Synthesis and Design of Thinned Planar Concentric Circular Antenna Array - A Multi-objective Approach

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Abstract. Thinned concentric antenna array design is one of the most important electromagnetic optimization problems of current interest. This antenna must generate a pencil beam pattern in the vertical plane along with minimized side lobe level (SLL) and desired HPBW, FNBW and number of switched off elements. In this article, for the first time to the best of our knowledge, a multi-objective optimization framework for this design is presented. Four objectives described above we are treated as four distinct objectives that are to be optimized simultaneously. The multi-objective approach provides greater flexibility by yielding a set of equivalent final solutions from which the user can choose one that attains a suitable trade-off margin as per requirements. In this article, we have used a multi-objective algorithm of current interest namely the *NSGA-II* algorithm. There are two types of design, one with uniform inter-element spacing fixed at 0.5λ and the other with optimum uniform inter-element spacing. Extensive simulation and results are given with respect to the obtained HPBW, SLL, FNBW and number of switched off elements and compared with two state-of-the-art single objective optimization methods namely DE and PSO.

1 Introduction

Circular antenna array, in which antenna elements are placed in a circular ring, is an array configuration of very practical use among all other antenna arrays present in modern day. It consists of a number of elements arranged on a circle [1] with uniform or non-uniform spacing between them. It possesses various applications in sonar, radar, mobile and commercial satellite communications systems [1-3]. Concentric Circular Antenna Array (CCAA), one of the most important circular arrays, contains many concentric circular rings of different radii and number of elements proportional to the ring radii. Uniform CCA (UCCA) is one of the most important configurations

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of the CCA [2] where the inter-element spacing in individual ring is kept almost half of the wavelength and all the elements in the array are uniformly excited.

In Concentric circular array, for reduction of the side lobe level, the array must be made aperiodic by altering the positions of the antenna elements. Thinning a large array will not only reduce side lobe level further but also reduce the number of antennas in the array and thereby cut down cost substantially. Global optimization tools such as Genetic Algorithms (GA) [6], Particle Swarm Optimization (PSO) [7], and Differential Evolution (DE) [9, 10] etc. have been used to solve these problems. In this article, for the first time to the best of our knowledge we have proposed a multi-objective framework [4] for the design of thinned concentric circular antenna array. Instead of going for the single objective weighted sum method which is however, subjective and the solution obtained will depend on the values of the weights specified, motivated by the inherent multi-objective nature of the antenna array design problems and the overwhelming growth in the field of Multi-Objective Evolutionary Algorithms [14], we have opted for a multi-objective algorithm named NSGA-II [11] to solve the thinned concentric circular array synthesis problem much more efficiently as compared to the conventional single-objective approaches like many other MO approaches previously [12-13]. This MO framework attempts to achieve a suitable number of switched off element in the thinned array close to the desired value, a desired half power beamwidth (HPBW) and first null beamwidth (FNBW) and also the a reduced side-lobe level (SLL). In order to show the effectiveness *NSGA-II* algorithm we have compared the obtained results of the *NSGA-II* algorithm with two traditional single objective evolutionary algorithms, DE [9,10] and PSO [7,8] which is outperformed by the NSGA-II in terms of the SLL, HPBW, FNBW and number off switched off elements.

2 General Description of NSGA-II

NSGA-II [11] is a non-domination based genetic algorithm for multi-objective optimization which incorporates elitism and no sharing parameter needs to be chosen *a priori*. The population is initialized as usual. Once the population is initialized the population is sorted based on non-domination into each front. The first front being completely non-dominant set in the current population and the second front being dominated by the individuals in the first front only and the front goes so on. Each individual in the each front are assigned rank (fitness) values or based on front in which they belong to. Individuals in first front are given a fitness value of 1 and individuals in second are assigned fitness value as 2 and so on. In addition to fitness value a new parameter called *crowding distance* is calculated for each individual. The crowding distance is a measure of how close an individual is to its neighbours. Large average crowding distance will result in better diversity in the population. Parents are selected from the population by using binary tournament selection based on the rank and crowding distance. An individual is selected in the rank is lesser than the other or if crowding distance is greater than the other. The selected population generates off-springs from crossover and mutation operators. The population with the current population and current off-springs is sorted again based on non-domination and only the best N individuals are selected, where N is the population size. The selection is based on rank and the on crowding distance on the last front.

