

Strategies for Selecting Common Elements Excitations to Configure Multiple Array Patterns

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Abstract—In this paper, a single linear antenna array with partially common element excitation amplitudes is used to reconfigure between Taylor-pencil beam and flat-top beam patterns. Two strategies are suggested to properly select the common elements while still satisfying the desired constraints on both patterns. The first strategy uses the central elements of the array as the common elements for the reconfiguration between the required two patterns, while the other one uses the side elements. Since the element excitation amplitudes of the corresponding Taylor and flat-top patterns usually tend to be maximum and similar at the array center, the central common elements approach outperforms the sided one. Compared with the conventional array pattern synthesized methods with completely two separable elements excitations arrays, only a single linear array with a number of common element excitations is needed in the proposed method. Hence, it has advantages of simple structure, low cost, and compact size. Simulation results show that the proposed array with the central common elements approach has the capability to efficiently reconfigure between Taylor and flat-top beams by modifying only 24 elements out of a total 40 array elements with all sidelobe levels of both patterns below -20 dB.

1. INTRODUCTION

Techniques of array pattern reconfigurations are very desirable in both satellite and terrestrial communication systems because they have the ability to perform multi-function operation which is impossible with the traditional single array antennas. Generally, the desirable shaped beam patterns of the reconfigurable arrays can be easily achieved by either using simple switches such as PIN diodes [1] or RF components such as attenuators and/or phase shifters to control the current excitations of the array elements [2]. It can also be achieved by means of parasitic elements [3]. In the literature, most attention has been paid toward the first and third categories of the array reconfigurations, while the second category gained less attention due to the complexity in modifying both the amplitude and phase excitations of every element in the array feeding network. The goal of this work is to reduce the complexity issue and provide a good control on the pattern reconfigurations by using a single linear array with common element excitations to generate two or more radiation patterns.

Most of the array pattern reconfiguration techniques have been developed by fully controlling and modifying the excitation amplitudes and phases of every array element [4–7]. For a large number of array elements, there may exist many possible configuration options for the RF components or switches to achieve the desired performance. Certainly, this can be achieved by using efficient optimization algorithms for searching and finding the most potential configurations that give the optimal solution [8, 9]. Apart from fully controllable arrays where every element excitation needs to be separately configured, the partially controllable arrays configure only a limited number of the elements' excitations

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amplitudes and phases. Hence, they have advantages of simple structure, low cost, and compact size. Therefore, the partially controllable arrays have been an attractive topic in the area of antenna pattern synthesis for the last few years. Simplicity in their feeding networks is the most important feature of such types of arrays [10–15].

This work exploits the concept of partially controllable arrays and proficiently combines it with the concept of common element excitations to generate two different array patterns, pencil-Taylor beam and flat-top beam, using a single linear antenna array. The common elements that may be used to generate both patterns can be selected from either the center or side elements of the array. Such an idea can greatly simplify the hardware implementation of the array feeding network. Also, since a single array antenna is needed to generate two different radiation patterns, the problem of space limitation which is crucial in some applications can be overcome. These applications that require the use of the flat-top beam pattern include broadcasting systems which require uniform illumination for more than one sector of the region from the satellite. Other applications include maritime navigation (underwater acoustics) and wireless communication systems [16].

Recently, the author presented an iterative fast Fourier transform method to generate sum and difference patterns with pre-specified percentage of common amplitude excitations of the elements at both end sides of the array [17]. This method has shown its ability to alter between the sum and difference patterns, since their corresponding amplitude excitations have very similar common tails at the array sides. However, applying this method to generate other patterns such as pencil, flat-top, or shaped beams may encounter a difficulty in finding the required common excitations especially at the sides of the array where their amplitude excitations are completely different. In other words, the element amplitudes of excitations of the corresponding pencil and flat-top patterns at the side elements are dissimilar, thus, they cannot be considered as common. Therefore, the choice of the central common elements has been found more useful in reconfiguration between pencil and flat-top patterns. The concept of the central common excitations has also been used with the sidelobe canceller system for reusing the same array elements as the auxiliary antennas instead of separate ones [18].

In this paper, a genetic optimization algorithm for generating multiple and different radiation patterns with partially common elements excitations amplitudes is presented. Two strategies based on the common central elements and common sided elements were examined to maintain the desired constraints that simultaneously imposed on both corresponding beam patterns. For both strategies, a limited number of array elements were made common for both array patterns, and only a specified number of elements on each side of the array were made adaptable with proper amplitudes and phases adjustments. The proposed method has been applied to reconfigure between Taylor-pencil and flat-top beams. Moreover, the proposed array is found to be also effective in designing a one dimension flat-top pattern with high beam efficiency. In the following sections of this paper, we will introduce the proposed array pattern reconfiguration method with two suggested strategies of the common elements and compare their results to identify the best one.

2. THE PROPOSED STRATEGIES

In the proposed method, the design of reconfigurable dual array patterns is based on finding a maximum percentage of common amplitude excitations of an array that can generate both Taylor-pencil and flat-top patterns. For selecting the common elements, the following two strategies are suggested:

2.1. Common Central Elements Strategy

In this strategy, the element excitations amplitudes of the central array elements are made common for reconfiguration between Taylor and flat-top patterns, and only the side elements are made separately adjustable through the use of a genetic optimization algorithm. All the element excitation phases are set to 0° for the Taylor mode, and they are varied in the range $0^\circ \leq \theta \leq 180^\circ$ for the flat-top mode.

