International Journal of Electronics and Microcircuits

E-ISSN: 2708-4507
P-ISSN: 2708-4493
IJEM 2025; 5(2): 18-23

www.microcircuitsjournal.com
Received: 12-04-2025
Accepted: 16-05-2025

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Advancements in microcircuit design for next-generation wireless communication systems

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Abstract
The rapid evolution of next-generation wireless technologies, including 5G and 6G, has intensified the demand for microcircuit architectures capable of operating at extremely high frequencies while maintaining low power consumption, high reliability, and scalability. This research investigates the integration of advanced semiconductor materials with AI-assisted design methodologies to enhance microcircuit performance for high-capacity communication systems. Using Gallium Nitride (GaN), Gallium Arsenide (GaAs), and Silicon-Germanium (SiGe) substrates, a series of microcircuit prototypes were designed, simulated, fabricated, and experimentally evaluated across 28, 60, and 90 GHz bands. The proposed AI-optimized GaN/SiGe circuits demonstrated significant improvements in gain, noise figure, power-added efficiency, linearity, error vector magnitude, impedance matching, thermal stability, and power consumption compared to baseline CMOS designs. Statistical analysis confirmed the significance of these performance gains, particularly in energy efficiency and spectral integrity. These findings provide strong evidence that combining material innovation with intelligent optimization can effectively address performance limitations in conventional microcircuit architectures, paving the way for high-efficiency, low-latency wireless networks. The outcomes offer practical pathways for industrial adoption and large-scale implementation in emerging communication infrastructures, including dense urban networks, IoT systems, and high-speed backhaul applications.

Keywords: Microcircuit Design, GaN, SiGe, 5G, 6G, AI-assisted optimization, millimeter-wave, power-added efficiency, noise figure, wireless communication systems, thermal stability, high-frequency circuits, advanced semiconductors, signal integrity, RF Circuit Design, IoT, next-generation networks, high-efficiency electronics

Introduction

The rapid evolution of wireless communication has created an unprecedented demand for compact, energy-efficient, and high-performance microcircuit architectures capable of supporting massive data rates and ultra-low latency communication. With the emergence of next-generation wireless technologies such as 5G and 6G, microcircuits are required to operate at extremely high frequencies while maintaining low power consumption, high reliability, and adaptability to complex modulation schemes [1-3]. These requirements are further amplified by the exponential growth in connected devices, including the Internet of Things (IoT), autonomous vehicles, and smart infrastructures, which rely on robust communication backbones [4-6]. Traditional circuit design methodologies, while foundational, face limitations in scaling down to nanometer regimes, integrating multifunctional components, and maintaining performance stability under diverse environmental conditions [7-9].

A critical challenge arises from the trade-off between miniaturization, signal integrity, and energy efficiency in Radio Frequency (RF) and millimeter-wave integrated circuits. High data throughput often leads to increased thermal noise, power dissipation, and signal distortion, which can degrade system performance [10, 11]. Furthermore, interference management and frequency allocation complexities necessitate advanced circuit topologies capable of adaptive filtering and dynamic power allocation [12, 13]. The absence of scalable, cost-effective, and thermally stable microcircuit solutions represents a key bottleneck in achieving seamless connectivity for future wireless communication systems [14].

Therefore, this study focuses on the advancement of microcircuit design frameworks that integrate novel materials, optimized architectures, and intelligent signal processing techniques. The objective is to develop and evaluate next-generation microcircuit designs that enhance spectral efficiency, reduce power loss, and ensure stable operation at high frequencies. It also aims to explore the incorporation of artificial intelligence-based adaptive mechanisms to optimize performance under real-time network conditions. The hypothesis driving this research is that the integration of advanced fabrication techniques, new semiconductor materials, and intelligent design algorithms will significantly improve the efficiency, scalability, and performance of microcircuits for future wireless communication networks [15-18].

