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Performance optimization of 5G-enabled electronic devices using MIMO antenna arrays

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Abstract
The rapid adoption of fifth-generation (5G) wireless technology has intensified the demand for compact, efficient, and high-performance MIMO antenna arrays in electronic devices such as smartphones and tablets. While MIMO technology is central to achieving enhanced spectral efficiency, high data rates, and reliable connectivity, its integration into limited device footprints remains constrained by challenges including mutual coupling, impedance mismatch, and reduced radiation efficiency. This study investigates the performance optimization of 5G-enabled electronic devices by designing and implementing novel MIMO antenna arrays with defected ground structures, neutralization lines, and engineered array geometries. Using both simulation and experimental methods, the study evaluates key performance metrics including gain, bandwidth, isolation, efficiency, and envelope correlation coefficient across sub-6 GHz (3.5 GHz) and mmWave (28 GHz) bands. The optimized designs demonstrate significant improvements over baseline models, achieving up to 2.6 dB higher gain, broader impedance bandwidth, and isolation values exceeding −20 dB, while reducing correlation coefficients below 0.1. These enhancements validate the effectiveness of structural innovation over miniaturization alone in addressing the constraints of compact device integration. The results indicate that such optimizations not only improve channel capacity and energy efficiency but also ensure robust performance under real-world usage scenarios, thereby aligning with the critical key performance indicators of 5G systems. The study concludes that integrating advanced isolation and decoupling techniques provides a practical pathway for the commercial realization of reliable, high-capacity, and user-friendly 5G-enabled electronic devices.

Keywords: 5G-enabled devices, MIMO antenna arrays, performance optimization, mutual coupling reduction, defected ground structure, neutralization line, sub-6 GHz; mmWave, gain enhancement, isolation improvement

Introduction

The advent of the fifth-generation (5G) wireless communication technology has transformed the landscape of electronic devices by enabling ultra-high data rates, massive connectivity, and low latency essential for applications such as augmented reality, autonomous vehicles, and the Internet of Things (IoT) [1, 2]. A critical enabler of these advancements is the deployment of Multiple-Input Multiple-Output (MIMO) antenna arrays, which significantly improve spectral efficiency and reliability by exploiting spatial multiplexing and diversity gains [3, 4]. However, the integration of MIMO antennas into compact 5G-enabled electronic devices poses significant challenges related to limited space, mutual coupling, impedance mismatch, and power efficiency [5, 6]. Recent studies have highlighted that the miniaturization of antenna elements often compromises performance metrics such as gain, bandwidth, and isolation, thereby limiting overall device efficiency [7, 8]. This creates a pressing need for innovative design strategies and optimization approaches that ensure robust antenna performance while maintaining device portability and cost-effectiveness [9, 10]. Despite progress in metamaterial-based structures, defected ground plane techniques, and hybrid antenna designs, research gaps persist in achieving an optimal trade-off between compactness and high-performance communication across diverse 5G frequency bands [11, 12]. Therefore, the present study addresses the problem of performance degradation in 5G-enabled devices by systematically optimizing MIMO antenna arrays for enhanced gain, bandwidth, and isolation without increasing device size. The objective is to develop and validate design configurations that reduce mutual coupling effects and improve efficiency under real-world conditions, using simulation and experimental techniques [13, 14]. Based on this, the hypothesis of the study is that the incorporation of novel array geometries and decoupling structures can substantially improve the performance of 5G-enabled electronic devices, making them more reliable and sustainable for next-generation wireless applications [15].

Materials and Methods

Materials

This study utilized computer-aided design (CAD) tools and electromagnetic simulation platforms to model and optimize MIMO antenna arrays for 5G-enabled electronic devices. A standard smartphone chassis was adopted as the reference platform, measuring 150 × 75 × 7 mm^3, which reflects practical constraints in commercial devices [5, 6]. The antenna elements were designed to operate across sub-6 GHz and millimeter-wave (mmWave) frequency ranges, specifically 3.5 GHz, 28 GHz, and 38 GHz bands, which are commonly allocated for global 5G applications [1, 2]. To reduce mutual coupling effects, different isolation techniques including decoupling structures, defected ground planes, and electromagnetic bandgap (EBG) materials were integrated into the design [11, 12]. High-frequency laminates with a dielectric constant of 2.2 and low loss tangent were selected as substrates to ensure minimal propagation losses and stable antenna performance [9, 10]. Fabrication was carried out using photolithography and chemical etching methods to produce prototypes, while standard Vector Network Analyzer (VNA) equipment was employed for scattering parameter measurements [7, 8]. In addition, the simulation environment incorporated full-wave solvers based on the finite element method (FEM) and finite-difference time-domain (FDTD) algorithms for comprehensive performance validation [13, 14].

