ARRAY PATTERN NULLING USING SIMULATED ANNEALING TECHNIQUE BY CONTROLLING ONLY THE ELEMENT AMPLITUDES

Ali Akdağlı Kerim Güney
e-mail:akdagli@erciyes.edu.tr *e-mail:kguney@erciyes.edu.tr*

Erciyes University, Faculty of Engineering, Department of Electronic Engineering, 38039, Kayseri, Turkey

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ABSTRACT

In this study, we use the simulated annealing technique to synthesise the pattern of a linear antenna array with the prescribed nulls. Forming nulls in the pattern is achieved by controlling only the amplitude of each array element. To show the versatility of the present technique, some design specifications such as the sidelobe level and the null depth are considered by introducing a set of weighting factors in the cost function constructed for the simulated annealing. Several examples of Chebyshev pattern with the imposed single, multiple and broad nulls are given to show the versatility of the present method.

I. INTRODUCTION

Due to increasing pollution of the electromagnetic environment, methods for forming nulls in the radiation pattern of an antenna have been extensively proposed in recent years in order to suppress unwanted interfering signals [1-15]. These methods become very important in radar, sonar and communication systems for minimising degradation in signal-to-noise ratio performance due to undesired interference. There has also been considerable interest in synthesising array patterns with broad nulls [12-15]. The broad nulls are needed when the direction of arrival of the unwanted interference may vary slightly with time or may not known exactly, and where a comparatively sharp null would require continuous steering for obtaining a reasonable value for the signal-to-noise ratio.

In general, array pattern nulling methods are based on appropriate selection of array parameters such as the complex weights (both the amplitude and the phase), the phase-only, the position only and the amplitude-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. Interference suppression with the complex weights is the most efficient because it has greater degrees of freedom for the solution space. However, it is also the most expensive considering the cost of the both phase shifter and variable attenuator for each array element [3, 10, 15]. The phase-only null synthesising is attractive since in a phased array the required controls are available at no extra cost, however, the problem for phase-only and element position only array nulling techniques is inherently nonlinear and can not be solved directly by an analytical method. By assuming that the phase perturbations are small, the nulling equations can be linearized [2], but it makes impossible to place nulls at symmetric location with respect to the main beam. In order to steer the nulls symmetrically with respect to the mainbeam, the methods based on nonlinear optimisation techniques [7, 8] have been proposed, however, the resultant patterns of these methods have considerable pattern distortion because the phase perturbations used are large. Another phase-only synthesising approach to steer array nulls at symmetric directions is presented by Ismail and Mismar [11]. But it uses a dual phase shifter for each array element, hence the number of phase shifters to be used is 4N for an array with 2N elements.

It can be achieved to place the nulls at symmetric direction with respect to the main beam by perturbing the element positions, however, it requires a mechanical driving system such as servomotors to place the desired locations of the array elements [8, 9].

The methods of amplitude-only control utilize an array of attenuators to adjust the element amplitudes [4-6]. If the array elements possess even symmetry about the center of the array, both the number of attenuators required and the computational time are halved. Amplitude-only control is also easy to implement and less sensitive to quantatization error [5]. For this reason, in this work, the pattern of a linear antenna array with the prescribed nulls is synthesised with the use of simulated annealing (SA) technique by controlling only the element amplitudes. Simulated annealing [16, 17] is a global optimisation technique which is based on the analogy between the annealing of the solids and the problem of solving combinatorial optimisation problems. Unlike many discrete optimisation methods, SA does not exploit any special structure that exists in the objective function. However, SA is relatively more effective when a problem is highly complex without any special structure. Thus, SA can be quite useful in solving the complex optimisation problems [16]. A major disadvantage of SA is that it requires much computation (with many function evaluations and tests for solution feasibility), however, it has great potential for yielding an optimal or near-optimal solution.