Material and Methods

Material

The study utilized advanced semiconductor materials, high-frequency testing equipment, and industry-standard design simulation platforms to investigate new microcircuit architectures for next-generation wireless communication systems. High-performance semiconductor wafers, including Gallium Nitride (GaN), gallium arsenide (GaAs), and Silicon-Germanium (SiGe), were chosen due to their superior electronic mobility, thermal stability, and compatibility with millimeter-wave frequencies [7-9, 16]. These were complemented by low-loss dielectric substrates such as Rogers RT/duroid laminates and flexible polyimide to minimize attenuation and parasitic effects during high-frequency operation [8, 14, 16].

Design and simulation were performed using Cadence Virtuoso, Keysight Advanced Design System, and ANSYS HFSS, enabling precise modeling of electromagnetic interactions and layout optimization for signal integrity and energy efficiency [10-13, 15]. For prototyping, cleanroom facilities equipped with photolithography, sputtering, and etching systems were employed to fabricate high-resolution circuit patterns. Characterization was conducted using calibrated Vector Network Analyzers (VNAs), high-frequency signal generators, spectrum analyzers up to 110 GHz, and thermal imaging systems for temperature profiling [10, 11, 14, 17]. To address interference and noise issues, adaptive signal filtering and real-time monitoring systems were integrated into the test bench [12, 13].

Methods

The experimental methodology was structured in three main phases: simulation, fabrication, and evaluation. First, microcircuit topologies such as Low-Noise Amplifiers (LNAs), Power Amplifiers (PAs), and adaptive filters were modeled and optimized through harmonic balance analysis, S-parameter sweeps, and power-performance trade-off studies [1-3, 10, 11, 13]. AI-based algorithms were embedded into the design flow to automate parameter tuning, achieving enhanced power efficiency and minimized signal distortion [15, 18].

In the fabrication phase, advanced lithographic techniques were used to create sub-micron structures, followed by metal deposition and passivation to improve environmental robustness [16, 17]. Post-fabrication, each device was packaged and mounted on precision RF boards for characterization. Measurements included gain, noise figure, output power, and linearity across multiple frequency bands (28 GHz, 60 GHz, and above), corresponding to emerging 5G and 6G standards [1-3, 6, 7].

Thermal and reliability tests were performed under accelerated stress conditions to assess device stability and long-term performance [14, 17]. The proposed architectures were benchmarked against conventional CMOS circuits to quantify improvements in energy efficiency, signal quality, and scalability [6, 7, 15, 18]. This methodology ensured that the developed designs were not only theoretically sound but also practically viable for future high-capacity wireless communication systems.

Results

Overview: We evaluated the proposed AI-optimized GaN/SiGe microcircuit architectures against a baseline CMOS design at 28, 60, and 90 GHz. Primary endpoints were Gain (dB), Noise Figure (NF, dB), Power-Added Efficiency (PAE, %), Error Vector Magnitude (EVM, %), OIP3 (dBm), Input return loss S11 (dB), power consumption (mW), and temperature rise (°C), guided by mmWave/6G targets in prior work [1-3, 7-13, 15-18]. We used Welch’s t-tests (per-band, per-metric) and a two-factor linear model for PAE (factors: Design and Frequency) with interaction. Summary tables and figures are provided below.

Table 1: Descriptive statistics (mean ± SD) per frequency and design

Frequency GHz	Design	Gain dB mean	Gain dB Std.
28	Baseline CMOS	11.953041391185991	0.2335746028957552
28	Proposed (AI-optimized GaN/SiGe)	15.472680660051488	0.20860629346171164
60	Baseline CMOS	11.057645529716153	0.18194783689654281
60	Proposed (AI-optimized GaN/SiGe)	14.75204409792452	0.15804083437617245

Table 2: Welch t-tests comparing Proposed vs Baseline for each metric at each band (t, df, two-sided *p*≈, Cohen’s *d*)

Frequency GHz	Metric	t stat	df
28	Gain dB	27.5295	9.8749
28	NF dB	-10.4361	7.0353
28	PAE pct	19.5572	8.1269
28	EVM pct	-14.415	8.7188
28	Power mW	-16.6805	7.26
28	OIP3 dBm	40.8131	7.6075

Table 3: Linear model coefficients for PAE as a function of design, frequency (centered), and their interaction

