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Scanned Antenna Arrays with Random Deactivated Elements

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ABSTRACT: Usually inactive or also known as thinned elements are used to simplify the array design complexity by turning off some of the active elements in uniformly filled arrays. Consequently, the far-field radiation characteristics such as sidelobe level, beamwidth, and directivity may be negatively changed if no optimizer is used. Further, these radiation characteristics may be unavoidably deteriorated when the main beam is scanned to new directions other than the referenced broadside direction. In this paper, an efficient optimization method based on the genetic algorithm and a dynamic deactivation method is proposed to randomly deactivate a number of array elements to minimize the peak sidelobe level and at the same time maintain the array directivity undistorted, while scanning the main beam. The deactivation method chooses optimally the suitable number of elements and their locations that need to be deactivated such that the resulting radiation characteristics positively change according to the specified cost function. Also, the proposed scanned array uses binary coefficients to activate and deactivate the array elements, thus, the feeding network of the proposed array is very simple, and it can be easily implemented in practice. Through extensive simulation results, we show that the proposed optimization method has good performance under wide range of scanned main beam directions. It is also found that the number of deactivation elements (i.e., the optimization variables) increases with larger scan angle.

1. INTRODUCTION

One important and useful feature of smart phased antennas in the current fifth-generation (5G) and future wireless communication systems is their capability to adaptively suppress the undesired signals and at the same time enhance the desired signals. To increase the coverage and efficient use of the spectrum, the undesired interfering signals should be effectively suppressed. The interference suppression can be performed by either reducing the sidelobes or by specifically pointing the nulls of the array patterns toward the directions of the interfering signals. Such operation results in a significant improvement in the output signal-to-interference plus noise ratio (SINR). Historically, all the element excitations have had their amplitude weighting [1] and/or phase weighting [2, 3] adjusted in order to achieve null steering [4] or sidelobe level (SLL) reduction [5, 6]. Other methods use two edge elements control [7] or a restricted subset of the array elements [8]. Compared to the uniformly stimulated arrays, these techniques are effective in cancelling interfering signals, but their performance may unavoidably deteriorated when the main beam is scanned to other directions than the referenced broadside one. Also, it may lead to more complex antenna array topologies than the referenced uniform array [9].

Thinning approaches have been widely presented in the literature to retain simplicity in the feeding network and antenna construction [10, 11]. In the thinned arrays, inactive elements with zero amplitude excitations are connected to matched loads, while a subset of active elements with unity amplitude excitations are connected to the feeding network. Outstandingly, these thinned arrays do not need phase shifters or attenuators to control the nulls or sidelobes of the array radiation patterns. On the other hand, the array designation with element positions control becomes a complicated and nonlinear challenge problem because of the unlimited number of possible element combinations and the nonlinear nature of the array factor. Dealing with scanned antenna arrays, i.e., steering main beams to other directions than the normal one adds more difficulties [12].

Currently, modern radar systems [13] and satellite communications [14] both make substantial use of thinned arrays. In these applications, thinning attempts to keep the final array pattern as close to a uniformly filled array's narrow beam width as possible, given the same array length, while minimizing the number of the active array elements and sidelobe levels.

Deactivation elements control can be used in these systems to overcome problems with element count, cost, weight, power consumption, and heat dissipation. A suitable optimizer is needed to be used with this controller to efficiently determine the number and location of the deactivated elements which results in antenna arrays that are more cost-effective in terms of hardware and control complexity than the fully populated arrays of the same size. These are the main objectives of this research work.

