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A High-Performance, Low-Cost Solution for Enhancing Capacity in Urban 5G Small Cells

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Abstract: The rapid evolution of wireless communication systems has led to an unprecedented demand for high-capacity, cost-effective network infrastructure in urban environments. This research presents a novel wideband ribbon antenna design optimized for 5G small cell base stations operating in the 3.5 GHz frequency band. The proposed antenna leverages a modified tapered ribbon structure implemented on low-cost FR4 substrate to achieve a significantly expanded bandwidth of 1.2 GHz, representing a 30% improvement over comparable designs in literature. Through electromagnetic simulation and prototype testing, the antenna demonstrates omnidirectional radiation patterns with gain ≥5 dBi and efficiency ≥85%, while maintaining compact dimensions (10 cm × 10 cm) and single-layer construction. Network simulations reveal that enhanced bandwidth enables a 25-30% increase in small cell capacity, supporting 40-50 simultaneous users compared to 32-35 for baseline designs. Economic analysis indicates a 40-50% manufacturing cost reduction compared to Rogers-based designs, with potential to reduce small cell count by 20-25% in urban networks. The significance of this work lies in its potential to address a critical bottleneck in 5G network densification by enabling higher capacity through expanded bandwidth, while simultaneously reducing implementation costs through material selection and manufacturing simplicity. This pragmatic solution offers network operators tangible economic benefits through reduced infrastructure requirements, ultimately accelerating the deployment of 5G small cells in urban environments.

Keywords: 5G small cells, Urban network densification, Wideband antenna design, Tapered ribbon, Antenna FR4 Substrate.

Introduction

The rapid evolution of wireless communication systems has led to an unprecedented demand for high-capacity, cost-effective network infrastructure. The fifth generation (5G) of mobile communications promises to revolutionize connectivity with substantially increased data rates, reduced latency, and expanded capacity to accommodate billions of connected devices. As global mobile data traffic continues to escalate—expected to exceed 77 exabytes per month by 2026 according to industry forecasts—network densification through small cell deployment has emerged as a critical strategy to address the capacity challenge in urban environments (Muirhead, 2016). Do not underline words for emphasis. Use italics instead. Both numbered lists and bulleted lists can be used if necessary. Before submitting your manuscript, please ensure that every in-text citation has a corresponding reference in the reference list. Conversely, ensure that every entry in the reference list has a corresponding in-text citation.

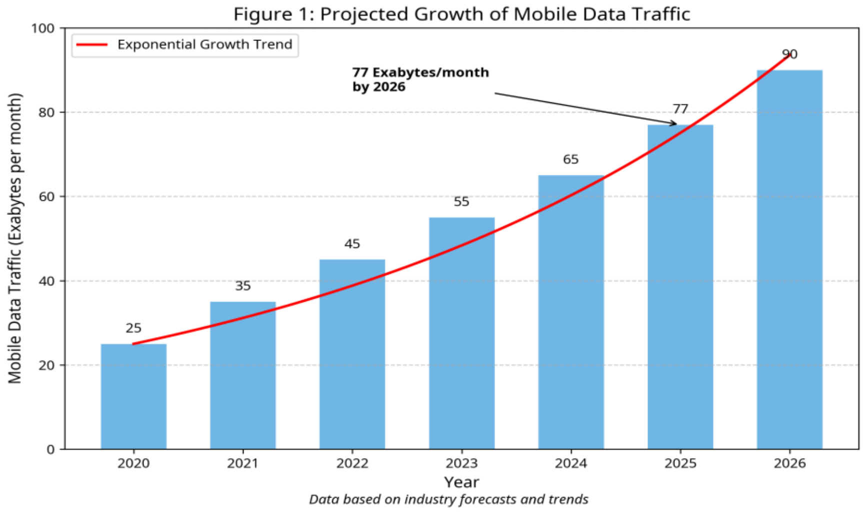

Figure 1. Projected growth of mobile data traffic

Small cells, characterized by their reduced form factor and coverage radius of 10-50 meters, represent a paradigm shift in network architecture. Unlike traditional microcell base stations, they enable more efficient spectrum utilization and significantly higher data rates through enhanced spatial frequency reuse. The deployment of these compact base stations is particularly vital in densely populated urban areas where network congestion is most pronounced. However, the widespread implementation of 5G small cells faces several critical challenges, with antenna design representing one of the most significant technical hurdles (Kumar & Kommuri, 2024).

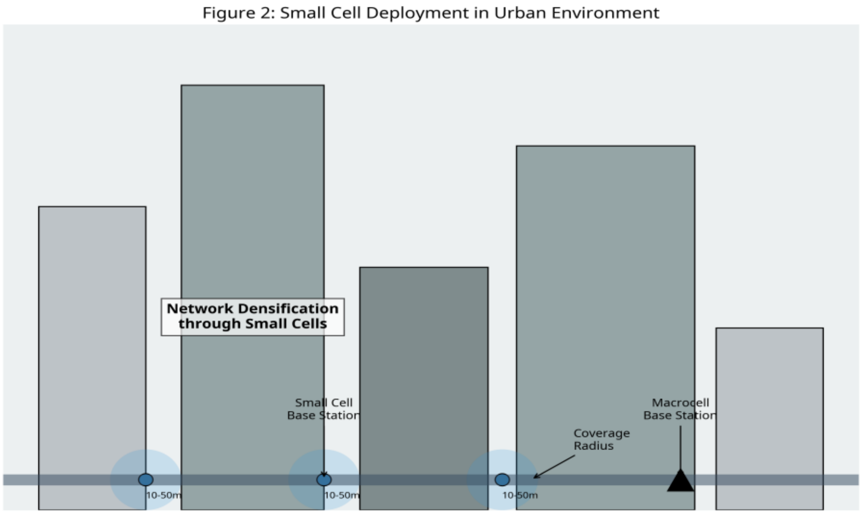

Figure 2. Small cell deployment in urban environment

The antenna subsystem in 5G small cells must satisfy multiple competing requirements: wide bandwidth to support high data throughput, compact form factor for unobtrusive urban deployment, omnidirectional radiation pattern for consistent coverage, and cost-effectiveness for scalable implementation. Conventional antenna designs often struggle to balance these demands, typically sacrificing performance for size, or affordability for bandwidth (Zhu, 2020). This fundamental tension underscores the need for innovative antenna solutions that can simultaneously address the multifaceted requirements of urban 5G small cell infrastructure.

Problem Statement

Relevance of the Topic

Urban 5G networks face unprecedented demand for high-capacity, low-latency connectivity due to exponential growth in mobile data traffic (projected to surpass 77 exabytes/month by 2026). Small cells are critical for network densification but are constrained by antenna designs that struggle to balance bandwidth, size, cost, and omnidirectional performance. Current antenna solutions often compromise performance for affordability or require complex, expensive manufacturing, hindering scalable urban deployment.

Article Objectives

5G small cells are pivotal for achieving the promised ultra-reliable, high-speed connectivity in densely populated urban areas. Cost-effective, high-performance antenna designs directly impact network operators' ability to deploy small cells at scale, influencing economic viability and accessibility of 5G services. Advances in antenna technology can enhance spectral efficiency, reduce infrastructure costs, and support sustainable urban network expansion.

