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Design of Linear Phased Array for Interference Suppression Using Array Polynomial Method and Particle Swarm Optimization

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Abstract In this work, a linear phased array pattern design with null steering is achieved using the array polynomial technique and the Particle Swarm Optimization (PSO) algorithm. The null steering for interference suppression is obtained by controlling some of the roots on the Schelkunoff's unit circle while keeping the roots responsible for the main beam unchanged. The rest of the roots are controlled to minimize the Side Lobe Level (SLL) of the array pattern using the PSO algorithm. It has been demonstrated that this technique achieved more than 50% reduction in the parameters needed to be optimized compared with the conventional complex coefficients optimization techniques. Consequently, the fitness function is only responsible for the SLL as the prescribed controlled nulls and the mainbeam characteristics are solved analytically. The simulated results show the effectiveness of the proposed technique.

Keywords Linear phased arrays · Null steering · Array polynomial · Pattern synthesis · PSO

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1 Introduction

Phased arrays are widely used in many communication systems such as radar, military, commercial communication, and recently in mobile communication to increase the capacity of the system. Pattern synthesis of phased arrays is used to suppress the interfering signals by imposing nulls at the array pattern in the direction of the interfering signals while preserving the main beam directed towards the desired signal [1,2]. However, imposing nulls in the side lobe region will cause the sidelobe level (SLL) of the array pattern to be degraded. The degradation will be worse as the number of imposed nulls is increased and when imposed null is close to the main beam. Therefore, synthesizing methods for interference suppression by null steering and/or sector suppression with minimizing the SLL for a given main beam width (MBW) is an important problem to be solved [3–6]. This problem is highly nonlinear and it has to be solved by a nonlinear optimization algorithm.

Recently, unconventional methods for linear antenna design are extensively applied; i.e., Genetic Algorithms (GA) [6–8], Simulated Annealing (SA) [9,10], Evolutionary Programming [11,12], Immune Algorithm (IA) [13], and Particle Swarm Optimization (PSO) [14–18], Ant Colony Optimization (ACO) [19]. Evolutionary optimization techniques, which are based on some natural behavior, are used to solve highly nonlinear problems. Therefore, they are suitable for antenna array pattern synthesis with minimum SLL and null control. Among them, PSO is very attractive technique because of its simplicity of implementation and its speed of convergence. Using PSO, the synthesis of linear array with minimum SLL and null control was described by Kodier and Christodoulou [2]. Also, Jin et. al. [15] applied a versatile PSO engine to antenna design as real-number swarm, binary swarm, single-objective fitness and multi-objective fitness. To speed up convergence, the modified PSO (MPSO) and the method of moment (MOM) was also proposed by Mahmoud et. al. [18]. In general, there are N coefficients to be optimized, which are the magnitudes and/or the phases of the N array elements. It is known that pattern synthesis with complex coefficient control will meat the specifications of the objective function better than phase-only control or amplitude-only control. This means that $2N$ parameters (amplitudes and phases) should be optimized with complex coefficient control. For large arrays the number of parameters to be computed to achieve the desired pattern will be very large. Therefore, if the number of parameters to be calculated using the optimization technique is reduced, then the complexity of the optimization problem is reduced too.

On the other hand, the array polynomial method is used to synthesize the equispaced linear array pattern with null steering [19,20]. This method considers the array pattern as a polynomial with roots that are located in the complex z-plane, and the desired array pattern can be achieved by appropriate placement of the roots on the Schelkunoff's unit circle. Therefore, with N array elements, the array factor is represented as product of $(N - 1)$ roots on the Schelkunoff unit circle. Because the roots are unity in magnitude then only $(N - 1)$ are to be determined for certain pattern array. In the pattern synthesis problem, if K pre-specified nulls are imposed, then only $(N - K - 3)$ parameters (root phases) should be optimized to obtain the lowest SLL as two pre-specific roots are chosen to design the main beam characteristics. Therefore, this technique will reduce the number of optimized parameters by more than 50% compared with the conventional complex coefficients optimization techniques. Thus, reducing the number of optimized parameters will improve the convergence rate. Moreover, specifying the roots that are responsible for the desired nulls will simplify the fitness function as the optimization algorithm needs only to minimize the SLL. In this paper, the PSO algorithm is used to minimize the SLL of the synthesized pattern with a given main beam and null control by controlling only $N - K - 3$ parameters. This method will achieve the required specification of the main beam and the accurate null placement while minimizing the SLL.