Due to the lack of closed-form solutions with the thinned arrays, generally analytical approaches are difficult to be used. Thus, the most common method in the literature is to use global evolutionary optimization algorithms to design these arrays, such as convex optimization [15], particle swarm optimizer (PSO) [16], and genetic algorithm (GA) [17]. It has been demonstrated that these optimization algorithms are effective in designing such thinned arrays. Nevertheless, a major disadvantage of these optimization methods is that each array el-

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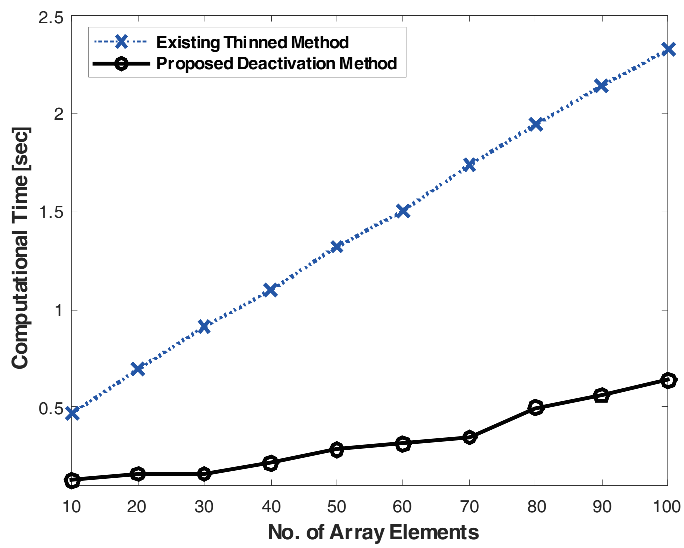

FIGURE 1. Variations of the computational time versus the number of the array elements.

ement is optimized and examined for possible thinning [18]. Thus, the computational time is high, especially when working with large arrays. This causes delayed convergence speeds which is a well-known problem that has been described in the literature [19]. Some hybrid approaches have been proposed by the scholars to overcome this problem [20]. Thinning arrays typically result in a drop in the antenna gain and loss of control over the undesirable sidelobe regions. However, the main beamwidth may be preserved if the last elements are excluded from the thinning process, and the overall array's aperture is kept unchanged.

In this paper, a new optimization strategy based on the genetic algorithm and an adaptive dynamic deactivation method is used to randomly deactivate a sufficient number of active array elements while minimizing the sidelobe level and at the same time preserving the array directivity undistorted. The directivity is preserved by making the proposed array's beam width as close as possible to that of a uniformly filled array under same array length constraint. Moreover, the number of deactivated elements and their locations are optimally determined by the optimizer during each scan angle of the main beam such that the peak sidelobe levels are kept under control. The proposed method can be considered as an alternative method to the conventional thinning methods due to its capability to provide faster solutions.

2. THE PROPOSED METHOD

The goal is to present a new optimization strategy with an efficient deactivation method to design the antenna arrays under scanned main beam assumptions. The proposed deactivation method optimally, randomly dynamically, adaptively, and sufficiently finds the required number of elements and their locations that need to be deactivated without negatively affecting the array's radiation characteristics. In particular, the beamwidth of the array is proportional to the largest dimension of the array aperture. Therefore, for a constant array length, deactivating elements will proportionally increase the directivity of the array while leaving the beamwidth relatively unchanged. To proceed, consider a symmetric phased linear array consisting of $N/2$ uniformly and symmetrically spaced elements on each side of the array. The overall array pattern of a linear antenna array in the elevation plane can be written as

$$AP\left(\theta\right)_{dB} = 10\log\left[EP(\theta) \times AF(\theta)\right] \tag{1}$$

where $EP(\theta)$ is the element pattern which is equal to one for isotropic elements, and $AF(\theta)$ is the elevation array factor of the phased linear antennas given by

$$AP\left(\theta\right) = \sum_{n=1}^{N/2} w_n \cos\left[\left(\frac{2n-1}{2}\right) kd(u-u_o)\right] \tag{2}$$