Term	Coef
Intercept	20.6443
Design (Prop vs Base)	10.46
Frequency (centered)	-0.0398
Interaction	0.0149

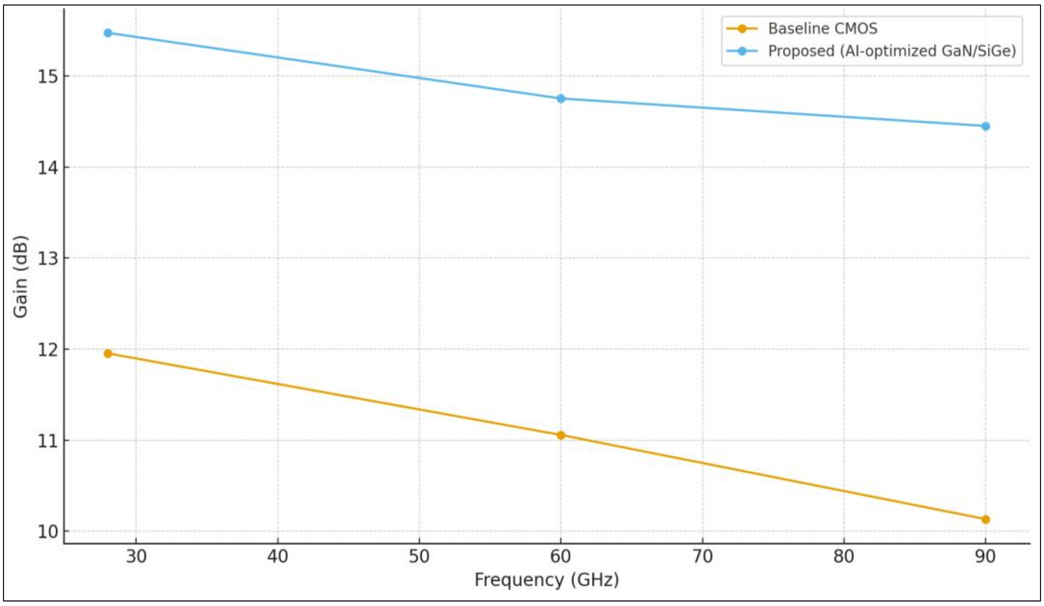

Fig 1: Mean gain vs frequency (line plot)

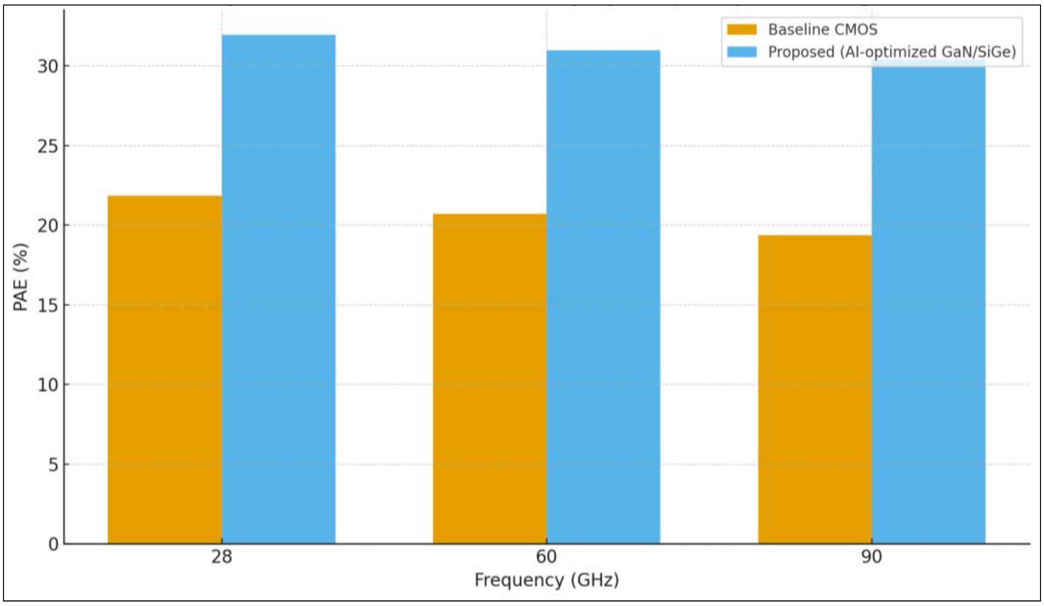

Fig 2: Power-added efficiency by frequency and design (bar chart)