Consider an array of N isotropic elements arranged along X axis and equally spaced by a distance equal to $d = 0.5\lambda$. The location of the first element is chosen at the origin. For simplicity, the mutual couplings between the array elements are neglected. The far-field radiation pattern of this array in the

XZ plane is given by

$$AF_{Taylor}(u) = \sum_{n=1}^N a_n e^{j\rho_n} e^{j(n-1)kdu} \quad (1)$$

Here, $k = 2\pi/\lambda$, where λ represents the wavelength; a_n and ρ_n are the element excitation amplitudes and phases respectively determined according to the Taylor distribution, and $u = \sin(\theta)$ where θ is the observation angle from broadside. The amplitude excitations of Eq. (1) are assumed symmetric, and they can be easily computed according to well-known Taylor distribution while the phases are assumed to be zero. According to Eq. (1), the resulting Taylor beam pattern can be generated with specific sidelobe level or pre-specified constraints. To generate another beam pattern like flat-top with some common element excitation amplitudes as those of the Taylor distribution, Eq. (1) can be rewritten in a new form such that the element excitations can be divided into two sets. The first set consists of M adjustable elements out of N array elements on each side of the array which are separate and have different values for Taylor and flat-top arrays, while the other set consists of $N - M$ elements which are common and unchangeable with same values. These common and unchangeable array elements are located around the center of the array as shown in Fig. 1.

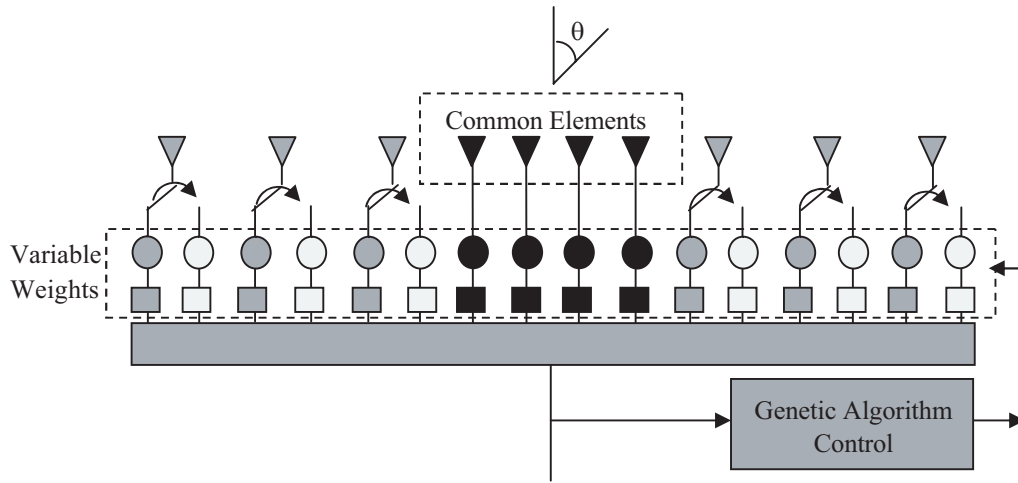


Figure 1. Common central elements configuration.

To alter the array radiation pattern from a Taylor-pencil to flat-top, only the amplitudes and phases of M adjustable outer elements are altered. Thus, Eq. (1) can be rewritten as

$$AF_{Flattop}(u) = \underbrace{\sum_{n=1}^{N-M} a_n e^{j\rho_n} e^{j(n-1)kdu}}_{\text{Common Central Elements}} + \underbrace{\sum_{m=N-M+1}^N \left\{ A_m e^{jP_m} e^{j(m-1)kdu} \right\}}_{\text{Adjustable Outer Elements}} \quad (2)$$

where A_m and P_m are the amplitudes and phases of the adjustable uncommon outer elements used to generate the corresponding flat-top beam pattern. A genetic algorithm is used to optimize the values A_m and P_m such that the desired sidelobe levels of the original Taylor pattern and the newly generated flat-top pattern are maintained within the pre-specified constraints. To verify the concept of pattern alteration with common central element strategy, a Taylor array with $N = 30$ elements and a sidelobe level equal to -20 dB is considered. The number of adjustable outer elements on both sides of the array was set to $M = 14$ such that two wide nulls can be configured in the Taylor pattern. These two symmetrical wide nulls are assumed to be centered at $u = \pm 0.45$ and ranged from $u = \pm 0.4$ to $u = \pm 0.5$. Fig. 2 shows the original and modified Taylor distributions and their corresponding beam patterns. From this figure, it can be seen that the concept of common central elements has been successfully verified, and the Taylor pattern has been easily altered to place the required nulls. Further, note that the depths