where w_n is the array weighting amplitude excitations which are chosen here to be binary coefficients that take a value of 1 if the element is chosen to be activate and 0 if the element is deactivate; $k = 2\pi/\lambda$; λ is the wavelength in the free space; $u = \sin(\theta)$, $u \in [-1, 1]$; θ is the elevation angle; and u_o is the scanning angle of the main beam. Note that the deactivated elements do not actually contribute to the array radiation pattern, and deactivating/removing them will cause nonuniform spacing between array elements. These spacing variables can change the array pattern in terms of their locations. The objective is to find a specific combination of 1s and 0s of the elements' status and their locations such that a new array radiation pattern without significant changes in the array's performances can be obtained. Specifically, the goal is to preserve the beamwidth as close as possible to that of the original uniformly spaced array pattern and minimized sidelobe level. Eq. (2) can be rewritten as

$$AP\left(u\right) = \left|\mathbf{a^H}(u-u_o)\mathbf{w}\right|^2 \tag{3}$$

where $\mathbf{a}\left(u-u_o\right) = \left[a_1(u-u_o)\ \ldots\ a_N(u-u_o)\right]^H$; $a_n\left(u-u_o\right) = e^{jkx_n(u-u_o)}$ is the radiation beam pattern of the n^{th} element; x_n is the element location of the n^{th} element; $\mathbf{w} = \left[w_1\ \ldots\ w_N\right]^T$ is the array excitation vector.

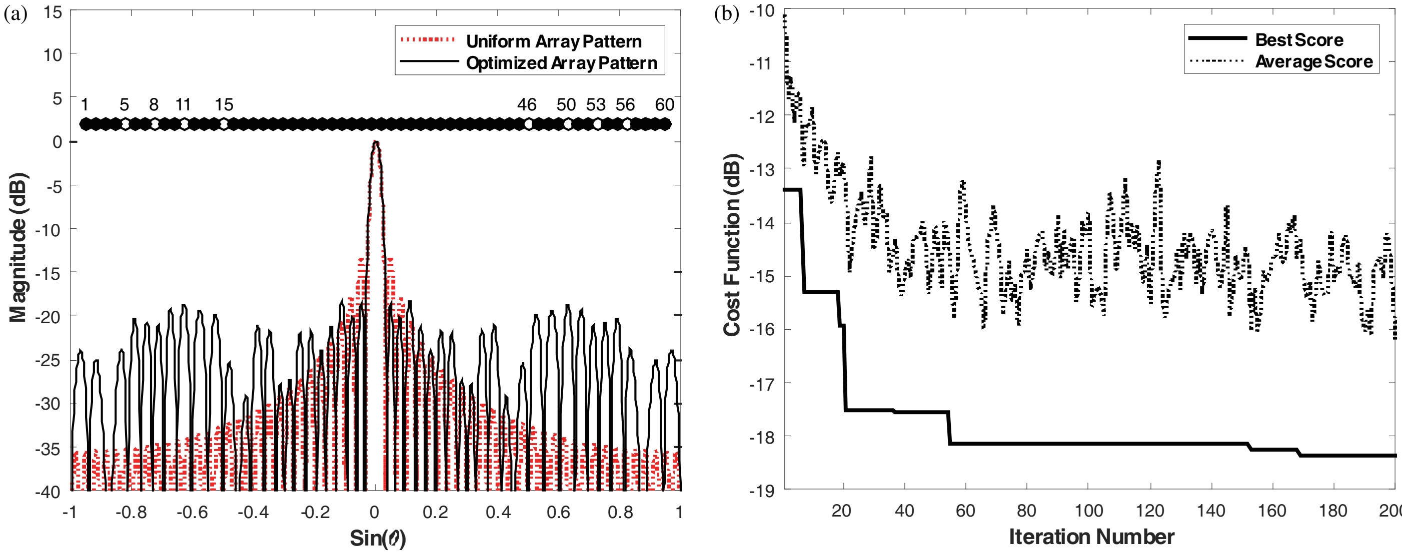

FIGURE 2. (a) Radiation pattern of the existing thinned array and (b) The cost function for 60 array elements and un-scanned main beam $u_o = 0°$.