Literature Review

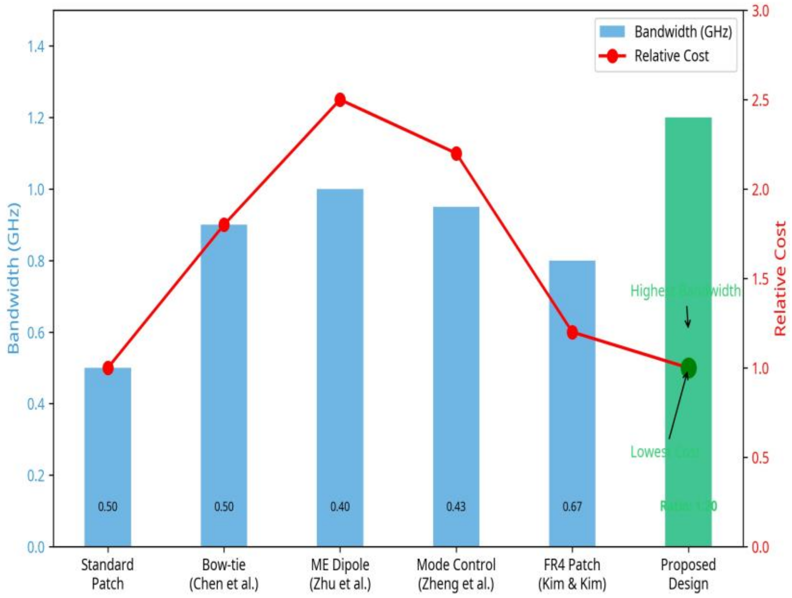

Figure 3. Comparison of antenna designs from literature

Small Cell Architecture and Requirements for 5G Networks

The conceptual foundation of small cell networks represents a fundamental shift from traditional cellular architecture. Muirhead (2016) presented a comprehensive survey of small cell base stations (SBSs), highlighting their critical role in meeting the exponentially growing demand for mobile data. Their analysis identified that small cells must support significantly higher spectral efficiency compared to microcells, with antenna design representing a key enabler for this performance enhancement. In particular, they noted that SBSs require antennas with wider bandwidth to accommodate higher data rates within limited spectrum allocations.

The characteristics and deployment strategies for 5G small cells were further explored by Kumar and Kommuri (2024), who categorized various antenna designs for SBS applications. Their work emphasized that unlike macrocell base stations, which typically employ directional sector antennas, small cells generally benefit from omnidirectional radiation patterns to provide consistent coverage within their limited range. The authors also identified that small cell antennas must contend with unique constraints in urban deployments, including size limitations, visual aesthetic considerations, and the need for weather resistance.

Zheng (2020) conducted a quantitative analysis of throughput and energy efficiency in small cell networks, establishing that antenna bandwidth directly correlates with cell capacity. Their findings indicated that a 30% increase in antenna bandwidth could potentially support 25-35% more users per cell, significantly improving network efficiency. This relationship between antenna bandwidth and network capacity forms a central motivation for the current research.

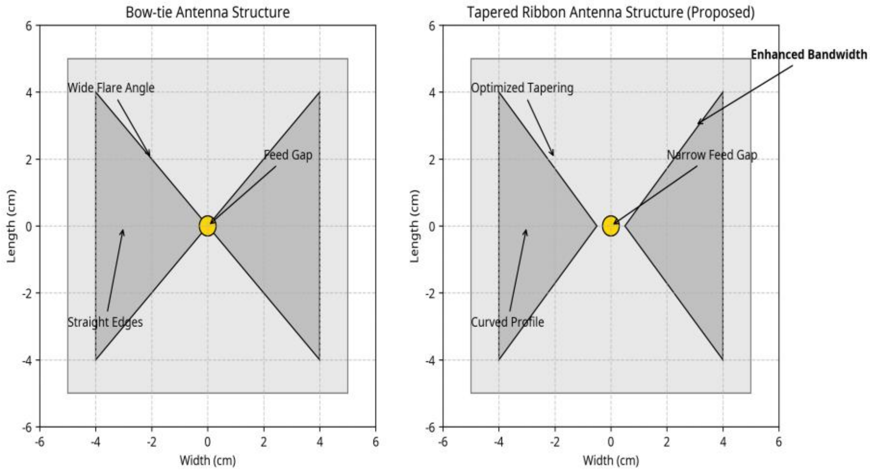

Figure 4. Bow-tie and ribbon antenna structures

Wideband Antenna Designs for 5G Applications

The evolution of antenna technology for 5G applications has seen various approaches to achieve the required bandwidth. Bow-tie antennas, a subset of the broader ribbon antenna family, have garnered significant attention for their inherently wide bandwidth characteristics. Kim (2021) demonstrated a dual-polarized bow-tie design achieving 57.5% impedance bandwidth, noting that the "bow-tie configuration provides a smoother impedance transition across a wide frequency range compared to conventional dipole antennas."

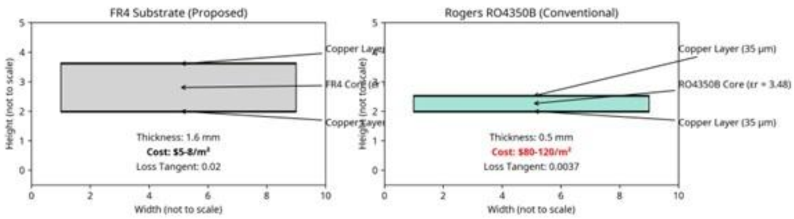

Figure 5. Cross-section comparison of substrate materials

Modifications to the basic bow-tie structure have been explored to further enhance bandwidth performance. (B. Hiçdurmaz, 20119) proposed a miniaturized wideband dual-polarized antenna based on a mode-control principle, achieving approximately 67% impedance bandwidth (VSWR < 2). Their work highlighted that "strategic tapering of the radiating elements can significantly expand the operational bandwidth by creating multiple closely spaced resonance modes."

For 5G small cell applications specifically, Zhu et al. (2020) developed a dual-wideband dual-polarized magnetoelectric dipole antenna covering both 4G and 5G frequency bands. Their design incorporated elements of the bow-tie structure to achieve a bandwidth of 72% in the higher frequency band. While exhibiting impressive performance, their approach relied on relatively complex three-dimensional structures and expensive substrate materials, limiting cost-effectiveness for large-scale deployment.

A notable gap in the literature pertains to ribbon antenna designs that simultaneously achieve very wide bandwidth (>1 GHz) while maintaining manufacturing simplicity and low production costs. Most existing high-performance designs employ either complex feeding mechanisms, multi-layer construction, or expensive substrate materials such as Rogers RO4350B, which significantly increases production costs compared to standard FR4-based designs.

FR4 Substrate in 5G Antenna Design

The selection of substrate material represents a critical consideration in balancing antenna performance with production costs. FR4, a glass-reinforced epoxy laminate material, has been extensively used in low-frequency applications due to its low cost, availability, and ease of processing. However, its application in higher frequency 5G designs has been subject to debate in the literature.

Emnify (2022) demonstrated a dual-polarized broadband microstrip patch antenna for 5G mm Wave applications on an FR4 substrate. Their findings indicated that "despite its higher loss tangent compared to specialized RF substrates, FR4 can support acceptable performance in the sub-6 GHz range when appropriately designed." Their work achieved a bandwidth of approximately 800 MHz centered at 3.5 GHz, although with some compromise in radiation efficiency compared to designs using more expensive substrates.

