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A review on Beamforming Techniques for Linear, Planar, and Circular Antenna Arrays

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Abstract

Antenna arrays play a pivotal role in modern communication systems by enabling highly directive radiation beams, beam steering, and interference reduction. They are configured in three fundamental geometries: linear, planar, and circular, each offering distinct features and advantages. This paper provides a comprehensive review of these geometries, examining their configurations, radiation patterns, and applications. It highlights how each geometry contributes to optimizing beam shaping, signal strength, and system efficiency through various optimization techniques. Additionally, the paper synthesizes recent advancements and challenges in array design, offering insights into their impact on emerging technologies such as 5G, radar systems, and satellite communications. By analyzing their performance characteristics, the study underscores the importance of antenna arrays in enhancing communication systems and addressing the demands of next-generation technologies. This review serves as a valuable resource for researchers and engineers, providing a deeper understanding of how geometric configurations influence signal quality, system efficiency, and adaptability to evolving technological needs. The findings emphasize the critical role of antenna arrays in shaping the future of wireless communication and advanced sensing systems.

Keywords: *Optimization methods, Beamforming, Linear antenna array, Planar antenna array, Circular antenna array*

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1. Introduction

In the rapidly evolving realm of wireless communication, delivering reliable and efficient signal transmission is paramount(Alkasassbeh et al., 2024). A cornerstone of this achievement lies in the ability to focus energy into highly directive radiation beams. Antenna arrays, composed of multiple radiating elements in carefully designed electrical or geometric arrangements, provide the precision needed for this task. The radiation pattern of these arrays is influenced by both their geometry and the individual behaviour of each element, enabling a versatile response to diverse communication demands. Key geometries such as linear, planar, and circular arrays each contribute unique benefits to system design and performance (Balanis, 2015). A key enabler of this technology is beamforming, which focuses the energy of the array in desired directions while suppressing unwanted signals. This enhances signal clarity and reduces interference, making beamforming an indispensable tool in modern communication systems.

Furthermore, to meet the growing demands of next-generation communication systems, optimization techniques are employed to fine-tune parameters such as side lobe levels, null placement, and beam width(Sharma, 2023). These refinements ensure that antenna arrays can deliver high performance across diverse applications and frequency ranges, solidifying their role in shaping the future of global connectivity.

2. Antenna arrays geometries

This section introduces three primary antenna array geometries: linear, planar, and circular arrays. The next subsections will thoroughly examine each geometry, detailing their unique characteristics, practical applications, and the optimization methods documented in the literature to enhance their performance.

2.1. Linear Antenna Array:

Linear antenna arrays consist of multiple antenna elements arranged in a straight line. The geometry is simple, with elements spaced evenly or unevenly along a single axis as shown in figure 1. In a linear array, the antenna elements are arranged along a straight line, either horizontally or vertically. The spacing between elements *d* is a critical parameter and is typically uniform, though non-uniform spacing can also be used for specific applications. The array can be oriented along the x-axis, y-axis, or z-axis, depending on the desired radiation pattern(Stutzman & Thiele, 2012). The radiation pattern of a linear array is typically directional in the plane perpendicular to the array axis, and the beam can be steered by adjusting the phase of the signals fed to each element. Linear arrays are widely used in applications such as broadcasting, radar systems, and wireless communication. They are particularly useful in scenarios where beam steering in one plane is sufficient.

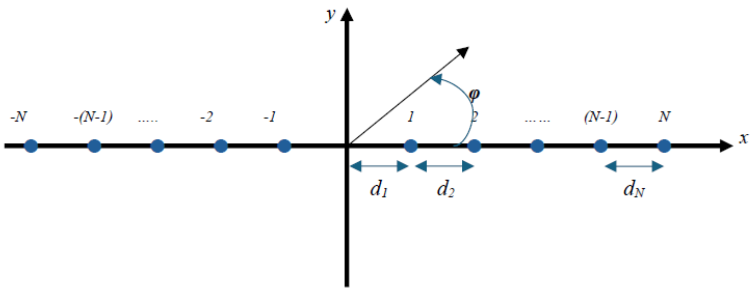

Figure 1. Structure of a symmetric linear array consisting of 2N-elements positioned along the x-axis.
Source: Researcher

