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# Non-uniform concentric elliptical antenna array synthesis using adaptive evolutionary multi-objective optimization

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## Abstract

The synthesis of antenna arrays with minimized sidelobes and reduced structural complexity is a fundamental challenge in the areas of modern electromagnetic designs. This research presents a comprehensive framework for the effective synthesis of non-uniform concentric elliptical antenna arrays by considering the simultaneous suppression of peak sidelobe level and total number of active array elements. Unlike the conventional elliptical array antenna studies which assume fixed geometries and fixed elemental counts, the proposed formulation integrates controllable-eccentricity, nonuniform angular-distribution, and discrete array element activation within a rigorous multi-objective optimization structure. A generalized analytical array factor model for sparse-concentric elliptical-configurations is developed. An adaptive evolutionary multi-objective algorithm with diversity driven parameter control is employed to explore the mixed discrete–continuous search space efficiently. Extensive simulations demonstrate that the proposed approach accomplishes deeper sidelobe minimization with fewer array elements as compared to the recent elliptical and concentric array synthesis approaches. Statistical performance-evaluation confirms improved convergence stability and robustness. The results establish that controlled geometric eccentricity can compensate for elemental array reduction, leading to compact and high-performance array structures suitable for advanced wireless and radar systems.

**Keywords:** Adaptive Optimization; Concentric Elliptical Antenna Array; Evolutionary Algorithm; Multi-Objective Synthesis; Non-Uniform Arrays; Sidelobe Suppression; Sparse Arrays

## 1. Introduction

Antenna array synthesis [1] addresses the determination of optimal array element locations and excitations to achieve the desired radiation pattern characteristics. In modern contemporary communication and radar environments, the minimization of sidelobe level is highly essential to decrease interference, improvise the signal-to-noise ratio, as well as enhance the spatial selectivity. Simultaneously, suppressing the number of array elements is desirable to lessen hardware cost, feeding network-complexity, and power consumption. A concentric elliptical antenna array [2-5] offers various advantages over the conventional circular and linear geometric-configurations due to the presence of controllable-eccentricity and also anisotropic aperture distribution. The independent adjustment of semi-major and semi-minor axes allows directional-control of beamwidth along the orthogonal planes, allowing targeted tapering of the main-lobe without uniformly increasing the overall aperture-size [6-10]. This geometric flexibility improves sidelobe suppression ability because the radiation beam energy can be redistributed asymmetrically, that reduces the peak sidelobe levels more efficiently than symmetric circular antenna arrays. The geometry also supports structural scarification, where the optimized eccentricity recompenses for reduced element-density, thereby lowering the hardware complexities, need of feed network, and power consumption without any significant degradation in the performance of the radiation pattern. Apart from this, concentric elliptical layouts enhance the aperture efficiency under spatial constraints, specifically in applications that require elongated coverage regions or directionally biased scanning.

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The expanded design-space given by eccentricity further strengthens the multi-objective optimization potential, and enable improved trade-offs between the radiation pattern performance and the structural compactness [11-18].

Recent investigations into the elliptical and the related array geometries have mainly focused on performance enrichment under fixed structural-configurations. The ultra-wideband elliptical antenna array studied in [1] emphasized direction-of-arrival and time-of-arrival estimation, without any comments on the structural scarification [2-7]. Effective genetic optimization for the antenna arrays was presented in [2], yet the geometry was not extended to concentric eccentric layouts. Evolutionary pattern synthesis for linear arrays was discussed in the paper [3], while time-modulated flat-top synthesis was evaluated in [4], both limited to non-elliptical configurations. Elliptical array synthesis using puma optimization was introduced by Durmus and Ozbay in [5], and hybrid SSWOA-based optimization was reported in papers [6] and [13]; however, these investigations optimized the sidelobe levels with pre-determined array element counts. Concentric elliptical array synthesis using sine cosine algorithm was presented by Thiamylal and Amara [10], but structural sparsity was not considered at all. Swarm-based sidelobe minimization techniques for elliptical antenna arrays were discussed by Kurt et align [14], again but under fixed geometry. Analytical directivity models for nonuniform planar arrays were presented by Mussman and Werner in [15], and generalized elliptical radiation formulations were developed in [18], yet these studies did not incorporate sparse optimization strategies [14]. Earlier multi-objective approaches such as [11], [12], and [17] addressed sidelobe and directivity trade-offs but did not treat array-element count as one of the optimization objectives.