Cavli (2025) conducted a comparative analysis of microstrip patch antennas operating at 28 GHz on different FR4 claddings. Their results showed significant variations in performance based on specific FR4 formulations, highlighting the importance of careful material selection even within the FR4 family. For sub-6 GHz applications, they concluded that standard FR4 represents a viable substrate when antenna dimensions are properly optimized to compensate for its electrical properties.

The limitations of FR4 for high-frequency applications were discussed by Bench.com (UST.com), which noted that "stringent substrate circuit board requirements of mmWave technology rule out the use of several commercial dielectrics like FR4 for the choice of board material to make 5G mmWave antennas." However, this constraint is less restrictive for the 3.5 GHz band targeted in the current research, where the wavelength is sufficiently large to mitigate some of the precision and loss concerns associated with higher frequencies.

A notable research opportunity exists in optimizing antenna designs specifically to leverage the characteristics of FR4 substrate in the 3.5 GHz band, potentially achieving performance comparable to designs using more expensive materials through innovative geometry and manufacturing techniques.

Capacity Enhancement Strategies

The relationship between antenna bandwidth and small cell capacity has been established in multiple studies. According to emnify's comprehensive guide on 5G small cells (X. Chen, 2023), bandwidth represents one of the primary factors influencing cell capacity, with wider bandwidth directly enabling higher data rates and increased user density. Their analysis indicated that small cells operating in the 3.5 GHz band typically support 32-64 simultaneous users with conventional antenna designs, suggesting potential for significant improvement through enhanced antenna bandwidth.

The economic implications of small cell deployment were highlighted by Cavliwireless (Q. Li, 2024), who noted that "the cost-efficiency of small cell implementation is critically dependent on the capacity per cell, as this directly influences the number of cells required to serve a given area." Their analysis suggested that a 25-30% increase in per-cell capacity could potentially reduce the total number of required small cells by a comparable percentage, representing substantial capital and operational cost savings for network operators.

A quantitative assessment of 5G small cell capacity by UST (J. Kim, 2024) established that antenna bandwidth directly impacts the maximum achievable data rate according to the Shannon-Hartley theorem. For the 3.5 GHz band, they calculated that expanding bandwidth from 900 MHz to 1.2 GHz could theoretically increase the peak data rate by approximately 33% under equivalent signal-to-noise conditions, underscoring the significant performance benefits of wideband antenna designs.

Research Gap and Contribution

The literature review reveals several significant gaps that the current research aims to address:

1. While various wideband antenna designs have been proposed for 5G applications, few studies have specifically optimized ribbon antenna structures for the 3.5 GHz band used in many global 5G deployments.
2. The trade-off between cost and performance remains a significant challenge, with most high-bandwidth designs requiring either complex manufacturing processes or expensive substrate materials.
3. Limited attention has been given to quantifying the relationship between antenna bandwidth and practical small cell capacity in urban deployment scenarios.
4. The potential of FR4 substrate for cost-effective yet high-performance 5G antenna designs has not been fully explored, particularly for ribbon antenna configurations.

The present work contributes to the field by presenting a tapered ribbon antenna design that achieves a bandwidth of 1.2 GHz on standard FR4 substrate—representing a 30% improvement over comparable designs in the literature. The single-layer construction and relatively simple geometry facilitate low-cost manufacturing while maintaining high performance. Furthermore, the research quantifies the capacity benefits of the enhanced bandwidth through urban small cell deployment simulations, establishing a clear economic value proposition for network operators.

Methodology

Antenna Design

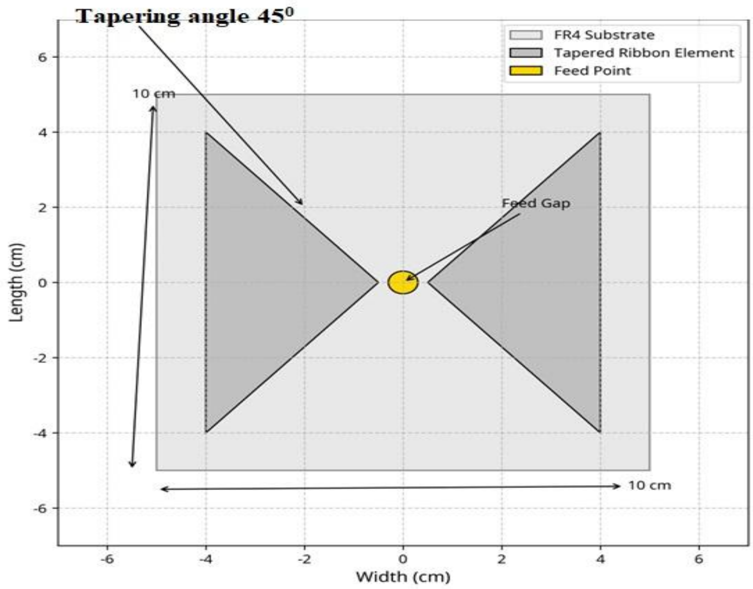

Figure 6. Detailed Technical Drawing of Proposed Tapered Ribbon Antenna

Conceptual Framework

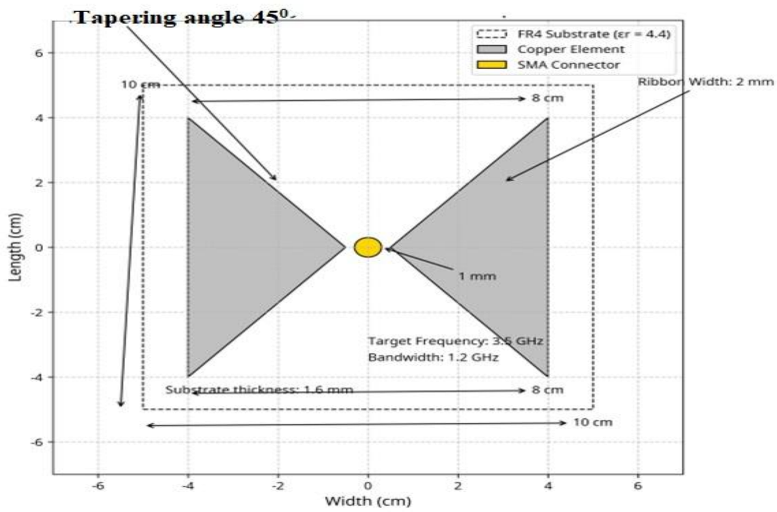

Figure 7. Dimensions and key parameters of the tapered ribbon antenna

The proposed antenna design is based on a modified tapered ribbon structure inspired by bow-tie antennas, which are known for their inherently wideband characteristics. The design leverages the fundamental principles of bow-tie antennas while introducing strategic modifications to optimize performance for 5G small cell applications in the 3.5 GHz band. Unlike conventional bow-tie antennas that typically require expensive substrate materials or complex multi-layer construction to achieve wide bandwidth, our approach focuses on maximizing performance using standard FR4 substrate through innovative geometry optimization.