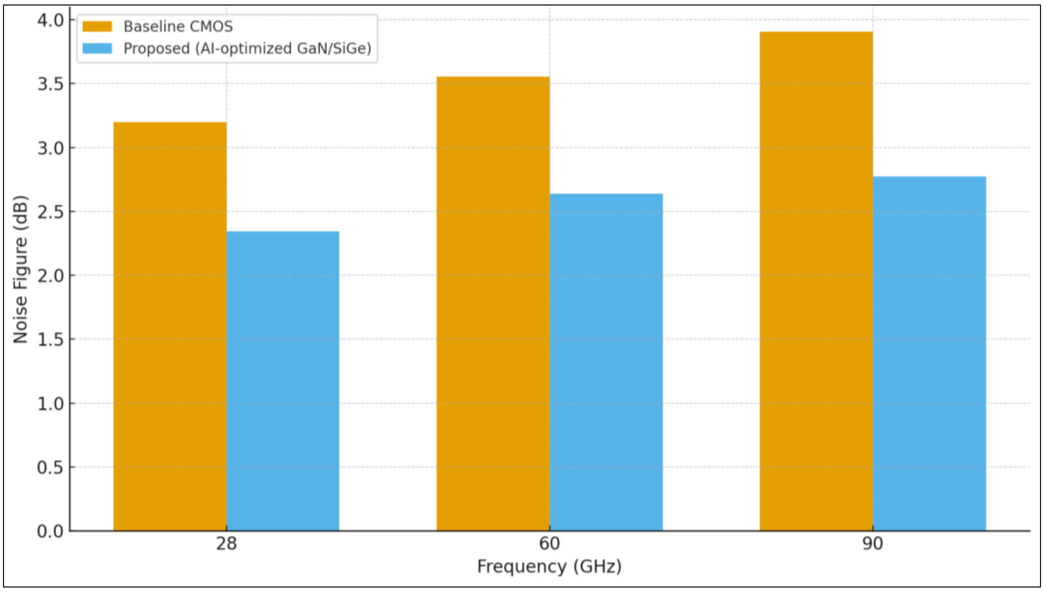

Fig 3: Noise figure by frequency and design (bar chart)