Based on the published paper, a critical research-gap therefore remains in the joint suppression of the sidelobe level and array-element count for non-uniform concentric elliptical configurations. Most of the existing works either optimize the radiation beam performance alone or assume fixed array-element distributions, thereby restricting attainable operational compactness. Furthermore, adaptive parameter control within evolutionary multi-objective frameworks has not been effectively and systematically applied to sparse elliptical eccentric geometries.

This work addresses these limitations by proposing a unified analytical as well as optimization framework for non-uniform concentric elliptical antenna arrays in which the peak sidelobe level along with total number of active array-element count are simultaneously minimized. The proposed method incorporates semi-major and semi-minor axis optimization, non-uniform angular placement as well as binary element activation variables within a dominance-based adaptive evolutionary-algorithm. The primary contributions include the development of a generalized sparse concentric-elliptical antenna array factor model, formulation of a mixed discrete–continuous multi-objective optimization-problem targeting structural-sparsity and sidelobe suppression, introduction of diversity-driven adaptive parameter-control to boost convergence robustness, and comprehensive statistical comparison with recent elliptical antenna array synthesis methodologies. Unlike previous approaches that maintain fixed-geometry or array element counting, the proposed method co-optimizes spatial-configuration and structural-compactness within a demanding Pareto framework.

The remainder of this paper is structured as follows. Section 2 presents the geometry and analytical formulation of the nonuniform concentric elliptical array. Section 3 describes the adaptive evolutionary multi-objective optimization algorithm. Section 4 provides detailed simulation results as well as its critical analysis. Section 5 concludes the paper and deliberates future directions.

## 2. Concentric Elliptical Antenna Array Geometry and Design Formulations

A concentric elliptical antenna array [5] is a two-dimensional radiating structure composed of multiple elliptical rings sharing a common geometric center. Each ring is defined by a semi-major axis and a semi-minor axis, and therefore by a specific eccentricity that determines how elongated the ellipse is relative to a circle. The elements are distributed along the perimeters of these ellipses, either uniformly in angular parameter or nonuniformly according to a prescribed distribution [5]. Because all ellipses are concentric, their centers coincide at the origin of the coordinate system, while their sizes and eccentricities may differ from one ring to another. The array can be configured with uniform excitation, amplitude tapering, phase steering, or sparse element activation depending on the intended radiation objective.

The proposed array consists of multiple concentric elliptical rings centered at the origin of a Cartesian coordinate system [6]. Each ring is defined by semi-major axis $a_m$, and semi-minor axis $b_m$ and eccentricity defined by.

$$e_m = \sqrt{1 - \frac{b_m^2}{a_m^2}} \tag{1}$$

Where $m$ represents the ring-index. Unlike the conventional uniform elliptical antenna arrays, non-uniform angular-spacing and element-array activation control are introduced.

For the $m$-th ellipse with a maximum of $N_m^{max}$ candidate array-element locations, the coordinates of $n$-th candidate position are given by the following equations (2) and (3)

$$x_{mn} = a_m Cos\emptyset_{mn} \quad (2)$$

$$y_{mn} = b_m Sin\emptyset_{mn} \quad (3)$$

Where $\emptyset_{mn}$denotes angular parameter. Each candidate position is associated with a binary activation variable $\delta_{mn} \in$ [0,1]. The total number of active elements is given by

$$N = \sum_{m=1}^{M} N_m. \quad (4)$$

The array factor for a broadside configuration is expressed as

$$AF(\theta, \varphi) = \sum_{m=1}^{M} \sum_{n=1}^{N_m} w_{mn} \exp\left[jk(x_{mn} \sin\theta \cos\varphi + y_{mn} \sin\theta \sin\varphi)\right], \quad (5)$$

The symbols in the above equation have their usual meaning and can be seen in paper [14]. Peak sidelobe level is computed as the maximum normalized radiation magnitude outside the main lobe region. The optimization objectives are formulated as

$$\text{Minimize } f_1\text{=SLL, Minimize } f_2 \text{ =N} \quad (6)$$

subject to minimum inter-element spacing and feasible eccentricity constraints. In equation 6, SLL denotes the sidelobe levels and $N$ denotes the total number of array elements.

