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Conflicting Parameter Pair Optimization for Linear Aperiodic Antenna Array using Chebyshev Taper based Genetic Algorithm

Laxmi Lavanya Yenneti[1], Aruna Singam[2], Sasibhushana Rao Gottapu[3]
[1]Department of ECE
AU College of Engineering (A),
Visakhapatnam, India.
email: lavanya9234@gmail.com
[2]Department of ECE
AU College of Engineering (A),
Visakhapatnam, India.
email: aruna9490564519@gmail.com
[3]Department of ECE
AU College of Engineering (A),
Visakhapatnam, India.
email: sasigps@gmail.com

Abstract— In this study, the peak side lobe level (PSLL) in the radiation pattern of a linear antenna array (LAA) is lowered without affecting its first null beam width (FNBW). Antenna array synthesis is commonly applied to achieve high directivity, low side lobes, high gain and desired null positions in the output radiation pattern. But output parameters like PSLL, null positions and beam width conflict with each other, i.e. as one parameter improves, the other deteriorates. To avoid this problem, a multi-objective optimization algorithm can be implemented, in which both the conflicting parameters can be simultaneously optimized. This work proposes a multi-objective algorithm, which takes advantages of the well-known Chebyshev tapering and genetic algorithm (GA), to lower the PSLL without broadening the beam further. Array elements are fed using Chebyshev tapered excitations while GA is incorporated to optimize the elemental spacing. The results of 28-element LAA are compared with those of multi-objective Cauchy mutated cat swarm optimization (MO-CMCSO) existing in literature, which has also been proven to be superior to multi-objective cat swarm optimization (MO-CSO) and multi-objective particle swarm optimization (MO-PSO). Results indicate that the proposed algorithm performs better by further reducing the PSLL from -21.57 dB (MO-CMCSO) to -28.18 dB, while maintaining the same FNBW of 7.4 degrees.

Keywords- Multi-Objective Optimization; Chebyshev tapering; Genetic Algorithm; Peak Side Lobe Level; First Null Beam Width.

I. INTRODUCTION

Wireless communication systems require continuous upgradation of their performance to cater to the needs of increasing demand for high data rate applications. Array antennas have a pivotal role in enhancing the communication system performance. To meet the requirements of existing and upcoming communication applications, array antennas use beamforming to generate electronically steerable beams of desired radiation properties such as side lobe levels (SLL), gain, directivity, beam width and null positions. But the radiation properties of an array antenna ultimately depend on the array size, excitation amplitudes, phases and elemental spacing [1].

Side lobes of radiation pattern occur in undesired directions, wasting power and causing interference and thus have to be minimized. The value of SLL must be maintained as minimum as possible in most of the applications. Many algorithms are proposed in literature to attain beam patterns with low SLL [2]-[9]. These include genetic algorithm (GA), grey wolf optimization (GWO), particle swarm optimization (PSO), biogeography based optimization (BBO), etc., by using amplitude, phase and spacing controls in antenna arrays. Amplitude control refers to varying the excitation amplitudes to the elements of the antenna array, while spacing control employs variable spacing between array elements. In phase control, the excitation phases of the array elements are varied.

With reduction in SLL, the beam broadens, which reduces the directivity. SLL and beam width are therefore called dissension parameters that conflict with each other and cannot be improved simultaneously using simple algorithms. For achieving low SLL with narrow beams or good directivity, multi-objective optimization is to be implemented [10]. Multi-

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objective optimization results in concurrent improvement of conflicting radiation parameters. It can be implemented using amplitude, phase or spacing controls or a combination of these. This results in a trade-off between the conflicting parameters, which can be graphically represented using a pareto front. It contains all the possible solutions to the problem. Any point can be considered on pareto front as a solution.

The paper is divided as follows: Section I introduces the work and presents the motivation behind it. Section II discusses the existing techniques to improve the conflicting parameters simultaneously. The antenna array design is elaborated in section III, which includes the array geometry, algorithm flow and fitness function formulations. The results obtained are analyzed in section IV and conclusions are drawn in section V.