II. FORMULATION

If the array element amplitudes are symmetrical about the center of the linear array, the far field array factor of this array with an even number (2N) of uniformly spaced isotropic elements can be written as:

$$F(\theta) = 2 \sum_{k=1}^{N} a_k \cos\left[\frac{2\pi}{\lambda} d_k \sin\theta\right] \tag{1}$$

where d_k is the distance between position of the k^{th} element and the array center and a_k is the amplitude of the k^{th} element. In this particular problem of null synthesising, we restricted ourselves to found an appropriate set of element amplitudes (a_k) to place array nulls at any prescribed directions. In the optimisation process, the relative importance between the null depth level and the sidelobe level is also considered by including the weighting factors w_1, w_2 and w_3 in the cost function given below.

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

where $F_o(\theta)$, $F_d(\theta)$, $NLDL_o$, $NLDL_d$, $MSSL_o$ and $MSSL_d$ are, respectively, the pattern of the SA, the desired pattern, the null depth level of the SA, the desired null depth level, maximum sidelobe level of the SA and the desired maximum sidelobe level. To obtain the desired pattern with the prescribed nulls, the cost function given in eq.(2) will be minimised by the SA, which is briefly described in the following section.

III. SIMULATED ANNEALING

Simulated annealing (SA) is a heuristic algorithm for solving combinatorial optimisation problems. It is based on a local search procedure, and can be viewed as a control strategy for the underlying heuristic search. SA has been shown to be a powerful stochastic search method applicable to a wide range of problems [16, 17].

The basic idea in SA is to track a path in the feasible solution space of the given optimisation problem. Starting with a valid solution, SA repeatedly generates succeeding solutions using the local search procedure. Some of them are accepted and some will be rejected, according to predefined acceptance rule. The acceptance rule is motivated by an analogy with annealing processes in metallurgy. In the beginning of the optimisation process the main control parameter- the temperature - is high and decreases until no improvement of the current solution is attainable. Starting with an arbitrary solution, every improvement is accepted. Deteriorations of the objective function are accepted according to the Boltzmann probability $e^{-\Delta C/T}$. An outline of the basic SA algorithm is given in Figure 1.

```
L:=GetInitialSolution()
T:=WarmingUp()
repeat
        repeat
        L1:=Neighbor(L)
        ΔC:=Obj(L1) - Obj(L)
        if   ΔC < 0  or Accept (ΔC, T)
        L:=L1
until Equilibrium()
T:=DecrementT()
until Frozen()
```

Figure 1. Basic simulated annealing algorithm.

After some iterations of the local search procedure, the temperature is decreased and the optimisation continues on a new temperature level. The best solution found during the optimisation is the output of the algorithm after the system is frozen, i.e. no improvements can be found.

IV. NUMERICAL RESULTS

In order to show the effectiveness of the SA for steering the single, multiple and broad-band nulls to imposed directions by the amplitude-only control, five examples of a linear array with one-half wavelength spaced 20 isotropic elements have been performed. Initially, a 30-dB Chebyshev array pattern given in Figure 2, which has 20 equispaced elements with $\lambda/2$ interelement spacing, is considered. In the optimisation process, The temperature decreasing factor, the number of temperature points and the initial population are fixed to 0.89, 15 and 100, respectively. This was sufficient to obtain satisfactory patterns with desired nulling performance on the average. The all calculations took almost 4 min on a personal computer with a Pentium III processor running at 750 MHz.

As the first example, the Chebyshev pattern with a single null imposed at 15^o is considered. The pattern is then obtained by the SA and illustrated in Figure 3.