The rest of the paper is organized as follows: Sect. 2 presents the problem statement and the system optimization. Results through examples to illustrate the effectiveness of the proposed algorithm are given in Sect. 3 and conclusions are in Sect. 4.

2 Problem Statement and System Optimization

Consider a linear array of N isotropic equispaced elements, then the array factor in the complex z plane can be written as

$$F(z) = \sum_{i=1}^{N} a_i z^{(i-1)} = a_N \prod_{i=1}^{N-1} (z - z_i) \tag{1}$$

where the complex coefficients a_i represent the excitation of each element of the array and $z = e^{j\psi}$,

$$\psi = k\ d\ \mathbf{sin}(\theta) \tag{2}$$

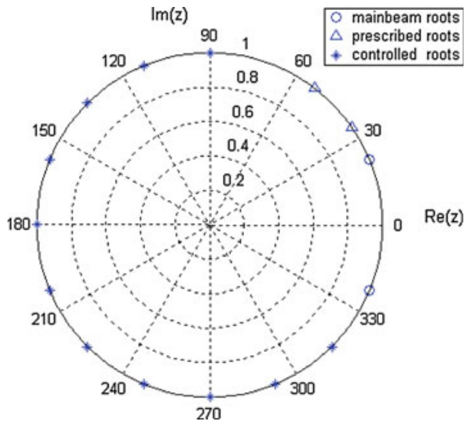
θ is the scanning angle from broadside, d is the inter-element spacing, and k is the wave number. The value (z_i) in Eq. (1) represents the ith root of the polynomial on the unit circle ($z_i = e^{j\psi_i}$;$\psi_i$is phase of the ith root). To suppress K narrow interfering signals in the sidelobe region impinging at angular directions $\theta_i (i = 1, 2, \ldots, K)$, K null are required in the perturbed pattern and hence the corresponding K desired roots on the Schelkunoff unit circle can be designated as $z_i^n = e^{j\psi_{n,i}}$, $(\psi_{n,i} = k\ d \sin(\theta_i) + \beta, i = 1, 2, \ldots, K)$. Moreover, assume that $z_1^m = e^{j\psi_{m,1}}$ and $z_2^m = e^{j\psi_{m,2}}$ are the two roots which are responsible to achieve the specified direction and bandwidth of the main beam, then the array pattern with the steered roots for interference suppression can be rewritten as

$$F_n(z) = a_N \prod_{i=1}^{2} (z - z_i^m) \prod_{i=1}^{K} (z - z_i^n) \prod_{i=1}^{(N-K-3)} (z - z_i^s) \tag{3}$$

where the ith root of the third sub-polynomial, z_i^s, represents the roots of the initial polynomial, $F(z)$, except the roots that specify the main beam and the prescribed nulls (z_1^m, z_2^m, z_i^n $i = 1, 2, \ldots, K$). Figure 1 illustrates how the locations of the roots of the array polynomial, $F_n(z)$, are distributed in the z domain when the angles of the two desired roots are $\psi_{n,1} = 34.4°$ and $\psi_{n,2} = 52.7°$ which correspond to the two prescribed nulls at $\theta_1 = 11°$ and $\theta_2 = 17°$. Notice that, from Eq. (3), $(K + 2)$ roots are fixed on the unit circle and only the roots of the third sub-polynomial group, z_i^s, i = 1, 2,..., $N - K - 3$, will be controlled to minimize the SLL of the array pattern and they are indicated by star symbol in Fig. 1. Also, note that because the roots are placed on the unit circle, only $(N - K - 3)$ parameters are used to optimize SLL compared with the conventional techniques where $2N$ parameters of the complex coefficients, a_i (amplitudes and phases), are controlled to achieve the required specifications. Therefore, this technique will reduce the number of optimized parameters by more than 50%, and consequently will reduce the complexity of the optimization problem and will speed up the convergence rate.