II. LITERATURE SURVEY

Several multi-objective optimization algorithms exist in literature, that aimed at simultaneously improving the dissention parameters of antenna array radiation pattern. One such parameter pair is SLL suppression – null control. Pal et al. [11] utilized spacing control for lowering SLL and controlling nulls simultaneously using multi-objective differential evolution (MOEA/D-DE). Decomposition-based multi-objective particle swarm optimization (dMOPSO) technique is implemented in [12] to reduce minimum average SLL and control nulls in specific direction. Gunes et al. [13] introduced pattern search (PSearch) algorithm to solve multi-objective problem in linear antenna arrays, that maximized side lobe suppressions and null generations in a given direction while maintaining highest possible gain. In [14], Saxena et al. introduced flower pollination algorithm (FPA) for minimizing SLL and placing deep nulls in specific directions by optimizing antenna positions in linear antenna arrays. Sankar et al. [15] developed collective social behavior (CSB) technique for SLL control and adaptive nulling by optimizing antenna weights.

SLL – beam width is one more conflicting pair, whose simultaneous improvement greatly contributes to antenna array performance. Some algorithms have also focused on this pair in the past decade. Panduro et al. [16] implemented multi-objective genetic algorithm (MO-GA) to obtain a trade-off between SLL and main beam width. Jin et al. [17] extended the design of non-uniform linear arrays to multi-objective particle swarm optimization (MO-PSO). Jayaprakasam et al. [18] proposed a multi-objective amplitude and phase optimization for minimizing peak side lobe and maximizing directivity using NSGA-II with selective distance. Jayaprakasam et al. [19] analyzed multi-objective metaheuristic algorithms such as GA, PSO and gravitational search algorithm (GSA) in distributed beamforming to obtain lower SLL and higher directivity.

Pappula et al. [20] introduced Cauchy mutation to cat swarm optimization (CMCSO) for minimizing side lobe level and controlling null positions in linear aperiodic arrays. This algorithm is further developed into multi-objective Cauchy mutated cat swarm optimization (MO-CMCSO) to trade-off conflicting parameters of linear antenna array, i.e. peak side lobe level (PSLL) and first null beam width (FNBW) by employing unequal spacing in [21]. The paper also implemented MO-CSO and MO-PSO and compared the results. A further reduction in SLL leads to increment in FNBW and reduction in directivity, which is a disadvantage.

In this paper, the advantages of two well-known techniques, viz., Chebyshev tapering and genetic algorithm are combined to further reduce the PSLL for a given FNBW. The results of this hybrid Chebyshev-GA based optimization are compared with those of MO-PSO, MO-CSO and MO-CMCSO in [21]. The goal is to obtain lower PSLL, for the same FNBW. The next section presents antenna array design.

III. ANTENNA ARRAY DESIGN

An aperiodic linear isotropic antenna array with 2N = 28 elements is placed along X-axis as indicated in Fig. 1. The array is positioned such that the excitations and spacing between elements are symmetrical about the Y-axis. The elements are fed with Chebyshev tapered excitation with side lobe level taken at -30 dB and spacing values are obtained by using multi-objective genetic algorithm (MO-GA). Since it is a symmetrical array, the array has to be optimized for N=14 element spacing values, considering the first element is at a distance d (1) from the origin.

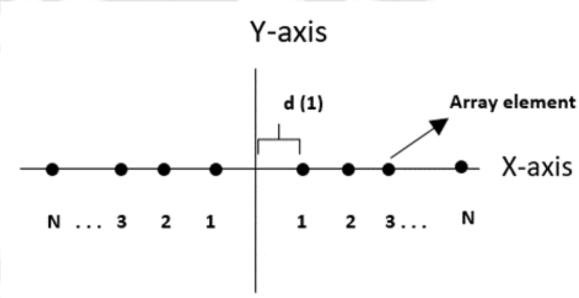

Figure 1. Proposed antenna array geometry

The radiation pattern for the isotropic antenna array reduces to its array factor since element pattern is unity. The array factor in θ direction for the antenna array in Fig. 1 can be written as

$$AF(\theta) = 2\sum_{n=1}^{N} A(n)\cos\big(kd(n)\cos\theta\big) \quad (1)$$

Where A(n) and d(n) represent excitation and distance from origin of n^{th} element of the array. Here k, the wave number equals to $\frac{2\pi}{\lambda}$, in which λ is the wavelength corresponding to operating frequency of the array. For the proposed antenna array, 'A' is the set of 14 Chebyshev excitation amplitudes, while 'd' is obtained by performing MO-GA on element spacing.