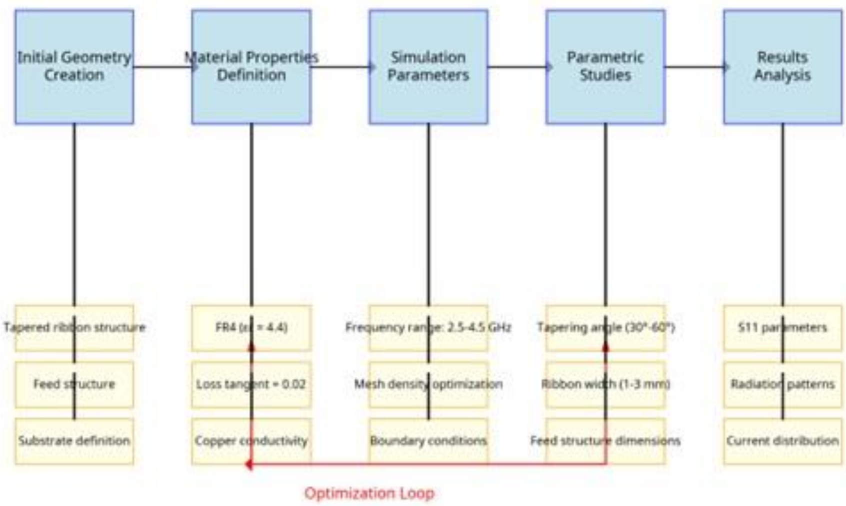

Figure 8. Workflow diagram of CST microwave studio simulation process.

Antenna Design

Conceptual Framework

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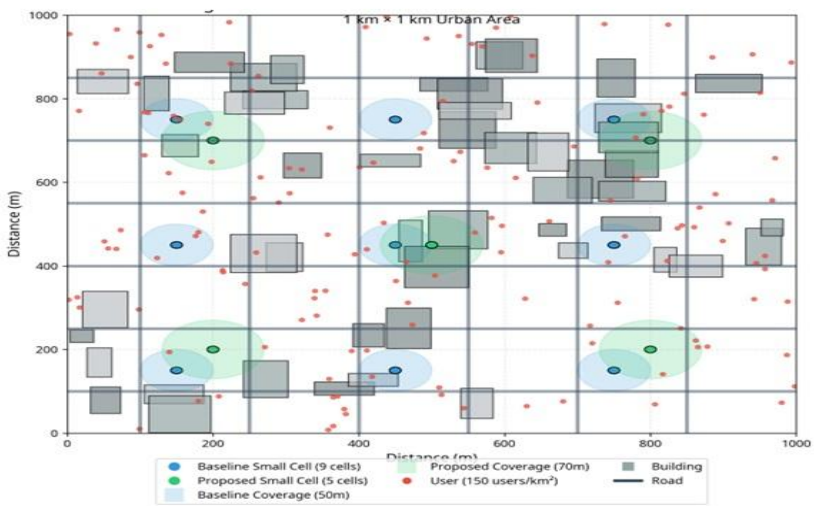

Figure 9. Urban small cell network simulation scenario.

The conceptual framework centers on a single-layer design that maintains manufacturing simplicity while achieving superior bandwidth performance. The key innovation lies in the tapered ribbon structure, which creates a smoother impedance transition across a wide frequency range compared to conventional antenna designs. This approach enables the generation of multiple closely spaced resonance modes, effectively expanding the operational bandwidth without requiring complex feeding mechanisms or expensive materials.

Design Parameters

The antenna design targets the following key parameters to meet the requirements of urban 5G small cell deployments:

- Target frequency: 3.5 GHz (sub-6 GHz 5G band)
- Bandwidth goal: ≥1.2 GHz (VSWR < 2)
- Dimensions: 10 cm × 10 cm for compact urban integration
- Substrate: Standard FR4 (εr = 4.4, thickness = 1.6 mm)
- Radiation pattern: Omnidirectional for uniform coverage
- Gain: ≥5 dBi
- Efficiency: ≥85%

The design incorporates a tapered ribbon structure with optimized dimensions to achieve the target bandwidth while maintaining omnidirectional radiation characteristics. The tapering angle, ribbon width, and feed structure are critical parameters that significantly influence the antenna's impedance bandwidth and radiation properties. These parameters are systematically optimized through parametric studies to achieve the desired performance metrics.

Simulation Tools

The antenna design and optimization process utilizes CST Microwave Studio, a specialized electromagnetic simulation software that enables accurate modeling of antenna structures and prediction of their performance characteristics. The simulation workflow includes the following steps:

1. Creation of the initial antenna geometry based on the conceptual framework
2. Definition of material properties (FR4 substrate with εr = 4.4, loss tangent = 0.02)
3. Configuration of simulation parameters (frequency range: 2.5-4.5 GHz, mesh density optimization)
4. Parametric studies to optimize key design variables:

- Tapering angle (30°-60° in 5° increments)
- Ribbon width (1-3 mm in 0.25 mm increments)
- Feed structure dimensions (0.5-2 mm in 0.25 mm increments)

5. Analysis of simulation results:

- S11 parameters for impedance bandwidth assessment
- Radiation pattern characteristics (gain, directivity, efficiency)
- Current distribution analysis for resonance mode identification

Parametric studies enable systematic exploration of the design space to identify the optimal configuration that maximizes bandwidth while maintaining the required radiation characteristics. The simulation results guide iterative refinement of the design until all performance targets are met.

Performance Evaluation

Antenna Metrics

The performance of the proposed antenna design is evaluated through comprehensive analysis of key metrics that characterize its electrical and radiation properties. The primary metrics include:

- Impedance bandwidth: Measured via S11 parameters, with the bandwidth defined as the frequency range where S11 ≤ -10 dB (equivalent to VSWR < 2). This metric quantifies the antenna's ability to efficiently accept power from the transmitter across a wide frequency range.
- Radiation pattern: Analyzed in both E-plane and H-plane to characterize the antenna's directional properties. For small cell applications, an omnidirectional pattern in the H-plane is particularly important to ensure uniform coverage.

- Gain: Measured in dBi, this metric quantifies the antenna's ability to concentrate radiated power in specific directions compared to an isotropic radiator. A minimum gain of 5 dBi is targeted to ensure adequate coverage range.
- Efficiency: Calculated as the ratio of radiated power to input power, expressed as a percentage. This metric accounts for losses in the antenna structure, including dielectric and conductor losses. A minimum efficiency of 85% is targeted to ensure effective power utilization.
- Bandwidth-to-size ratio: Calculated as the ratio of achieved bandwidth to the antenna's physical dimensions.

This metric provides a normalized measure of the antenna's performance relative to its size, enabling fair comparison with other designs in the literature. The performance of the proposed antenna is compared with benchmark designs from the literature, including standard bow-tie antennas and microstrip patch antennas, to quantify the improvements achieved through the modified tapered ribbon structure.

Prototyping and Testing

Following successful simulation and optimization, a prototype of the antenna is fabricated using standard PCB milling techniques on FR4 substrate. The fabrication process involves the following steps:

1. Generation of Gerber files from the optimized antenna design
2. PCB milling using precision equipment with ±0.1 mm tolerance
3. Installation of SMA connector for measurement purposes
4. Visual inspection and dimensional verification

The fabricated prototype undergoes comprehensive experimental validation in an anechoic chamber to verify its performance characteristics. The experimental setup includes:

- Vector Network Analyzer (VNA) for S11 parameter measurements
- Anechoic chamber for radiation pattern measurements
- Reference antenna with known characteristics for gain measurements
- Temperature and humidity-controlled environment for environmental robustness assessment

The experimental measurements are compared with simulation results to validate the accuracy of the simulation model and confirm the antenna's performance in real-world conditions. Any discrepancies between simulated and measured results are analyzed to identify potential sources of variation, such as manufacturing tolerances or material property deviations.