In this work, it is required to use the PSO algorithm to minimize the SLL of $F_n(z)$ by optimizing the roots, z_i^s (i = 1, 2,..., $N - K - 3$), of the third sub-polynomial of Eq. (3) while preserving the first and the second sub-polynomials unchanged. Let the angles of the

Fig. 1 Roots of the array polynomial $F_n(z)$ on the unit circle. (z_1^m, z_2^m) are the two roots that specify the main beam (*circle*), ($z_i^n i = 1, 2$) are the desired roots for interference suppression (*triangle*) and s_i, ($i = 1, 2,\ldots, 11$) are the controlled roots to optimize the SLL (*star*)



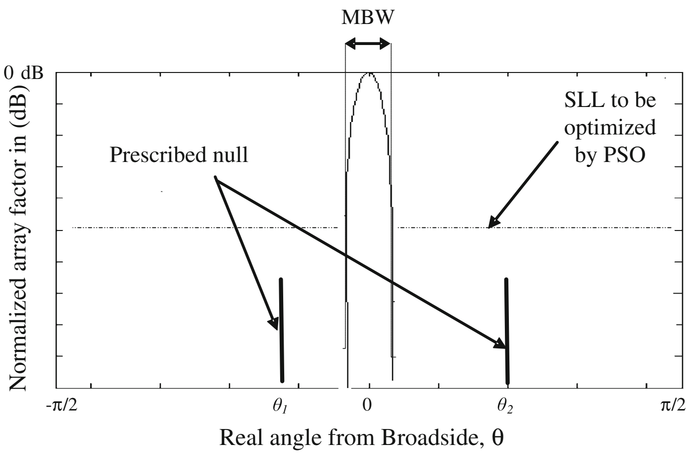


Fig. 2 The objective function with two nulls imposed at a given arbitrary directions using the array polynomial and optimal SLL by PSO

controlled roots, z_i^s, be designated as $\psi_{s,i}$, then the optimized array factor can be rewritten as

$$F_O(z, \boldsymbol{\psi}_s) = a_N \prod_{i=1}^{2} (z - z_i^m) \prod_{i=1}^{K} (z - z_i^n) \prod_{i=1}^{(N-K-3)} (z - e^{j\psi_{s,i}}) \tag{4}$$

Where

$$\boldsymbol{\psi}_s = [\psi_{s,1},\ \psi_{s,2}, \ldots, \psi_{s,N-K-3}] \tag{5}$$

Therefore, searching the best locations of the controlled roots, z_i^s, is achieved by searching the best vector $\boldsymbol{\psi}_s$ on the Schelkunoff unit circle using PSO algorithm to minimize the SLL of $F_n(z)$. Because, a suitable fitness function is the key issue in successfully implementing PSO algorithm, then carefully choosing the objective function where the direction of the mean beam and the mean beam width (null to null) MBW and the prescribed nulls' locations are specified as shown in Fig. 2. The desired nulls and the main beam characteristics of the objective function are achieved by accurately locating predetermined roots on the unit circle. Therefore, a suitable fitness function for the PSO algorithm will be

$$\mathit{fitness}(\boldsymbol{\psi}_s) = \mathit{SLL}\left|F_O(z, \boldsymbol{\psi}_s)\right|_{dB} \tag{6}$$

Hence, the objective function can be expressed as

$$\mathit{Objective\ function} = \underset{\boldsymbol{\psi}_s}{\boldsymbol{min}}\left[fitness(\boldsymbol{\psi}_s)\right]_{dB} \tag{7}$$

The PSO is a multiple-agents optimization algorithm developed by Kennedy and Eberhart [21] in 1995. It starts by randomly initializing the position matrix **X** (particles of the swarm), velocity matrix **V**, and the personal best of each particle in the swarm **P**. **X** is a matrix in which every row represents a set of possible angles of the roots for the third sub-polynomial of Eq. (4) and it can expressed as:

$$\mathbf{X} = \begin{bmatrix} \boldsymbol{x}_1 \\ \vdots \\ \boldsymbol{x}_i \\ \vdots \\ \boldsymbol{x}_M \end{bmatrix} = \begin{bmatrix} \psi_{11} & \psi_{12} & \cdots & \psi_{1(N-K-3)} \\ \vdots & \vdots & \ddots & \vdots \\ \psi_{i1} & \psi_{i2} & \cdots & \psi_{i(N-K-3)} \\ \vdots & \vdots & \ddots & \vdots \\ \psi_{M1} & \psi_{M2} & \cdots & \psi_{M1(N-K-3)} \end{bmatrix} \tag{8}$$

Notice that, one row of the position matrix will be the initial phases of the controlled roots, $\boldsymbol{\psi}_s$.