A. Chebyshev tapering

The advantage of Chebyshev tapering makes it quite suitable for this work. It is known to produce the least possible null-to-null beam width for a specified SLL [22]. Chebyshev tapered weights are calculated by equating array factor (AF) in normalized form to Chebyshev polynomial of the same order. The Chebyshev polynomials in x are calculated by using a recursion formula given as

$$T_m(x) = 2xT_{m-1}(x) - T_{m-2}(x) \qquad (2)$$

Here m is the polynomial order and is taken as N-1, with N being the array size. The variable m takes values 2,3,4 so on. The lower order terms (m=0,1) are defined as

$$T_m(x) = \cos[m\cos^{-1}(x)], -1 \le x \le 1 \qquad (3)$$

The Chebyshev tapered weights so obtained gives array radiation pattern with specified SLL.

B. Genetic algorithm

The genetic algorithm based on natural selection is one of the most efficient optimization methods, that can solve constrained and unconstrained problems. It offers several advantages like ease of implementation, faster convergence, better suited for multi-objective problems, etc. It uses selection, crossover and mutation on a set of individuals called population to find the fittest of them. A fitness function is used to evaluate the fitness of the individuals. The procedure is repeated several times until a stopping criterion is reached. This results in optimum solution to the problem [23].

Since multi-objective GA is used, two fitness functions given in (4) and (5) have to be minimized simultaneously.

$$\text{Fitness1} = \max\left\{20log\left|\frac{AF(\theta)}{AF(\theta_m)}\right|\right\} - SLL_{desired} \quad (4)$$

$$\text{Fitness2} = \text{FNBW} = 2|\theta_m - \theta_n| \qquad (5)$$

Where $AF(\theta_m)$ denotes the peak value of $AF(\theta)$, $SLL_{desired}$ is desired value of side-lobe level which is considered as -30dB for this work, θ_m is the angle corresponding to $AF(\theta_m)$ and θ_n is the angle at first null after main lobe peak. It is to be noted that in Fitness1 equation, calculation of $AF(\theta)$ takes all values of θ except for the main lobe. Thus in (4), first term represents the PSLL and (5) represents the FNBW.

C. Proposed Algorithm

The following are the steps of the proposed Chebyshev inspired multi-objective genetic algorithm for optimization of element spacing.

Step-1: Chebyshev excitations for N=28 and SLL of 30 dB below the main lobe are assigned to array elements. Criteria for stopping the optimization are defined.

Step-2: A random population of element spacing is generated. Their range is between 0.2λ and 0.8λ.

Step-3: Fitness1 and Fitness2 are evaluated for the generated population.

Step-4: Check for stopping criterion. If it is reached, go to step-8. If not, execute step-5.

Step-5: Select the individuals based on fitness.

Step-6: Crossover and mutation of selected individuals that further generates new offspring.

Step-7: With this new population created, go to step-3.

Step-8: End.

This multi-objective optimization results in a pareto front, which is a non-dominant solution set. Each point in this set is a solution, which trades-off between PSLL and FNBW.

IV. NUMERICAL RESULTS

For the 28-element linear antenna array, Chebyshev tapered excitations are considered and the elemental spacing are optimized using MO-GA. The minimum and maximum possible values for the spacing are taken as 0.2λ and 0.8λ. The optimization is repeated for 20 times and the optimal pareto front is taken, which is shown in Fig. 2 below.