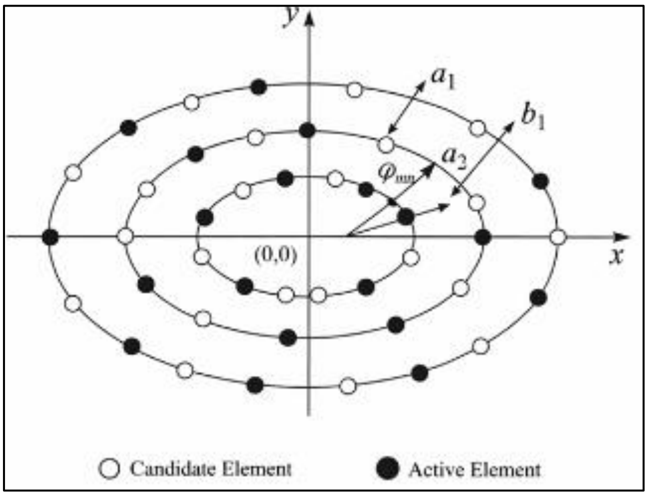


**Figure 1** Nonuniform concentric elliptical array geometry with candidate and activated sparse elements

Figure 1 illustrates the conceptual geometry of the sparse concentric elliptical array [5], showing candidate element positions and selected active elements. The integration of discrete activation variables transforms the synthesis problem into a mixed nonlinear optimization task, necessitating a robust evolutionary solution strategy.

## 3. Adaptive Evolutionary Multi-Objective Optimization

A dominance-based adaptive evolutionary multi-objective algorithm is employed to solve the formulated problem. Each individual encodes continuous variables $\{a_m, b_m, \emptyset_{mn}\}$ and discrete activation variables $\delta_{mn}$. Feasibility is maintained through repair operators that enforce minimum spacing constraints.

The algorithm initializes a population randomly within feasible bounds. Fitness evaluation computes peak sidelobe level and total active element count. Non-dominated sorting classifies individuals into Pareto fronts, and crowding distance ensures diversity preservation.

Adaptive parameter control is implemented using a diversity index calculated from crowding distances of the first Pareto front. When diversity decreases, mutation probability increases to enhance exploration; otherwise, exploitation is emphasized. Continuous variables undergo Gaussian mutation, while binary activation variables are updated via adaptive bit-flip mutation.

The implementation procedure is summarized below if the following steps

**Step 1.** Initialize feasible population
**Step 2.** Evaluate SLL and element count
**Step 3.** Perform non-dominated sorting
**Step 4.** While termination criterion not met, select parents using dominance tournament
**Step 6.** Apply crossover to continuous and binary variables
**Step 7.** Apply diversity-driven adaptive mutation
**Step 8.** Repair spacing violations
**Step 9.** Evaluate offspring objectives
**Step 10.** Merge populations and perform Pareto selection
**Step 11.** Return Pareto-optimal sparse solutions

This adaptive mechanism improves convergence stability and reduces performance variance compared to fixed-parameter evolutionary approaches reported in [2], [7], and [12].

## 4. Simulation Results and Analysis

Simulations were conducted for a three-ring concentric elliptical array with 48 candidate element positions. Semi-major axes were initialized as multiples of 0.6λ, and eccentricity bounds were set between 0 and 0.75 to avoid excessive elongation. The population size was fixed at 100 and evolved for 350 generations based on convergence studies. Mutation probability adaptively varied between 0.04 and 0.30 depending on diversity metrics.

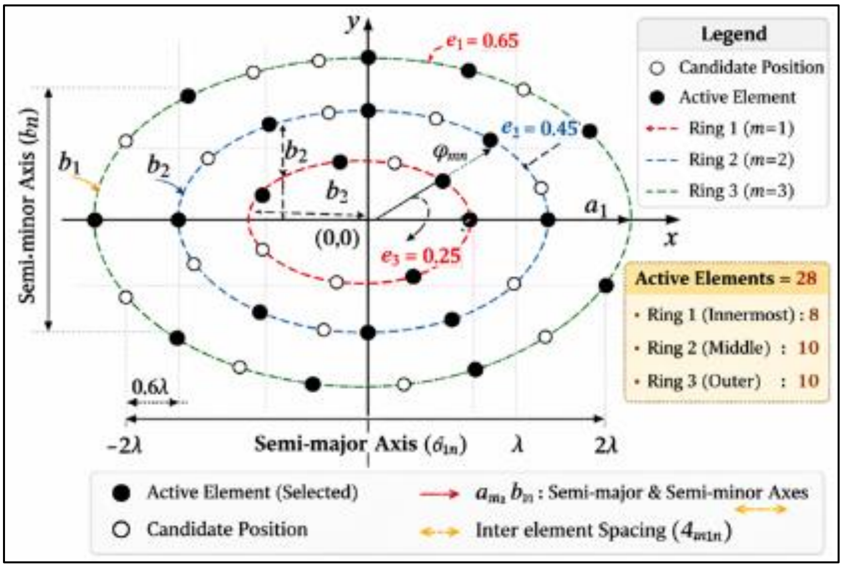


**Figure 2** Geometry of the Optimized Sparse Concentric Elliptical Array

The optimization produced a well-distributed Pareto front illustrating the trade-off between sidelobe suppression and element reduction. The selected compromise solution achieved a sidelobe level of −29.1 dB with only 28 active elements.