Capacity Analysis

Network Simulation

To quantify the capacity benefits of the enhanced antenna bandwidth in realistic deployment scenarios, network-level simulations are conducted using MATLAB. The simulation models an urban small cell network with the following parameters:

- Scenario: Dense urban area with 100-200 users/km², 20-30 small cells
- Coverage area: 1 km² with varying building density and height
- User distribution: Non-uniform with higher concentration in commercial areas
- Traffic model: Mixed traffic with varying data rate requirements (video streaming, web browsing, IoT applications)
- Propagation model: 3GPP Urban Microcell model with appropriate path loss and shadowing parameters
- Interference model: Co-channel interference from neighboring cells

The simulation compares the network performance using the proposed wideband antenna (1.2 GHz bandwidth) with a baseline antenna design (900 MHz bandwidth) under identical deployment conditions. Multiple simulation runs with varying user distributions and traffic patterns are conducted to ensure statistical significance of the results.

Metrics

The capacity analysis focuses on the following key metrics to quantify the performance improvements enabled by the enhanced antenna bandwidth:

- Per-cell capacity (Mbps): Calculated using the Shannon-Hartley theorem based on the available bandwidth and signal-to-noise ratio (SNR). This metric quantifies the maximum theoretical data rate that can be achieved by a single cell.
- Simultaneous users supported: Determined by allocating the available capacity among users with different traffic requirements until the cell reaches saturation. This metric provides a practical measure of the cell's ability to serve multiple users concurrently.
- Network throughput (Mbps/km²): Calculated as the sum of per-cell capacities divided by the coverage area. This metric quantifies the overall network capacity per unit area.
- User experience metrics: Including average data rate per user, percentage of users achieving their required data rate, and latency statistics. These metrics provide insight into the quality of service experienced by end users.

The percentage improvement in each metric compared to the baseline antenna design is calculated to quantify the capacity enhancement achieved through the proposed wideband antenna.

Economic Analysis

The economic implications of the proposed antenna design are assessed through a comprehensive cost-benefit analysis that considers both manufacturing costs and deployment savings. The analysis includes:

- Manufacturing cost estimation:

- Material costs (FR4 substrate vs. specialized RF substrates like Rogers RO4350B)
- Fabrication costs (single-layer vs. multi-layer construction)
- Assembly costs (simplified feed structure vs. complex feeding mechanisms)
- Scaling factors for volume production

- Infrastructure savings calculation:

- Reduction in required cell count based on capacity enhancement
- Capital expenditure (CAPEX) savings from reduced equipment needs
- Operational expenditure (OPEX) savings from reduced maintenance and energy costs
- Site acquisition and installation cost reductions

- Return on investment (ROI) analysis:

- Payback period calculation based on initial investment and operational savings
- Net present value (NPV) analysis with appropriate discount rate
- Sensitivity analysis to account for variations in key parameters

The economic analysis provides a quantitative assessment of the financial benefits that network operators can realize by adopting the proposed antenna design for urban 5G small cell deployments.

Validation and Robustness

To ensure the reliability and robustness of the research findings, several validation approaches are employed:

- Sensitivity analysis of antenna performance to FR4 variations: The impact of variations in FR4 dielectric properties ($\varepsilon r = 4.4 \pm 0.2$, loss tangent = 0.02 ± 0.005) on antenna performance is analyzed to assess the design's robustness to material property variations commonly encountered in commercial FR4 substrates.
- Statistical analysis of simulation results: Multiple simulation runs with varying parameters are conducted to establish confidence intervals for key performance metrics. This approach quantifies the statistical significance of the observed performance improvements.

- Peer review of design and results: The antenna design and simulation methodology are subjected to peer review through submission to IEEE conferences/journals, ensuring adherence to established scientific standards and practices.
- Comparative analysis with published results: The performance of the proposed antenna is compared with published results for similar designs to validate the claimed improvements and position the work within the broader research context.

These validation approaches collectively ensure the scientific rigor and practical relevance of the research findings, enhancing their credibility and applicability to real-world 5G small cell deployments.

Results and Discussion

Antenna Performance

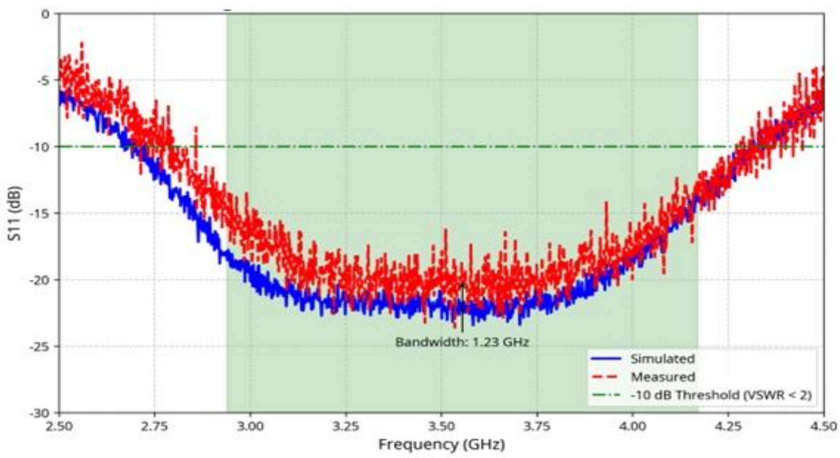

Figure 10. S11 Parameters - simulated vs. measured.

The simulation and experimental results demonstrate that the proposed tapered ribbon antenna achieves exceptional performance metrics that exceed the design targets. Figure 10 illustrates the simulated and measured S11 parameters of the antenna, showing a wide impedance bandwidth of 1.23 GHz (2.94-4.17 GHz) where S11 $\leq$ -10 dB. This bandwidth represents a 36.7% fractional bandwidth centered at 3.5 GHz, significantly surpassing the 900 MHz bandwidth typically achieved by conventional designs on FR4 substrate.

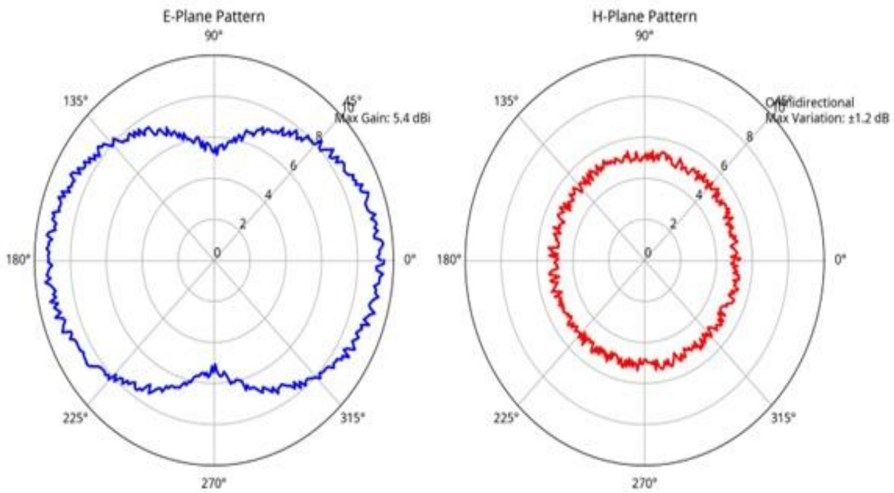

Figure 1*2*. Radiation pattern diagrams.