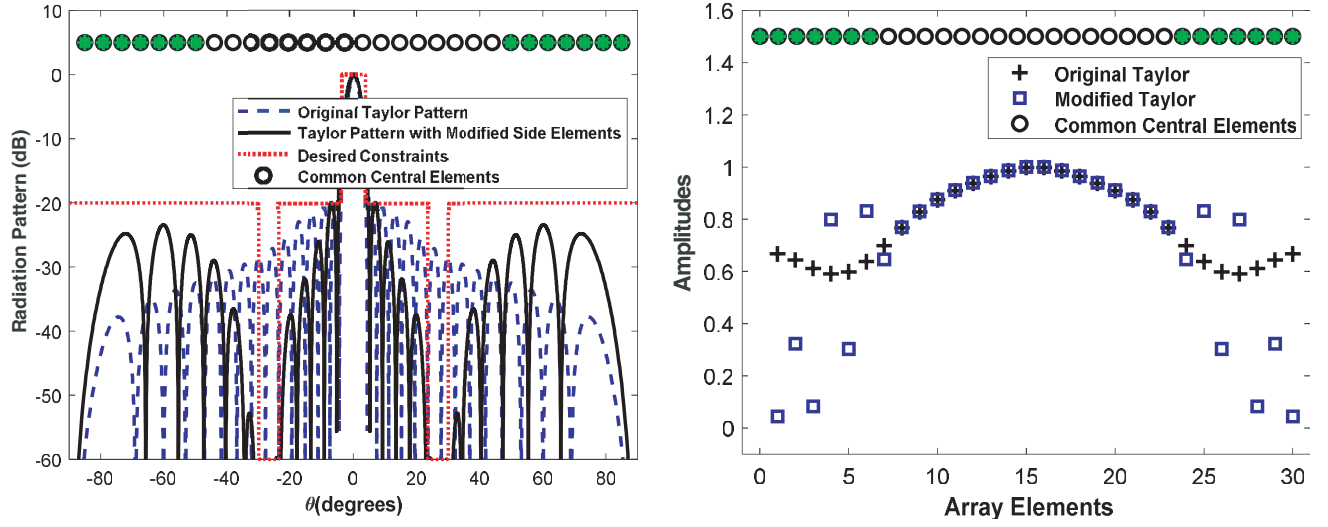


Figure 2. The original and the modified Taylor distributions and their corresponding beam patterns for $M = 14$ common central elements.

of the placed nulls were at -60 dB as specified by the desired constraints. Moreover, the directivities of the original and modified Taylor patterns are 12.7 dB and 12.107 dB, respectively. In addition, the taper efficiencies of the original and modified Taylor patterns were 0.965 and 0.939, respectively.

2.2. Common Outer Elements Strategy

In the second strategy, the element excitation amplitudes of the outer array elements are made same as those of the original Taylor distribution to generate the flat-top beam pattern from the Taylor beam alteration. Here, the amplitude excitations of the central elements are made changeable as shown in Fig. 3.

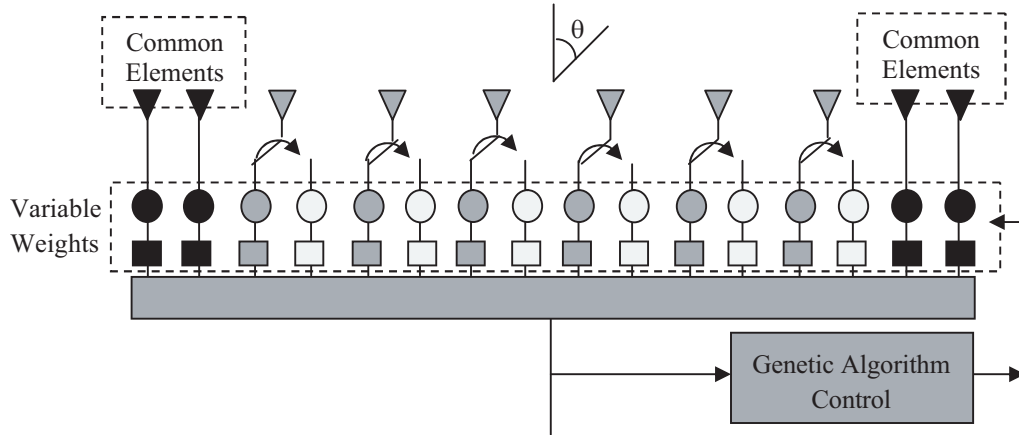


Figure 3. Common outer elements configuration.

To perform such alteration in the array patterns, Eq. (2) can be rewritten as follows

$$AF_{Flatop}(u) = \underbrace{\sum_{n=1}^{N-M} A_n e^{jP_n} e^{j(n-1)kdu}}_{\text{Adjustable Center Elements}} + \underbrace{\sum_{m=N-M+1}^N \left\{ a_m e^{j\rho_m} e^{j(m-1)kdu} \right\}}_{\text{Common Outer Elements}} \quad (3)$$

