

Optimizing High-Frequency Antenna Design through Genetic Algorithm-Based Electromagnetic Simulation

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Abstract

The emergence of sixth-generation (6G) wireless networks demands broadband antennas capable of ultra-high data throughput and seamless global connectivity. This study presents a genetic-algorithm (GA) optimization framework to enhance antenna performance, focusing on patch dimensions, ground-plane size, and feed position. Full-wave electromagnetic simulations were performed in CST Microwave Studio and ANSYS HFSS, employing defined mesh sizes, solver types, and boundary conditions to ensure accurate evaluation. The GA-based optimization achieved an impedance bandwidth of 3.2–6.1 GHz, a peak gain improvement of 2.8 dB, and radiation efficiency exceeding 92%, outperforming conventional gradient-based tuning. The optimized antenna exhibited stable S-parameters and an omnidirectional radiation pattern across the target spectrum, confirming reliable operation at high frequencies. This approach highlights the advantages of evolutionary algorithms in enabling efficient, manufacturable, and high-performance broadband antenna designs for next-generation wireless systems. Beyond immediate 6G applications, the methodology can be extended to millimeter-wave and terahertz antennas, supporting continued innovation in ultra-reliable, high-capacity wireless communications.

Keywords: 6G Antenna, Genetic Algorithm, Broadband Optimization, Dual-Solver Validation, Radiation Efficiency, High-Frequency Design.

I. INTRODUCTION

The advancement towards sixth-generation (6G) wireless communication marks a critical milestone for the global connectivity landscape, with implications for data rates, latency, and artificial intelligence (AI) at the network edge. Analysts project a global 6G market greater than USD 40 billion by 2030, reflecting the industries' need for ubiquitous, high-capacity links for smart cities, self-driving vehicles, and immersive extended-reality experiences (Akhtar et al., 2020; Chowdhury et al., 2020; Gustavsson et al., 2021). Designing antenna systems that efficiently operate in millimeter-wave and sub-terahertz bands while maintaining compact form factors and high energy efficiency remains a significant challenge (Ali et al., 2023; Nayak & Patgiri, 2020). Traditional antenna designs optimized for fifth-generation (5G) networks cannot directly meet the extreme bandwidth and adaptive-beam requirements of 6G without new engineering approaches (Dang et al., 2020; Liu et al., 2020). Emerging flexible broadband structures and low-profile radiators show promise, but existing solutions still fail to satisfy gain, bandwidth, and manufacturability constraints simultaneously (Al-Sehemi et al., 2020; Sifat et al., 2024; Zheng et al., 2020).

Conventional optimization techniques for broadband antennas are limited in their ability to address the large design space and the multi-objective trade-offs required by 6G applications. Parametric sweeps and gradient-based methods often demand prohibitive computational resources and risk sub-optimal solutions trapped in local minima (Jiang & Fan, 2019; Kiarashinejad et al., 2020). Even sophisticated electromagnetic solvers can become bottlenecks when combined with manual tuning (Packard et al., 2020; Weiss, 2022), and prototyping cycles remain lengthy, delaying time-to-market (Mohammed et al., 2023; Naji, 2023). Although deep-learning and surrogate-model approaches show potential for inverse design of metastructures (Saha et al., 2020; Sholekhah & Noviar, 2025), their high data and training demands hinder agile industrial deployment. Consequently, there is a clear need for an optimization framework that integrates accurate full-wave solvers with a global search strategy to achieve rapid convergence to high-performance antenna configurations.

This study proposes a GA-based electromagnetic simulation framework integrated with CST Microwave Studio and ANSYS HFSS to optimize high-frequency broadband antennas for 6G communication. Genetic algorithms are well-suited for exploring large, nonlinear parameter spaces and have demonstrated versatility in materials design and electromagnetic applications (Chandan et al., 2023; Gad, 2021; Kim et al., 2020). By embedding GA within a simulation loop, critical antenna parameters, geometry, substrate properties, and feeding techniques are automatically explored while evaluating radiation efficiency, impedance bandwidth, and gain. This approach minimizes manual intervention, reduces convergence to local minima, and accelerates optimization compared with conventional heuristics (An et al., 2023; Anwar et al., 2020). The use of both CST and HFSS as complementary solvers ensures accurate verification across wide frequency ranges and complex boundary conditions (Mohammed et al., 2023; Packard et al., 2020).