3 Design of Thinned Concentric Circular Array: The Proposed Multi-objective Framework

Thinning an array means turning off some elements in a uniformly spaced or periodic array to generate a pattern with low side lobe level. In our method, we kept the antennas positions fixed, and all the elements can have only two states either "on" or "off" (Similar to Logic "1" and "0" in digital domain). An antenna will be considered to be in "on" state if and only if it contributes to the total array pattern. While an antenna will be considered "off" if and only if either the element is passively terminated to a matched load or open circuited. If an antenna element does not contribute to the resultant array pattern, they will be considered "off". As for non-uniform spacing of the element one has to check an infinite number of possibilities before final placement of the elements, thinning an array [12-14] to produce low side lobes is much simpler than the more general problem of non-uniform spacing of the elements. The arrangement of elements in planar circular arrays [2, 3] may contain multiple concentric circular rings, which differ in radius and number of elements. Figure 1 shows the configuration of multiple concentric circular arrays [2, 3] in *XY* plane in which there are M concentric circular rings. The m-th ring has a radius r_m and number of isotropic elements N_m where $m = 1,2,3,,,,,,10$. Elements are equally placed along a common circle. The far-field pattern [1] in free space is given by:

$$E(\theta,\phi) = \sum_{m=1}^{M} \sum_{n=1}^{N_m} I_{mn} e^{j2\pi r_m \sin\theta \cos(\phi - \varphi_{mn})} \tag{1}$$

Normalized power pattern in dB denoted by $P(\theta,\phi)$ can be expressed as follows:

$$P(\theta,\phi) = 10\log\left[\frac{|E(\theta,\phi)|}{|E(\theta,\phi)|_{\max}}\right]^2 = 2010\log\left[\frac{|E(\theta,\phi)|}{|E(\theta,\phi)|_{\max}}\right] \tag{2}$$

r_m = radius of the m-th ring = $\frac{N_m d_m}{2\pi}$, d_m=inter-element distance of the m-th ring.

$\phi_{m,n} = \frac{2n\pi}{N_m}$ = angular position of the mn-th element with $1 < n \le N_m$, θ,ϕ = polar and azimuthal position of mn-th element with $= \frac{2\pi}{\lambda}$, λ = wave-length. $I_{m,n}$ = excitation amplitude of mn-th element. In our case the excitation amplitude of the an element is said to be turned "on" when it takes a value of "1" and is said to be turned "off" if it takes a value of "0". All the elements have the same excitation phase of zero degree. The value of ϕ is taken as 0^0.

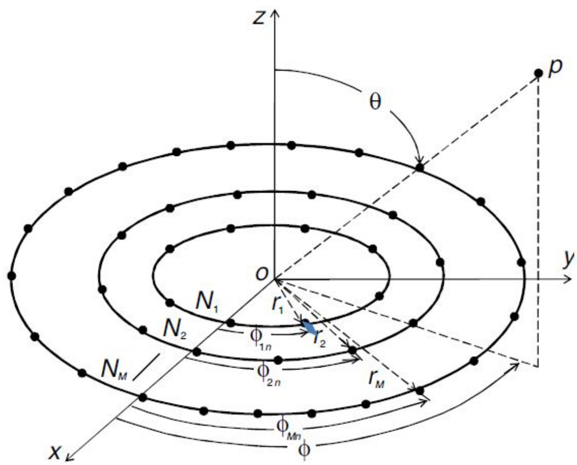

Fig. 1. Multiple concentric circular ring arrays of isotropic antennas in *XY* plane

There are four objectives for the multi-objective framework. They are the reduced maximum SLL, desired HPBW (-4.5dB), desired FNBW (15 degree) and the desired no. of switched off elements. So, the following objectives are:

$$f_1 = (SLL_{\max}), \quad f_2 = (HPBW_o - HPBW_r)^2, \qquad (3)$$
$$f_3 = (FNBW_o - FNBW_r)^2 \; and \quad f_4 = \left(T_o^{off} - T_r^{off}\right)^2 H(T)$$

where, SLL_{max} is the value of maximum side lobe level. $HPBW_o$, $HPBW_r$ are obtained and desired value of half-power beam width respectively. $FNBW_o$, $FNBW_r$ are obtained and desired value of first null beam width respectively. T_o^{off}, T_r^{off} are obtained and desired value of number of switched off element respectively. $H(T)$ is Heaviside step functions defined as follows:

$$H(T) = \begin{cases} 0 & if \quad T \le 0 \\ 1 & if \quad T > 0 \end{cases} \qquad (4)$$

where $T = T_o^{off} - T_r^{off}$.

In this way, an MOEA will allow us to find the right balance between the four objectives shown above. So an MOEA will allow us greater flexibility in designing a of thinned concentric circular antenna array because a single-objective EA gives us only one solution in one performance which might not completely satisfy the designer's needs.