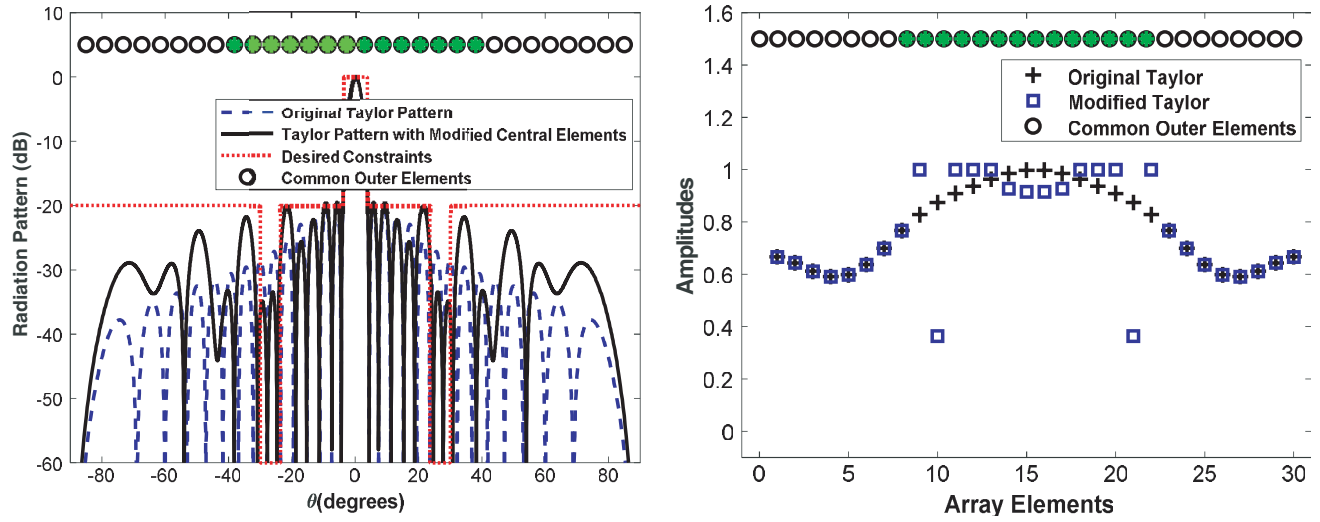


Figure 4. The original and the modified Taylor distributions and their corresponding beam patterns for $M = 14$ common outer elements.

where $a_m = a_n$ and $\rho_m = \rho_n$ for outer array elements. A_n and P_n are the amplitudes and phases of the changeable uncommon center elements optimized by means of genetic algorithm to generate the corresponding flat-top beam pattern. To verify this concept, the results of Fig. 2 are re-plotted as shown in Fig. 4. Here, the same original Taylor distribution with modified central elements to place the same wide nulls is considered. For fair comparison, the number of adjustable elements was also set to $M = 14$. From this figure, it can be seen that the concept of common outer elements has been successfully verified, but its performance was found to be not good as that of the common central elements approach where the depth of the placed nulls was at -34 dB. Moreover, the directivities of the original and modified Taylor patterns for this case were 12.7 dB and 12.68 dB, respectively. More important, the taper efficiencies of the original and modified Taylor patterns were 0.965 and 0.828, respectively. Clearly, with this strategy, the taper efficiency has been reduced.

2.3. The Cost Function

The cost function of the used optimization algorithm that needs to be minimized for generating Taylor and flat-top beam patterns can be expressed as

$$\begin{aligned}
 Cost = & \underbrace{(SLL_d - SLL_o)^2 + (FNBW_d - FNBW_o)^2}_{\text{Pencil Beam}} \\
 & + \underbrace{(SLL_d - SLL_o)^2 + (FNBW_d - FNBW_o)^2 + (R_d - R_o)^2}_{\text{Flat-top Beam}} \quad (4)
 \end{aligned}$$

where SLL_d and SLL_o represent the desired and obtained sidelobe levels, respectively. $FNBW_d$ and $FNBW_o$ are the desired and obtained first null-to-null beam widths, respectively. $FNBW_d$ is ranged by $-\frac{\lambda}{Nd} \leq \theta \leq \frac{\lambda}{Nd}$. The last term is the ripple in the main lobe region for the flat-top pattern. All the desired values should be given in advance. Then, the lower value of the cost will produce array patterns closer to the desired values. The desired maximum ripple level in the main beam region ($-0.3 \leq u \leq 0.3$) is assumed to not exceed -1 dB from the peak value of the normalized main beam 0 dB. The genetic algorithm is used to optimize the amplitudes and phases of the adjustable elements such that the generated patterns in Eq. (2) or (3) and the pre-specified desired constraints according to the cost function in Eq. (4) are satisfied.

3. SIMULATION RESULTS

To assess the proposed method, a number of numerical results have been presented. In all examples, an equally spaced ($d = 0.5\lambda$) linear array composed of 40 elements is considered to generate a Taylor-pencil beam and a flat-top beam using either central or outer common element excitations. The amplitude and phase excitations of the adjustable elements are assumed symmetric with respect to the center of the array. The number of common elements on each side of the array is varied from $M = 0$ up to $M = 20$ with a step equal to 2 where the starting value $M = 0$ corresponds to the case of completely independent amplitude excitations in which the Taylor and flat-top patterns are generated separately under perfect constraints, while the final value $M = 20$ corresponds to the fully common amplitude excitations in which only the original Taylor pattern is generated. Any other values of M correspond to the partially common amplitude excitations in which both patterns can be generated with a certain sharing percentage of the element excitation amplitudes. Generally, we examined the performance of the proposed strategies under various sharing percentage starting from 0%, 10%, 20%, up to 100% to find the maximum sharing percentage that compromise between the two patterns with satisfied constraints. Due to symmetry, only half number of common amplitudes and phases are optimized. For