The velocity matrix is

$$\mathbf{V} = \begin{bmatrix} \boldsymbol{v}_1 \\ \vdots \\ \boldsymbol{v}_i \\ \vdots \\ \boldsymbol{v}_M \end{bmatrix} = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1(N-K-3)} \\ \vdots & \vdots & \ddots & \vdots \\ v_{i1} & v_{i2} & \cdots & v_{i(N-K-3)} \\ \vdots & \vdots & \ddots & \vdots \\ v_{M1} & v_{M2} & \cdots & v_{M1(N-K-3)} \end{bmatrix} \tag{9}$$

The personal best position can be defined by the matrix

$$\mathbf{P} = \begin{bmatrix} \boldsymbol{pbest}_1 \\ \vdots \\ \boldsymbol{pbest}_i \\ \vdots \\ \boldsymbol{pbest}_M \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1(N-K-3)} \\ \vdots & \vdots & \ddots & \vdots \\ p_{i1} & p_{i2} & \cdots & p_{i(N-K-3)} \\ \vdots & \vdots & \ddots & \vdots \\ p_{M1} & p_{M2} & \cdots & p_{M1(N-K-3)} \end{bmatrix} \tag{10}$$

The global best solution denoted by (***gbest***) is the row of personal best matrix, P, with the best fitness function that is

$$\boldsymbol{gbest} = min(fitness(\boldsymbol{pbest}_i)) \tag{11}$$

The following steps summarize the action encountered on each particle, $\boldsymbol{x}_i$, in the swarm [14,21]:

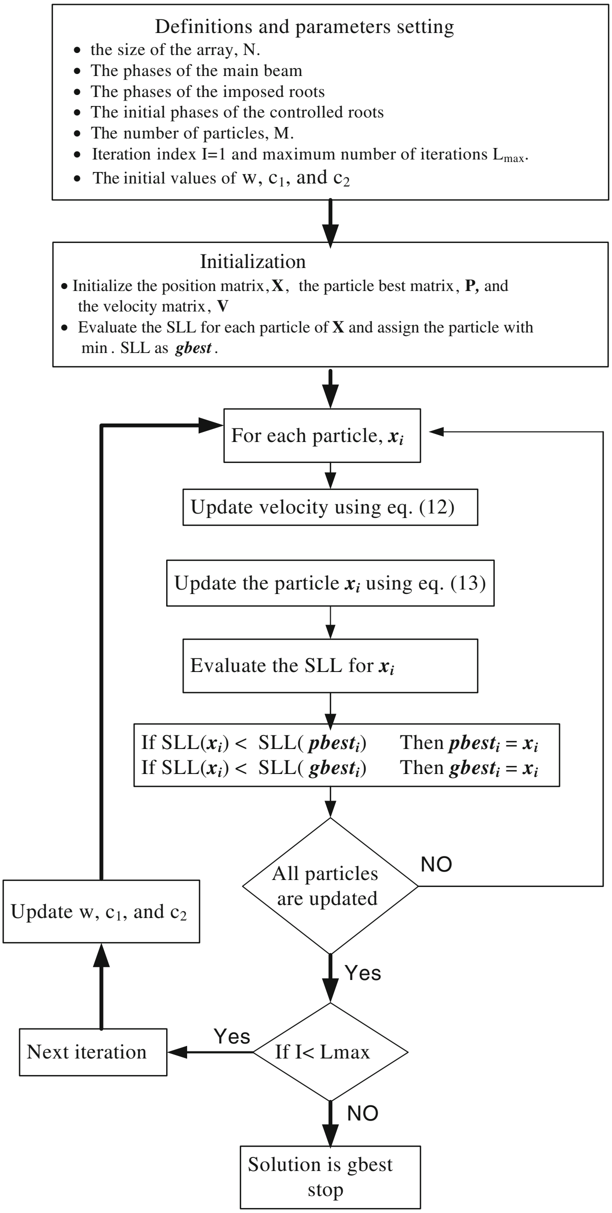


Fig. 3 Flow chart of the PSO algorithm

1. For each particle, the velocity update is

$$\boldsymbol{v}_i^{t+1} = w^{t+1}\boldsymbol{v}_i^t + c_1\eta_1(\boldsymbol{pbest}_i^t - \boldsymbol{x}_i^t) + c_2\eta_2(\boldsymbol{gbest} - \boldsymbol{x}_i^t) \tag{12}$$

The superscript $t+1$ and $t$refer to the time index of the next and the current iterations. $\eta_1$and η_2 are two uniformly random numbers in the interval [0,1]. A good choice for c_1

and c_2 are both 2.0. The parameter w^t is a number called the inertial weight which is a scaling factor of the previous velocity of the particles.