In (Lakshm, Rajkamal, Prasad, & Rahman, 2016) , the Firefly Optimization Algorithm (FFA) was applied to linear antenna arrays, focusing exclusively on the amplitude excitations of individual elements to achieve specific radiation characteristics, particularly the placement of deep nulls at predetermined angles. The FFA, inspired by the behaviour of fireflies, used brightness and attraction-based movements to iteratively improve solutions, enabling precise placement of deep nulls at specified angles and significant sidelobe suppression. This approach avoided altering phase or positional parameters, making it computationally efficient. The study demonstrated the method's effectiveness in minimizing interference and preserving main lobe integrity compared to conventional techniques. Numerical results validated the robustness of the method, showcasing its ability to balance main beam directivity and sidelobe reduction. Its practical applications, especially in radar systems and communication networks, highlighted its relevance for modern antenna design, where high precision is critical.

In (You et al., 2017), an innovative synthesis method was introduced for unequally spaced linear antenna arrays using the Alternating Convex Optimization (ACO) technique, which effectively addressed the challenge of imposing minimum element spacing constraints. Unlike conventional methods such as reweighted ℓ1-norm optimization that required post-processing to enforce spacing constraints, ACO seamlessly integrated these constraints into the optimization process. The method alternated between optimizing the excitation vector and a dynamically updated weighting vector, ensuring the synthesized arrays meet both physical spacing and radiation pattern requirements. Two detailed case studies were presented: the synthesis of a focused beam pattern and a shaped beam pattern, each demonstrating the method's ability to maintain low sidelobe levels and achieve precise control over array characteristics. Comparisons with other approaches, such as element-merging techniques, underscored ACO's advantages in preventing performance degradation due to post-synthesis adjustments. Numerical results validated the method's effectiveness in generating arrays with controlled minimum spacing and optimal radiation performance, making it particularly valuable for applications in radar, satellite communications, and sonar systems. The paper highlighted the scalability of ACO for larger arrays and its potential for extension to planar and conformal antenna configurations.

In (Kaur & Banga, 2013), The Firefly Algorithm (FA) was employed and compared with other optimization methods like Taguchi's Optimization Method (TM) and Self-Adaptive Differential Evolution (SADE), with results indicating that FA provided significant improvements over existing methods. Antenna arrays were essential for improving communication processes and were used in RADAR, SONAR, and wireless communication systems. Results showed that FA significantly outperformed these methods in minimizing the maximum sidelobe level (SLL) and performing null steering by optimizing the phase of array elements. The study emphasized the importance of antenna arrays in applications like RADAR, SONAR, and wireless communication. The optimization goal was to adjust phase, position, and amplitude to achieve desired radiation patterns, focusing on reducing SLL and steering nulls. FA, inspired by the flashing behaviour of fireflies, operated by iteratively updating firefly positions based on attraction and brightness (determined by a cost function). Simulation results demonstrated FA's superior performance, achieving maximum SLL reductions of -13.07 dB for a 20-element array, -19.06 dB for a 32-element array, and -16.96 dB for a 40-element array, outperforming TM and SADE. The study highlighted the advantages of FA, including its efficiency and effectiveness in achieving optimized radiation patterns. Future work aimed to enhance the algorithm and explore additional array geometries. Key insights included the role of antenna arrays, FA principles, and its comparative advantages for SLL reduction and null steering.

In (Khodier, 2019), The Cuckoo Search (CS) algorithm was provided as an advanced optimization tool for the design and control of linear antenna arrays. Inspired by cuckoo birds' breeding behaviour, the CS algorithm excelled at solving complex, non-linear optimization problems, such as minimizing sidelobe levels, optimizing beamwidth, and placing deep nulls at specific angles. Key features included its ability to avoid local minima by discarding suboptimal solutions and generating new candidates through Lévy flights. The study explored various design scenarios where the CS algorithm simultaneously optimized amplitude, phase, and position parameters. Comparative analyses with methods like Particle Swarm Optimization and Biogeography-Based Optimization demonstrated the CS algorithm's consistent superiority in reducing sidelobe levels and achieving sharper beam patterns. Numerical examples validated its reliability and adaptability, particularly in adaptive and high-precision applications such as radar and wireless communication systems. The authors highlighted the algorithm's robustness, ease of implementation, and effectiveness, establishing it as a state-of-the-art tool for antenna array optimization.