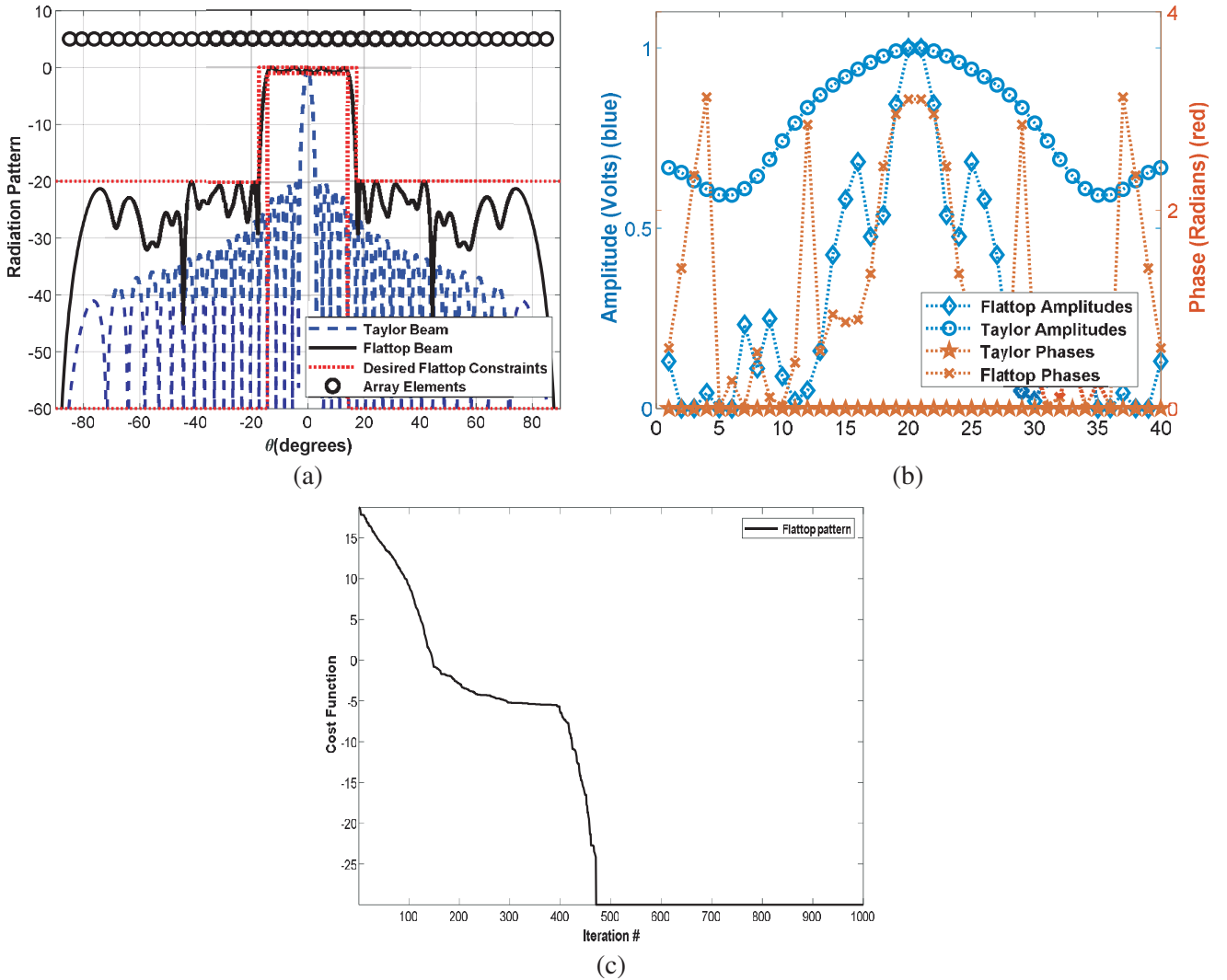


Figure 5. (a) Taylor and flattop patterns, (b) their corresponding amplitudes and phases, and (c) the cost function for $N = 40$ and $M = 0$ (i.e., Separate element excitations).

the optimization process, the minimum and maximum values of the optimized amplitudes are restricted to lie between 0 and 1, with the phases between 0° and 360° . The amplitude excitations of every element of the Taylor array were first determined, then the common elements were made fixed, and only the adjustable elements were optimized to generate the flat-top pattern. In all examples, the used specifications of the genetic algorithm were set as follows: an initial population size is 20; selection is roulette; crossover is single point; mutation rate is 0.15; and mating pool is chosen to be 4.

In the first example, the independent element excitations $M = 0$ (i.e., sharing percentage = 0%) are considered, and the original (or reference) Taylor and flat-top patterns are generated for comparison purpose. The original Taylor-pencil beam is designed such that it has the following specifications, $SLL_d = SLL_o = -20$ dB and $FNBW_d = FNBW_o = 6.7^\circ$, while for the flat-top beam these values were $SLL_d = SLL_o = -20$ dB, $FNBW_d = FNBW_o = 36^\circ$, and $Ripple_d = Ripple_o = -1$ dB. Fig. 5 shows the results of the independent element excitations and their corresponding array patterns. The cost function variation according to Eq. (4) is also shown in this figure. From this figure, it can be seen that all the obtained results are within the desired constraints, and the cost function reaches the lowest value. Moreover, the optimized flat-top array pattern was found to be very satisfactory with high beam efficiency (see Fig. 5(a)).

