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Array Pattern Nulling by Phase and Position Perturbations with the Use of a Modified Tabu Search Algorithm

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Abstract

A useful and flexible method based on the tabu search algorithm for the pattern synthesis of linear antenna arrays with the prescribed nulls is presented. Nulling of the pattern is achieved by controlling both the phase and the position of each array element. To show the versatility of the present method, some design specifications such as the maximum sidelobe level and the null depth level are considered by introducing a set of weighting factors in the cost function constructed for the tabu search algorithm. Several illustrative examples of a Chebyshev pattern with the imposed single, multiple and broad nulls are given.

1. Introduction

The increasing pollution of the electromagnetic environment has prompted the study of array pattern nulling techniques [1-23]. These techniques are very important in radar, sonar and communication systems for minimizing degradation in signal-to-noise ratio performance due to undesired interference. There has also been considerable interest in synthesizing array patterns with broad nulls [19-23]. The broad nulls are needed when the direction of arrival of the unwanted interference may vary slightly with time or may not be known exactly, and where a comparatively sharp null would require continuous steering obtain a reasonable value for the signal-to-noise ratio.

Most of the methods of null steering available in the literature include controlling the complex weights (both the amplitude and the phase), the amplitude-only, the phase-only and the position only of the array elements, so that the main beam remains pointing towards the desired signal, while the nulls are formed in the directions of undesired sources. Null steering with the complex weights is the most efficient method because it has greater degrees of freedom for the solution space [3,7,16-18]. However, it is also the most expensive control method considering the cost of both a phase shifter and a variable attenuator for each array element [3]. The methods of amplitude-only control utilize an array of attenuators to adjust the element amplitudes [4-7]. If the array elements possess even symmetry about the center of the array, the number of attenuators required and the computational time are halved. Amplitude-only control is also easy to implement and less sensitive to quantization error [5]. However, patterns with satisfactory null depth, sidelobe level and dynamic range ratio cannot be obtained by amplitude-only control. The problem for excitation phase-only and element position only nulling methods is inherently nonlinear and cannot be solved directly by an analytical method. By assuming that the phase perturbations are small, the nulling equations can be linearized, but it is impossible to place nulls at a symmetrical location with respect to the main beam [2]. In order to steer the nulls symmetrically with respect to the main beam, methods based on nonlinear optimization techniques [8, 10] have been proposed; however, the resultant patterns of these methods have considerable pattern distortion because the phase perturbations used are large. Another phase-only synthesizing approach to steer array nulls in symmetrical directions is presented by Ismail and Mismar [11]; but it uses a dual phase shifter for each array element, and hence the number of phase shifters to be used is 4N for an array with 2N elements. The phase-only null synthesizing is attractive since in a phased array the required controls are available at no extra cost [3]. Furthermore, it is also easier to control the main beam direction by controlling phase instead of controlling amplitude only. The nulls in symmetrical directions with respect to the main beam can be achieved by perturbing the element positions using a mechanical driving system such as servomotors [10,13-15].

From practical viewpoint, it is desirable that array elements be symmetrically situated and excited. When the array elements are symmetrically situated and excited, the amplitude-only and position only nulling methods are not suitable to produce the array pattern having asymmetrical nulls with respect to the main beam. The asymmetrical nulls can be achieved by phase-only control. However, in this case, there is an unavoidable sidelobe level increase in the direction symmetrical to the nulling direction with respect to the main beam [3,10,18]. The asymmetrical nulls can easily be obtained with a higher nulling performance by controlling both the phase and position. In this work, a tabu search algorithm (TSA) [24,25], which is one of the latest meta-heuristic optimization techniques, is used to steer the single, multiple and broad nulls to the directions of interference by perturbing both the phases and the positions. It should also be noted that the main objective of this paper is to obtain the pattern having asymmetrical nulls rather than symmetrical ones.