In (Saleem, Ahmed, Rafique, & Ahmed, 2016), A meta-heuristic optimization algorithm named Particle Swarm Optimization (PSO) was used in optimizing linear antenna arrays for achieving superior performance metrics, including high directivity, minimized side-lobe levels (SLL), and precise null placement to mitigate interference. PSO, a global optimization algorithm, effectively handled the non-convex nature of the problem by optimizing three interdependent parameters: inter-element spacing, excitation amplitude, and signal phase. A custom fitness function was employed to minimize SLL and place nulls at specific angles. Results showed that arrays with 16 or more elements achieved narrower half-power beamwidths (HPBW), reduced SLL, and improved interference suppression. The study highlighted that inter-element spacing significantly affected beam shaping, while adjusting excitation amplitudes balanced power efficiency and radiation pattern control. Simultaneous optimization of phase, amplitude, and spacing outperformed independent optimization of these parameters. This comprehensive approach demonstrated the potential of PSO for designing advanced antenna arrays, making it highly suitable for applications requiring precision and efficiency, such as communication and radar systems.

In (Lakhlef, Oudira, & Dumond, 2020), an enhanced approach to antenna array optimization using the Modified Grey Wolf Optimization (MGWO) algorithm was introduced, which built upon the classical Grey Wolf Optimization (GWO) by incorporating competitive exclusion from genetic algorithms to improve selection dynamics. MGWO optimized inter-element spacing, excitation amplitude, and phase to achieve reduced sidelobe levels (SLL), improved main beam directivity, and precise null placement.
Using a Gaussian function centered at 90° to define the desired radiation pattern, MGWO effectively suppressed secondary lobes while maintaining high main lobe gain. Experimental results showed MGWO's superiority over traditional GWO and PSO algorithms in convergence speed and SLL reduction. For a 16-element array, MGWO achieved an SLL of -33.98 dB, outperforming GWO (-12.14 dB) and PSO (-29.43 dB). Simultaneous optimization of all three parameters yielded the best performance compared to optimizing individual or paired parameters. The findings emphasized MGWO's effectiveness in designing advanced antenna arrays for noise-free wireless communication and its adaptability to complex optimization scenarios, making it a robust tool for multi-parameter antenna design challenges.

2.2. Planar Antenna Array:

Planar antenna arrays are two-dimensional arrays where antenna elements are arranged in a flat plane, often in a rectangular or hexagonal grid. The elements are spaced uniformly along both the x-axis and y-axis, with spacings d_x and d_y as shown in figure 2. The array can be square, rectangular, or hexagonal in shape, depending on the application. This

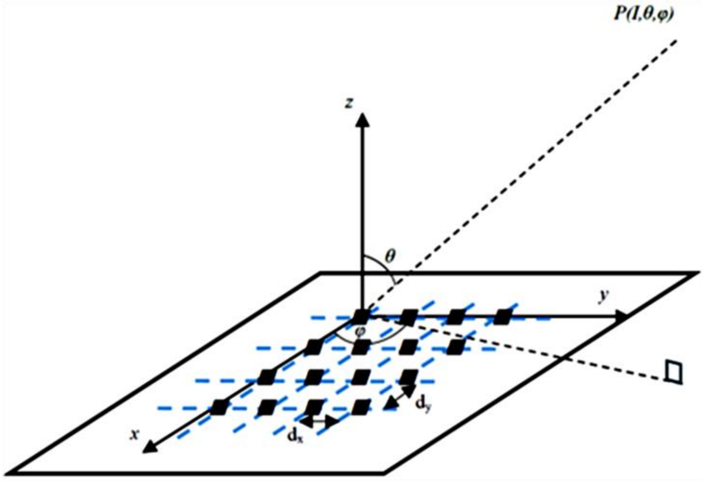

Figure 2. Geometry M × N-elements of a planar array positioned along the x-axis and y- axis.
Source: Researcher

geometry allows for beam steering in both azimuth and elevation planes, providing more flexibility in controlling the radiation pattern. Planar arrays are commonly used in advanced radar systems, satellite communication, and MIMO systems for wireless networks. Their ability to form narrow beams and nulls in specific directions make them ideal for applications requiring high spatial resolution and interference mitigation(Mailloux, 2017).

