Design Analysis of Uniformly Weighted Circular Planar Antenna Array Using Efficient Meta-heuristic Algorithm in MATLAB

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Abstract Circular planar array antenna with minimized peak side lobe levels is desired in many advanced wireless applications. In this paper, an innovative strategy is applied to the designing problem of the planar array antenna having concentric rings that are uniformly weighted with circular aperture using a human intelligence-based meta-heuristic algorithm, namely teaching–learning-based optimization. The objective of this work is to design the concentric circular array antenna with constraints like number of array elements as well as radius of each ring and then finally present an analysis of the same using different examples. Four cases with different number of rings are presented considering different constraints individually. Firstly, concentric circular array antenna with 5 and 6 rings is discussed with optimized ring radii. Secondly, with optimized number of array elements, 7 and 8 rings are taken into account. Results are superior in the example having rings in larger number. The statistical data for every design are also presented to showcase the effectiveness of the simulation approach. The result comparison of the proposed work with state of the art further confirms the effectiveness of the proposed design.

Keywords Circular planar array antenna · Teaching–learning-based optimization algorithm · Side lobe levels · Evolutionary algorithms

1 Introduction

Concentric circular array antenna (CCAA) [1] has multiple circular rings with a common centre. Each ring in CCAA has different number of array elements. Regardless of there being many different types of antenna array, CCAA has an important role to play in wireless communication [1, 2]. CCAA has numerous advantages over

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other antenna. It has insufficient edge element, thus it is less sensitive to mutual coupling. Also, the main lobe of CCAA is capable of radiating isotropically and provide 360○ azimuth scanning feature without any variation in beam pattern. It offers the radiation pattern that covers the whole space [1, 3].

In spite of its numerous advantages, it has one drawback. Though having a large directivity, they have side lobe levels with higher value which is not desirable [3, 4]. We customize CCAA in order to achieve better performance with respect to minimized value of the side lobes. To solve antenna design problem by optimizing inter-element spacing with fixed radii, optimizing using radii with fixed inter-element spacing and optimizing inter-element spacing and ring radii [6, 7]. Customizing CCAA not only targets in reduction of SLL, but also decreases the manufacturing cost and weight of antenna arrays. For these reasons, CCAA has been applied extensively to a variety of application over last 42 years [1–7].

Readers can refer to a number of synthesis techniques for planar antenna array that are available in the literature [6–20]. Hybrid approach (HA) [7], moth flame optimization (MFO) [8], genetic algorithm (GA) [9], global and local real-coded genetic algorithms [10], chaotic bee colony algorithms (CBCAs) [11], Gaussian tapering window technique [12], seeker optimization algorithm (SOA) [13], modified teaching–learning-based optimization (MTLBO) [14], QPSO [15], chaotic adaptive invasive weed optimization (CAIWO) [16, 19], and symbiotic organism search (SOS) [20] algorithm are few of the distinguished methods with notable contributions in this area.

In a nutshell, there exists a rich literature that addresses the solving of the synthesis problem of planar array antenna. However, as per the no free lunch theorem by Wolpert and Macready [21], any evolutionary/meta-heuristic algorithm is not sufficient to solve all types of the problems related to the optimization. Hence, meta-heuristics with proven performance and computational efficiency are always welcoming towards applying to some specific problem.

In this article, we propose the application of well-established evolutionary algorithm specifically teaching–learning-based optimization (TLBO) [8] in the designing analysis of the CCAA that yields optimized side lobe levels. The impact of the constraints like number of array elements in each ring and inter-ring radii is analyzed with four different examples that include 5, 6, 7 and 8 rings separately with constraints. Unlike other optimization algorithms, TLBO is a easy to use tool that has no additional tuning parameter other than the common algorithm specific free optimization parameter [8, 17] like number of runs, population size, etc. Hence, users need not to bother paying special attention for appropriate tuning of any algorithm specific control. This is not only attributed for a faster convergence rate but also simplifies the entire simulation process, thereby reducing the operational complexities. Due to its effectiveness, TLBO has been used to address optimization problems related to diverse engineering problems [8, 14, 17, 18].

