Progress In Electromagnetics Research, PIER 60, 95–106, 2006

SMART ANTENNA ARRAY PATTERNS SYNTHESIS: NULL STEERING AND MULTI-USER BEAMFORMING BY PHASE CONTROL

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Abstract—In this article, an efficient method for the pattern synthesis of the linear antenna arrays with the prescribed null and multi-lobe Beamforming is presented. Multi-lobe pattern and adaptive nulling of the pattern is achieved by controlling only the phase of each array element. The proposed method is based on the Sequential Quadratic Programming (SQP) algorithm and the linear antenna array synthesis was modelled as a multi-objective optimization problem. Multi-objective optimization is concerned with the maximization (or minimization) of a vector of objectives functions in the directions of desired signal that can be subject of a number of constraints (in our case, the constraints can be imposed as the null in the direction of interfering signal). To verify the validity of the technique, several illustrative examples of uniform excited array patterns with the main beam is placed in the direction of the useful signal and null is placed in the direction of potential interferers, and multi-beam patterns are demonstrated.

1. INTRODUCTION

The reuse of spectrum in current cellular radio systems is limited by the level of co-channel interference that can be tolerated. A smart antenna has the potential to reduce multipath interferences, to increase signal to noise ratio and enhance system capacity [1, 2]. The smart antenna systems can be divided into two categories [3]. These are: switched beam system, and adaptive arrays.

In this paper, we will concentrate on the dynamically phased arrays or adaptive arrays pattern. The dynamically phased arrays make use of the Angle of Arrival (AOA) information from the desired user to steer the main beam towards the desired user [3]. The signals received by each antenna element are weighted and combined to create a beam in the direction of the mobile. Only the phases of the weights are varied and the amplitudes are held constant. An adaptive array can adjust its antenna pattern to enhance the desired signal, null or reduce interference, and collect correlated multipath power. Adaptive array antennas can adjust their pattern to track mobile user if we including a direction of arrival (DOA) algorithm. However, several challenges remain in the development of these adaptive systems. The techniques of placing nulls in the antenna patterns to suppress interference and the maximizing their gain in the direction of desired signal has received considerable attention in the past and still of great interest [4–14]. These techniques are very important in communication system, sonar, and radar applications for maximizing signal-to-interference ratio (or signal to interference and noise ratio) [11].

The technique of null steering including controlling the complex weights (the amplitude and phase) the excitation amplitude only and phase-only, and the element position only have been extensively considered in the literature [6, 7, 9, 14]. The phase-only is of particular interest in pattern null steering [4]. In article [10] the author presents a method of control by phase for forming nulls in prescribed directions with a main lobe in broadside. The technique proposed in this paper is based on algorithm SQP [15] to synthesis steered beams with zero in desired direction and multi-beams patterns in the directions of the different users by phase control. This method is the generalization is the Newton method for the constrained case. They are considered the most efficient general purpose nonlinear programming algorithms today. The basic principle of sequential approximations is to replace the given nonlinear problem by a sequence of quadratic subproblems that are easier to solve.

2. PROBLEM FORMULATION

Interference suppression in adaptive antenna arrays is obtained by steering beam pattern nulls in the direction of interference signal while maintaining the main lobe in the direction of user activity by adjusting the parameters positions and the current of excitation (amplitude and/or phase) of the sources constituting the array. This operation of synthesis for antenna arrays in essential in the conception of an optimized antenna.

2.1. Multi-objective Optimization technique

We consider a linear array of N equispaced isotropic antenna elements positioned along the x-axis. These antennas are supplied with same current amplitude and with a gradient of phase φ_n.

The array factor can be obtained by considering the elements to be point source which is given by:

$$F(\theta)=\sum_{n=0}^{N-1} e^{j(kx_n \sin\theta+\varphi_n)} \tag{1}$$

Where $\varphi_n \in [\varphi_0, \varphi_1, \ldots, \varphi_{N-1}]$ represents the phase excitation of the nth element (the antenna in the beginning is taken as reference of phase: $\varphi_0 = 0$), x_n represents the position of the nth element, $k = 2\pi/\lambda$ is the wave number, θ is the angle of incidence of desired signal or interfering signal, and λ is the signal wavelength.