It has seven possible solutions which are marked on the plot given below. X-axis represents FNBW given in (5) and Y-axis represents Fitness1 function given in (4). All the seven points are non-dominated solutions, i.e. each solution is such that it is not dominated by any other solution. The optimized spacing between elements corresponding to the solution is obtained. Out of the solutions, the point (7.4, 1.82) has been considered as the solution so as to compare with MO-PSO, MO-CSO and MO-CMCSO in [21]. This implies that a PSLL of -28.18 dB (i.e. 1.82 dB-30 dB) and FNBW of 7.4º is achieved in the proposed optimization technique. PSLL has improved over the MO-CMCSO technique, which has a PSLL of -21.57 dB and FNBW of 7.4º. Chebyshev excitations and optimized spacing values for the 14 array elements are given in Table I along with excitation and spacing values of the reference algorithms in [21]. Observed radiation pattern, comparison of the normalized radiation patterns and tabular results are presented in Fig. 3, Fig. 4 and Table II respectively.

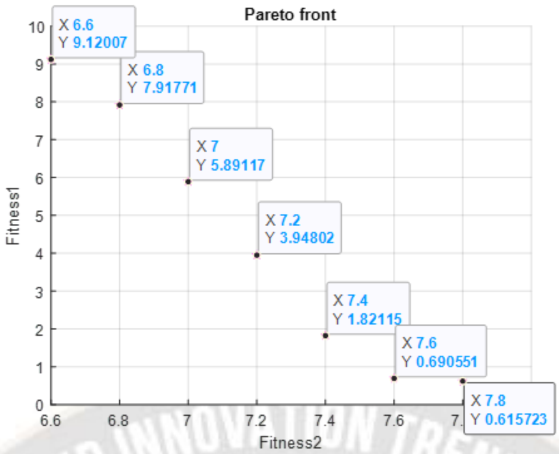

Figure 2. Pareto front obtained for the hybrid Chebyshev based MO-GA

TABLE I. SYMMETRIC EXCITATION AND SPACING VALUES OF THE PROPOSED AND REFERENCE OPTIMIZATION TECHNIQUES

S.No	Optimization Technique	Excitation Amplitude A(n)	Optimized position from origin d(n)
1.	Proposed Chebyshev-GA based hybrid technique	1.0000 0.9850 0.9555 0.9126 0.8578 0.7929 0.7202 0.6421 0.5610 0.4793 0.3993 0.3233 0.2528 0.4032	0.3966λ 1.1773λ 1.9705λ 2.7556λ 3.5459λ 4.3293λ 5.1191λ 5.9105λ 6.6936λ 7.4900λ 8.2445λ 8.9660λ 9.7174λ 10.4459λ
2.	MO-CMCSO [21]	1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000	0.2000λ 0.7500λ 1.2500λ 1.7552λ 2.3153λ 2.8231λ 3.4277λ 3.9495λ 4.5873λ 5.3567λ 6.1288λ 6.9563λ 7.9881λ 8.6758λ
3.	MO-CSO [21]	1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000	0.2000λ 0.7500λ 1.2903λ 1.8691λ 2.4332λ 3.0463λ 3.6311λ 4.1609λ 4.8884λ 5.7744λ 6.5767λ 7.5768λ 8.3889λ 9.3055λ
4.	MO-PSO [21]	1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000	0.2000λ 0.7945λ 1.5241λ 2.1173λ 2.9927λ 3.7345λ 4.2670λ 4.9412λ 5.8073λ 6.9102λ 7.7286λ 8.6519λ 9.6752λ 10.4363λ