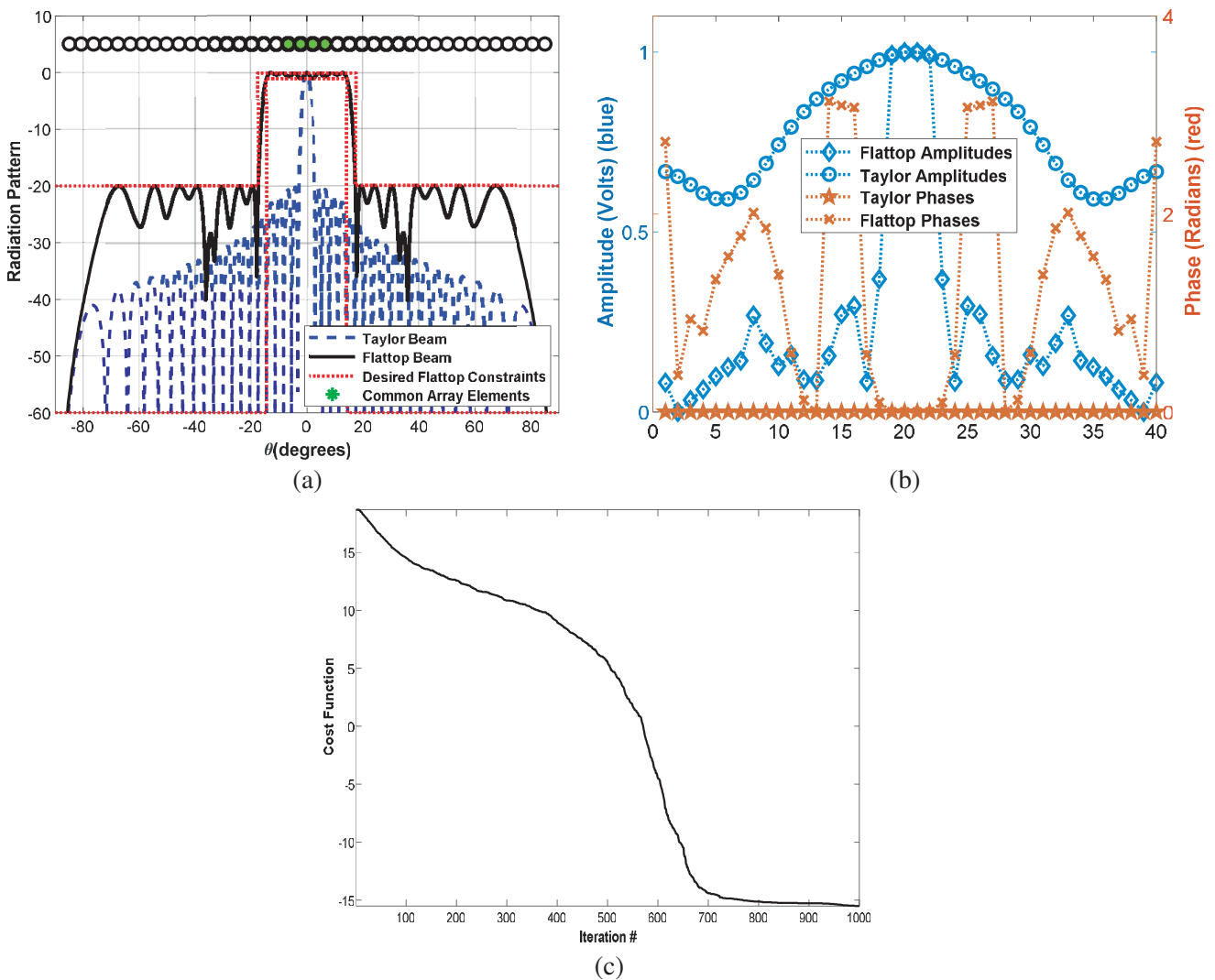


Figure 6. (a) Taylor and flattop patterns, (b) their corresponding amplitudes and phases and (c) the cost function for $N = 40$, $M = 4$, and sharing percentage = 10%.

In the second example, the central common element excitations for $M = 4$ elements (i.e., sharing percentage = 10%) were investigated. Fig. 6 shows the results of generating both Taylor and flat-top patterns and their corresponding element excitations as well as the cost function variation. It can be seen that the generated patterns are still within the desired constraints. Moreover, the performances in terms of taper efficiency, main beam ripple, directivity, peak sidelobe level, average sidelobe level, and the first null-to-null beam width of these two patterns are listed in Table 1. It is found that the taper efficiency and directivity of the flat-top pattern were improved as the sharing percentage increased. In contrast, the main beam ripple and peak sidelobe level got worse as the sharing percentage increased. Nevertheless, a reasonable compromise between these two configuration patterns can be obtained for $M = 12$ (i.e., sharing percentage = 30%) or less.