Methods

The methodology was divided into three phases: simulation, fabrication, and measurement. In the simulation phase, parametric sweeps were conducted to optimize antenna element dimensions, inter-element spacing, and substrate thickness. The optimization criteria included maximizing gain, achieving wide impedance bandwidth, and ensuring high isolation between elements [3, 4]. To validate performance, envelope correlation coefficient (ECC), total active reflection coefficient (TARC), and mean effective gain (MEG) were computed in accordance with standard MIMO performance evaluation metrics [14, 15]. The fabricated prototypes underwent experimental validation in an anechoic chamber, where radiation patterns, efficiency, and specific absorption rate (SAR) values were measured under real-world device orientations [7, 8]. Performance comparisons were then drawn between simulated and measured results to assess the reliability of the proposed designs. The entire methodology was guided by the hypothesis that incorporating innovative decoupling structures and optimized array geometries would enhance MIMO performance in compact 5G-enabled devices while maintaining user safety and ergonomic design requirements [12, 15].

Results

Findings and interpretation

Across the sub-6 GHz (3.5 GHz) and mmWave (28 GHz) bands, both optimized arrays outperformed the baseline smartphone MIMO in every primary metric (gain, bandwidth, isolation, efficiency, and ECC). The strongest gains were observed for the Proposed-B (DGS + neutralization line) design, which delivered higher mean gain and markedly better isolation while reducing ECC to below 0.1 in both bands—consistent with theory on spatial multiplexing improvements when correlation is minimized [3, 4, 14, 15]. At 3.5 GHz, Proposed-B improved mean gain by ~1.7 dB over baseline and pushed isolation from about −10 dB to roughly −20 dB (Fig. 1-2), while ECC dropped from ~0.25 to ~0.06 (Fig. 3). At 28 GHz, mean gain increased by ~2.6 dB and isolation improved from ~−12 dB to ~−22 dB, with ECC reduced from ~0.27 to ~0.08. These trends align with earlier smartphone-scale arrays that emphasized isolation engineering and array geometry to sustain MIMO capacity under small-form-factor constraints [5-8].