2. The position will be updated as:

$$\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + \Delta t \boldsymbol{v}_i^t \tag{13}$$

For simplicity Δt is chosen to be unity.

3. Evaluate the fitness function for the new position matrix, **X**, and determine the new **P** matrix and the new ***gbest*** vector as illustrated in the flow chart of Fig. 3.

The flow chart of the complete algorithm is given in Fig. 3.

3 Numerical Examples

Several computer simulation examples were conducted and discussed to demonstrate the validity of pattern synthesis with complex coefficients control by optimizing the roots of the array polynomial using the PSO algorithm. Although the roots of array polynomial can be anywhere in the z-domain, in this work the roots are arbitrary chosen but restricted on the unit circle.

In the first example, consider a linear array of 16 equispaced isotropic elements with interelement spacing of $\frac{\lambda}{2}$. It is required to synthesis an antenna pattern of the objective function with the following specifications: the main beam is chosen to be the main beam of the 16 equispaced linear array and a two prescribed nulls at $\theta_1 = 11°$ and $\theta_2 = 17°$ where the direction of the interference signals are assumed at the peaks of the first and the second sidelobes. Hence the corresponding angles of desired roots on the unit circle will be $\psi_{n,1} = 34.4°$ and $\psi_{n,2} = 52.7°$. The array polynomial with null steering can be achieved by replacing the

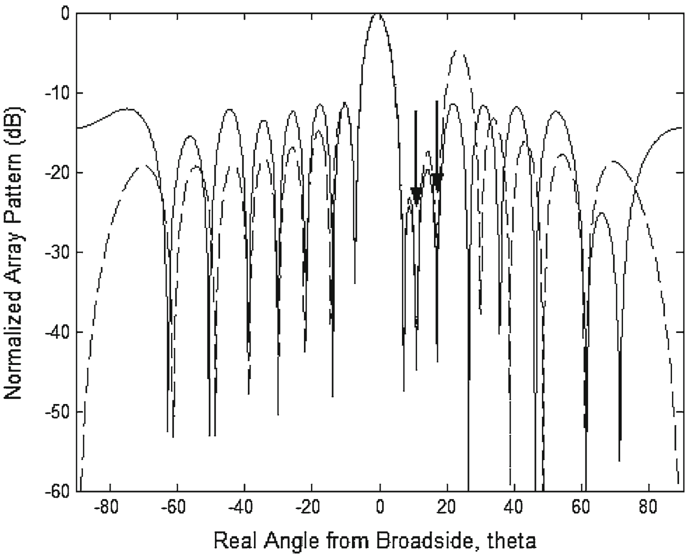


Fig. 4 The optimized array pattern with two nulls imposed at $\theta_1 = 11°$ and $\theta_2 = 17°$ (*Solid*). The array pattern when the two nulls are imposed at the array pattern of a uniformly excited linear array, $N = 16$, $d_0 = \lambda/2$ (*Dotted*)

Table 1 The computed element complex coefficients for Fig. 4 (solid) where two nulls are imposed at $\theta_1 = 11°$ and $\theta_2 = 17°$

Elem. No.	Complex coefficient, a_n	
	$\|a_n\|$	$\angle a_n$ deg.
1	1.0000	0
2	0.3414	−16.6641
3	0.2657	−54.1167
4	0.5459	−42.1170
5	0.4707	−27.6736
6	0.5635	−34.7209
7	0.5714	−13.9224
8	0.5261	−44.0372
9	0.5261	−16.8268
10	0.5714	−46.9416
11	0.5635	−26.1431
12	0.4707	−33.1904
13	0.5459	−18.7470
14	0.2657	−6.7473
15	0.3414	−44.1999
16	1.0000	−60.8640