It is well known that the classical optimization techniques need a starting point that is reasonably close to the final solution, or they are likely to be stuck in local minima. As the number of parameters and hence the size of the solution space increases, the quality of the solution strongly depends on the estimation of initial values. If the initial values fall in a region of the solution space where all the local solutions are poor, a local search is limited to finding the best of these poor solutions. Because of these disadvantages of the classical optimization techniques, the techniques based on meta-heuristic search such as genetic and simulated annealing algorithms have received much attention for solving array pattern synthesis problems [6,10,15,18,26-33]. A tabu search algorithm was developed to be an effective and efficient scheme for combinatorial optimization that combines a hill-climbing search strategy based on a set of elementary moves and heuristics avoid to stops at sub-optimal points and the occurrence of cycles. One characteristic of the tabu search is that it finds good near-optimal solutions early in the optimization run. It does not require initial guesses, does not use derivatives, and it is also independent of the complexity of the objective function considered. Because of these fascinating features, in this paper the tabu search algorithm is used as an optimization tool to produce the radiation pattern with the prescribed nulls to the interference directions, at the same time, controlling the maximum sidelobe level and null depth level. Applications of the TSA as an optimization procedure to solve electromagnetic and antenna problems [7, 34-40] are very new, and few examples can be found compared to other heuristic optimization techniques such as genetic and simulated annealing algorithms.

The TSA used in this study is the modified tabu search algorithm (MTSA) proposed by Karaboğa et al. [38]. The classical TSA [24, 25] uses a solution vector consisting of a string of bits. Thus, in solving a numerical problem, the transformation from binary to real numbers should be used. However, the MTSA uses a real-valued solution vector and an adaptive mechanism for producing neighbors. This neighbor production mechanism enables us to find the most promising region of the search space. In [7], MTSA was used to determine only the element excitations (amplitude only and both amplitude and phase) of a linear antenna array to synthesize the pattern with the prescribed nulls. In previous works [38-40], the MTSA is also successfully introduced to compute the various parameters of microstrip antennas.

2. Formulation

If the element amplitudes have even symmetry, and the phases and positions have odd symmetry with respect to the center of the linear array, the far field array factor of this array with an even number of isotropic elements (2N) can be written as

$$F(\theta) = 2\sum_{k=1}^{N} a_k \cos(\frac{2\pi}{\lambda} d_k \sin\theta + \delta_k) \tag{1}$$

where θ is the scanning angle from broadside, λ is the wavelength, a_k and δ_k are the amplitude and phase of the kth element, respectively, and d_k is the distance between position of the kth element and the array center. In the optimization process, the maximum sidelobe level and the desired null depth level are also considered by including a set of weighting factors in the cost function given below.

$$\begin{aligned} C = \; & w_1|F_o(\theta) - F_d(\theta)| + w_2|NLDL_o - NLDL_d| \\ & + w_3|MSLL_o - MSLL_d| \end{aligned} \tag{2}$$

where $F_o(\theta)$, $F_d(\theta)$, $NLDL_o$, $NLDL_d$, $MSLL_o$, and $MSLL_d$ are, respectively, the pattern of MTSA, the desired pattern, the null depth level of the MTSA, the desired null depth level, the maximum sidelobe level of the MTSA, and the desired maximum sidelobe level. The weighting factors w_1, w_2 and w_3 should be selected by experience such that the cost function is capable of guiding potential solutions to obtain satisfactory array pattern performance with desired properties. To obtain the desired pattern with the prescribed nulls, the cost function given in Eq. (2) will be minimized by the MTSA, which is described in the following section.

3. Modified Tabu Search Algorithm

The tabu search is a general heuristic search procedure devised for finding a global optimum of a function that may be linear or non-linear. It is a form of iterative search and does not use derivative-based transition rules. The classical TSA uses a solution vector consisting of a string of bits. Thus, in solving a numerical problem, the transformation from binary to real numbers should be used. This process has two major disadvantages. The first disadvantage is that the process yields a large number of neighbors (e.g., too many evaluations) when the word chosen is very long. The second disadvantage is the difficulty with neighborhood processing. This difficulty is that while a neighbor of the solution vector (e.g., a string of bits) is obtained, a change in the most significant bit of the binary string does not result in a vector in the neighborhood of the present solution. In order to overcome these difficulties, the MTSA was proposed in our previous work [38].