A general multi-objective or multicriteria problem that we study consists of a number of objectives (numbers of desired signals) and is associated with a number of inequality constraints (numbers of null steering) and bounds. Mathematically, the problem can be written as follows:

$$\begin{array}{ll} \textit{minimize} & -f_{\theta_i}(\varphi) \\ \text{subject to} & f_{\theta_j}(\varphi) \le \delta_j \quad j = m_e+1, \ldots, m \\ & -2\pi \le \varphi_n \le 2\pi \quad n = 1, \ldots, N-1 \end{array} \tag{2}$$

Where

$$f_\theta(\varphi)=\left|1+\sum_{n=1}^{N-1} e^{j(kx_n \sin\theta+\varphi_n)}\right|^2;$$

$f_{\theta_i} = [f_{\theta_1}\ f_{\theta_2}\ \cdots\ f_{\theta_{m_e}}]^T$ is the vector of objective functions, m_e is the numbers of the desired signal, θ_i, θ_j and δ_j are the ith directions of the desired signals, the jth directions of interfering signals, and the levels in the regions of the suppressed sectors respectively, and m is the number of the sampled angular direction. Note that any maximization objective can be converted into a minimization objective by simply changing its sign.

The problem (2) is solved by combining the multiple objectives into one scalar objective whose solution is optimal point for the original multi-objective problem (MOP). A technique for solve the MOP is to minimize one objective while constraining the remaining objectives to be less than given target values.

2.2. Goal Programming Using Sequential Quadratic Programming (SQP) Algorithm

We are interested in computing the excitation phases and radiation pattern for linear antenna arrays. For this purpose, we propose, to use the goal programming combining with the SQP technique [15, 16]. In this formulation of the problem, the designer sets goals to be attained for each objective and a measure of the deviations of the objective functions from their respective goals is minimized, and the residual problem is solved by SQP algorithm. The SQP method solves a quadratic programming subproblem in each iteration which is obtained by linearizing the constraints and approximating the Lagrangian function. The Lagrangian of the problem is defined as

$$L(\varphi, \lambda) = -f_{\theta_1}(\varphi) + \sum_{i=2}^{m} \lambda_i (f_{\theta_i}(\varphi) - \delta_i) \tag{3}$$

Where $\varphi \in \mathbb{R}^{N-1}$, $\lambda = (\lambda_1, \ldots, \lambda_m)^T \in \mathbb{R}^m$ is the vector of the Lagrange multiplier.

In each iteration k of the algorithm, a quadratic subproblem

$$\begin{array}{ll} \textit{minimize} & -\nabla f_{\theta_1}(\varphi_k)^T d + \frac{1}{2} d^T M_k d \\ \text{subject to} & \nabla f_{\theta_i}(\varphi_k)^T d + f_{\theta_i}(\varphi_k) = \delta_i \quad i = 2, \ldots, m_e \\ & \nabla f_{\theta_j}(\varphi_k)^T d + f_{\theta_j}(\varphi_k) \leq \delta_j \quad j = m_e + 1, \ldots, m \\ & d \in \mathbb{R}^{N-1} \end{array} \tag{4}$$

is formed, where M_k is usually a positive semi-definite approximation to the Hessian matrix of the Lagrangian function with to respect to φ. This quadratic subproblem can be solved using any Quadratic Programming (QP) algorithm. If d_k is the solution to (4) in iteration k, then the solution is used to form a new iterate

$$\varphi_{k+1} = \varphi_k + \alpha_k d_k$$

Where $\alpha_k \in]0, 1]$ is the step length parameter.

We can now define the SQP algorithm:

1. set $k := 1$

2. solve the QP subproblem described on equation (4) to determine d_k and let λ_{k+1} be the vector of the Lagrange multiplier of the linear constraints obtained from the QP.
3. Compute the length α_k of the step and set $\varphi_{k+1} = \varphi_k + \alpha_k d_k$
4. Compute M_{k+1} from M_k using a quasi-Newton formula
5. Increment k. Stop if a solution is found. Otherwise, go to step 2.