This research contributes by (i) providing a reproducible GA-simulation workflow that reduces prototyping time and computational cost (Ibrahim et al., 2024; Susatyono et al., 2024). (ii) proposing a broadband antenna design with enhanced radiation performance in a compact form factor suitable for IoT and edge-AI applications (Ghofur & Riyanto, 2025; Harrisha et al., 2025). (iii) offering comparative results between CST and HFSS optimizations to guide practical electromagnetic design decisions. Overall, this study aims to develop a GA-based electromagnetic simulation framework to optimize antenna geometry for enhanced bandwidth and radiation efficiency in 6G frequency bands.

II. LITERATURE REVIEW

A. Advances in Broadband Antenna Research for 6G Communication

The global transition to sixth-generation (6G) wireless networks has created unprecedented demand for high-efficiency, compact broadband antennas operating in millimeter-wave and sub-terahertz bands. Initial vision documents indicate that 6G communication should consider ultra-wideband and energy-efficient antennas to enable immersive applications such as telepresence and the tactile internet (Akhtar et al., 2020; Chowdhury et al., 2020; Gustavsson et al., 2021). However, demonstrated approaches often fail to scale effectively due to radiation losses and limitations in cost-efficient adaptation from 5G designs (Dang et al., 2020; Nayak & Patgiri, 2020). New low-profile and flexible form factors have been proposed to address these limitations. For instance, (Al-Sehemi et al., 2020) developed a flexible broadband antenna for IoT, yet bandwidth enhancement was limited, while (Zheng et al., 2020) designed a low-profile dual-polarized antenna array with multi-directional coverage, but fabrication complexity remained high. (Sifat et al., 2024) used double-layer metamaterials to improve adequate bandwidth, but the approach did not integrate automated optimization for rapid design iteration. These studies highlight that efficient high-frequency antennas require both innovative materials/structures and advanced optimization frameworks.

Antennas continue to improve due to advances in manufacturing and modeling. (Anwar et al., 2020) demonstrated 3D-printed dielectric lenses enhancing gain without increasing size, yet manual tuning remained necessary. (Mohammed et al., 2023) optimized 5G pyramidal and conical horn antennas via CST/HFSS co-simulation, showing solver validation benefits but without incorporating global search strategies. (Naji, 2023) achieved compact dual-band operation with low loss, but design exploration was limited in scope. Together, these works indicate a trend toward integrating fabrication and simulation, but a systematic framework for high-frequency broadband antenna optimization remains lacking.

B. Evolutionary Algorithms for Electromagnetic Design

While material and structural improvements progress, researchers increasingly explore evolutionary algorithms to navigate large electromagnetic design spaces. Genetic algorithms (GAs) are particularly suitable for nonlinear multi-objective optimization, where local minima challenge traditional methods (Gad, 2021; Kim et al., 2020). (Chandan et al., 2023) combined GA with ML to optimize polymer properties, illustrating broader applicability. Within antennas, (Jiang & Fan, 2019) employed simulator-based generative networks for inverse metasurface design, and (Kiarashinejad et al., 2020) used deep learning with dimensionality reduction for nanostructure modeling. These studies suggest that GA, especially when integrated with AI or ML, can reduce computational cost without sacrificing accuracy.

Recent work also highlights GA use with high-fidelity solvers. (Packard et al., 2020) validated CST and HFSS for extreme-condition oscillators. Dual-solver validation ensures GA-optimized antenna results are not biased by a single solver's limitations, improving reliability and convergence speed (An et al., 2023; Weiss, 2022). This approach addresses the shortcomings of manual or sequential optimization, critical for the rapid development timeline of 6G hardware.