In (Petrella et al., 2006), A comprehensive study on planar array synthesis was introduced, focusing on achieving minimal sidelobe levels (SLL) while ensuring precise null control for effective interference mitigation using particle swarm optimization. The authors developed an advanced convex optimization framework capable of handling both uniform and non-uniform array designs, accommodating constraints such as limited array size, specific null placement, and stringent sidelobe suppression requirements. The proposed method employed sophisticated tapering techniques and refined array factor manipulations, ensuring main lobe integrity and achieving substantial sidelobe reduction. The framework's versatility allowed designers to customize radiation patterns for specific applications, including interference suppression in densely populated electromagnetic environments. Extensive numerical simulations validated the approach, highlighting its superiority over traditional methods by demonstrating robust SLL suppression and highly accurate null control. These findings underscored the optimization method's relevance for critical applications in radar, satellite communications, and advanced wireless networks. The ability to manage sidelobes and interference effectively enhanced the reliability and overall performance of systems operating in challenging electromagnetic conditions, marking this work as a significant contribution to the field of antenna array synthesis.

In (Rocca & Morabito, 2015), A novel synthesis method was proposed for reconfigurable planar antenna arrays tailored to monopulse radar applications, which demanded precise sum and difference radiation patterns for accurate target tracking. The authors introduced a convex programming (CP) approach to maximize radiation performance under arbitrary sidelobe constraints while minimizing computational complexity. By leveraging centrosymmetric array layouts, the synthesis problem was reformulated into a linear programming (LP) framework, enabling the efficient design of large-scale planar arrays. The method innovatively addressed the complexity of beamforming networks (BFNs) by introducing shared excitation amplitudes between sum and difference modes, reducing hardware requirements and overall system costs. Numerical results demonstrated the method's versatility, providing precise optimization of azimuth and elevation angle estimations while maintaining high computational efficiency. The study further explored hybrid architectures with shared subarrays, offering a balance between design simplicity and performance. These advancements enabled the creation of high-resolution, narrow-beam antennas suitable for applications in satellite communications, radar systems, and biomedical imaging. This comprehensive approach not only improved the design and functionality of planar arrays but also established a foundation for future innovations in reconfigurable antenna systems, addressing critical challenges in cost, scalability, and performance.

In (Mukherjee, Mandal, & Ghatak, 2018), An innovative technique was proposed using the Sierpinski Carpet fractal pattern to improve directivity and reduce sideband radiation (SBR) in time-modulated planar arrays (TMPA) while maintaining low sidelobe levels (SLL). The fractal geometry created subarrays with unmodulated elements, reducing the number of RF switches required and simplifying the design of large antenna arrays. Differential Evolution (DE) was used to optimize the on-time durations of switches, resulting in patterns with low SLL, reduced SBR, and increased directivity. The approach addressed the challenges of traditional TMPAs, such as high SLL and the complexity of controlling numerous switches in large arrays. The Sierpinski Carpet pattern minimized circuit complexity while maintaining performance, leveraging its recursive structure to simplify implementation. Simulation results confirmed that the fractal-based TMPA achieved superior performance, including lower SLL, reduced SBR, and enhanced directivity compared to conventional TMPAs. The study concluded that integrating fractal geometry with TMPAs improved performance and simplified design, making it suitable for radar and satellite communication applications. Future research aimed to explore alternative fractal patterns and further optimize circuit design.

In (Shen et al., 2019), The Improved Chicken Swarm Optimization (ICSO) algorithm was used, an advancement over traditional Chicken Swarm Optimization (CSO), focused on reducing sidelobe levels (SLL) in planar antenna arrays (PAAs) to improve wireless power transmission (WPT) efficiency, critical for applications like RF-based energy transfer, solar satellites, and mobile charging. ICSO enhanced solution updates with attraction-based movements, adaptive hierarchical modeling, and duplicate solution removal, improving exploration and exploitation of the solution space. ICSO achieved highly focused energy beams with reduced sidelobe interference while maintaining narrow mainlobes for efficient power delivery. The optimization process balanced sidelobe suppression and mainlobe beamwidth to maximize energy concentration. Simulations and electromagnetic validations showed ICSO's superiority over classical methods like Chebyshev and other evolutionary algorithms like Particle Swarm Optimization (PSO). The results highlighted ICSO's effectiveness in optimizing energy distribution for large-scale antenna arrays, making it ideal for both space and terrestrial WPT systems. The paper positioned ICSO as a leading solution for addressing WPT system challenges, including scalability, dynamic beam adjustment, and energy efficiency.