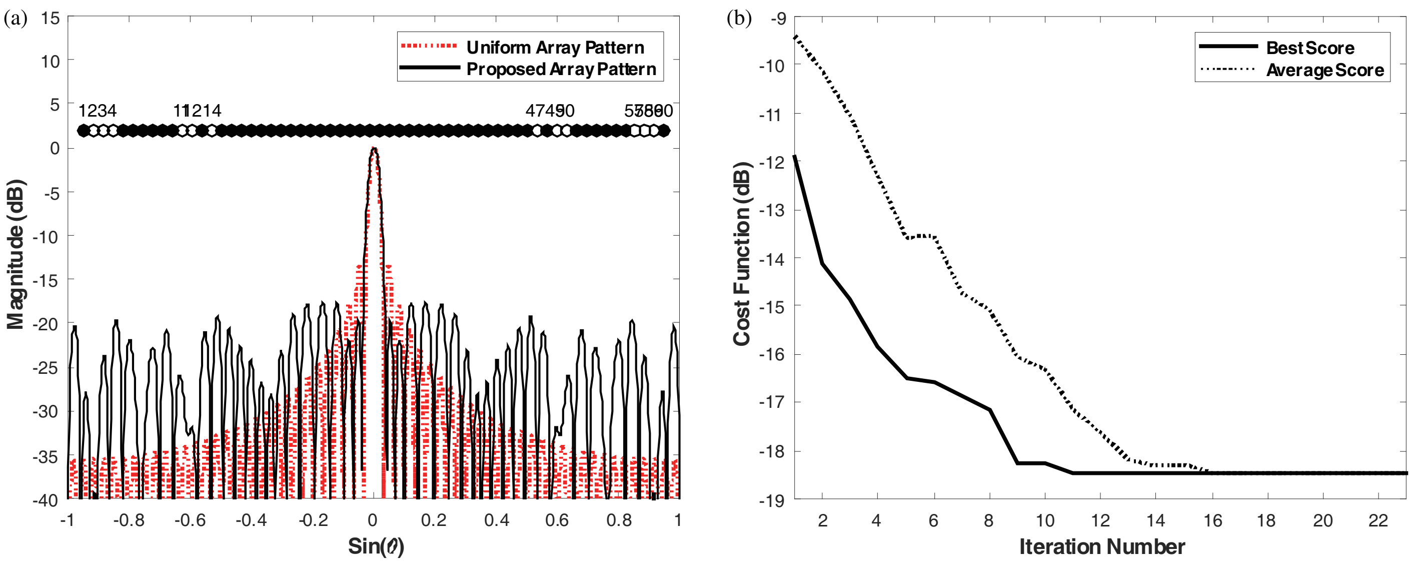

FIGURE 3. (a) Radiation pattern of the proposed array and (b) The cost function for 60 array elements and un-scanned main beam $u_o = 0°$.

Then, the objective functions can be written mathematically as:-

- Scanned main beam region constraint

$$|\mathbf{a}(u-u_o)\mathbf{w}|^2 = 1, \; -\text{FNBW}+u_o \le u-u_o \le \text{FNBW}+u_o \tag{4}$$

- Sidelobe level constraint

$$|\mathbf{a}(u-u_o)\mathbf{w}|^2 \le SLL_{u=u_{sll}}, \quad \text{FNBW}+u_o \le u_{sll} \le 1 \tag{5}$$

- For null constraint, the depression will be at interfering direction(s) only, u_{Null},

$$|\mathbf{a}(u-u_o)\mathbf{w}|^2 \le Null\,(u), \quad u = \text{u}_{\text{Null}} \tag{6}$$

where FNBW representing the first null beamwidth in the array pattern which is equal to $\text{FNBW} = \frac{\lambda}{Nd} + u_o$. In order to preserve the array length and also the beamwidth of the main beam of the resulting array pattern, the binary coefficients of the first and last elements on each side of the array are set to 1s always.