3. NUMERICAL RESULTS

To illustrate the performance of the method described in the previous section for steering single and multiple beams in desired direction, and imposed null in the direction of interfering signal by controlling the phase excitation of each array element, nine examples of uniform excited linear array with $N = 10$ and $N = 8$ one-half wavelength spaced isotropic elements were performed.

The results of steering beam in the direction of the desired signal and creating single suppressed wide band interferences are presented in Figures 1, 2, 3, 4.

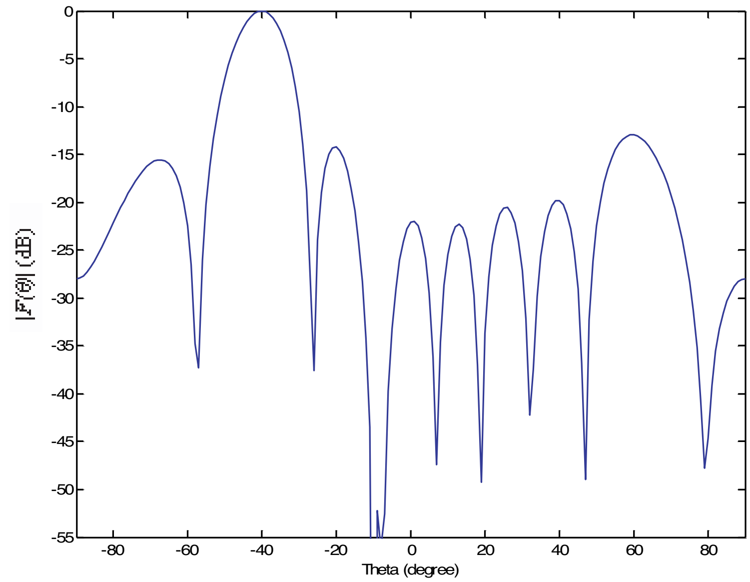

Figure 1. Pattern synthesis with a single null imposed at −10° and steering lobe at −40°.

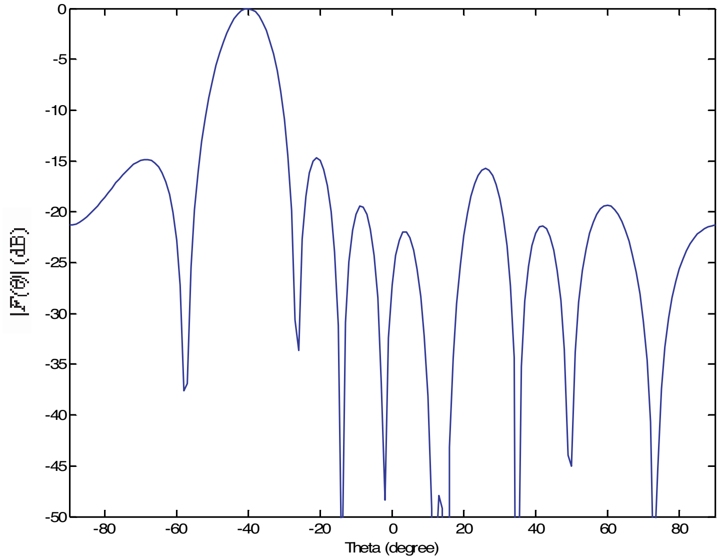

Figure 2. Pattern synthesis with a single null imposed at 15° and steering lobe at −40°.