In (Tsai et al., 2022), A 60 GHz rhombic patch array antenna was designed for high-throughput wireless communication systems, combining high gain, low sidelobe levels (SLL), and a compact size. The innovative rhombic configuration used a unique patch-to-patch ratio to achieve equivalent taper excitation, eliminating the need to resize individual patches or feed lines. The antenna featured a slot-coupled substrate-integrated waveguide (SIW) center-fed structure, which reduced insertion loss and simplified the feed network design. The antenna incorporated a -25 dB Dolph-Chebyshev SIW eight-way feed network to suppress H-plane SLL, ensuring uniform power distribution and phase alignment. The measured performance achieved a gain of 18.2 dBi, with E-plane and H-plane SLLs below -20 dB and -25 dB, respectively. Compared to a reference 8×10 array, the rhombic array offered equivalent gain while reducing the array area by 23% and improving SLL characteristics. An array factor-based analytical formula was also developed to predict radiation patterns and optimize the design. Simulation and experimental results confirmed the antenna's excellent performance, making it suitable for next-generation millimeter-wave communication standards like IEEE 802.11ad/WiGig and 802.11ay. Its scalability and efficient interference suppression made it a promising solution for future wireless networks.

In (Schmalenberg, Dede, Nomura, & Nishiwaki, 2022), A gradient-based nonlinear programming approach was proposed to optimize the placement of elements in a two-dimensional (2-D) array, aiming to minimize sidelobe power for typical automotive beam steering angles. The study aimed to achieve a wide-angle azimuth field-of-view (FOV) with high angular resolution while maintaining cost-effective implementation. It introduced a novel extension of the uv-projection plane beyond the unit circle to improve optimization efficiency. The optimized design increased the azimuth scanning FOV by 11° (±54° range) compared to a baseline 24-element triangular grid array. Three-dimensional electromagnetic simulations validated the array's performance, enhancing radar capabilities for vehicular object detection, which was critical for autonomous driving systems. The paper highlighted the need for 2-D arrays in vehicular radar, as traditional linear arrays were insufficient for elevation target bearing. The proposed method enabled sparse arrays with irregular element placement, reducing sidelobe power and avoiding grating lobes. The optimization was designed to minimize sidelobe power while adhering to array size and element position constraints. Simulation results showed significant improvements in azimuth scanning and sidelobe suppression.

In (Ghattas, Ghuniem, Abdelsalam, & Magdy, 2023), A novel two-dimensional (2D) optimization method was proposed using the Improved Grey Wolf Optimization (I-GWO) algorithm. It delved into the optimization of beamforming for planar antenna arrays (PAAs), focusing on minimizing the peak sidelobe level (PSLL) to improve overall system performance in advanced wireless communications. This approach simultaneously adjusted the amplitude excitations and spatial positions of the antenna elements, enabling precise control over the radiation pattern. The performance of I-GWO was benchmarked against a range of well-known metaheuristic algorithms, including Particle Swarm Optimization (PSO), Gravitational Search Algorithm (GSA), Hybrid PSO-GSA (PSOGSA), Slime Mould Algorithm (SMA), Runge Kutta Optimizer (RUN), and the original Grey Wolf Optimizer (GWO). I-GWO consistently outperformed these methods by achieving significantly lower PSLLs with fewer array elements, effectively reducing hardware costs and system complexity. This made I-GWO particularly suitable for next-generation communication systems like 5G and 6G, which required high directivity and minimal interference for reliable high-speed data transmission. The paper further validated the proposed optimization framework through extensive electromagnetic simulations, demonstrating its adaptability across various array geometries, including linear and circular configurations. These results positioned I-GWO as a robust and scalable solution for designing cost-effective and high-performance antenna arrays in diverse wireless network applications.