3. SIMULATION RESULTS AND DISCUSSIONS

In all examples, a symmetrical scanned linear array of $N = 60$ isotropic elements with uniform spacing $d = 0.5\lambda$ was considered. For the used genetic optimization algorithm, the number of population is set to 50. The stopping criteria are the maximum number of generations set to 500 and the minimum cost set to -80 dB. The other parameters were chosen as follows: a uniform crossover; selection was tournament; the mutation rate was 0.2; finally, the mating pool was chosen to be 4. The binary coefficients of the amplitude excitations were set to 0s for deactivated elements and 1s for activate elements. The scan angle of the main beam in the elevation plane is chosen to be

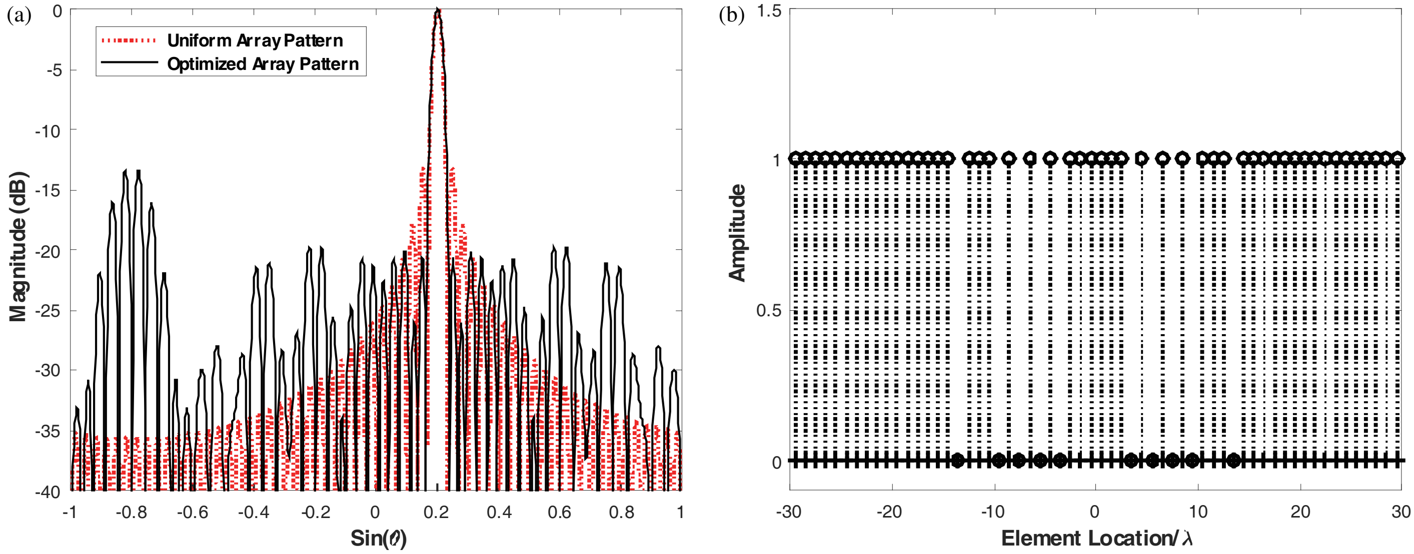

FIGURE 4. (a) Radiation patterns of both uniform and proposed arrays. (b) Optimized binary.