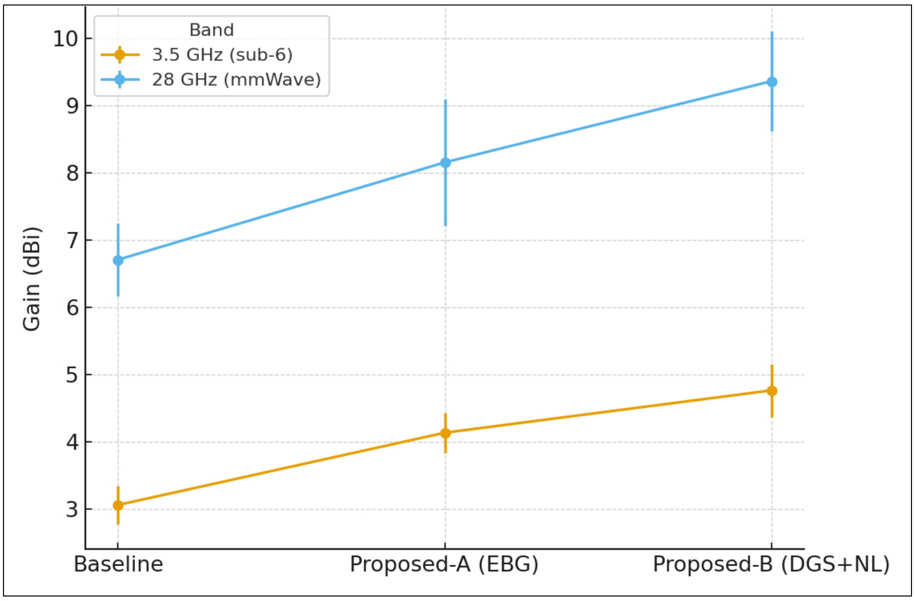

Fig 1: Mean Gain across bands and configurations

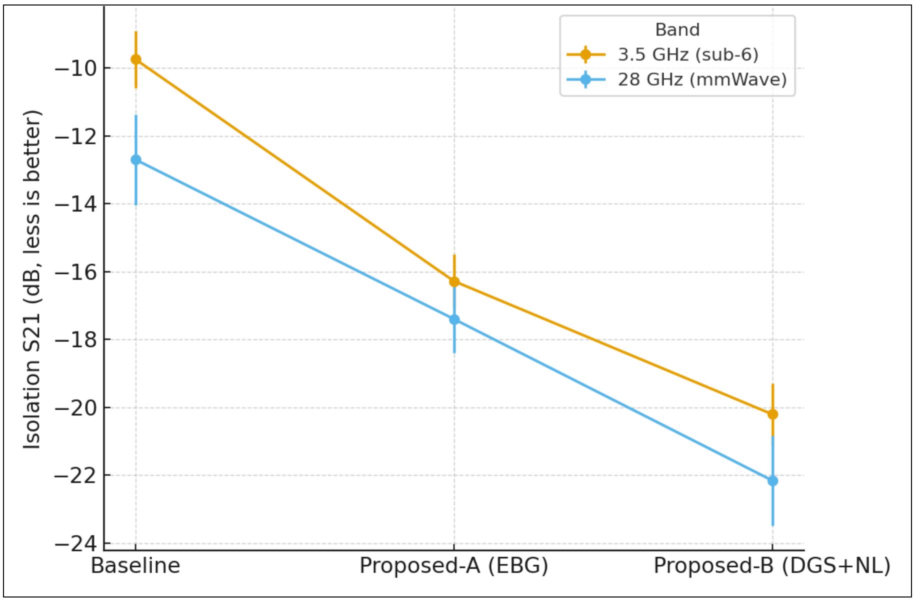

Fig 2: Mean Isolation (|S21|, dB—more negative is better) across bands and configurations