2.3. Circular Antenna Array:

Circular antenna arrays consist of antenna elements arranged in a circular or ring-shaped geometry. In a circular array, the antenna elements are arranged in a circular or ring-shaped configuration. The elements are typically spaced uniformly around the circumference of the circle, with the radius ***r*** determining the size of the array as shown in figure 3. The angular spacing between elements is $\boldsymbol{d} = 2\pi / N$, where ***N*** is the number of elements. This configuration provides omnidirectional coverage with the ability to steer the beam in any direction within the plane of the circle (Hansen, 2009). Circular arrays are particularly useful in applications requiring 360-degree coverage, such as direction finding, radio direction finding (RDF), and certain types of radar systems. The symmetry of the circular array allows for uniform performance in all directions, making it suitable for applications where the signal source direction is unknown or variable.

(Zha, Wang, & Ren, 2008) introduced a hybrid optimization method to refine the amplitude distribution of current excitations in circular planar slot array antennas for achieving a desired 3D radiation pattern. It combined the Davidon-Fletcher-Powell (DFP) and Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithms, known for fast convergence and low computational cost. The method minimized an objective function measuring the difference between the desired and actual antenna patterns. While the DFP algorithm offered ultra-linear convergence, the BFGS algorithm enhanced stability, ensuring robust optimization. The paper detailed the mathematical formulation, including the far-zone radiation E-field and array factor calculations, and emphasized the significance of initial values for achieving global optimization. A practical example demonstrated the method's ability to produce a main lobe width of ~3 degrees and suppress sidelobes below -23 dB, resulting in a radiation pattern closely matching the desired outcome. The method offered advantages like fast convergence, numerical stability, and reduced dependency on initial values, making it suitable for applications requiring precise beam shaping and low sidelobe levels.

(Y. Zhang, Woods, Ko, Marshall, & Zhang, 2018) explored the use of a uniform circular array (UCA) to enhance wireless security through exposure region (ER)-based beamforming. The authors introduced the concept of spatial secrecy outage probability (SSOP) and derived a closed-form upper bound for it, focusing on optimizing the UCA's configuration, particularly its radius, to minimize information leakage to eavesdroppers while improving the legitimate user's signal quality. The optimization algorithm developed in this paper aimed to minimize the SSOP by adjusting the UCA's radius. This involved calculating the array factor and the channel gain vector, then iteratively adjusting the radius to find the optimal value that reduced the SSOP. The algorithm used numerical simulations to account for mutual coupling effects and ensured that the optimized radius provided enhanced security performance across various angles of the legitimate user. The results demonstrated that the proposed method significantly reduced the SSOP, making it a valuable approach for secure wireless communications.

(Sun et al., 2018) proposed a hybrid optimization method for synthesizing the radiation beam pattern of Concentric Circular Antenna Arrays (CCAAs), aiming to minimize sidelobe levels (SLL) while preserving array performance. It combined the Improved Discrete Cuckoo Search Algorithm (IDCSA) for efficient thinning of antenna elements and the

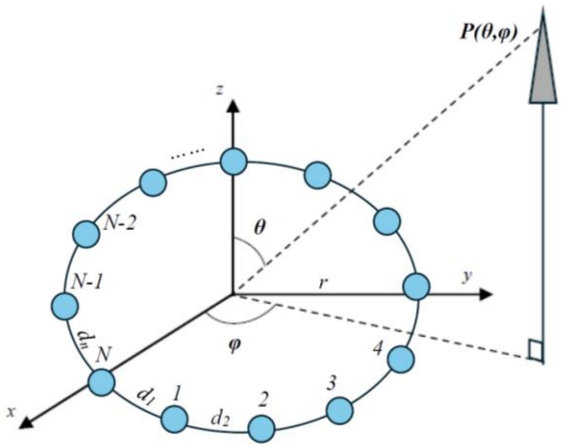

Figure 3. Structure N-elements of a circular array positioned along the x-axis and y- axis.
Source: Researcher

Cuckoo Search-Invasive Weed Algorithm (CSIWA) for refining excitation currents. The IDCSA employed advanced techniques like location coding discretization and Lévy flight-based mapping to reduce active elements by over 50%, leading to cost savings, lower energy consumption, and simpler feedback networks. The CSIWA enhanced global search and balanced exploration and exploitation using chaotic initialization and invasive weed-inspired Lévy flights. This two-step process achieved superior SLL suppression, faster convergence, and high directivity compared to traditional algorithms like Genetic Algorithm (GA) and Differential Evolution (DE). Simulations and validations confirmed its effectiveness for radar, satellite communication, and other large-scale applications requiring precise beam control.