The rest of our paper is structured as with the following sections. Section 2 discusses CCAA geometry with problem formulation, Sect. 3 gives the detailed discussion on the TLBO algorithm, and Sect. 4 presents the results of the simulation and their analysis. The conclusions were presented in the Sect. 5 followed by the references.

2 CCAA Geometry and Problem Formulation

Uniformly, weighted concentric circular antenna array (CCAA) yields radiation beam that is capable of covering the whole space with $360\circ$ azimuthal scanning ability. Its elements are organized in different concentric circular rings that have common-centre, different radii and unlike number of antenna array elements in each circle. They are supplied with current excitations that are of uniform value for each of the antenna elements. The CCAA array geometrical layout is shown in Fig. 1.

Considering the central array element feed, the array factor symbolized by $\mathrm{AFactor}(\theta, \emptyset, I)$ of the CCAA geometry lying on the x-y plane is expressed by (1).

$$\mathrm{AFactor}(\theta, \emptyset, I) = 1 + \sum_{m=1}^{M} \sum_{n=1}^{N_m} I_{mn} e^{j[\mathrm{kR}_m \sin\theta \cos(\emptyset - \emptyset_{mn}) + \alpha_{mn}]} \tag{1}$$

where M symbolizes total rings in the CCAA, N_m represents total array elements (isotropic in nature) in the mth ring, d_m is separation between each array element in the mth ring. $\mathrm{R}_m = N_m d_m / 2\pi$. This represents the radius of mth ring, $\emptyset_{mn}$ is angular-position of nth element of the mth ring such that$1 \leq n \leq N_m$. θ and $\emptyset$ are polar and

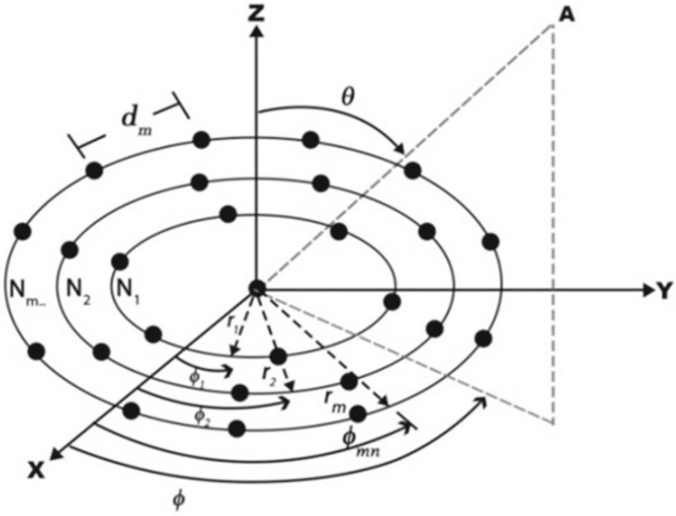


Fig.1 Concentric circular planar array geometry layout presented in the x–y plane

azimuthal angles, respectively. K gives the wave-number which equals $2\pi/\lambda$, whereas λ represents wave length in operation, j is complex number (imaginary unit). α_{mn} is phase of individual array element, and I_{mn} is current amplitude excitation of the mnth array elements of that is set to uniform but unity value. Uniform phase excitation of $0\circ$ is associated with each element.

We have designed the objective (or cost or fitness) function in such a style that the side lobe levels (SLL) get optimized applying appropriate searching of the inter-ring radii, and the number of the antenna array elements present in each concentric circle.

3 Teaching–Learning-Based Optimization (TLBO) Algorithm

TLBO [17, 20] was proposed by R. V. Rao, V. J. Savsani and D. Vakharis in 2011. TLBO is a novel optimization technique applied in diverse engineering applications. It has basically two phases such asthe teacher's phase and the learner's phase. The readers may refer papers [17] and [20] for the theoretical details and implementation steps of TLBO.

4 Simulation Results

The bundles of elements are considered as isotropic antenna. Simulation is done using four cases. In case 1 and case 2, we try to optimize the ring radii (R_{m}) using 5 and 6 concentric rings, respectively. And in case 3 and 4, we have attempted optimizing the array elements in each particular ring using 7 and 8 concentric rings, respectively. These are examples only and one is free to consider any number of rings as per choice. We have used TLBO in MATLAB for the simulation purpose. TLBO does not have any tuning parameter, it has only common parameters to design antenna array like population density number of generations [20].