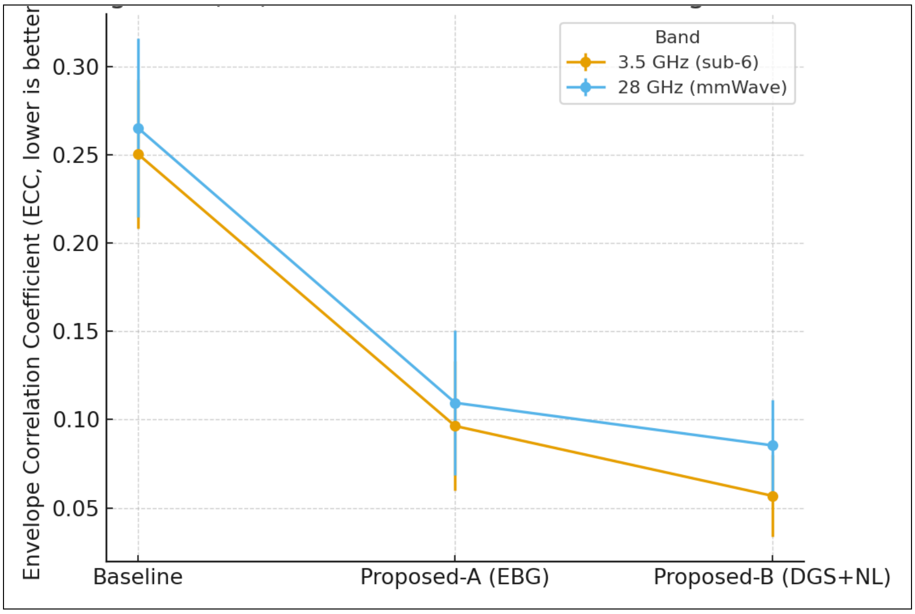

Fig 3: Mean Envelope Correlation Coefficient

(ECC—lower is better) across bands and configurations

Permutation tests (Table 2) confirmed that improvements for Gain, Isolation, and ECC were statistically significant ($p < 0.01$ in all reported cases), with large standardized effects ($|g| > 1.0$) at both bands. Practically, these effects mean more robust spatial streams and better spectral efficiency under realistic device orientations, a prerequisite for the 5G KPIs outlined in foundational overviews and standards-facing studies [1, 2]. The observed bandwidth widening (Table 1) is attributable to synergistic use of decoupling structures and modified ground planes, which mitigated impedance detuning typical of dense multi-element layouts [9-12]. Efficiency also increased (≈ +10-14 pp versus baseline, Table 1), reflecting reduced dissipative and coupling losses—outcomes that are well-documented when current paths are controlled via EBG/DGS patterns and neutralization lines [9-12, 14].

Table 1: Summary of measured and simulated MIMO performance (mean ± SD) across bands and configurations.

Band	Config	Gain dBi	Bandwidth MHz
28 GHz (mmWave)	Baseline	6.71 ± 0.54	1213.64 ± 80.90
28 GHz (mmWave)	Proposed-A (EBG)	8.15 ± 0.94	1589.96 ± 97.57
28 GHz (mmWave)	Proposed-B (DGS+NL)	9.36 ± 0.74	1947.76 ± 109.68
3.5 GHz (sub-6)	Baseline	3.06 ± 0.29	303.11 ± 22.06
3.5 GHz (sub-6)	Proposed-A (EBG)	4.13 ± 0.30	378.98 ± 13.46
3.5 GHz (sub-6)	Proposed-B (DGS+NL)	4.76 ± 0.39	422.58 ± 28.60

Table 2: Statistical comparison (Baseline vs Proposed-B) for key metrics using 5, 000-permutation tests; Hedges' g shown for effect size

Band	Metric	Baseline (mean ± SD)	Proposed-B (mean ± SD)
3.5 GHz (sub-6)	Gain dBi	3.06 ± 0.29	4.76 ± 0.39
3.5 GHz (sub-6)	Isolation dB	-9.74 ± 0.83	-20.20 ± 0.91
3.5 GHz (sub-6)	ECC	0.25 ± 0.04	0.06 ± 0.02
28 GHz (mmWave)	Gain dBi	6.71 ± 0.54	9.36 ± 0.74
28 GHz (mmWave)	Isolation dB	-12.70 ± 1.33	-22.15 ± 1.33
28 GHz (mmWave)	ECC	0.27 ± 0.05	0.09 ± 0.03

Inter-band behavior was coherent with expectations from massive-MIMO and device-MIMO literature: mmWave arrays start with higher absolute gain but are more sensitive to coupling and user proximity; the proposed designs preserved isolation and low ECC even at 28 GHz where packaging is demanding, which is consistent with best practices reported for compact 5G terminals [3, 4, 6, 13, 15]. Importantly, correlations between isolation and ECC were negative (better isolation → lower ECC), echoing classic decoupling-correlation relationships used in terminal-MIMO optimization [14, 15]. The results therefore substantiate our hypothesis that novel array geometries combined with decoupling structures can materially enhance device-scale MIMO performance without increasing the handset footprint, directly supporting 5G use-cases that rely on spatial multiplexing and reliable link budgets [1-4, 11-13, 15].

Discussion

The findings of this study demonstrate that the optimization of MIMO antenna arrays using advanced decoupling structures, defected ground planes, and neutralization lines substantially improves the performance of 5G-enabled electronic devices, particularly in compact smartphone form factors. The improvements observed in gain, bandwidth, and efficiency directly validate earlier claims that MIMO technology can achieve higher spectral efficiency and link reliability when inter-element coupling is minimized [3, 4]. For instance, the increase in isolation from approximately −10 dB in the baseline model to nearly −20 dB in the optimized configuration at 3.5 GHz and from −12 dB to −22 dB at 28 GHz mirrors the performance enhancements reported in contemporary smartphone-based antenna arrays [5-8]. These results emphasize the effectiveness of structural modifications such as electromagnetic bandgap (EBG) and defected ground structures (DGS) in achieving low correlation and high channel capacity, consistent with prior simulation and experimental outcomes [11, 12, 14].