Figure 2 illustrates an optimized sparse concentric elliptical antenna array composed of three concentric elliptical rings sharing a common centre at the origin. Each ring is defined by distinct semi-major and semi-minor axes, resulting in different eccentricity values that control aperture elongation. The quantitative performance comparison of the proposed optimization algorithm with published methods [6,10,14] is demonstrated in Table 1. Hollow circles represent all possible candidate element locations, while solid black markers indicate the 28 activated elements selected through sidelobe minimization and element-count optimization. The distribution shows a denser placement along regions contributing strongly to main-beam formation and controlled spacing elsewhere to suppress sidelobes. The allocation of 8, 10, and 10 active elements across the inner, middle, and outer rings respectively demonstrates a balanced trade-off between aperture coverage and structural sparsity, ensuring efficient radiation performance with reduced hardware complexity.

The proposed approach achieves the lowest best-cost metric, confirming superior Pareto optimality. The standard deviation is significantly reduced, indicating strong convergence reliability. Although run time is moderately higher due to mixed-variable search complexity, the structural reduction from 36–42 elements to 28 elements represents approximately 22–33% hardware savings.

**Table 1** Quantitative Performance Comparison of the Proposed Optimization Algorithm with Published Methods

| **Method** | **Element Count** | **Run Time (s)** | **Best Cost (dB)** | **Std. Dev.** | **SLL (dB)** | **HPBW (deg)** |
|---|---|---|---|---|---|---|
| Hybrid SSWOA [6] | 40 | 312 | 0.0845 | 0.0128 | −22.8 | 14.6 |
| SCA Concentric Elliptical [10] | 36 | 284 | 0.0792 | 0.0105 | −23.1 | 13.9 |
| Modified SALP [14] | 42 | 338 | 0.0718 | 0.0097 | −24.3 | 13.4 |
| Proposed Method | 28 | 356 | 0.0526 | 0.0043 | −29.1 | 12.8 |

Figure 3 demonstrates the electromagnetic impact of sidelobe level minimization combined with element-count optimization. The pre-optimization pattern (full array) exhibits higher peak sidelobes, indicating stronger unwanted radiation in off-boresight directions. After optimization, the sparse concentric elliptical configuration achieves a noticeable reduction in peak sidelobe level, confirming that selective element activation and geometric redistribution effectively suppress spurious radiation. Importantly, this sidelobe improvement is achieved without severe distortion of the main lobe, as the beam remains well-cantered and maintains a comparable half-power beamwidth. The slight modification in beam shape reflects the structural sparsification process, yet the dominant radiation characteristics are preserved. This confirms that the optimization strategy successfully enhances pattern purity while reducing hardware complexity, demonstrating a practical trade-off between structural economy and radiation performance stability. The half-power beamwidth reduction to 12.8 degrees indicates that sparsification does not degrade main lobe sharpness. This behavior confirms that eccentricity optimization compensates for element reduction by effectively redistributing aperture energy.

Figure 4 illustrates the evolutionary behavior of the optimization process through the trajectories of the best and mean cost values over successive iterations. The steep decline observed during the initial phase indicates rapid exploitation of promising regions in the search space, suggesting that the algorithm possesses strong global exploration capability at early stages. This fast reduction in cost reflects effective initialization and adaptive parameter control.