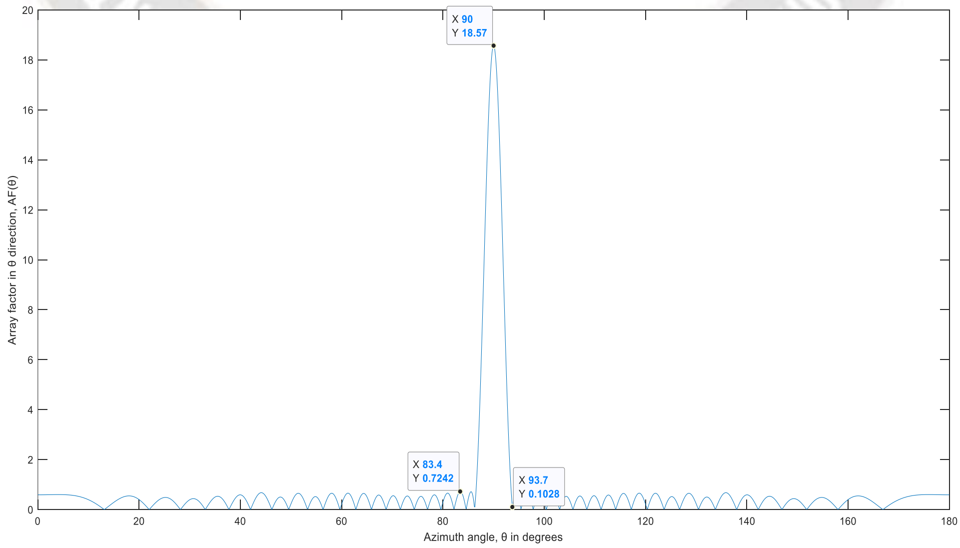

Figure 3. Radiation pattern obtained with the proposed technique

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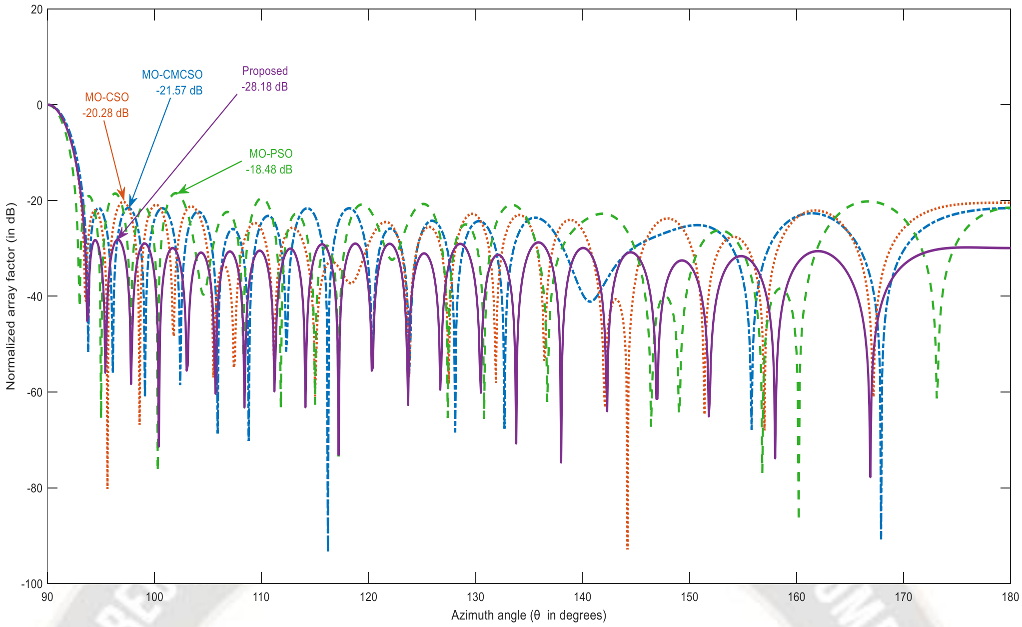

Figure 4. Radiation pattern comparison of other techniques with the proposed technique

TABLE II. PSLL AND FNBW OF THE PROPOSED TECHNIQUE AND REFERENCE OPTIMIZATION TECHNIQUES.

Optimization technique	PSLL (dB)	FNBW (degrees)
MO-PSO [21]	-18.48	6.2
MO-CSO [21]	-20.28	7.4
MO-CMCSO [21]	-21.57	7.4
Proposed technique	-28.18	7.4

The proposed technique has lower PSLL compared with MO-PSO, MO-CSO and MO-CMCSO. This reduction in PSLL is achieved while the FNBW is same as that of MO-CSO and MO-CMCSO, i.e. 7.4^{o}.

V. CONCLUSIONS

This work presents a 28-element aperiodic linear array antenna, which uses a hybrid optimization technique based on Chebyshev tapering and multi-objective genetic algorithm. While the array is excited with Chebyshev weights, the spacing between elements is modified using MO-GA. This resulted in radiation pattern plot having much lower PSLL, without increasing the FNBW. Comparisons are made with MO-CMCSO algorithm, which showed a decrease in PSLL of proposed technique by 6.6 dB.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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