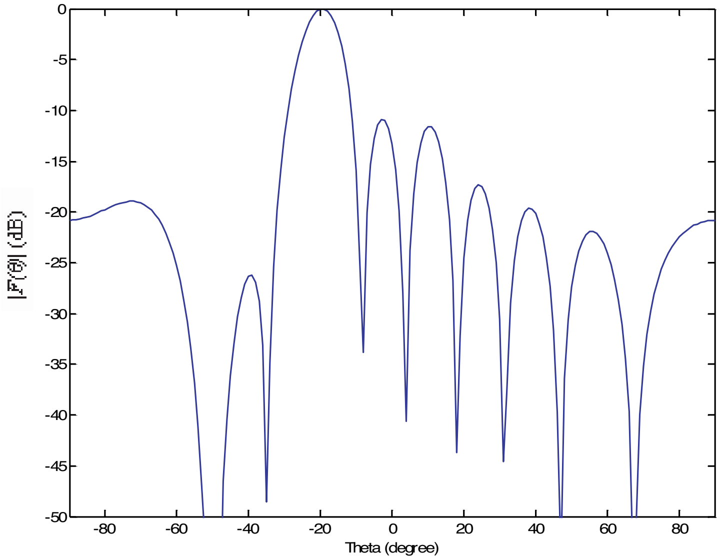

Figure 3. Pattern synthesis with a single null imposed at −50° and steering lobe at −20°.

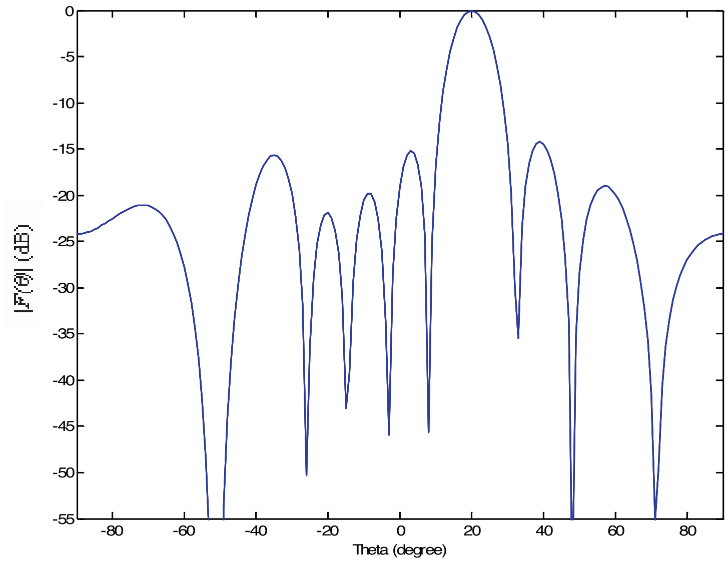

Figure 4. Pattern synthesis with a single null imposed at −50° and steering lobe at 20°.

The Figures 1 and 2 show the ability of creating null in the direction of interference (at −10° and 15°, respectively), while maintaining the main lobe in the direction of useful signal (at −40°).

In case, the interfering is fixed, the Figures 3 and 4 show that one can follow the mobile user, while maintaining the zero fixed in the direction of interference (at −50°). The Figures 1, 3, and 4 shows that one can track at the same time the user and the interfering signals (desired signals at −40, −20, and 20, respectively, and undesired signals at −10, and −50, respectively).

In this approach, the adaptive array can track the signals, and allocate beams in the direction of the useful signal while simultaneously nulling unwanted sources of interference. The phases of antenna elements are computed as given in Table 1.

Also, this proposed method can create the multiple mainbeams in the directions of the different users (Figures 5, 6, 7, 8 and 9). In Figures 5 and 6, we have shown the result of a simulation with 10 isotropic elements, cancelling an interferer with DOA −60°, 10°, respectively and receiving signal from the user of interest with DOA −20 and 40.

One of the benefits which accrue from the use of smart beams is that users residing in different beams but in the same cell are able

Table 1. Computed element phases φ_n for Figures 1, 2, 3, 4 and 5.

Elem. No.	φ_n (Degrees)				
	Fig.1	Fig.2	Fig.3	Fig.4	Fig.5
1	0	0	0	0	0
2	-217.9513	-236.8733	15.6321	-57.0293	-26.9948
3	-112.1810	225.5366	71.0790	-132.1477	-234.1519
4	-11.9364	-360.0000	150.4896	-174.3008	98.7540
5	-254.8919	-265.3106	218.0826	-258.0691	-108.2719
6	-116.6248	-127.0742	-92.9737	65.3605	-135.2938
7	-360.0000	328.0877	-25.3807	-18.4078	17.6289
8	-265.6383	-257.5351	54.0299	-60.5609	350.4343
9	204.3091	204.0814	109.4767	-135.6793	-216.5651
10	-17.9959	327.2896	125.1089	-192.7086	116.3884

to reuse intra-cell frequency [1]. This spatially separate of the signals, allow different users to share the same spectral resources, provided that they are spatially-separate at the base station. This Space Multiple Access (SDMA) allows multiple users to separate in the same cell, on the same frequency/time slot provided, using the adaptive antenna to separate the signals.