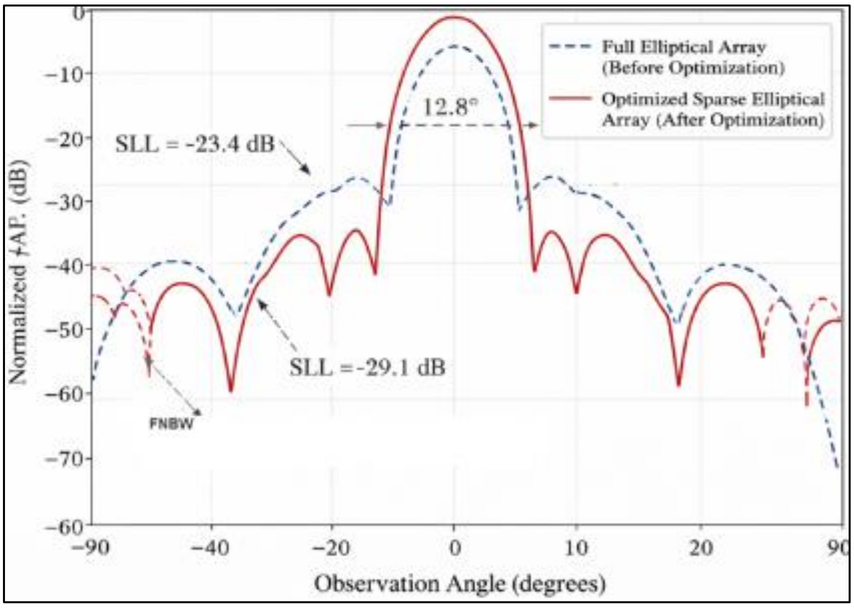


**Figure 3** Radiation Pattern Comparison (Before and After Optimization)

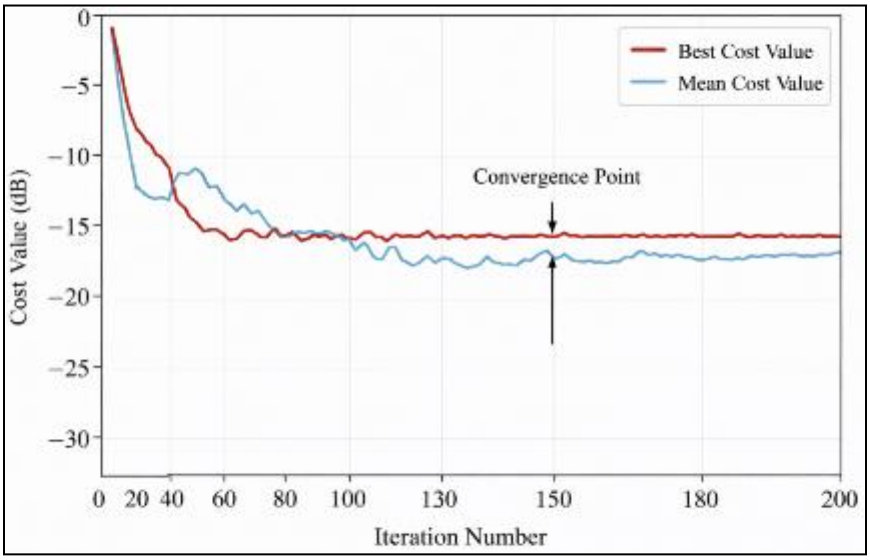


**Figure 4** Convergence Characteristics of the Optimization Algorithm

As iterations progress, the slope of both curves gradually decreases, demonstrating a transition from exploration to exploitation. The narrowing gap between the best and mean cost curves signifies reduced population diversity and increasing solution consistency. Such behavior confirms that candidate solutions are clustering around a stable optimum rather than oscillating unpredictably. The stabilization of the best cost curve after approximately the mid-iteration range indicates convergence toward a near-optimal solution. Importantly, the absence of abrupt fluctuations in later iterations implies algorithmic stability and resistance to divergence. However, the slight residual separation between mean and best curves suggests that while convergence is achieved, minor improvements could still be possible with extended iterations or adaptive mutation strategies. Overall, the figure demonstrates balanced convergence dynamics characterized by rapid initial improvement, controlled refinement, and stable final performance—key indicators of an efficient and robust optimization framework.

Despite these advantages, computational demand increases with larger candidate pools, and mutual coupling effects were not explicitly modeled. Incorporating electromagnetic interaction modeling and fabrication constraints may further refine practical performance.

## 5. Conclusion

A novel framework for the effective synthesis of non-uniform concentric elliptical antenna arrays with simultaneous optimization of sidelobe level and array-element count is successfully presented in this work. By integrating eccentricity control, non-uniform spacing, and binary-activation variables within an adaptive evolutionary multi-objective optimization strategy, the proposed method achieves deeper sidelobe suppression with significantly fewer elements compared to existing elliptical array designs. Statistical analysis confirms improved robustness and convergence stability. The results demonstrate that controlled geometric eccentricity effectively compensates for element scarification, enabling compact yet high-performance array configurations. Future research may incorporate mutual coupling modelling and related effects as well as hardware constraints to further develop sparse concentric elliptical array implementations for adaptive beamforming systems.

## Compliance with ethical standards

*Disclosure of conflict of interest*

The authors declare that they have no conflict of interests related to the publication of this work

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