As per the results obtained after simulation, TLBO yields better results than the results available in the existing literature as far as suppression of the SLL is concerned with respect to total number of array antenna elements in each concentric rings as constraints.

TLBO algorithm is implemented in MATLAB software with the help of a laptop having 8 GB RAM, i5 processor with 2.20 GHz of clock frequency.

Case 1. Optimized Ring Radii with 5 Rings

This is the first case where we used 5 concentric rings and with ring radii as the constraints. The simulations were done using 4 trials. The simulation results are shown in Table 1 from where we see that the synthesized array is very bulky in nature with a large number of array elements counting up to 492. This array will also

Table 1 Simulation results and their comparison with [7, 9]

Algorithm	Array type	N_R	N	Aperture (λ)	SLL (dB)	Std. deviation	Worst (dB)
HA [7]	Opt R_m	8	201	4.98	–29.03	–	–
TLBO (Case 1)	Opt R_m	5	492	13.4	–19.98	0.11	–19.69
TLBO (Case 2)	Opt R_m	6	147	3.86	–23.03	0.08	–22.83
GA [9]	Opt N_m	9	183	4.5	–25.58	–	–
TLBO (Case 3)	Opt N_m	7	115	3.5	–31.28	0.5	–30.05
TLBO (Case 4)	Opt N_m	8	184	4	–34.26	1.25	–31.07

be larger in size as the array aperture is as large as 13.41λ. Due to large number of array elements, there will be existence of the grating lobes. Moreover, the costing and the maintenance of such a bulky array will be difficult and thus not desirable. More importantly, the SLL in this case is found as –19.98 dB which is infact very high and against the objective of this work.

Case 2. Optimized Ring Radii with 6 Rings

In this case, also the common control parameters are same as that in case 1. The simulation results are summarized in Table 1 given which clearly indicates that the related SLL found is –23.03 dB. This result is better than the previous case (–19.98 dB). The worst value found here is–22.83 dB. That means, the worst value seen here is even better than the best value of case 1. The aperture size of the array is found to be 3.86λ which is also far better and smaller than found in case 1 (13.41λ).

Case 3. Optimized Number of Array Antenna Elements with 7 Rings

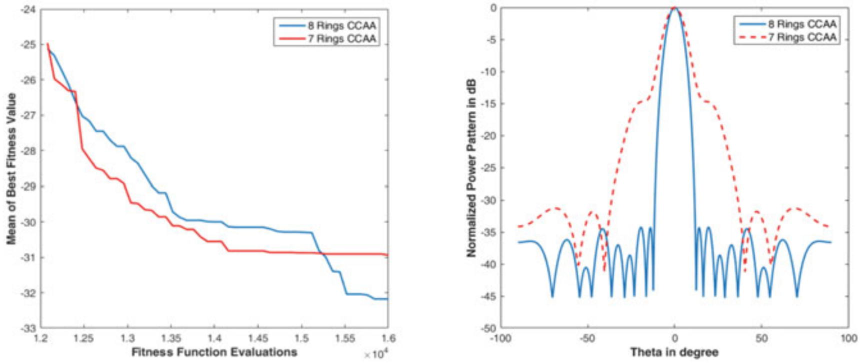
This case demonstrates the value of minimized SLL as –31.28 dB with a maximum ring-aperture size of 3.5λ. These results are showcased in Table 1 from where readers can easily see the worst value obtained in this case is –30.05 dB. As far as individual ring is concerned, it may be stated from Table 2 that the first ring contains 31 elements, second ring yields 20 elements, third, fourth, fifth and sixth rings hold 13, 15, 18 and 8 array elements, respectively. The last ring that is seventh ring yields 10 number of array elements. In other words, we can say that to obtain this design, a total number of only 115 elements were used. The standard deviation obtained from simulation results in this case is 0.50. The graph of the mean of best fitness value vs fitness function evaluations is presented in Fig. 2a. Also, Fig. 2b gives the normalized power pattern for 7 rings CCAA obtained after the MATLAB simulation.