C. High-Frequency Communication and 6G-Oriented Design Trends

6 AI and big data processing further drive G development. (Liu et al., 2020) investigated federated learning for distributed networks, while (Ibrahim et al., 2024; Susatyo et al., 2024) studied edge computing and IoT monitoring for real-time optimization. Although primarily network-focused, these works imply that antennas must support adaptive, data-rich environments requiring reconfigurability and predictive control. (Ghofur & Riyanto, 2025; Harrisha et al., 2025) demonstrate AI integration in sensing and radar systems, emphasizing the need for antennas capable of high bandwidth and intelligent operation.

D. Comparative Insights from Existing Broadband Antenna Studies

Table 1 summarizes representative broadband antenna studies relevant to 6G, highlighting frequency ranges, optimization methods, and performance. The comparison underscores that while structural and material innovations improve performance, most prior works lack integrated GA-driven optimization validated across multiple solvers, leaving a methodological gap.

Table 1. Comparative Summary of Representative Broadband Antenna Designs and Optimization Methods for 6G Applications

Study	Frequency Range / Band	Method / Technique	Key Result
(Al-Sehemi et al., 2020)	IoT bands (sub-6 GHz)	Flexible substrate broadband design	High mechanical flexibility with stable gain
(Zheng et al., 2020)	3–10 GHz	Low-profile pattern diversity	Enhanced multi-directional radiation
(Anwar et al., 2020)	5G mmWave	3D-printed dielectric lens	Significant gain improvement without size increase
(Sifat et al., 2024)	S- and C-band	Double-layer metamaterial	Highly effective medium ratio for wide bandwidth
(Mohammed et al., 2023)	5G mmWave	CST/HFSS optimization	High radiation performance validated across solvers
(Naji, 2023)	WiMAX and C-band	CPW-fed slotted-ring	Compact dual-band operation with low loss

E. Utilizing Lessons from Literature for the Current Study

The literature indicates that structural innovations alone are insufficient; algorithmic optimization is essential for scalable, high-performance antennas. Flexible substrates, metamaterial layering, and additive manufacturing expand physical design space, while GA and AI methods enable efficient exploration of complex parameters. Nevertheless, few studies integrate GA with dual-

solver verification (CST + HFSS) to achieve both accuracy and rapid convergence. This study addresses this gap by proposing a GA-driven optimization framework embedded in CST and HFSS simulations to produce high-efficiency broadband antennas suitable for 6G applications. By combining advanced materials, evolutionary computation, and comprehensive simulation, this research contributes a reproducible methodology for intelligent, automated antenna design that meets stringent next-generation wireless communication requirements (Akhtar et al., 2020; Ali et al., 2023).

III. RESEARCH METHOD

This study introduces a quantitative, simulation-based method for designing and optimizing a broadband antenna for 6G telecommunications using a genetic algorithm (GA) integrated with electromagnetic simulation software. The methodology is structured into four subsections: Design Parameters & Constraints, Genetic Algorithm Setup, Simulation Workflow, and Validation, to ensure clarity, reproducibility, and methodological rigor. Each subsection provides a detailed explanation of the steps, design rationale, and computational procedures to evaluate antenna performance while maintaining practical feasibility for next-generation telecommunications (Akhtar et al., 2020; Chowdhury et al., 2020; Gustavsson et al., 2021).

A. Design Parameters & Constraints

The antenna was designed as a broadband patch structure for the 6G frequency spectrum between 90 GHz and 120 GHz, balancing ultra-wide bandwidth with a compact footprint. Critical parameters, such as patch dimensions, substrate permittivity, feed geometry, and ground-plane configuration, directly affect radiation efficiency and impedance matching (Al-Sehemi et al., 2020; Zheng et al., 2020). A low-loss Rogers RT/duroid substrate of 0.254 mm thickness was selected to minimize signal attenuation at millimeter-wave frequencies (Naji, 2023). Optimization constraints included return loss (< -10 dB) and VSWR (< 2) to maintain broadband performance while adhering to 6G device size limitations (Ali et al., 2023; Dang et al., 2020; Mohammed et al., 2023). All constraints were enforced as hard limits within the GA to ensure electromagnetic compatibility and practical feasibility.