Table 2 gives the computed element phases for the Figures 6, 7, 8 and 9

4. CONCLUSION

A synthesis method for the adaptive Beamforming using the phase-only control has been presented. The problem can be modeled as a multicriteria optimization, where the optimization objectives are the maximization of the signal at the directions of wanted sources subject to the constraints of minimization of the signal at the direction of unwanted sources. The excitation phases are computed using the Sequential Quadratic Programming (SQP) algorithm that transforms the nonlinear minimization problem to a sequence of quadratic subproblems, based on a quadratic approximation of the Lagrangian function. The simulation results show that the phase-only control using the SQP algorithm is efficient for tracking multiple users while simultaneously nulling interference.

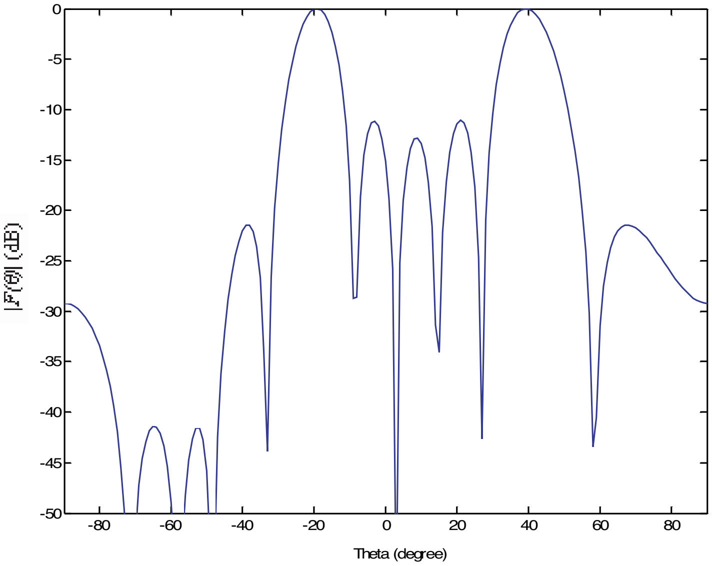

Figure 5. The radiation pattern with a wide sectors interference nulling around −60° and two steering lobes at −20° and 40°.

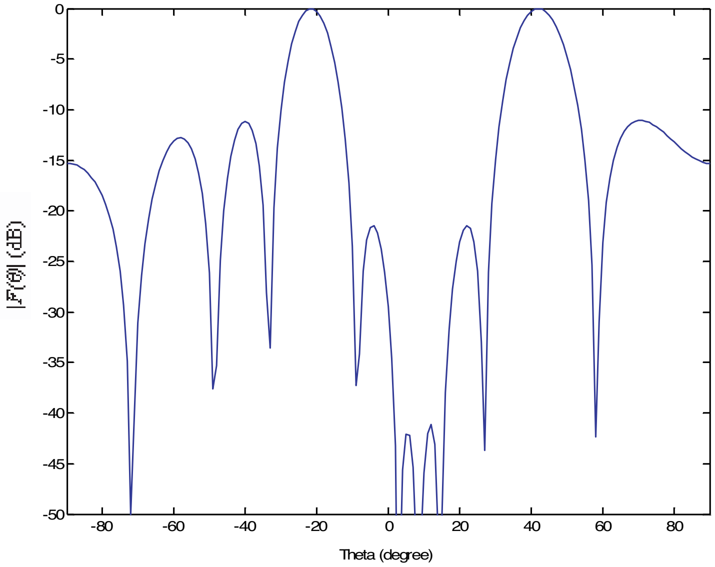

Figure 6. The radiation pattern with a wide sectors interference nulling around 10° and two steering lobes at −20° and 40°.