Table 1. Performances of the common center elements strategy.

Performances	Optimized Taylor Pattern	Optimized Flat-top Pattern											
		Sharing Percentage (%) - Center Case											
			10	20	30	40	50	60	70	80	90	100	
Taper Efficiency	0.96	0.09	0.1	0.11	0.13	0.13	0.17	0.2	0.28	0.32	0.55	0.96	
Beam Ripple (dB)	—	−1	−1	−1.4	−2.1	−1.6	−2.4	−0.8	−0.3	−0.2	−0.1	—	
Directivity (dB)	13.93	4.30	4.2134	4.9523	5.5556	5.6331	6.6156	7.3531	8.8206	9.3362	11.7665	13.9379	
Peak SLL (dB)	−20	−20	−20	−18.3	−16.5	−15.7	−15.7	−15	−20	−19	−13	−20	
Average SLL (dB)	−35.61	−23.98	−22.8966	−23.4775	−20.1566	−21.9593	−21.5035	−20.2086	−21.7526	−21.9353	−21.9675	−31.7855	
FNBW (deg.)	6.7	36	35	26	21.4	16.4	13.4	11.2	10	9	8.2	6.7	
Element Excitation Amplitudes	$a_n^T = a_{-n}^T$	$a_n^F = a_{-n}^F$											
	0.66	0.00	0.00	0.08	0.63	0.60	0.70	0.91	1.00	1.00	1.00	0.66	
	0.65	0.00	0.06	0.05	0.26	0.56	0.90	0.91	1.00	1.00	1.00	0.65	
	0.63	0.25	0.00	0.23	0.40	0.83	0.78	1.00	1.00	1.00	0.63	0.63	
	0.60	0.00	0.01	0.51	0.44	0.73	0.59	1.00	1.00	1.00	0.60	0.60	
	0.59	0.00	0.04	0.49	0.63	0.75	0.99	1.00	1.00	0.59	0.59	0.59	
	0.59	0.08	0.13	0.48	0.52	0.40	1.00	1.00	0.86	0.59	0.59	0.59	
	0.60	0.00	0.20	0.48	0.12	0.00	1.00	1.00	0.60	0.60	0.60	0.60	
	0.64	0.27	0.24	0.29	0.29	0.69	1.00	0.99	0.64	0.64	0.64	0.64	
	0.69	0.27	0.21	0.62	0.85	1.00	0.75	0.69	0.69	0.69	0.69	0.69	
	0.74	0.33	0.06	0.03	1.00	1.00	0.00	0.74	0.74	0.74	0.74	0.74	
	0.79	0.66	0.00	0.31	1.00	0.75	0.79	0.79	0.79	0.79	0.79	0.79	
	0.83	0.70	0.00	0.72	0.90	0.37	0.83	0.83	0.83	0.83	0.83	0.83	
	0.86	0.65	0.16	0.83	0.68	0.86	0.86	0.86	0.86	0.86	0.86	0.86	
	0.89	0.23	0.32	0.60	0.85	0.89	0.89	0.89	0.89	0.89	0.89	0.89	
	0.92	0.20	0.61	0.29	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	
	0.94	0.58	0.54	0.77	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	
	0.96	0.79	0.54	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	
	0.97	0.79	0.51	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	
	0.99	0.96	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

In the next example, the central and outer common elements excitations for a number of sharing percentages equal to 20%, 30%, and 40% were examined and compared. Fig. 7 shows the results for the case of central common elements, while Fig. 8 shows the results for the outer common elements cases for these three sharing percentages. It is found from these two figures that the central common element strategy gives better results than that of the outer common element strategy. Further, all the obtained flat-top patterns from the use of outer common elements strategy were found to exceed the desired constraints in the sidelobe region as well as in the main beam ripple even when the smallest value was chosen for $M = 2$ (i.e., sharing percentage = 5%).

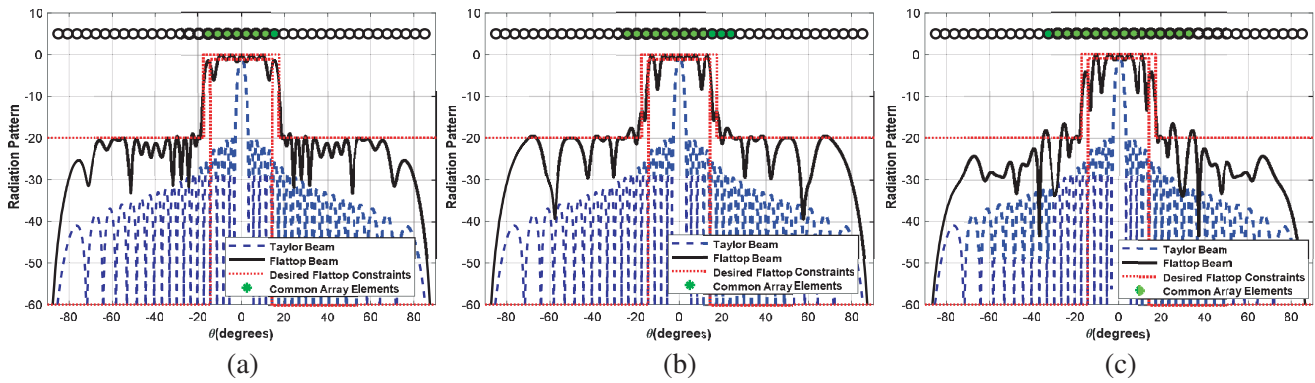


Figure 7. Taylor and flattop patterns for central common elements and various sharing percentages, (a) 20%, (b) 30%, (c) 40%.