A real-valued solution vector is used by the MTSA; thus, a new neighbor production mechanism is constructed. In this mechanism, the neighbors are chosen adaptively, adding an adaptive coefficient at each iteration. Due to the diversification principle, the coefficient is large at early iterations; therefore, the neighbors are chosen too far from the present solution. This neighbor production mechanism enables us to find the most promising region of the search space. After some iterations, the coefficient gets smaller; thus, an intensive search in the most promising region can be done.

The MTSA starts with an arbitrary solution created by a random number generator. In this particular problem, it is equivalent to starting with randomly generated perturbation values for the element phases and positions. A solution is represented by a vector of phase and position values and an associated set of neighbors. A neighbor is reached directly from the present solution by an operation called a "move". Successive moves are carried out to transform the arbitrary solution into an optimal one. The new solution is the highest evaluation move among the neighbors in terms of the performance value and tabu restrictions that help avoid moves that were already evaluated in earlier iterations.

The tabu search used in this paper employs an adaptive mechanism for producing neighbors. The neighbors of a present solution for the element phases and positions are created by the following procedure. If F(t) = $(d_1, d_2, ..., d_k; \delta_1, \delta_2, \ldots, \delta_k)$ is the solution vector at the tth iteration, two neighbors $F(n_1, n_2)$ of this solution that are not in the tabu list are produced by

$$F(n_1, n_2) = \text{Remain}(F(\bar{n}_1, \bar{n}_2),\, d_{\max}) \text{ for } d_k \tag{3}$$

$$F(n_1, n_2) = \text{Remain}(F(\bar{n}_1, \bar{n}_2),\, \delta_{\max}) \text{ for } \delta_k \tag{4}$$

where

$$F(\bar{n}_1, \bar{n}_2) = \begin{cases} \begin{rcases} d_k + \Delta_d(t) \\ \delta_k + \Delta_\delta(t) \end{rcases} & \text{for odd neighbors} \\ \begin{rcases} d_k - \Delta_d(t) \\ \delta_k - \Delta_\delta(t) \end{rcases} & \text{for even neighbors} \end{cases} \tag{5}$$

with

$$\Delta_d(t) = c_1 \left[\frac{\text{LatestImprovementIterationOfd}_k}{t^{c_2} + \text{LatestImprovementIterationOfd}_k} \right]^{c_3} \tag{6}$$

$$\Delta_\delta(t) = c_1 \left[\frac{\text{LatestImprovementIterationOf}\delta_k}{t^{c_2} + \text{LatestImprovementIterationOf}\delta_k} \right]^{c_3} \tag{7}$$

In Eqs. (3) and (4), the "remain function" keeps the elements of the solution within the desired range. In Eqs. (6) and (7), c_1 determines the initial magnitude of Δ_d(t) and Δ_δ(t), c_2 and c_3 control the change of Δ_d(t) and Δ_δ(t), and LatestImprovementIterationOfd$_k$ and LatestImprovementIterationOfδ_k are the iteration number at which the latest improvement was obtained for d_k and δ_k, respectively. The index, t, represents the iteration number.

The tabu restrictions used here are based on the recency and frequency memory storing the information about the past steps of the search. The recency-based memory prevents cycles of length less than or equal to a predetermined number of iterations from occurring in the trajectory. The frequency-based memory keeps the number of changes of solution vector elements. If an element of the solution vector does not satisfy the following tabu restrictions, then it is accepted as tabu

$$\text{Tabu Restrictions} = \begin{cases} \text{recency(k)} \; > \; \text{recency limit} \\ \text{or} \\ \text{frequency(k)} \; < \; \text{frequency limit} \end{cases} \tag{8}$$

To select the new solution from the neighbors, performance values of all neighbors are evaluated using the cost function given in Eq.(2) and the non-tabu neighbor producing the highest improvement compared to the present solution is then selected as the next solution. If there are some tabu-neighbors that are better than the best solution found so far, then these tabu solutions are freed.