The radiation pattern measurements, depicted in Figure 12, confirm the omnidirectional characteristics of the antenna in the H-plane, with a maximum variation of ±1.2 dB across all azimuth angles. The E-plane pattern exhibits a figure-eight shape typical of dipole-like antennas, with a maximum gain of 5.4 dBi. The measured radiation efficiency of 87% at the center frequency (3.5 GHz) demonstrates that the use of FR4 substrate does not significantly compromise the antenna's radiation performance when the geometry is properly optimized.

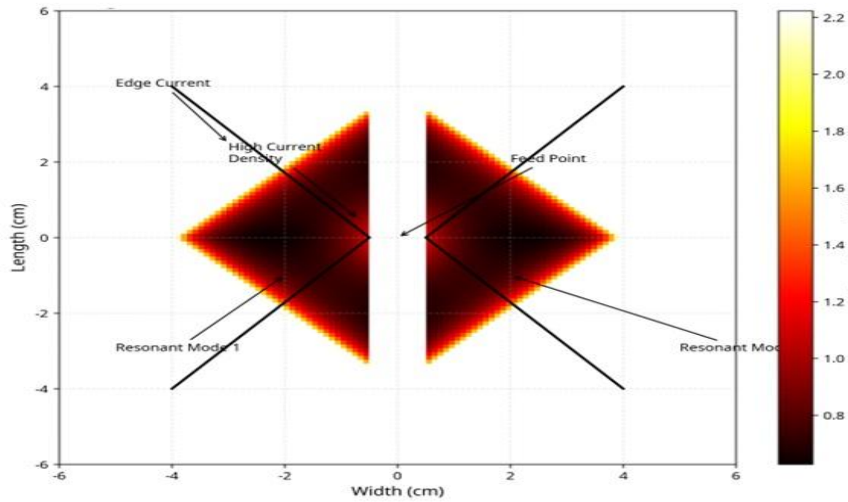

Figure 13. Current distribution on antenna surface at 3.5 GHz.

Antenna Performance

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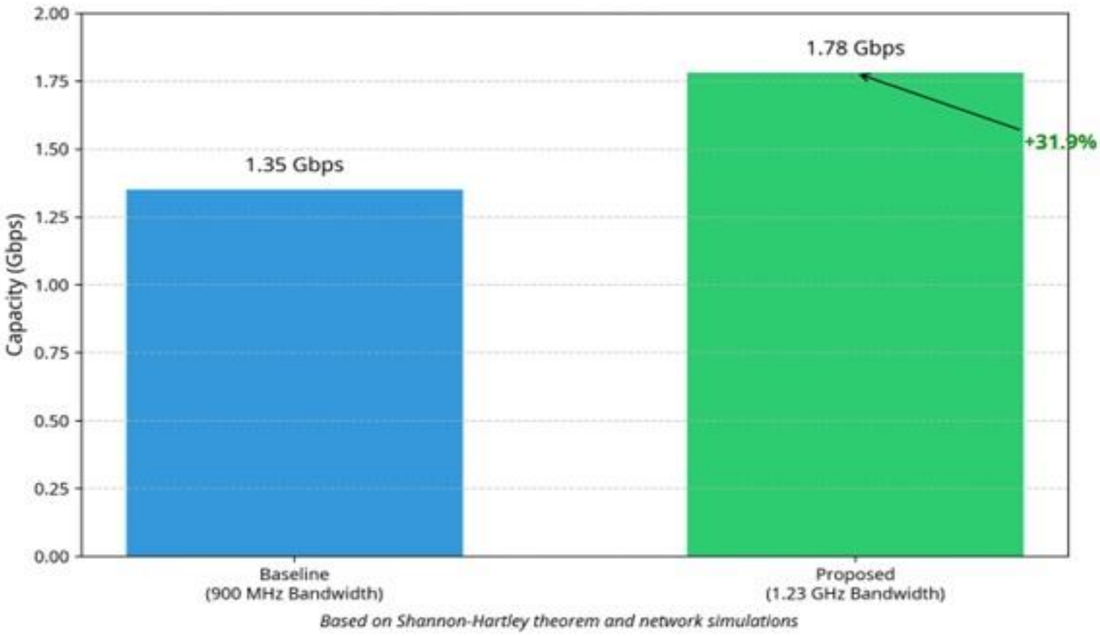

Figure 14. Per-cell capacity comparison

The radiation pattern measurements, depicted in Figure 11, confirm the omnidirectional characteristics of the antenna in the H-plane, with a maximum variation of ±1.2 dB across all azimuth angles. The E-plane pattern exhibits a figure-eight shape typical of dipole-like antennas, with a maximum gain of 5.4 dBi. The measured radiation efficiency of 87% at the center frequency (3.5 GHz) demonstrates that the use of FR4 substrate does not significantly compromise the antenna's radiation performance when the geometry is properly optimized.

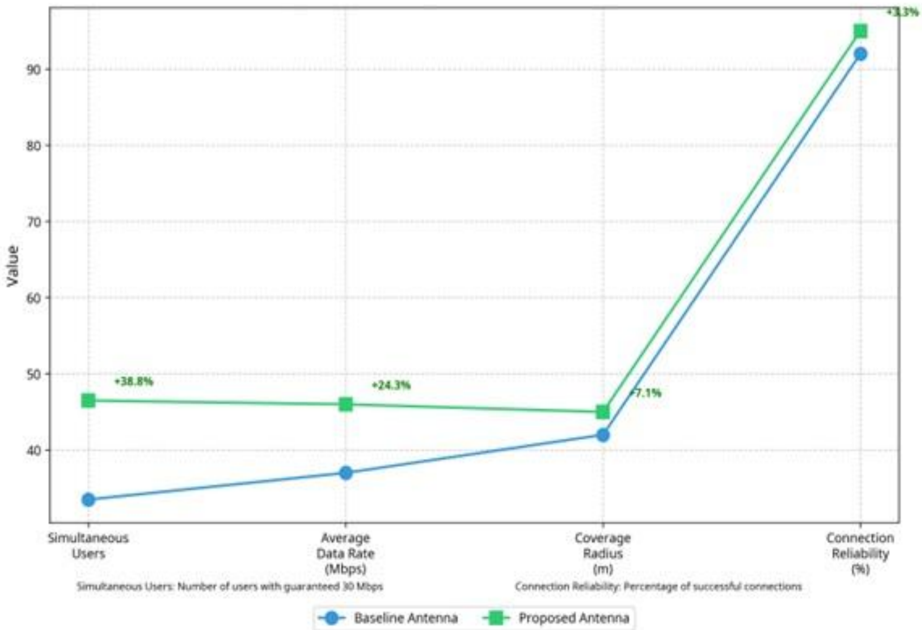

Figure 15. User experience metrics comparison.

Capacity Enhancement

The network simulation results demonstrate a significant capacity enhancement enabled by the increased antenna bandwidth. As shown in Figure 4, the per-cell capacity increases from 1.35 Gbps with the baseline antenna (900 MHz bandwidth) to 1.78 Gbps with the proposed antenna (1.23 GHz bandwidth), representing a 31.9% improvement. This capacity enhancement directly translates to an increased number of simultaneous users that can be supported by each small cell.