Case 4. Optimized Number of Array Antenna Elements with 8 Rings

This is the fourth case where best results are obtained in terms of SLL. The results obtained are shown in Tables 1 and 2. The maximum minimized SLL that we found

Table 2 Distribution of array elements in each ring and inter-elemental separation

Array type	N_{total}	N	Circle number							
			Ring 1	Ring 2	Ring 3	Ring 4	Ring 5	Ring 6	Ring 7	Ring 8
Opt R_m	492	N_m	44	75	90	114	169	–	–	–
		R_m	3.50	5.96	7.15	9.07	13.4	–	–	–
Opt R_m	147	N_m	5	12	18	27	36	49	–	–
		R_m	0.36	0.92	1.42	2.12	2.89	3.86	–	–
Opt N_m	115	N_m	31	20	13	15	18	8	10	–
		R_m	0.5	1	1.5	2	2.5	3	3.5	–
Opt N_m	184	N_m	14	20	29	30	30	27	16	18
		R_m	0.5	1	1.5	2	2.5	3	3.5	4



(a) Mean of best fitness value Vs fitness function evaluation in case 3 and case 4

(b) Normalised radiation pattern obtained in case 3 and case 4

Fig. 2 Comparative performance of results obtained in case 3 and case 4

here is–34.23 dB. The optimal number of total array elements is found to be 184. The worst value obtained is –31.07 dB where as the standard deviation is 1.25. If we talk about the ring wise distribution of array elements, the first ring has the lowest number of array antenna elements (14) whereas the fourth and fifth ring have equal number of array elements (30 each) both counting to the maximum value. The second, third, sixth and seventh ring yield 20, 29, 27 and 16 array elements, respectively. The 8th ring has a total of 18 antenna elements. The array synthesis results of all cases are summarized in Table 1 whereas Table 2 presents the ring radii, total number of array elements and ring wise array element distribution. The mean of best fitness value versus fitness function evaluations is presented in Fig. 2a. Also, Fig. 2b gives the normalized power pattern.

In general, it is observed that case 4 yields best result in terms of SLL suppression which is better than case 3, case 2 and case 1 with values of 2.98 dB, 11.24 dB and 14.28 dB, respectively. However, case 3 gives lowest number of array elements (115) with lowest aperture of 3.5λ. As compared to case4, case 3 saves 69 array elements. As a result, it can be said that though case 3 and case 4 are demonstrated to achieve peak SLL with optimized antenna array elements, however, both these cases establish a trade-off between SLL versus optimal number of array elements.

In other words, if we work on the higher SLL, the number of array elements increases. And if we work on decreasing the later one in order to reduce the designing cost, the SLL is increased. Initially, in paper [7], we observed hybrid approach was used to optimize ring radii. The ring radii are optimized using HA with 8 rings having 201 elements and give –29.03 dB of peak SLL. Similarly, in paper [9], ring radii were optimized using GA with 6 rings having 201 elements and give –25 dB peak SLL. We approached with TLBO algorithm for same constraints. And, as a consequence, our optimal results obtained in both case 3 and case 4 are better. As compared to [7], case 3 and case 4 give 2.25 dB and 5.23 dB lower SLL, respectively. Similarly, as compared to [9], the SLL achieved in cases 3 and 4 are better with dB values of 5.7 and 8.68, respectively. Apart from this, this work is different from [17] as well in a way that in [17], 9 rings are considered to achieve the optimal results; however, in the present work, we have used a maximum of 8 rings only. Here, better algorithmic specific settings have yielded to preferred results. This will not only save the cost of the array but also reduce the design complexities, bulkiness and weight of the antenna system when subjected to real-time implementation. Figure 2 displays the comparative performance of results obtained in cases 3 and 4.

5 Conclusions

The MATLAB-based simulation using TLBO as an efficient meta-heuristic algorithm was successfully conducted. Four cases with different number of rings were considered in which the third and the fourth cases with total number of array elements as constraints were found to be more effective. The fourth case outperformed all other cases in terms of SLL suppression, however, case 3 obtained best results with maximum savings on the part of array antenna elements. Using the proposed approach, this work overtakes the prior arts [7, 9]. TLBO being an algorithm having no tuning parameter makes the computation easier, more simple but yet efficient. This approach may be implemented for different other array geometries.