4. Numerical Results

In order to illustrate the capabilities of the MTSA for steering single, multiple and broad nulls with the imposed directions by controlling both the phase and the position of each array element, various demonstrative examples are considered. Initially, a 30-dB Chebyshev array pattern given in Figure 1 for 20 equispaced elements with $\lambda/2$ interelement spacing is assumed. In the optimization process, the values of c_1, c_2, c_3, recency and frequency factors are chosen as 90 000, 3, 3, 3, and 2, respectively. The number of iterations is fixed to 800, which is found to be sufficient to obtain satisfactory patterns with desired nulling performance. The calculations are performed on a personal computer with a Pentium III processor running at 750 MHz, and for all of the examples considered here the optimization results are obtained within 10 min.

In the first example, the Chebyshev pattern with a single null imposed the direction of the third peak from the main beam, which occurs at -20°, is considered. The pattern is then obtained with MTSA by both phase and position control and illustrated in Figure 2. To show the effects of the weighting factors given in the cost function on the array pattern, the weighting value of the NLDL (w_2) is increased for the second example, while the other design parameters are the same as those of the first example. The corresponding pattern is shown in Figure 3. The maximum sidelobe level and the null depth of Figure 3 are -27.2 dB and 144.9 dB, respectively. However, the maximum sidelobe level and the null depth of Figure 2 are -28.8 dB and 106.9 dB, respectively. These results apparently confirm that the trade-off of the relative importance between the null depth and sidelobe level can easily be obtained by changing the weighting factors.

In the third example, the pattern with a broad null sector centered at -25° with $\Delta\theta = 5°$ is obtained. The resultant pattern is shown in Figure 4. A null depth level of 55 dB is achieved over the spatial region of interest.

In Figures 5 and 6, we have shown the nulling patterns with double nulls imposed in the directions of the third and the fourth peaks from the main beam (-20° and +25°), and with triple nulls imposed in the directions of the third, fourth and fifth peaks from the main beam (-20°, +25° and -33°), respectively. As can be seen from Figures 5 and 6, all desired nulls are deeper than 90 dB.