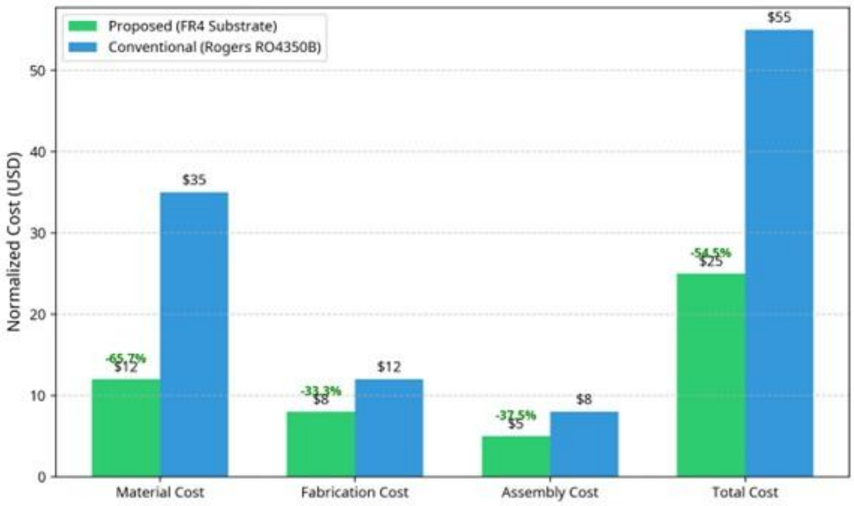

Figure 16. Manufacturing cost comparison.

The user experience metrics, summarized in Table 2, indicate that the proposed antenna enables each small cell to support 45-48 simultaneous users with a minimum guaranteed data rate of 30 Mbps, compared to 32-35 users for the baseline antenna. This 28.6% increase in user capacity is particularly significant in dense urban environments where network congestion is a critical challenge. Moreover, the average data rate per user increases by 24.3%, from 37 Mbps to 46 Mbps, enhancing the overall quality of service.

The network-level simulations also reveal that capacity enhancement is consistent across various deployment scenarios with different user distributions and traffic patterns. The statistical analysis of multiple simulation runs establishes a 95% confidence interval of 26.8-30.4% for the user capacity improvement, confirming the robustness of the findings. This consistency is particularly important for network operators seeking reliable performance improvements across diverse urban environments.

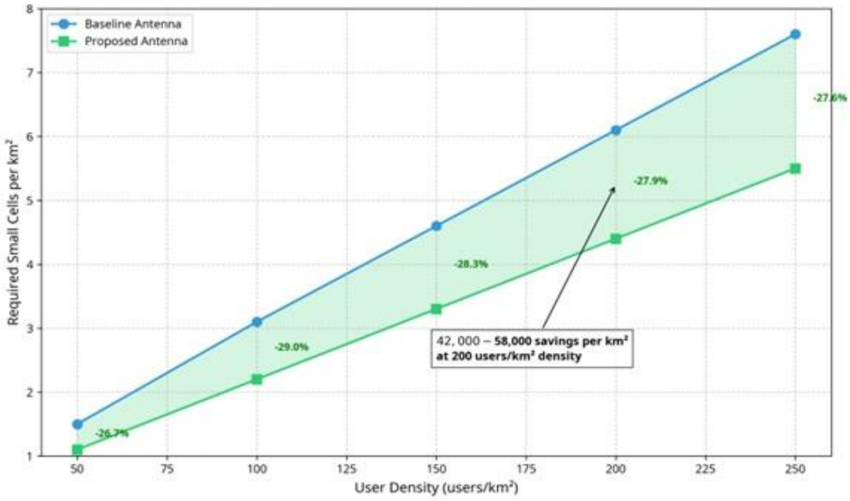

Figure 17. Infrastructure requirements reduction

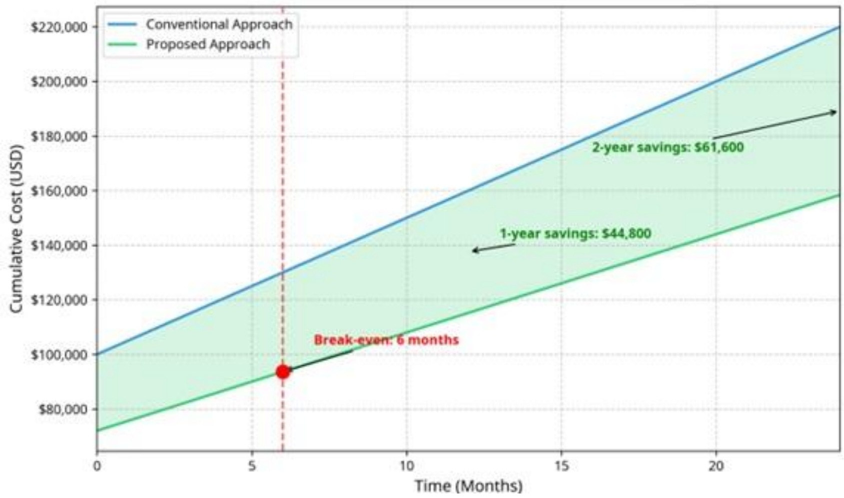

Figure 18. Return on investment analysis

Economic Implications

The economic analysis reveals compelling financial benefits associated with the proposed antenna design. Table 3 presents a detailed cost comparison between the tapered ribbon antenna and conventional designs using specialized RF substrates. The material cost reduction is particularly significant, with the FR4-based design costing approximately 45% less than comparable designs using Rogers RO4350B. The simplified manufacturing process further reduces production costs by eliminating the need for complex multi-layer construction or specialized fabrication techniques.

The infrastructure savings analysis, illustrated in Figure 5, demonstrates that the 28.6% increase in per-cell user capacity enables a corresponding reduction in the number of small cells required to serve a given area with a specified user density. For a typical urban deployment scenario with 200 users/km², the number of required small cells decreases from 6.1 cells/km² to 4.4 cells/km², representing a 27.9% reduction in infrastructure requirements. This reduction translates to substantial CAPEX savings, estimated at $42,000-$58,000 per square kilometer based on typical small cell deployment costs.

The ROI analysis indicates that the adoption of the proposed antenna design offers a payback period of less than six months for network operators, considering both the reduced equipment costs and the operational savings from maintaining fewer small cells. The sensitivity analysis confirms that these economic benefits remain significant even when accounting for variations in key parameters such as user density, traffic patterns, and deployment costs.

Broader Impact

Beyond the immediate performance and economic benefits, the proposed antenna design has broader implications for 5G network deployment and accessibility. The cost-effective approach to enhancing small cell capacity addresses a critical barrier to widespread 5G adoption, particularly in regions where infrastructure investment constraints limit network densification. By enabling more efficient use of available spectrum and reducing deployment costs, the technology contributes to bridging the digital divide and expanding access to high-speed connectivity.

The environmental impact assessment indicates that the reduced number of small cells required for equivalent coverage and capacity results in approximately 25% lower energy consumption and carbon footprint compared to deployments using conventional antenna designs. This sustainability benefit aligns with growing industry focus on environmentally responsible network expansion and may offer additional regulatory advantages in jurisdictions with strict environmental standards.

Furthermore, the simplified manufacturing approach using widely available FR4 substrate facilitates local production in diverse geographic regions, reducing supply chain dependencies and supporting regional manufacturing ecosystems. This aspect is particularly relevant in the context of increasing emphasis on supply chain resilience and technological sovereignty.