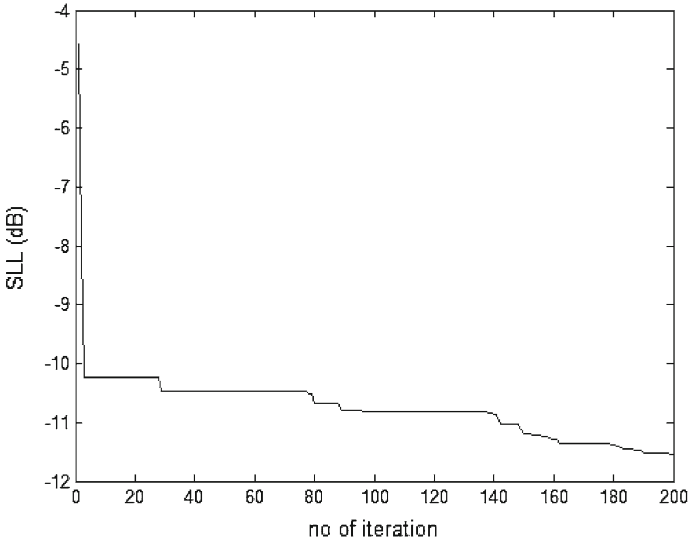


Fig. 5 Fitness (SLL) versus number of iterations for Example one

closest roots of the initial polynomial, $F_0(z)$, to the desired roots ($z_1^n = e^{j\psi_{n,1}} z_2^n = e^{j\psi_{n,2}}$) to yield the null steered array pattern, $F_n(z)$. The roots of $F_n(z)$ is shown in Fig. 1 and the corresponding array pattern is shown in Fig. 4 (dotted) where the SLL is degraded from 13 dB of the uniformly excited array to 4.5712 dB.

Although the initial roots are not required in the optimization process, it is reasonable to include ψ_s as a particle in initial position matrix. This will force the algorithm to choose the global best (***gbest***) solution to be better or as the initial pattern from the first iteration. The complex coefficients of the array elements are computed by optimizing the best location of the controlled roots on the unit circle using the PSO algorithm. Table 1 gives the coefficients when M= 20 and L_{max} = 200 and Fig. 4 (solid) shows the corresponding optimized array

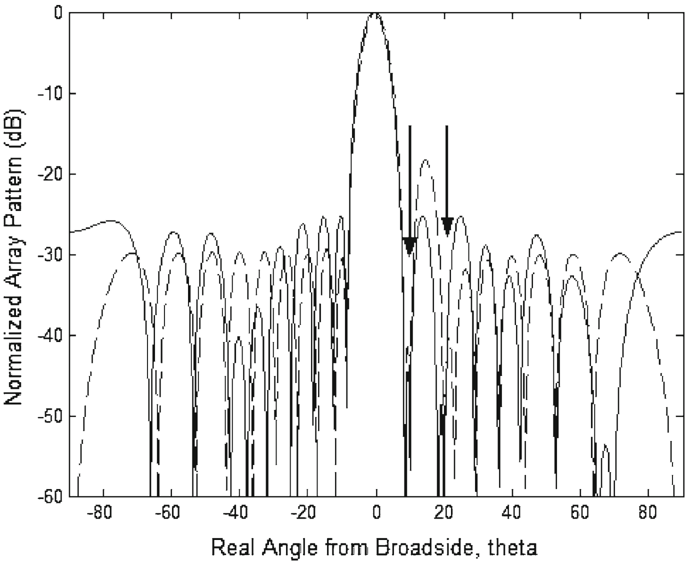


Fig. 6 The optimized array pattern with two nulls imposed at $\theta_1 = 10°$ and $\theta_2 = 20°$. and ($\psi_{n,1} = 31.26°$ and $\psi_{n,2} = 61.56°$) (*Solid*). The array pattern when the two nulls are imposed at the array pattern of a 30 dB Chebyshev array, $N = 20$, $d_0 = \lambda/2$ (*Dotted*)

Table 2 The computed element complex coefficients for Fig. 6 (solid) where two nulls are imposed at $\theta_1 = 10°$ and $\theta_2 = 20°$

Elem. No.	Complex coefficients,	
	$\lvert a_n \rvert$	$a_n \angle a_n$ deg.
1	1.0000	0
2	0.9869	−3.3451
3	1.3096	−8.6670
4	1.6150	−21.5157
5	1.8079	−12.8610
6	2.3267	−18.3869
7	2.4299	−17.7590
8	2.6527	−25.1632
9	3.0390	−24.6157
10	3.1606	−26.9849
11	3.1586	−23.8382
12	3.0417	−26.3525
13	2.6550	−25.6580
14	2.4246	−33.1570
15	2.3288	−32.5588
16	1.8095	−37.9042
17	1.6144	−29.3721
18	1.3122	−42.2185
19	0.9849	−47.4812
20	1.0019	−51.0140

pattern. From the Figure the SLL of the optimized array pattern is 11.5 dB which means that about 7 dB improvement is obtained compared to the steered initial pattern. The fitness versus the number of iterations for Fig. 4 (solid) is shown in Fig. 5.