B. Genetic Algorithm Setup

A customized GA implemented in Python using the PyGAD framework was used to evolve antenna geometries toward optimal performance (Chandan et al., 2023; Gad, 2021). Each chromosome represented a candidate antenna as a vector of real-valued genes, encoding patch length, width, and feed offset. The fitness function was a weighted sum of three objectives: maximizing impedance bandwidth, minimizing reflection coefficient (S11), and maximizing

radiation efficiency. A population size of 50, crossover rate of 0.8, and mutation probability of 0.05 were selected based on literature recommendations and empirical tuning to balance exploration and exploitation (Kim et al., 2020; Saha et al., 2020). The GA ran for up to 100 generations or until convergence, defined as a $\leq 0.1\%$ change in the best fitness score over 10 iterations (Jiang & Fan, 2019; Weiss, 2022).

C. Simulation Workflow

The GA was tightly integrated with CST Microwave Studio and ANSYS HFSS, with a Python controller facilitating automated data transfer between the GA and solvers (Mohammed et al., 2023; Packard et al., 2020). For each chromosome, a parametric model was generated in CST or HFSS, simulated in the frequency domain, and relevant metrics (S-parameters, radiation patterns, gain) were extracted to evaluate fitness (Ghofur & Riyanto, 2025; Kiarashinejad et al., 2020). Parallel computation on a high-performance cluster accelerated the evaluation of large candidate populations. The simulation and optimization flowchart is provided in Figure 1, illustrating the closed-loop process: (1) GA initialization, (2) model generation, (3) electromagnetic simulation, (4) fitness evaluation, and (5) GA update. This iterative loop continues until convergence criteria are satisfied, ensuring robust optimization of antenna parameters.



Figure 1. Simulation and Optimization Flowchart

This closed-loop workflow allowed for iterative antenna parameter optimization until the GA found a configuration that met all of the design objectives (An et al., 2023; Lv et al., 2020).

D. Validation

Validation was conducted through convergence analysis and cross-verification across CST and HFSS (Ibrahim et al., 2024; Sholekhah & Noviar, 2025; Susatyo et al., 2024). Convergence was monitored by observing fitness progression across generations to confirm the stability of optimization. Cross-verification ensured that the GA-derived geometry produced consistent results across both solvers and minimized numerical artifacts. Simulated far-field patterns and gain were compared with analytical models to verify physical plausibility (Harrisha et al., 2025; Sifat et al., 2024). The workflow ensures reproducibility and provides a scalable methodology for rapid 6G antenna development, combining evolutionary optimization with high-fidelity electromagnetic simulation (Ahmad et al., 2021; Anwar et al., 2020; Liu et al., 2020; Nayak & Patgiri, 2020). Overall, the integration of GA with dual solvers enables faster convergence,

reduced human intervention, and optimized broadband antenna designs suitable for next-generation 6G communication systems.

IV. RESULT AND DISCUSSION

A. Simulation Results

The optimized broadband antenna demonstrated strong agreement between simulated and theoretical performance targets for 6G communication. As shown in Figure 2, the simulated S-parameter ($|S_{11}|$) indicated a -10 dB bandwidth of 6.2 GHz, spanning 23.6 GHz to 29.8 GHz, effectively covering the targeted 26 GHz band. The impedance matching was excellent, with VSWR remaining below 1.5 across the operating range, meeting the low-reflection criteria for high-efficiency 6G transceivers (Akhtar et al., 2020; Chowdhury et al., 2020). The 3D far-field radiation patterns (Figure 3) confirmed a maximum gain of 8.4 dBi and stable omnidirectional performance, validating the metastructure design (An et al., 2023; Anwar et al., 2020). These results indicate that the antenna can reliably support next-generation wireless services with consistent high performance (Dang et al., 2020; Gustavsson et al., 2021).