References

1. Ballanis A (1997) Antenna theory analysis and design, 2nd edn. Willey Inc., New York
2. Sotirios K, Christos K, Mittra R (2016) Evolutionary algorithms applied to antennas and propagation: emerging trends and applications. Int J Antennas Propag 2016:1–12
3. Magill E, Wheeler H (1966) Wide-angle impedance matching of a planar array antenna by a dielectric sheet. IEEE Trans Antennas Propag 14(1):49–53

4. Hsu SH, Ren YJ, Chang K (2009) A dual-polarized planar-array antenna for s-band and x-band airborne applications. IEEE Antennas Propag Mag 51(4):70–78
5. Keizer WPMN (2007) Fast low-sidelobe synthesis for large planar array antennas utilizing successive fast fourier transforms of the array factor. IEEE Trans Antennas Propag 55(3):715–722
6. Stearns C, Stewart A (1965) An investigation of concentric ring antennas with low sidelobes. IEEE Trans Antennas Propag 3(6):856–863
7. Guo Q, Chen C, Jiang Y (2017) An effective approach for the synthesis of uniform amplitude concentric ring arrays. IEEE Antennas Wirel Propag Lett 16:2558–2561
8. Dutta KP, Mahanti GK (2020) Meta-heuristic optimization algorithms for simultaneous optimization of sidelobe level and directivity of uniformly excited concentric ring array antennas. Int J Microw Wirel Technol 12(2):183–192
9. Haupt RL (2008) Optimized element spacing for low sidelobe concentric ring arrays. IEEE Trans Antennas Propag 56(1):266–268
10. Martínez CG, Lozano M, Herrera F, Molina D, Sánchez AM (2008) Global and local real-coded genetic algorithms based on parent-centric crossover operators. Eur J Oper Res 185(3):1088–1113
11. Alatas B (2010) Chaotic bee colony algorithms for global numerical optimization. Expert Syst Appl 37:5682–5687
12. Dessouky MI, Sharshar HA, Albagory YA (2007) Optimum normalized-Gaussian tapering window for side lobe reduction in uniform concentric circular arrays. Prog Electromagnet Res 69:35–46
13. Dhali M, Sindhu C, Mandal D, Ram G, Kar R (2018) Thinned concentric circular array antenna synthesis using seeker optimization algorithm. Int Electr Eng Congress (iEECON) 2018:1–4. https://doi.org/10.1109/IEECON.2018.8712326
14. Zailei L, He X, Chen X, Luo X, Li X (2015) Synthesis of thinned concentric circular antenna arrays using modified TLBO algorithm. Int J Antennas Propag 2015:1–9
15. Dutta KP, Sundi S, Khalkho SS, Tirkey J, Hembrom KK (2020) Minimization of sidelobe level of uniformly excited concentric circular array antenna using evolutionary technique. In: Raj JS, Iliyasu AM, Bestak R, Baig ZA (eds) Innovative data communication technologies and application. Lecture notes on data engineering and communications technologies, vol 59. Springer
16. Wu H, Liu C, Xie X (2014) Pattern synthesis of planar nonuniform circular antenna arrays using a chaotic adaptive invasive weed optimization algorithm. Math Probl Eng. https://doi.org/10.1155/2014/575860
17. Dutta KP, Mahanti GK Synthesizing uniform concentric circular array antenna for minimized sidelobes using teaching–learning-based optimization algorithm. In: Hassanien AE, Bhattacharyya S, Chakrabati S, Bhattacharya A, Dutta S (eds) Emerging technologies in data mining and information security. In: Advances in intelligent systems and computing, vol 1286. Springer. https://doi.org/10.1007/978-981-15-9927-9_25
18. Chen X, Xu B, Yu K, Du W (2018) Teaching–learning-based optimization with learning enthusiasm mechanism and its application in chemical engineering. J Appl Math. https://doi.org/10.1155/2018/1806947
19. Goto N, Tsunoda Y (1977) Sidelobe reduction of circular arrays with a constant excitation amplitude. IEEE Trans Antennas Propag 25(6):896–898
20. Dutta KP, Mahanti GK (2020) Evolutionary algorithms for optimal synthesis of thinned multiple concentric circular array antenna with constraints. Int J Electron 107(10):1649–1662
21. Wolpert DH, Macready WG (1997) No free lunch theorems for optimization. IEEE Trans Evolutionary Comput 1(1):67–82