In order to show the effects of the weighting factors given in eq. (2) on the pattern, the weighting value of the MSLL (w_3) 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 4. As a result of this change, the maximum sidelobe and null

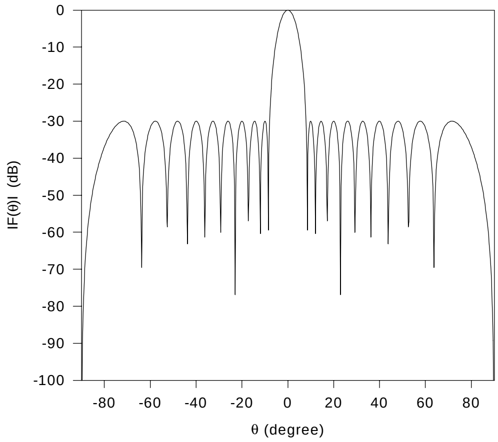

Figure 2. The initial 30-dB Chebyshev pattern.

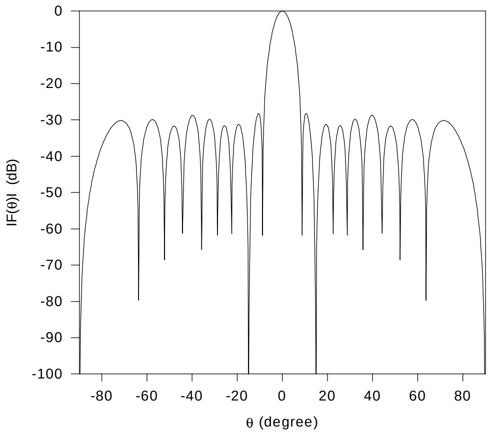

Figure 3. Radiation pattern with one imposed null at 15^o.

depth levels of Figures 4 are achieved as -29.5 dB and 94.7 dB while those of Figure 3 are achieved as -28.5 and 117.6, respectively. These results apparently confirm that the trade-off of the relative importance between the maximum sidelobe level and the null depth can easily be obtained by changing the weighting factors.

In the fourth example, the pattern with a broad null sector centered 25^o with $\Delta\theta$=5^o is obtained. The resultant pattern is shown in Figure 5. The desired broad null sector is achieved with a null depth level of 60 dB over the spatial region of interest.

In Figures 6 and 7, we have shown the nulling patterns with double nulls imposed at 15^o and 32^o, and with triple nulls imposed at 15^o, 32^o and 48^o. As can be seen from Figures 5 and 6 that all the desired nulls are deeper than 90 dB.

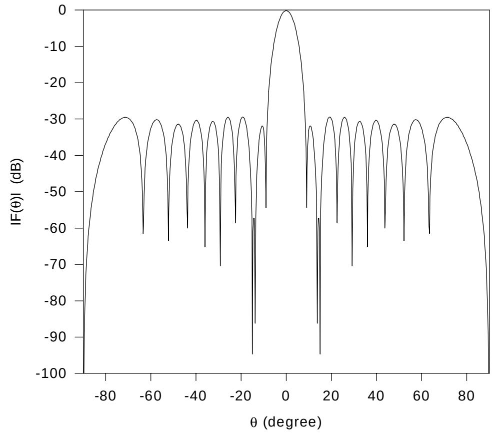

Figure 4. Radiation pattern with one imposed null at 15^o and the constrained maximum sidelobe level.

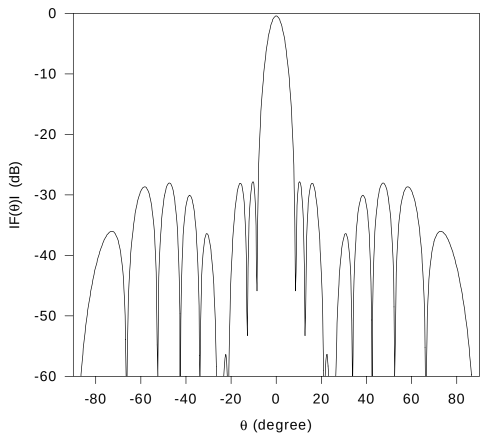

Figure 5. Radiation pattern with a wide-band null sector centered 25^o with $\Delta\theta$ = 5^o.

