighted in red color.

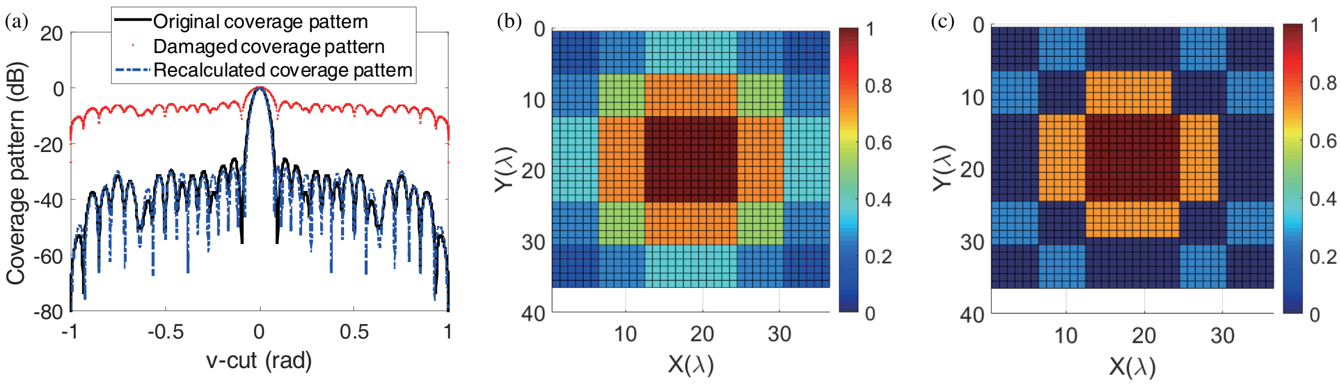

FIGURE 5. (a) The original, damaged and the recalculated coverage patterns for (b) free-faulty subarrays, (c) 16 faulty subarrays.

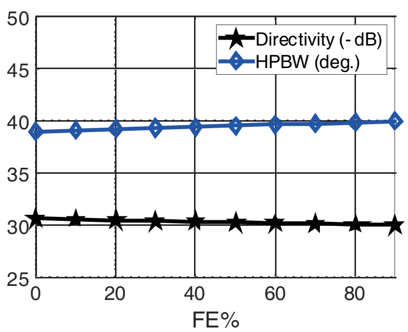

FIGURE 6. The directivity and HPBW vers FE%.

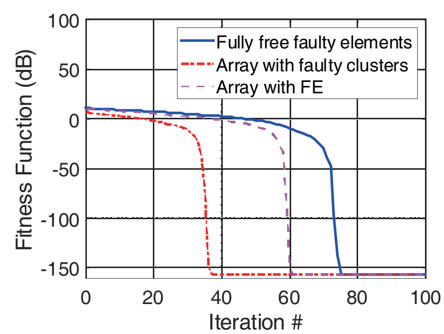

FIGURE 7. The relationship between the fitness function with the number of iterations.

aperture maintains its performance by relying on the active elements, as these elements are always more than the defective elements. It can be viewed from this figure that directivity and HPBW have been largely maintained even if there is 90% of the elements fault, as well as if there is a large number of subarrays fault.

Figure 7 shows the relationship between the fitness function with the number of iterations. It can be observed from this figure that the failure of some elements or some clusters gives a positive advantage to the system in recalculating the required pattern due to the small number of active radiating elements in the optimization process. As clear from this figure, the number of iterations in the case of faulty clusters is approximately 38 and 60 in the case of FE, while in the case of fully free-fault, the number of iterations was 77. This is useful in reducing the implementation time of the algorithm.

Finally, in order to demonstrate the robustness of the proposed approach, a set of comparisons were made with the results of other research in the same field, as shown in Table 1. The comparison included several parameters such as the type of array (linear or planar), the algorithm used, the method of dealing with failed elements (detection or correction or both), preserving the characteristics of the original coverage pattern (before damage), reducing the complexity rate, and reducing the number of iterations during recalculation of the coverage pattern. It can be seen from this table that the proposed approach in this paper works to recalculate the coverage pattern

TABLE 1. A set of comparison between proposed approach with other research.

Ref.	Type of array	Method	Detection or correction?	Verified coverage pattern specifications?	Reducing Complexity after recalculating coverage pattern?	Reducing No. of iteration after recalculating coverage pattern?
[18]	Linear	Whale and Choatic	Correction	yes	No	No
[19]	linear	PSO	Detection	No	yes	-
[20]	Linear	Nature Inspired Cuckoo	Detection and correction	yes	No	-
[5]	Planar	Fourier transform	Correction	yes	No	-
[21]	Linear	Cultural with Differential Evolution	Correction	No	No	-
[2]	Linear	PSO	Correction	Yes	Yes	-
This work	Planar	GA	Detection	Yes	Yes	Yes

and maintain its characteristics with a low complexity rate and a small number of iterations compared to the rest of the research.

5. CONCLUSION

Problems of faulty elements are unavoidable in many modern communications applications due to the requirements of long operation of the communication system. All types of array structures are vulnerable to this type of problem, whether arrays with individually fed elements or in the form of subarrays. An efficient method for identifying faulty elements in square-type TDA using a GA has been proposed. Therefore, this method gives the possibility of dealing with various types of defects in large arrays, and this is what distinguishes it from other optimization methods. In order to be able to recalculate the damaged coverage pattern, it was assumed that the defective elements (whether individually, as a cluster, or as a subarray) are randomly distributed within the array aperture. In this case, damaged elements in the center of the array are avoided, which makes the problem of recalculating the coverage pattern very difficult. The process of recalculating the coverage pattern depends on the active elements only, which greatly reduces the complexity of the system, whether in terms of RF components or computation.

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