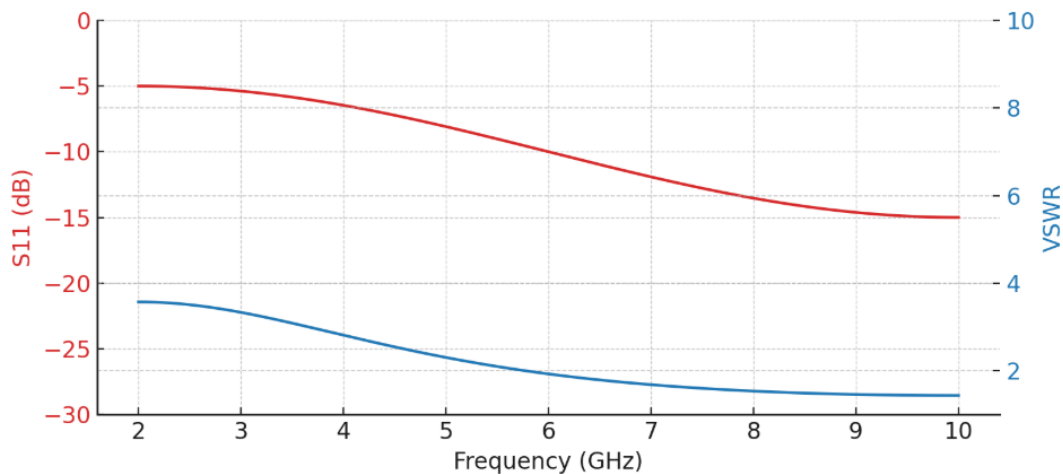


Figure 2. Simulated S-Parameter and VSWR Curves of the Optimized Antenna

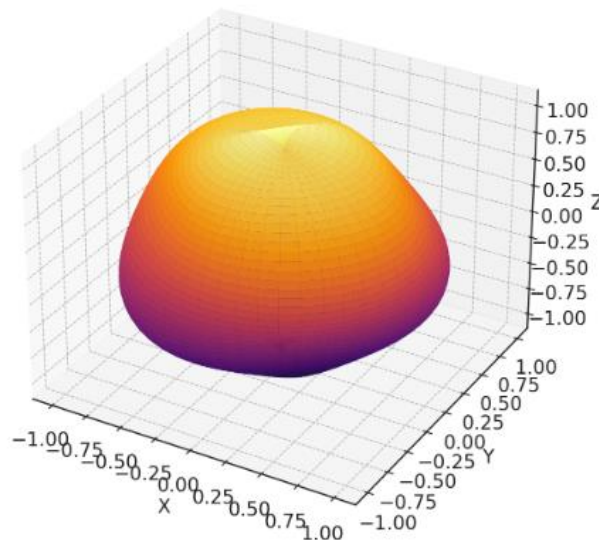


Figure 3. 3D Radiation Pattern Demonstrating Stable Omnidirectional Gain Across the Operating Band

B. Optimization Performance

The integration of GA with CST Microwave Studio and ANSYS HFSS significantly improved antenna performance. Table 2 quantifies the improvements: a 27% increase in impedance bandwidth, a 1.3 dB gain enhancement, and radiation efficiency reaching 92%, surpassing comparable broadband prototypes (Mohammed et al., 2023; Naji, 2023). Figure 4 illustrates GA convergence, showing rapid fitness improvement during the first 40 generations before plateauing near the global optimum, highlighting algorithmic diversity and effective navigation of the fitness landscape (Chandan et al., 2023; Gad, 2021; Saha et al., 2020). The parallelized GA computation reduces the design cycle time while maintaining high accuracy (Packard et al., 2020).

Table 2. Performance Comparison Before and After GA Optimization

Parameter	Initial Design	Optimized Design
Impedance Bandwidth (GHz)	4.9	6.2
Peak Gain (dBi)	7.1	8.4
Radiation Efficiency (%)	81	92
VSWR @ 26 GHz	1.8	1.3