4 Simulation and Results

The simulation and results for the design of the thinned concentric circular antenna array has been given on one instantiation of the design problem, namely ten concentric circular rings. In the example, each ring of the antenna contain 8*m* equi-spaced isotropic elements (a total of 440), where *m* is the ring number counted from the innermost ring 1. The optimal inter-element arc spacing (d_m), the Side-lobe level (SLL), the first null beamwidth (FNBW), the half power beam width (HPBW) and the optimal set of “on” and “off” are determined with respect to the best compromised solution which will be (HPBW) discussed below. For *NSGA-II*, the best compromise solution was chosen from the PF using the method described in [15]. Over the thinned circular concentric antenna array design instances and cases we also compare the performance of *NSGA-II* with that of two single-objective optimization techniques, namely the original DE [9] (DE/rand/Bin/1) and PSO [7] where objective function is the weighted sum of the four objectives (weights are taken as unity). Parameters for all the algorithms are selected with guidelines from their respective literatures. In what follows, we report the best results obtained from a set of 25 independent runs of *NSGA-II* and its competitors, where each run for each algorithm is continued up to 3×10^5 Function Evaluations (FEs).

Cases-I and II: In this case, inter-element arc spacing (d_m) in all the rings is 0.5λ. For such a fully populated and uniformly excited array, the maximum side lobe level is calculated to be -17.37 dB and HPBW and the FNBW is taken as 4.5 and 15 degree. Problem is now to find the optimal set of “on” and “off” elements keeping the half-power beam width (HPBW) and the first null beamwidth (FNBW) unchanged and fixing the number of switched off elements to be equal to 220 or more and reducing the maximum side lobe level (SLL) further. Number of vectors is taken to be 100 and the algorithm is run for 50 generations. In the second case, inter-element arc spacing (d_m) in all the rings is made uniform and same but not fixed. Optimum values of inter-element arc spacing along with optimal set of “on" and “off" elements are found out using this *NSGA-II* that will generate a pencil beam in the *XZ* plane with reduced side lobe level. Results in the Table 1 clearly show that the synthesized pattern of thinned array using *NSGA-II* and optimum inter-element arc spacing is better than a fully populated array in terms of side lobe level. Optimized inter-element arc spacing is found to be $d = 0.4316\lambda$. Table 2 depicts the excitation amplitude distributions for the two cases. Table 3 clearly shows that *NSGA-II* has outperformed its competitor algorithms like DE and PSO. Here, figure 2 shows the normalized power pattern in dB scale for fully populated, optimized $d = 0.4316\lambda$ and $d = 0.5\lambda$.

Table 1. Obtained results for Case I and Case II for *NSGA-II*

Design Parameters	Synthesized Thin Array with Optimum $d = 0.4316\lambda$	Synthesized Thin Array with fixed $d = 0.5\lambda$	Fully Populated Array with $d = 0.5\lambda$
Side Lobe level (SLL, in db)	**-21.29**	-19.61	-17.37
Half Power Beamwidth (HPBW, in degree)	**4.5**	**4.5**	**4.5**
First Null Beamwidth (FNBW, in degree)	**15**	**15**	**15**
Number of Switched Off Elements	**220**	**220**	0

Table 2. Excitation Amplitude Distributions $\left(I_{mn}\right)$ using *NSGA-II* with fixed $d = 0.5\lambda$ and optimal $d = 0.4316\lambda$ respectively

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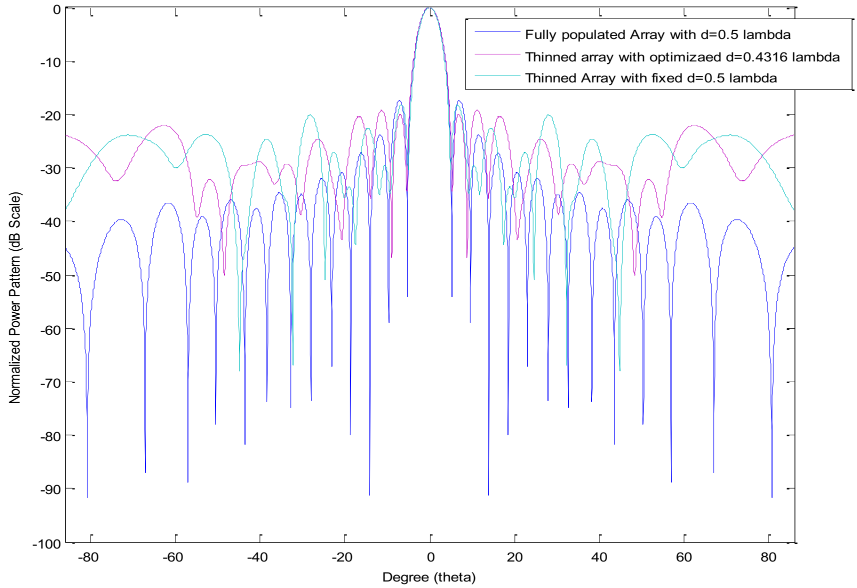