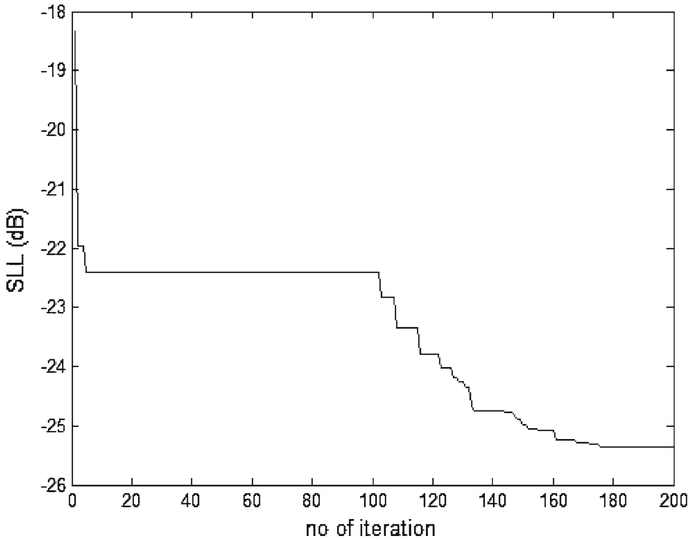


Fig. 7 Fitness (SLL) versus iteration number for Example two

In the second example, we consider the two prescribed nulls to be imposed at 10° and 20° when a 30 dB Chebyshev equispaced isotropic linear array of 20 elements and with interelement spacing of $\frac{\lambda}{2}$ is assumed. The direction of the interference signals are imposed at the peaks of the first and the third sidelobes to deteriorate the SLL of the initial 30 dB Chebyshev array. Therefore, the main beam of the objective function is chosen to be the main beam of the 30 dB Chebyshev array. Replacing the closest roots to the imposed nulls of the 30 dB Chebyshev array with $z_1^n = e^{j\psi_{n,1}}$ and $z_2^n = e^{j\psi_{n,2}}(\psi_{n,1} = 31.26°$ and $\psi_{n,2} = 61.56°)$ will degrade SLL of the initial pattern $F(z)$, to 18.33 dB as shown in Fig. 6 (dotted). Table 2 gives the complex coefficients using the PSO algorithm when M = 20 and L_{max}= 200 and Fig. 6 (solid) shows the corresponding optimized array pattern. Figure 7 shows the fitness versus the number of iterations for the optimized array pattern (Fig. 6 solid). From Figs. 6 and 7 the SLL of the optimized array pattern is 25.3 dB which means about 7 dB improvement is obtained compared to the steered initial pattern.

4 Conclusions

Design of linear phased array was achieved by employing the array polynomial method with Schelkunoff unit circle and the PSO algorithm. The design is achieved by the proper placement of the roots of the array polynomial on the unit circle. The roots are subdivided into three sets. The first set contains the two roots responsible for the mainbeam characteristics, the second set corresponds to the prescribed nulls, and the third set is the rest of the initial roots of the array factor. The root locations of the first and the second sets are imposed on the unit circle while the root locations of the third set are optimized by the PSO algorithm. Using this method, the optimized parameters of the synthesis problem are reduced by more than 50% compared to the conventional complex weights array design. In addition, the fitness function is simplified by only minimizing the SLL of the array pattern. Examples are given to demonstrate the validity of this method. A reduction of about 6 dB is achieved by optimizing the root locations of the third set.