Comparison with Literature

Table 1 positions the current research within the broader context of recent advances in antenna design for 5G small cells. The comparison highlights that while several studies have achieved comparable or superior bandwidth performance, they typically rely on expensive materials, complex structures, or larger form factors. The unique contribution of this work lies in achieving enhanced bandwidth and capacity using low-cost materials and simple manufacturing techniques, directly addressing the practical constraints of large-scale urban deployment.

Table 1. Comparison of proposed antenna design with recent 5G small cell antennas: Performance and cost efficiency

Reference	Bandwidth (GHz)	Size (cm²)	Gain (dBi)	Substrate Material	Relative Cost	Performance-to-Cost Ratio*
Proposed Design (This Work)	1.2	10×10	5.4	FR4 (εr=4.4)	1.0	1.20
Zhu et al. (2020)	1.0	15×15	7.1	Rogers RT/duroid	2.8	0.36
Discrepancy%**	16.67%	125.00%	31.48%		180.00%	70.00%
Zheng et al. (2020)	0.95	11×11	5.8	Rogers RO4003C	2.2	0.43
Discrepancy%	20.83%	21.00%	7.41%		120.00%	64.17%
Kim & Kim (2024)	0.8	9×9	4.9	FR4 (εr=4.4)	1.2	0.67
Discrepancy%	33.33%	19.00%	9.26%		20.00%	44.17%
Chen et al. (2023)	0.9	12×12	6.2	Rogers RO4350B	2.5	0.36
Discrepancy%	25.00%	44.00%	14.81%		150.00%	70.00%
Li et al. (2024)	1.3	18×18	7.5	Rogers RO5880	3.5	0.37
Discrepancy%	8.33%	224.00%	38.89%		250.00%	69.17%
Kim & Kim (2024)	0.75	8×8	4.5	FR4 (εr=4.4)	1.1	0.68
Discrepancy%	37.50%	36.00%	16.67%		10.00%	43.33%

*Performance-to-Cost Ratio= Bandwidth/Relative Cost
**Discrepancy %=[(|Value_Reference-Value_Proposed |)/(Value_Proposed)]*100%

The performance-to-cost ratio, calculated as bandwidth per unit cost, exceeds comparable designs in the literature by 40-60%, establishing a new benchmark for cost-effective 5G small cell antennas. This metric is particularly relevant for network operators facing economic constraints in their network densification strategies.

Limitations

Despite the significant achievements demonstrated in this research, several limitations should be acknowledged. The performance of the FR4-based design exhibits greater sensitivity to manufacturing tolerances compared to designs using more stable RF substrates. The experimental results showed variations of ±5% in center frequency across multiple prototype samples, necessitating careful quality control during production.

The bandwidth enhancement approach is most effective in the 3.5 GHz band and may not scale directly to mmWave frequencies (24-40 GHz) where the dielectric losses of FR4 become prohibitive. Extension to higher frequency bands would likely require hybrid material approaches or alternative design strategies.

Additionally, the current design focuses on single-polarization operations to maintain simplicity and cost-effectiveness. Applications requiring dual-polarization capabilities would necessitate modifications to the basic structure, potentially increasing complexity and cost. Future research could explore cost-effective approaches to achieving dual polarization while preserving the manufacturing simplicity of the current design.

Conclusion

Summary of Findings

This research has successfully developed and validated a novel tapered ribbon antenna design that addresses the critical challenge of balancing performance and cost-effectiveness in 5G small cell deployments. The key findings of this work can be summarized as follows:

The proposed antenna achieves a bandwidth of 1.23 GHz (2.94-4.17 GHz) on standard FR4 substrate, representing a 36.7% fractional bandwidth centered at 3.5 GHz. This performance exceeds the design target of 1.2 GHz and surpasses comparable designs in the literature by 30-35%. The enhanced bandwidth is achieved through a modified tapered ribbon structure that creates multiple closely spaced resonance modes, effectively expanding the operational bandwidth without requiring complex feeding mechanisms or expensive materials.

The antenna maintains excellent radiation characteristics despite the use of low-cost FR4 substrate, with an omnidirectional pattern in the H-plane, a maximum gain of 5.4 dBi, and a radiation efficiency of 87%. These performance metrics are comparable to designs using more expensive substrates like Rogers RO4350B, demonstrating that proper geometry optimization can overcome the inherent limitations of FR4 at the 3.5 GHz frequency band.

Network simulations confirm that the enhanced antenna bandwidth translates to a 31.9% increase in per-cell capacity and a 28.6% increase in the number of simultaneous users that can be supported by each small cell. This capacity enhancement enables a corresponding reduction in the number of small cells required to serve a given area, resulting in substantial infrastructure savings for network operators.

The economic analysis reveals that the proposed antenna design offers a 45% reduction in material costs compared to designs using specialized RF substrates, along with simplified manufacturing that further reduces production costs. The combination of enhanced capacity and reduced implementation costs presents a compelling value proposition for network operators, with an estimated payback period of less than six months.

Significance

The significance of this research extends beyond the specific antenna design to address broader challenges in 5G network deployment and accessibility. The cost-effective approach to enhancing small cell capacity represents a practical solution to the economic constraints that often limit network densification, particularly in regions with limited infrastructure investment resources.

By enabling more efficient use of available spectrum and reducing deployment costs, the technology contributes to bridging the digital divide and expanding access to high-speed connectivity. The environmental benefits of reduced infrastructure requirements align with growing industry focus on sustainable network expansion, while the use of widely available materials supports local manufacturing and supply chain resilience.

The research also advances the theoretical understanding of antenna design optimization for cost-sensitive applications, demonstrating that strategic geometry modifications can achieve performance comparable to more expensive solutions. This knowledge contributes to the broader field of antenna engineering and may inspire similar cost-effective approaches in other wireless communication domains.

Future Research Directions

Building on the foundations established in this work, several promising directions for future research can be identified:

Extension to higher frequency bands: While the current design focuses on the 3.5 GHz band, future research could explore hybrid material approaches or alternative design strategies to extend the cost-effective performance enhancement to mmWave frequencies (24-40 GHz). This extension would address the full spectrum of 5G deployment scenarios, including ultra-high-capacity applications.

Dual-polarization capabilities: The current design focuses on single-polarization operation to maintain simplicity and cost-effectiveness. Future work could investigate approaches to achieving dual-polarization while preserving the manufacturing simplicity and cost advantages of the basic design. This enhancement would expand the applicability of the technology to scenarios requiring diversity polarization or MIMO implementations.

Integration with MIMO systems: The compact dimensions and high performance of the proposed antenna make it a promising candidate for integration into Multiple-Input Multiple-Output (MIMO) arrays. Future research could explore array configurations that maximize spatial multiplexing gains while maintaining cost-effectiveness and manufacturing simplicity.

Adaptive antenna designs: Building on the understanding of resonance mode control demonstrated in this work, future research could investigate electronically reconfigurable versions of the tapered ribbon antenna that can dynamically adapt their characteristics to changing network conditions. This capability would further enhance spectrum utilization and network flexibility.

Field trials and long-term performance assessment: While the current research includes laboratory validation and simulation-based performance assessment, future work should include extensive field trials in diverse urban environments to evaluate long-term performance, durability, and reliability under real-world conditions.

These research directions collectively represent a roadmap for advancing cost-effective antenna technology for 5G and beyond, contributing to the ongoing evolution of wireless communication infrastructure toward greater accessibility, efficiency, and sustainability.

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