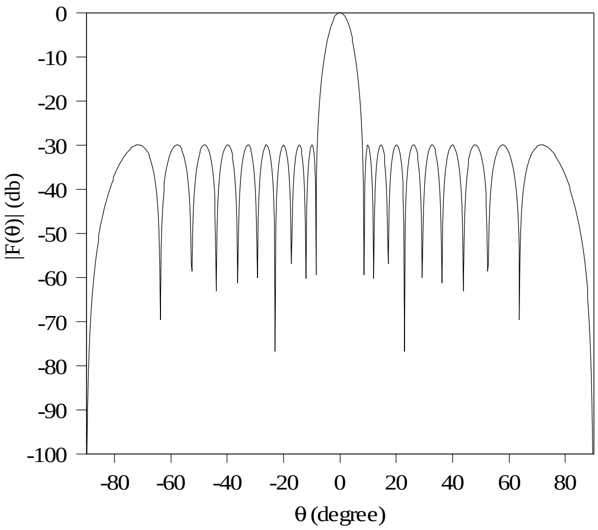

Figure 1. The initial 30-dB Chebyshev pattern

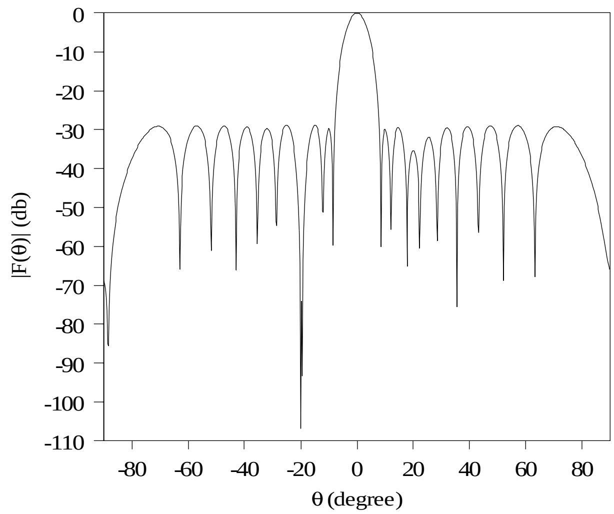

Figure 2. Radiation pattern with one imposed null at –20°

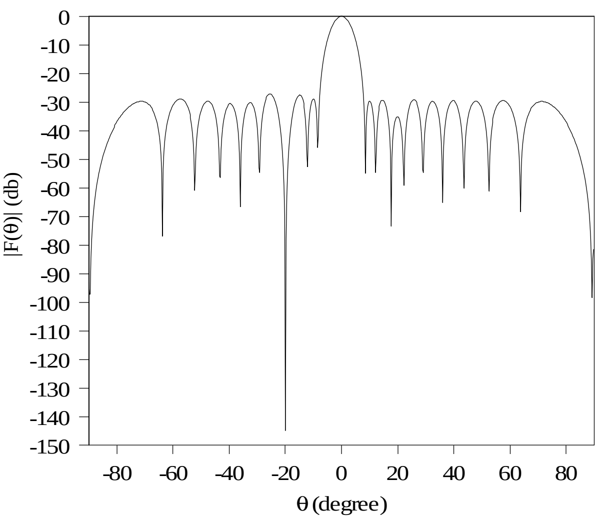

Figure 3. Radiation pattern with one imposed null at –20° and the constrained null depth level

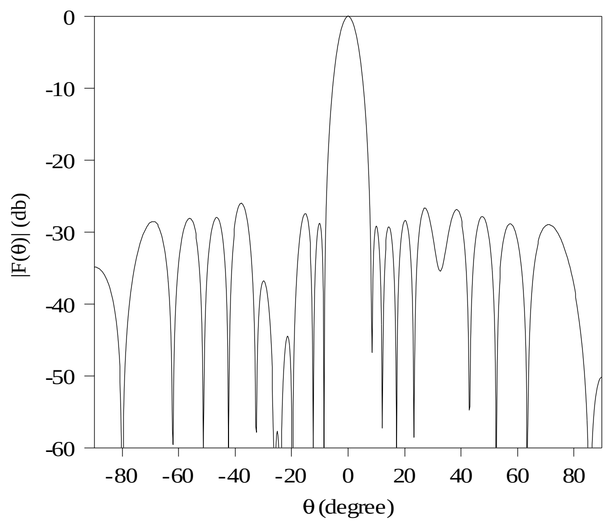

Figure 4. Radiation pattern with a broad null sector centered at –25° with $\Delta\theta = 5^\circ$

The element positions and phases obtained by MTSA for the array patterns presented in Figures 2-6 are listed in the Table. If the number of imposed nulls is increased, the maximum perturbation values of element positions and phases become larger accordingly, because increasing the number of imposed nulls requires a larger degree of freedom for the solution space. It should also be noted that since the element phases have odd symmetry about the center of the array the number of phase shifters to be used is 2N, but the number of controllers for phase shifters is N.

It can be observed from Figures 2-6 that this technique is capable of determining the element phases and positions for array patterns with single, multiple and broad nulls imposed in the directions of interference while the main beam and the sidelobes are quite close to the initial Chebyshev pattern. The half power beam width for nulling patterns by the MTSA is almost equal to that of the initial Chebyshev pattern. The achieved null depths and the perturbed patterns also have very good performance.

Table. Element positions (λ) and phases (degree) computed by the MTSA for the array patterns given in Figures 2-6