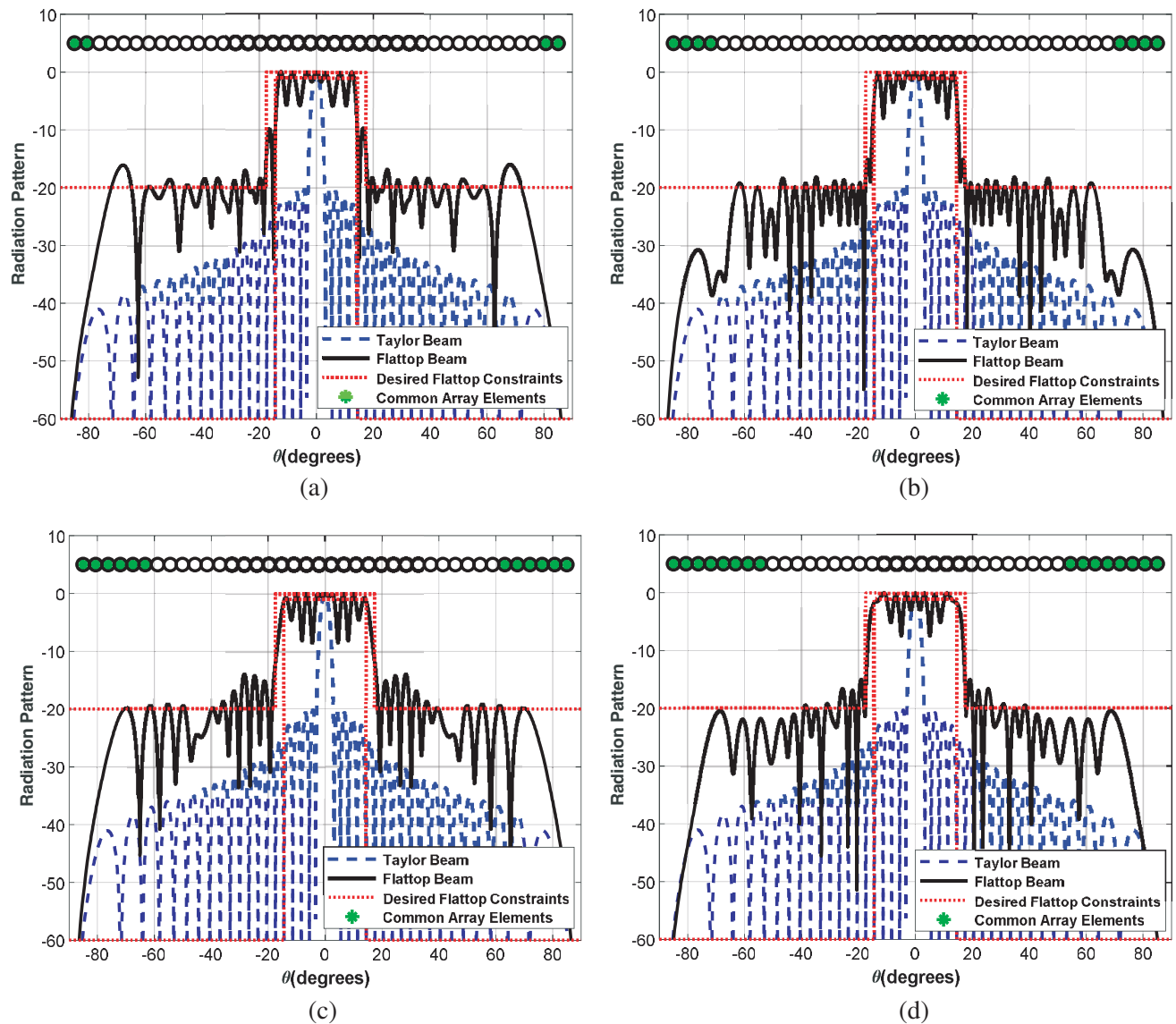


Figure 8. Taylor and Flattop Patterns for outer common elements and various sharing percentages, (a) 10%, (b) 20%, (c) 30%, (d) 40%.

4. CONCLUSIONS

It has been shown that the use of a single linear array with either central or outer common element excitation amplitudes was able to perform dual functions by altering between Taylor and flat-top patterns. The results of the central common elements strategy outperformed those of the outer counterpart and enjoyed minimum deviations in the flat-top beam ripple. For the central common elements strategy, the generated array patterns in terms of peak sidelobe level and flat-top beam ripple were found satisfactory and within the desired constraints for sharing percentage up to 30% which is quite enough to simplify the complexity of the feeding network. Simulated results demonstrate the feasibility of the proposed technique.

The proposed technique can be easily extended to other pattern reconfigurations such as sum and difference patterns that are used in the monopoles radar for tracking purpose.

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