Fig. 2. Normalized power pattern in dB

Table 3. Set of comparison table for Case I and Case II

Design parameters	Synthesized thinned array with optimum value of $d = 0.5\lambda$			Synthesized thinned array with optimum value of *d* obtained		
	Simple DE	PSO	NSGA-II	Simple DE	PSO	NSGA-II
Optimum Value of *d*	-	-	-	.5249	.4987	.4316
Side Lobe level (SLL, in db)	-15.32	-16.83	**-19.61**	-20.34	-21.03	**-21.29**
Half Power Beamwidth (HPBW, in degree)	3.8	4.0	**4.5**	3.5	3.7	**4.5**
First Null Beamwidth (FNBW, in degree)	13.45	14.21	**15**	12.69	13.98	**15**
Number of Switched Off Elements	198	206	**220**	195	205	**220**

5 Conclusion

In this article we have proposed a new technique as a multi-objective optimization framework for designing a thinned concentric planar circular antenna array of isotropic elements to generate a pencil beam in the vertical plane with reduced SLL, desired HPBW (4.5 degree) and FNBW (15 degree) and desired number of switched off elements. We have employed the *NSGA-II* to solve the multi-objective problem. The obtained results with the *NSGA-II* are quite compatible with the desired values. In this paper, the desired number of switched off elements is taken as 220 which is half of the total number of 440. On the aggregate basis our designed array is the best among them as it successfully achieves almost all the assigned design parameter values compared to its competitor algorithms like the DE and PSO. In this way, this method can also be used to design antenna with any reduced SLL while maintaining the number of switched off element to a reasonable value. This method is very effective and can be applied in practice to thin an array of other shapes. Our further work will be focused on the design of more complex practical antenna problems by using other popular MO algorithms like SNOV_IS [5], 2LB-MOPSO [4] and MOEA/D-DE [8].

References

1. Elliott, R.S.: Antenna Theory and Design, 2nd edn. John Wiley, New Jersey (2003)
2. Dessouky, M.I., Sharshar, H.A., Albagory, Y.A.: Efficient sidelobe reduction technique for small-sized concentric circular arrays. Progress in Electromagnetics Research 65, 187–200 (2006)
3. Dessouky, M.I., Sharshar, H.A., Albagory, Y.A.: Optimum normalized-Gaussian tapering window for side lobe reduction in uniform concentric circular arrays. Progress in Electromagnetics Research 69, 35–46 (2007)
4. Zhao, S.Z., Suganthan, P.N.: Two-lbests Based Multi-objective Particle Swarm Optimizer. Engineering Optimization 43(1), 1–17 (2011), doi:10.1080/03052151003686716
5. Qu, B.Y., Suganthan, P.N.: Multi-Objective Evolutionary Algorithms based on the Summation of Normalized Objectives and Diversified Selection. Information Sciences 180(17), 3170–3181 (2010)
6. Goldberg, D.E.: Genetic Algorithms in Search Optimization and Machine Learning, vol. 41. Addison-Wesley (1989)
7. Kennedy, J., Eberhart, R.C.: Particle swarm optimization. In: Proc. IEEE Conf. Neural Networks IV, Piscataway, NJ (1995)
8. Zhang, Q., Li, H.: MOEA/D: A Multiobjective Evolutionary Algorithm Based on Decomposition. IEEE Trans. Evolutionary Computation, 712–731 (2007)
9. Das, S., Suganthan, P.N.: Differential Evolution: A Survey of the State-of-the-Art. IEEE Trans. Evolutionary Computation 15(1), 4–31 (2011)
10. Storn, R., Price, K.V.: Differential evolution - A simple and efficient adaptive scheme for global optimization over continuous spaces. Technical Report TR-95-012, ICSI (1995), `http://http.icsi.berkeley.edu/~storn/litera.html`
11. Deb, K., Pratap, A., Garwal, S.A., Meyarivan, T.: A fast and elitist multi-objective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation 6(2), 182–197 (2002)

12. Pal, S., Das, S., Basak, A., Suganthan, P.N.: Synthesis of difference patterns for monopulse antennas with optimal combination of array-size and number of subarrays - A multi-objective optimization approach. Progress in Electromagnetics Research, PIER B 21, 257–280 (2010)
13. Pal, S., Qu, B.Y., Das, S., Suganthan, P.N.: Optimal Synthesis of Linear Antenna Arrays with Multi-objective Differential Evolution. Progress in Electromagnetics Research, PIER B 21, 87–111 (2010)
14. Zhou, A., Qu, B.-Y., Li, H., Zhao, S.-Z., Suganthan, P.N., Zhang, Q.: Multi-objective Evolutionary Algorithms: A Survey of the State-of-the-art. Swarm and Evolutionary Computation 1(1), 32–49 (2011)
15. Abido, M.A.: A novel multi-objective evolutionary algorithm for environmental/economic power dispatch. Electric Power Systems Research 65, 71–81 (2003)