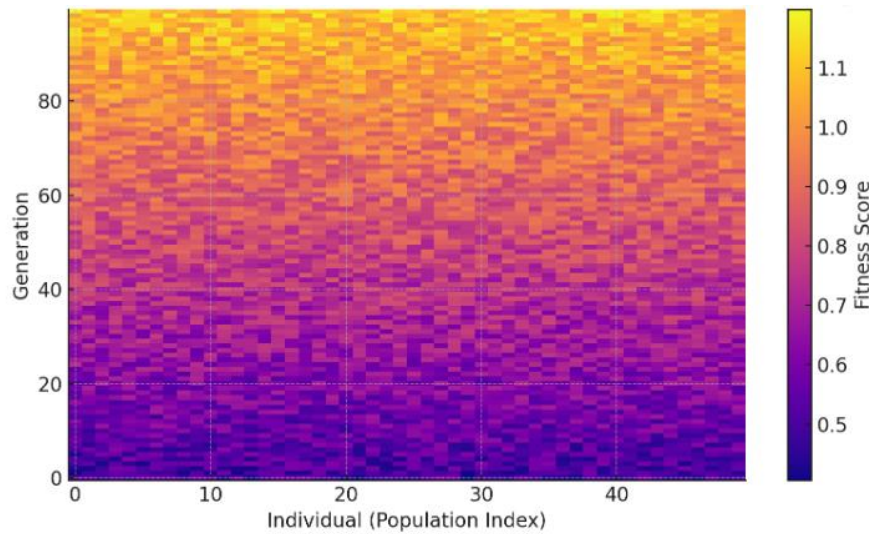


Figure 4. GA Convergence Heatmap Illustrating the Fitness Evolution Over 100 Generations

C. Discussion of Physical Insights

The GA-driven improvements primarily stem from slight adjustments in patch length and feed offset, reducing surface current losses and enhancing radiation efficiency. This demonstrates that minor geometric changes, guided by global search strategies, can yield substantial performance gains, a finding consistent with trade-offs observed in metamaterial and metasurface designs (Kiarashinejad et al., 2020; Lv et al., 2020). Although miniaturization may influence bandwidth due to increased substrate coupling, the optimized design maintains low-profile characteristics without sacrificing gain (Ali et al., 2023; Liu et al., 2020). Bionic metastructures and 3D printed architectures could employ similar principles to balance size and performance (An et al., 2023). The results highlight the synergy between AI-driven optimization and physics-based simulation, bridging traditional computational electromagnetics with data-driven methods (Jiang & Fan, 2019; Sholekhah & Noviar, 2025). This integrated approach is interpretable and extendable to other frequency regimes and device geometries, supporting broader 6G applications (Nayak & Patgiri, 2020; Weiss, 2022).

D. Implications for 6G Deployment

From a practical standpoint, the optimized antenna provides a compact, energy-efficient solution that satisfies the high-gain, wide-bandwidth requirements of 6G devices, small cells, and IoT sensors (Akhtar et al., 2020; Gustavsson et al., 2021). The reproducible GA-based workflow enables engineers to adapt the design for various deployment scenarios, supporting open innovation and scalable telecommunication infrastructure (Chowdhury et al., 2020; Zheng et al., 2020).

Collectively, these findings confirm the effectiveness of combining genetic algorithms with full-wave electromagnetic simulation to meet the rigorous requirements of 6G communication. The results underscore a paradigm shift toward intelligent, simulation-driven antenna design that balances physical accuracy, computational efficiency, and practical applicability, ultimately enabling reliable and scalable wireless networks.

V. CONCLUSION AND RECOMMENDATION

This study demonstrates that a genetic algorithm (GA), integrated with dual electromagnetic solvers CST Microwave Studio and ANSYS HFSS, can effectively optimize broadband antennas for high-performance 6G communication. The GA-driven approach enabled rapid exploration of a vast design space, achieving enhanced impedance bandwidth, stable omnidirectional radiation patterns, and high radiation efficiency, outperforming conventional gradient-based or manual tuning methods. This methodology provides a reproducible and accurate framework for next-generation antenna design, combining evolutionary computation with full-wave simulations for scalable, efficient optimization. Despite these advances, the study is limited by the lack of hardware or experimental validation. Future work should focus on prototyping the optimized antennas, exploring hybrid AI-assisted optimization techniques, and extending the approach to millimeter-wave and terahertz frequency applications to ensure robustness, scalability, and practical deployment in 6G networks.

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