(Liang et al., 2020) addressed the critical challenge of reducing sidelobe levels (SLL) in planar antenna arrays to improve energy efficiency and minimize interference in wireless power transmission systems. It proposed an Improved Chicken Swarm Optimization (ICSO) algorithm, which enhanced the traditional CSO by adding features like global and local search refinement, dynamic hierarchical structures, and duplicate solution removal for faster convergence and higher accuracy. ICSO optimized excitation currents and element positions, producing focused mainlobes with significantly reduced SLL. Compared to algorithms like Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), ICSO consistently achieved the lowest SLL. Simulations in both ideal and electromagnetic (EM) environments demonstrated its robustness and effectiveness for applications such as long-range wireless power transfer, solar satellite systems, and mobile device charging. ICSO proved to be an efficient, versatile, and practical tool for advancing energy beamforming in modern wireless systems.

(Alnaggar, Abd-Elnaby, & Hussein, 2021) presented a novel beamforming technique for Uniform Circular Antenna Arrays (UCAAs) that reduced the number of elements by up to 50% while preserving the original 3D radiation pattern. The approach divided the 3D pattern into 2D azimuth planes, synthesized each individually by optimizing excitation coefficients for a reduced element count, and then averaged the results to create final coefficients. This ensured a symmetrical, minimally distorted 3D radiation pattern. The technique simplified the feeding network, reduced RF chain requirements, and lowered costs while addressing challenges like mutual coupling and distortion from element reduction. Simulations in CST Microwave Studio demonstrated highly matched synthesized and original patterns, reduced sidelobe levels, and improved 3D symmetry. This method was cost-effective, computationally efficient, and ideal for wireless communication, satellite systems, and radar applications demanding low complexity and high radiation performance.

(Y.-X. Zhang, Gao, Zhang, Jiao, & Ni, 2023) presented an efficient optimization framework for designing large circular phased arrays with low sidelobe levels, optimized for beam scanning applications. Using the Differential Evolution (DE) algorithm, the method adjusted the radii and element counts in each concentric ring to minimize sidelobe levels while maintaining high gain and uniform beam coverage. A notable innovation involved rotating the array structure to align the main beam along the Z-axis, simplifying sidelobe identification by isolating it within specific ϕ cut-planes. To enhance accuracy and efficiency, the method used unequal-density random sampling, focusing finely near the main beam and coarsely elsewhere. A distributed computation framework divided radiation pattern calculations across multiple computers, reducing memory usage and computational time for large arrays. The process ensured consistent performance across beam scanning angles by targeting worst-case sidelobe conditions. Numerical experiments confirmed the framework's effectiveness in sidelobe suppression, fast optimization, and computational efficiency. The approach was well-suited for applications in radar, satellite communications, remote sensing, and biomedical imaging, where precise beam scanning with minimal sidelobe interference was critical.

3. Challenges and Future Work

The implementation of recent optimization algorithms for antenna array beamforming offers significant advantages, particularly in minimizing system complexity. Future research should focus on exploring advanced optimization techniques, such as three-dimensional (3-D) methods, to optimize sparse phased planar antenna arrays. This approach involves simultaneously refining amplitude, element positions and phase excitations using novel algorithms to achieve reduced peak side-lobe levels (PSLL). Furthermore, the adoption of diverse antenna array geometries, tailored to meet the specific requirements of various communication applications, is strongly recommended.

4. Conclusion

This paper reviewed synthesis approaches for linear, planar, and circular antenna arrays, emphasizing their applications in modern communication systems. Linear arrays, with their simplicity and precise null control, are ideal for radar and basic communication systems. Planar arrays excel in beam shaping and interference suppression, making them critical for satellite communication and 5G networks. Circular arrays, known for their symmetrical radiation and adaptability, are highly effective in omnidirectional coverage and secure communication, supporting 6G systems and advanced radar applications. The study highlighted the role of beamforming in enhancing performance by efficiently directing energy and minimizing interference, alongside optimization techniques for improving sidelobe levels, null placement, and beamwidth. These advancements enable antenna arrays to meet the demands of applications such as high-speed wireless networks, remote sensing, and next-generation radar systems. Future work should focus on integrating emerging technologies like AI-driven optimization and reconfigurable intelligent surfaces to further enhance adaptability and efficiency in these critical applications.

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