The element amplitudes obtained by the SA for Figures 3-7 have even symmetry about the center of the array and are listed in Table 1. It is seen from Table 1 that if the number of imposed nulls are increased, the maximum amplitude perturbation values become larger accordingly, because increasing the number of imposed nulls requires a larger degree of freedom for the solution space.

It is clear that the patterns in Figures 2-7 are symmetric with respect to the main beam. This is a consequence of the even-symmetry of the element amplitudes around the array center, results in a pattern that is symmetric about the maim beam peak at 0^o. It should be also noted that since the element amplitudes have even-symmetry about the center of the array, the number of attenuators to be used is N for an array of 2N elements.

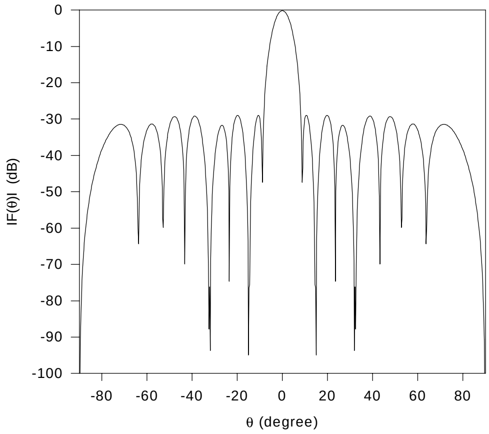

Figure 6. Radiation pattern with double imposed null at 15^o and 32^o.

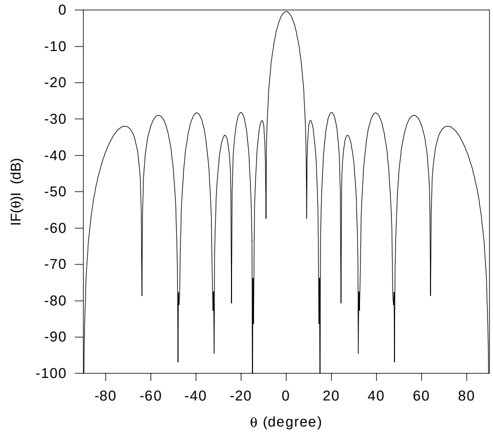

Figure 7. Radiation pattern with tripple imposed null at 15^o, 32^o and 48^o.

Table 1. The element amplitudes (a_k) for Figures 2-7.

Index	**Element amplitudes of the initial Chebyhsev array**	**Element amplitudes computed with the SA**				
k	Fig. 2	Fig. 3	Fig. 4	Fig. 5	Fig. 6	Fig. 7
±1	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
±2	0.97010	0.97120	0.97210	0.94540	0.94600	0.87940
±3	0.91243	0.95913	0.93783	0.87673	0.92383	0.97503
±4	0.83102	0.87592	0.86452	0.77412	0.91352	0.87542
±5	0.73147	0.75867	0.74857	0.71377	0.75897	0.70457
±6	0.62034	0.64734	0.61454	0.57354	0.56594	0.57374
±7	0.50461	0.49651	0.44901	0.57761	0.48421	0.43721
±8	0.39104	0.34294	0.33154	0.39414	0.36854	0.36294
±9	0.28558	0.22548	0.22488	0.18578	0.21978	0.21868
±10	0.32561	0.29171	0.29181	0.22751	0.25901	0.22661

It is evident from the Figures 3-7 that this technique is capable of determining the element amplitudes for the array pattern with the single, multiple and broad nulls imposed at 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 SA is almost equal to that of initial Chebyshev pattern. The achieved null depths and the perturbed patterns have also very good performance.

The weighting factors used 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.

V. CONCLUSIONS

A simulated annealing technique is efficiently presented for forming nulls to any prescribed directions by controlling only the amplitude of each array element while keeping the pattern as close as possible to initial pattern. The trade-off of the relative importance between the maximum sidelobe level and the null depth by changing the weighting factors is also apparently observed.

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