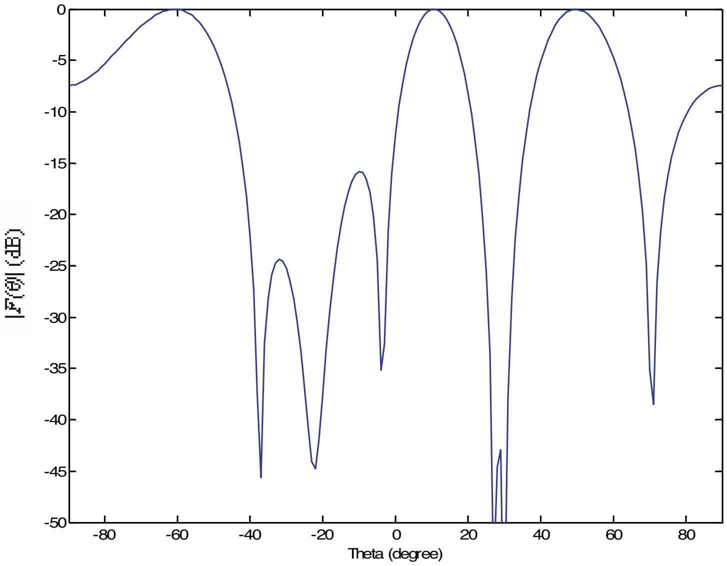

Figure 7. The radiation pattern with interference nulling at 30° and tree steering lobes at $-60°$, 10 and 50°.

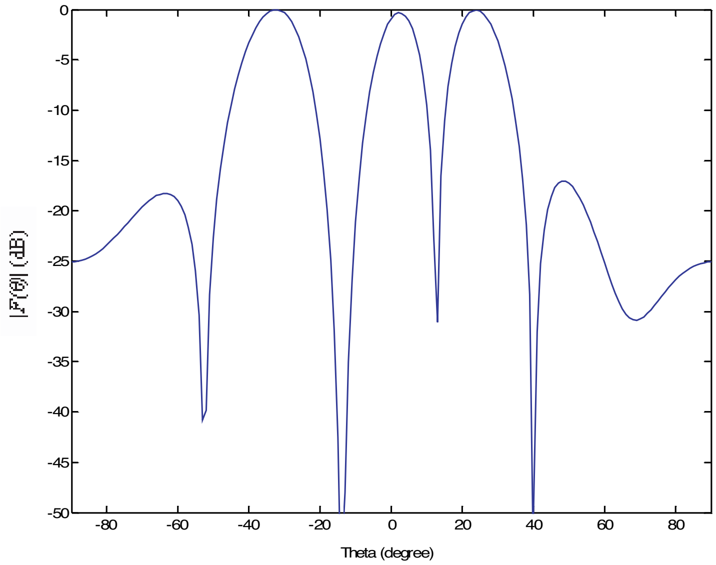

Figure 8. The radiation pattern with interference nulling at $-14°$ and tree steering lobes at $-32°$, 2 and $N = 8,\ d = \lambda/2$.

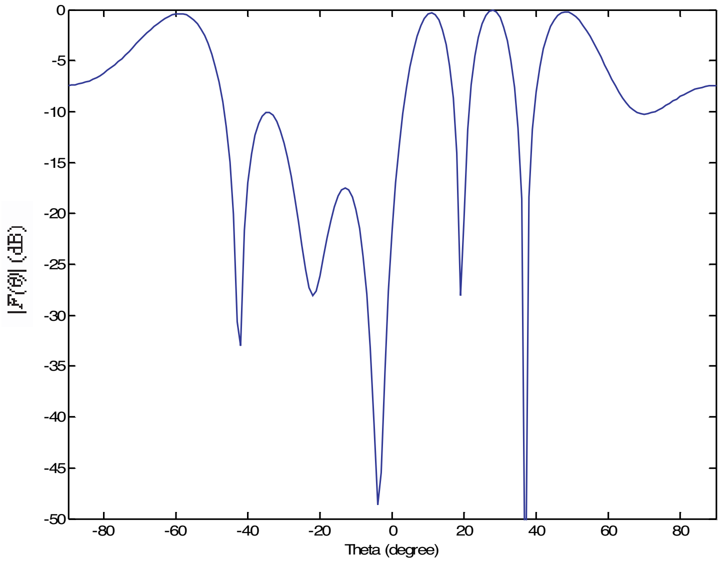

Figure 9. The radiation pattern with four steering lobes at −60°, 10°, 28 and 48°, uniform excited linear array, 24°.