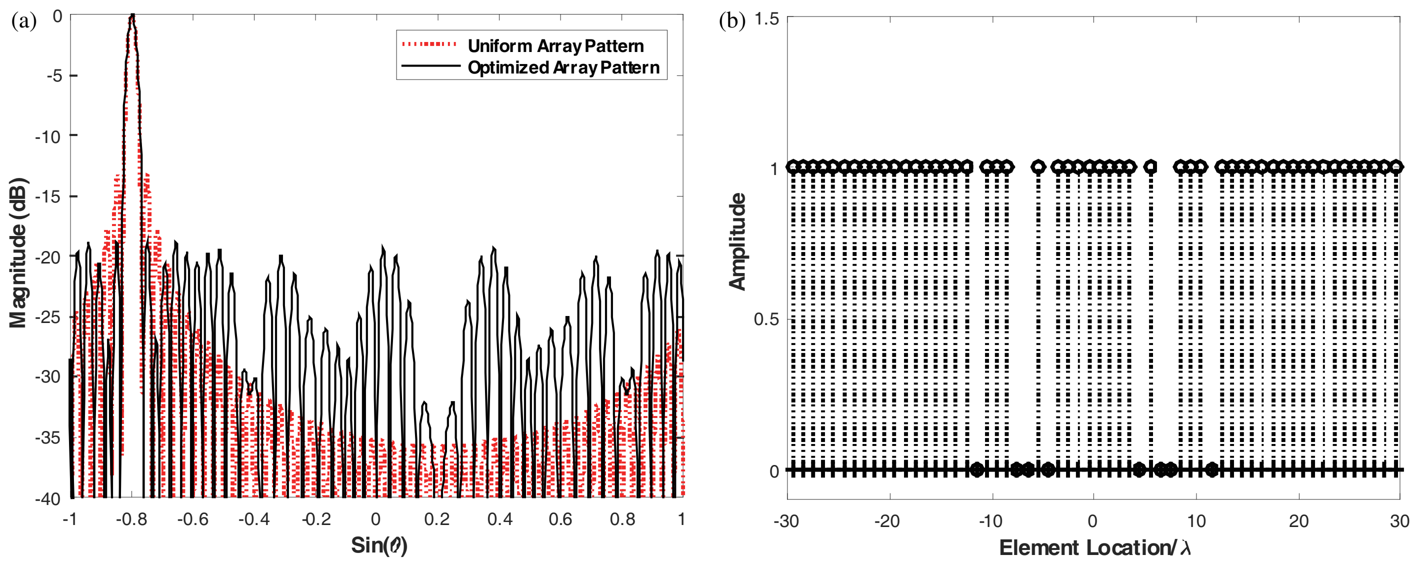

FIGURE 5. Results of the proposed array for scanned main beam $u_o = [-0.8]^\circ$.

$-0.9 \leq u_o \leq 0.9$. All the optimization processes were implemented on a laptop with windows 10 Pro 64 bit operating system, processor type Intel (R) Core TM i5, CPU @ 1.6 GHz 1.8 GHz and memory size of 4 G byte RAM.

In the first example, the computational time of the proposed deactivation method is determined under various numbers of the array elements. To illustrate the effectiveness of the proposed method, the computational time for an existing thinned method that was presented in [10] is also determined. Fig. 1 shows the computational time results of these two considered methods. It can be seen that the computational time of the proposed method is much lower than that of [10] for all array sizes.

Moreover, the array radiation patterns of these two methods as well as the cost function values for both average and best scores are shown in Fig. 2 and Fig. 3. In the top of the radiation pattern plots, the activation (i.e., black holes) and deactivation (i.e., small white circles) array elements are included. The superiority of the proposed method was evident.

In the second example, the effect of the steering angle of the main beam on the proposed array pattern is investigated. Fig. 4 shows the results of the proposed array for the case of steered main beam to an angle equal to $u_o = 0.2$ radian in the u space. For this case, the resultant binary coefficients are [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 0 1 0 1 0 1 0 1 1]; the directivities of the standard and proposed arrays are 32.1125 dB, 31.1408 dB, respectively, while the number of deactivated elements is 5 on each side of the array.