References

1. Steyskal, H., Shore, R. A., & Haupt, R. L. (1986). Methods for null control and their effects on radiation pattern. *IEEE Transactions on Antennas and Propagation, 34*, 404–409.
2. Khodier, M. M., & Christodoulou, C. G. (2005). Linear array geometry synthesis with minimum sidelobe level and null control using particle swarm optimization. *IEEE Transactions on Antennas and Propagation, 53*(8), 2674–2679.
3. Bevelacqua, P. J., & Balanis, C. A. (2007). Minimum sidelobe levels for linear arrays. *IEEE Transactions on Antennas and Propagation, AP-55*, 3442–3449.
4. Quevedo-Teruel, O., & Rajo-Iglesias, E. (2006). Ant colony optimization in thinned array synthesis with minimum sidelobe level. *IEEE Transactions on Antennas and Propagation, 5*(1), 349–352.
5. Bray, M., Werner, D., Boeringer, D., & Machuga, D. (2002). Optimization of thinned aperiodic linear phased arrays using genetic algorithms to reduce grating lobes during scanning. *IEEE Transactions on Antennas and Propagation, AP-50*(12), 1732–1742.
6. Mahanti, G. K., Pathak, N., & Mahanti, P. (2007). Synthesis of thinned linear antenna arrays with fixed sidelobe level using real-coded genetic algorithm. *Progress in Electromagnetics Research, PIER, 75*, 319–328.
7. Haupt, R. L. (1997). Phase-only adaptive nulling with a genetic algorithm. *IEEE Transactions on Antennas and Propagation, 45*(6), 1009–1015.
8. Awan, H., Abdullah, K., & Faryad, M. (2008). Implementing smart antenna system using genetic algorithm and artificial immune system. *17th international confernece on microwaves, radar and wireless communications*, (pp. 1–4) May 19–21, 2008.
9. Murino, V., Trucco, A., & Regazzoni, C. (1996). Synthesis of unequally spaced arrays by simulated annealing. *IEEE Transactions on Signal Processing, 44*(1), 119–123.
10. Coleman, C. M., Rothwell, E. J., & Ross, J. E. (2004). Investigation of simulated annealing, ant-colony optimization, and genetic algorithms for self-structuring antennas. *IEEE Transactions on Antennas and Propagation, 52*(4), 1007–1014.
11. Kurup, D. G., Himdi, M., & Rydberg, A. (2003). Synthesis of uniform amplitude unequally spaced antenna arrays using differential evolution algorithm. *IEEE Transactions on Antennas and Propagation, 51*(9), 2210–2217.
12. Rattan, M., Patterh, M. S., & Sohi, B. S. (2008). Antenna array optimization using evolutionary approaches. *Apeiron, 15*(1), 78.
13. Jianfeng, Y., Weizheng, P., & Jim, Z. (2008). Immune algorithm in array-pattern synthesis with side lobe reduction. *International conference on microwave and millimeter wave technology, ICMMT 2008*, (pp. 1127–1130) April 21–24, 2008.
14. Robinson, J., & Rahmat-Samii, Y. (2004). Particle swarm optimization in electromagnetics. *IEEE Transactions on Antennas and Propagation, 52*(2), 397–407.
15. Jin, N., & Rahmat-Samii, Y. (2007). Advances in particle swarm optimization for antenna designs: Real-number, binary, single-objective and multi-objective implementations. *IEEE Transactions on Antennas and Propagation, 55*(3), 556–567.
16. Boeringer, D. W., & Werner, D. H. (2004). Particle swarm optimization versus genetic algorithms for phased array synthesis. *IEEE Transactions on Antennas and Propagation, 52*(3), 771–779.
17. Donelli, M., Azaro, R., De Natale, F., & Massa, A. (2006). An innovative computational approach based on a particle swarm strategy for adaptive phased-arrays control. *IEEE Transactions on Antennas and Propagation*. AP-54(3).
18. Mahmoud, K., El-Adawy, M., Ibrahem, S., Bansal, R., & Zainud-Deen, S. (2008). MPSO-MOM: A hybrid modified particle swarm optimization and method of moment algorithm for smart antenna synthesis. *Electromagnetics, 28*, 411–426.
19. Monorchio, A., Genovesi, S., Bertini, S., & Brizzi, A. (2007). An efficient interpolation scheme for the synthesis of linear arrays based on Schelkunoff polynomial method. *IEEE Antennas and Wireless Letters, 6*, 484–487.
20. Mismar, M. J., Ismail, T. H., & Abu-Al-Nadi, D. I. (2007). Analytical array polynomial method for linear antenna arrays with phase-only control. *AEÜ -International Journal of Electornics and Communications, 61*(7), 485–492.
21. Kennedy, J., & Eberhart, R. C. (1995). Particle swarm optimization. In *Proceedings of the IEEE conference on neural networks IV*, Piscataway, NJ.

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