REFERENCES

1. Joseph, C. L. and J. R. Theodore, *Smart Antennas for Wireless Communications: IS — 95 and Third Generation CDMA Applications*, Prentice Hall, NJ, USA, 1999.
2. Wells, M. C., "Increasing the capacity of GSM cellular radio using adaptive antennas," *IEE Proc. — Commun.*, Vol. 143, No. 5, 304–310, October 1996.
3. Lehne, P. H. and M. Pettersen, "An overview of smart antenna technology for mobile communications systems," *IEE Communications Surveys*, Vol. 2, No. 2, 2–13, 1999.
4. Baird, D. and G. Rassweiler, "Adaptive side lobe nulling using digitally controlled phase shifters," *IEEE Trans. on Antennas and Propagation*, Vol. 24, No. 5, 638–649, Sept. 1976.
5. Steyskal, H., "Synthesis of antenna pattern with prescribed nulls," *IEEE Trans. on Antennas and Propagation*, Vol. 31, 273–279, 1982.
6. Steyskal, H., "Simple method for pattern nulling by phase perturbation," *IEEE Trans. on Antennas and Propagation*, Vol. 31, 163–166, 1983.

7. Vu, T. B., "Simultaneous nulling in sum and difference patterns by amplitude control," *IEEE Trans. on Antennas and Propagation*, Vol. 34, 214–218, 1986.
8. Haupt, R. L., "Phase-only adaptive nulling with a genetic algorithm," *IEEE Trans. on Antennas Propagation*, Vol. 45, 1009–1015, 1997.
9. Liao, W. P. and F. L. Chu, "Array pattern nulling by phase and position perturbations with the use of the genetic algorithm," *Microwave and Optical Technolo. Letters*, Vol. 15, No. 4, July 1997.
10. Vescovo, R., "Null synthesis by phase control for antenna array," *Electronics Letters*, Vol. 36, No. 33, February 2000.
11. Karaboga, N., K. Güney, and A. Akdagli, "Null steering of linear antenna arrays with use of modified touring Ant Colony Optimization Algorithm," *Int. J. RF and Microwave CAE*, Vol. 12, 375–383, Wiley Periodicals, Inc., 2002.
12. Abu-Al-Nadi, D. I. and M. J. Mismar, "Genetically evolved phase-aggregation technique for linear arrays control," *Progress In Electromagnetics Research*, PIER 43, 287–304, 2003.
13. Ismail, T. H., D. I. Abu-AL-Nadi, and M. J. Mismar, "Phase-only control for antenna pattern synthesis of linear arrays using Levenberg-Marquart algorithm," *Electromagnetic.*, Vol. 24, 555–564, 2004.
14. Abu-Al-Nadi, D. I., T. H. Ismail, and M. J. Mismar, "Interference suppression by element position control of phased arrays using LM algorithm," *Int. J. Electron. Commun. (AEÜ)*, March 13, 2005.
15. Boggs, P. T. and J. W. Tolle, "Sequential quadratic programming," *Acta Numerica*, 1–51, Cambridge University Press, 1995.
16. Stoer, J., "Foundations of recursive quadratic programming methods for solving nonlinear program," *Computational Mathematical Programming*, K. Schittkowski (ed.), NATO ASI Series, Series F: Computer and Systems Sciences, Vol. 15, Springer, 1985.
17. Sunar, M., "A comparative study of multiobjective optimization methods in structural design," *Turk. J. Engin. Environ. Sci.*, Vol. 25, 69–78, 2001.