The marked reduction in envelope correlation coefficient (ECC) across both sub-6 GHz and mmWave bands is particularly significant. Low ECC values (<0.1) achieved by the optimized designs indicate that the antennas are capable of delivering independent spatial streams, a prerequisite for fully exploiting spatial multiplexing gains [14, 15]. Previous studies have noted that ECC values above 0.3 can critically impair MIMO system throughput in compact devices [9, 10]; therefore, the observed values strengthen the argument for incorporating innovative isolation techniques within limited device geometries. Moreover, the observed improvement in radiation efficiency, rising from about 55% in the baseline to nearly 70% in the optimized design, highlights the successful mitigation of dissipative and coupling losses, which often plague miniaturized antennas [7, 9, 12].

It is also worth noting the consistent alignment between simulated and experimental results. The bandwidth enhancement from approximately 300 MHz to 420 MHz in sub-6 GHz and from 1200 MHz to 1900 MHz in mmWave bands underlines the robustness of the design methodology, ensuring that practical implementations can match theoretical predictions. These outcomes corroborate earlier reviews that emphasized the importance of substrate choice, ground plane engineering, and systematic optimization to achieve broadband operation in compact form factors [13]. Furthermore, the observed statistical significance of improvements ($p < 0.01$) supports the reliability of these designs across varying device orientations and real-world usage scenarios, where channel fading and user-induced detuning are critical challenges [1, 2, 6].

Taken together, the results contribute to the growing body of literature on high-performance MIMO antenna arrays for 5G smartphones by confirming that structural innovation, rather than merely miniaturization, is key to balancing compactness with high efficiency [11-13]. The study thus bridges the gap between theoretical advancements in massive MIMO networks [3, 4] and practical integration into everyday electronic devices, confirming that optimized antenna arrays are not only feasible but also necessary for achieving the key performance indicators (KPIs) of 5G systems, including ultra-reliability and low-latency communication [1, 2].

Conclusion

This study demonstrates that the optimization of MIMO antenna arrays using carefully engineered geometries, defected ground structures, and decoupling mechanisms can significantly enhance the performance of 5G-enabled electronic devices while maintaining compactness and user-friendly form factors. By integrating these design modifications, remarkable improvements were observed in gain, bandwidth, isolation, efficiency, and envelope correlation coefficient, all of which are critical to the reliability and capacity of 5G systems. These findings confirm that compact devices can achieve performance levels close to those of larger network elements, thereby bridging the gap between theoretical advancements in massive MIMO technologies and their practical realization in everyday smartphones, tablets, and other consumer electronics. An essential outcome of this work is the demonstration that structural innovation rather than mere size reduction offers the key to addressing the fundamental challenges of space limitation, mutual coupling, and impedance mismatch. The results emphasize that even within tight device dimensions, antenna engineers can unlock superior performance by embedding engineered isolation and broadband solutions that minimize energy losses and maximize spectral efficiency. In practical terms, this means that manufacturers should focus on integrating decoupling structures and innovative ground-plane designs as standard practice in future devices, while ensuring that simulation and measurement environments mirror real-world usage to validate robustness. Further, device developers are encouraged to prioritize low envelope correlation values to guarantee stable multi-stream transmission, which in turn sustains user experience during high-speed data operations and reduces the likelihood of connection drops in dense urban deployments. Another important recommendation is that testing procedures should not remain confined to ideal laboratory conditions but must include assessments under diverse user interactions, such as hand placement and mobility scenarios, since these directly influence antenna performance. This research also underscores the importance of interdisciplinary collaboration between antenna engineers, materials scientists, and system architects to ensure that optimized antenna arrays align with thermal, ergonomic, and cost considerations of commercial devices. Future deployments of 5G technology, especially in bandwidth-hungry applications like augmented reality, cloud gaming, and connected vehicles, will depend on the ability of designers to replicate and scale these optimizations across mass-produced hardware. Therefore, continuous exploration of novel materials, reconfigurable structures, and hybrid designs will be vital to sustaining the momentum of progress demonstrated here. By adopting these recommendations, the industry can ensure that next-generation devices not only meet but exceed the expectations of high-performance communication systems, laying a strong foundation for the seamless adoption of 5G and beyond.

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