In the next example, the steering angle of $u_o = -0.8$ radian is considered as depicted in Fig. 5, where the resultant binary coefficients are [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 0 0 1

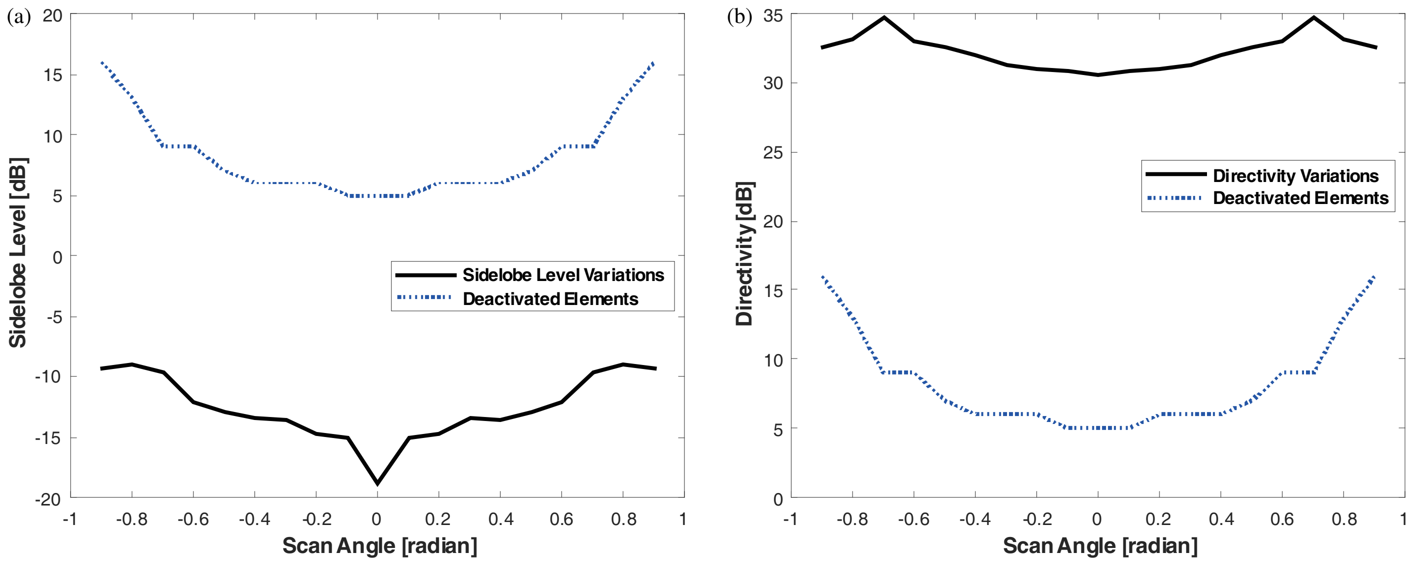

FIGURE 6. Variations of the sidelobe level and directivity versus the scanned angle.

0 1 1 1]; the directivity of the uniform array is 31.6778 dB; the directivity of the optimized array is 30.2995 dB.

Finally, Fig. 6 shows the variations of the peak SLL and the directivity versus the steering angle of the main beam. For each scan angle, the needed number of the randomly deactivation elements that computed by the optimizer are also shown in this figure. It can be seen that, in general, the SLL increases with increased scan angle, while the directivity remains approximately constant above 30 dB. Also, it is observed that the optimizer chooses randomly more deactivated elements when there is an increase in the scan angle.

4. CONCLUSIONS

An efficient deactivation method with the genetic optimizer is proposed to efficiently deactivate the required array elements such that the good features of the radiation performance were preserved under the scanned main beam situations. Performance measures in terms of peak sidelobe level, directivity, feeding network design complexity, i.e., number of deactivating elements, and the computational time, i.e., the convergence speed of the proposed method were analyzed. It has been shown that the sidelobe level of the proposed array pattern could be minimized to more than -20 dB for un-scanned main beam case, and the directivity could be almost maintained at 30.4935 dB with an optimum number of deactivating elements equal to only 5, while for scanned main beam range $-0.6 \leq u_o \leq 0.6$, the sidelobe level could be minimized to more than -15 dB, and the directivity is higher than 30 dB for all the scanned directions. Clearly, the proposed deactivating strategy attempts to keep the resultant array pattern as close to a uniformly filled array's narrow beamwidth as possible, given the same array length, while minimizing the sidelobe levels. Moreover, the computational time of the proposed method was found to be lower than that of the existing thinned methods.

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