	Figure 2		Figure 3		Figure 4		Figure 5		Figure 6	
k	d_k	δ_k	d_k	δ_k	d_k	δ_k	d_k	δ_k	d_k	δ_k
±1	0.2439	±0.4870	0.2405	±0.5214	0.2354	∓0.6417	0.2481	±1.2433	0.2479	±2.9565
±2	0.7347	±1.0256	0.7319	±1.0084	0.7355	∓0.2636	0.7443	±2.8190	0.7471	±2.6986
±3	1.2413	±0.2120	1.2434	±0.4698	1.2589	±2.0913	1.2419	∓0.6933	1.2616	∓0.5214
±4	1.7557	∓0.8136	1.7656	∓0.9855	1.7538	±1.7418	1.7402	∓1.7533	1.7705	∓1.8793
±5	2.2690	∓0.8938	2.2742	∓1.1287	2.2358	∓2.4866	2.2538	∓2.5955	2.2791	∓0.3839
±6	2.7594	±0.1261	2.7592	±0.1662	2.7639	∓2.9737	2.7665	±0.1547	2.7915	±0.5099
±7	3.2404	±0.8537	3.2403	±0.2120	3.2750	±2.0340	3.2485	±1.7303	3.2912	±1.1516
±8	3.7048	±0.8021	3.7210	±0.9855	3.7011	±4.9332	3.7063	±1.0829	3.7329	±1.3293
±9	4.2315	±0.1662	4.2326	±1.1230	4.1577	±6.1478	4.2016	±2.1371	4.1995	±0.3094
±10000	4.7851	∓1.0943	4.7576	∓0.2063	4.7595	∓6.3827	4.7634	∓1.8220	4.7801	∓2.3835

The weighting factors used in the cost function give the antenna designer greater flexibility and control over the actual pattern. The antenna designer should make a trade-off between the achievable and the desired pattern. By adjusting the weighting factors it is possible to obtain very reasonable approximations and trade-offs.

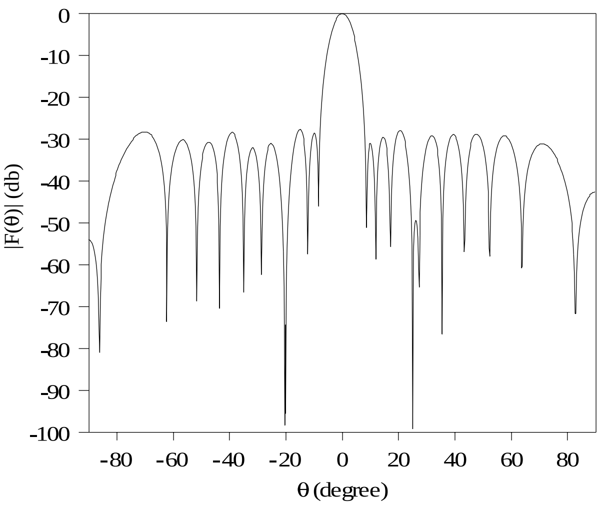

Figure 5. Radiation pattern with double imposed nulls at –20° and +25°

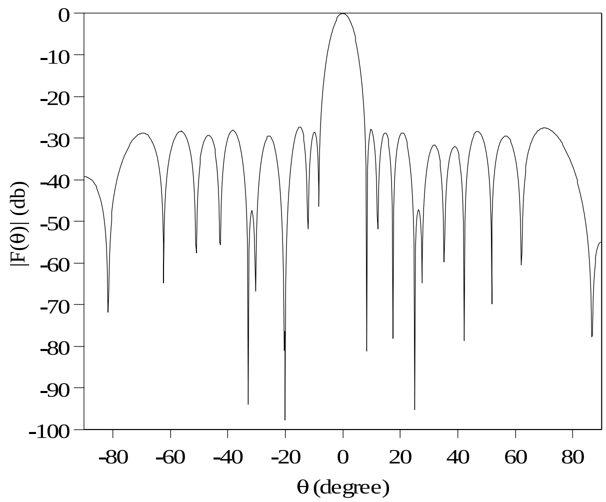

Figure 6. Radiation pattern with triple imposed nulls at –33°, –20° and +25°

5. Conclusions

A method based on the tabu search algorithm is efficiently presented for forming nulls to any prescribed directions by controlling both the position and the phase of each array element while keeping the pattern as close as possible to the initial pattern. Numerical results show that the algorithm can obtain patterns with satisfactory null depth and maximum sidelobe level.

It is worth noting that although the algorithm proposed here is implemented to constrained synthesis for a linear array with isotropic elements one can observe from the proposed technique that it is not limited to this case. It can easily be implemented to nonisotropic-element antenna arrays with different geometries for the design of various array patterns including superdirective, difference, and shaped-beam. Finally, it is hoped that this optimization approach can be helpful for antenna engineers as a simple, robust and flexible alternative to the other techniques used so far.

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