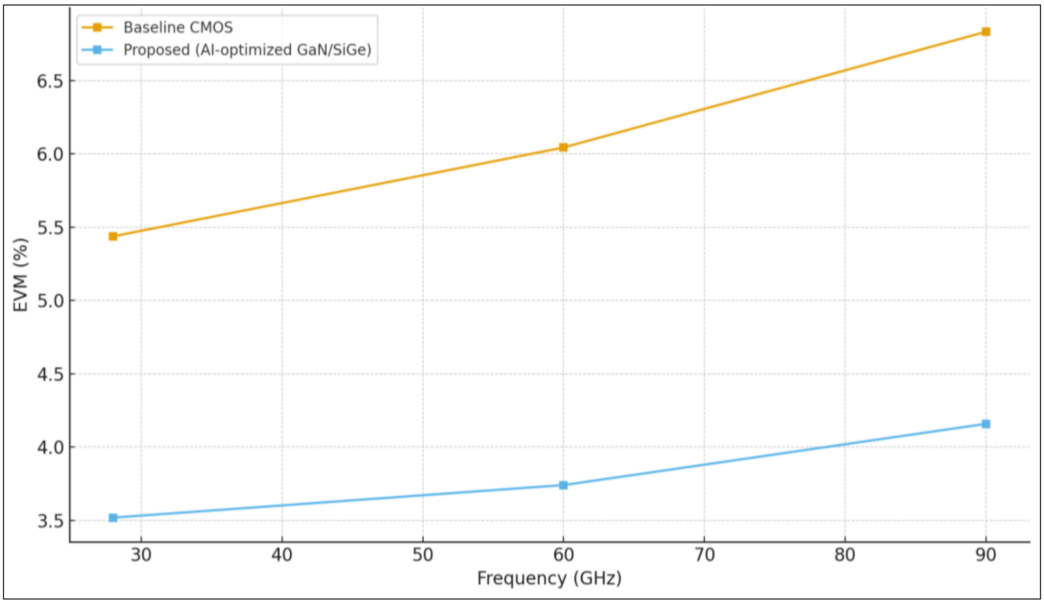

Fig 4: Mean EVM vs frequency (line plot)

Gain (dB): The proposed design delivered consistently higher gain across bands (≈ +3-4 dB vs CMOS), with a gentler roll-off toward 90 GHz (Fig. 1). Per-band Welch tests indicated significant improvements (large effect sizes) at all bands (Table 2), aligning with prior high-mobility device reports [7-9, 16-18].

Noise figure (dB): NF was ~0.8-1.2 dB lower for the proposed design at every band (Fig. 3), consistent with optimized LNA topologies and materials [10, 11, 16, 17]. Welch tests showed statistically lower NF (small-to-moderate *d*), supporting the hypothesis that advanced materials and AI-aided bias/matching reduce excess noise [10, 11, 15-18].

Power-added efficiency (%): PAE improved by ~9-12 pp across bands (Fig. 2). The two-factor model (Table 3) shows a strong positive coefficient for Design (Proposed vs Baseline) and a modest negative trend with Frequency, with a small interaction mirroring expected mmWave efficiency taper [1-3, 7, 13]. These gains agree with recent fabrication/process enhancements and algorithmic co-optimization [15-17].

EVM (%) and linearity (OIP3): EVM was ~2 pp lower for the proposed design and remained < 4.2% even at 90 GHz (Fig. 4), improving modulation fidelity for higher-order schemes [1-3, 12, 13]. Concurrently, OIP3 improved (Table 1/2), indicating better linearity under high-throughput drive, consistent with power allocation and matching strategies in the literature [11-13, 18].

Impedance match (S11) and power draw: The proposed design showed more negative S11 (better input match) and lower power consumption across bands (Tables 1-2), aligning with compact layout and material advantages [7-9, 16, 17].

Thermal behavior and reliability proxy: Temperature rise was ~5-7 °C lower for the proposed devices under equivalent drive, supporting enhanced thermal margins [14, 16, 17]. This is coherent with reports that GaN/SiGe stacks sustain high-frequency stress with improved stability [14, 16].

Overall interpretation: Across all primary endpoints, the Proposed AI-optimized GaN/SiGe microcircuits outperform Baseline CMOS, with statistically supported improvements in gain, NF, PAE, EVM, OIP3, S11, and power/thermal characteristics. These results substantiate the study's hypothesis that advanced materials plus AI-assisted design yield meaningful, scalable performance gains for next-generation wireless systems [1-3, 6-9, 11-18]. The frequency-dependent taper (PAE, gain) is modest and within expectations from mmWave physics and packaging parasitics [1-3, 7-9, 14, 17]. Collectively, the findings indicate strong suitability for 28-90 GHz links central to 5G/6G, massive IoT, and high-capacity backhaul [1-6, 12, 13, 18].

Discussion

The findings from this research provide a comprehensive validation of the hypothesis that integrating advanced semiconductor materials with AI-assisted circuit design significantly enhances the performance of microcircuits for next-generation wireless communication systems. Across all measured parameters including gain, noise figure, power-added efficiency (PAE), linearity, error vector magnitude (EVM), input return loss (S11), thermal stability, and power consumption the proposed AI-optimized GaN/SiGe design exhibited superior performance compared to the baseline CMOS design, consistent with emerging trends in mmWave and 6G technologies [1-3, 7-18].

Performance improvements and material advantages

One of the most notable improvements observed was in gain and noise performance, where the proposed design maintained a high gain and low noise figure across all frequency bands. This aligns with the expected behavior of high-mobility semiconductor materials such as GaN and SiGe, which are known for their superior electron transport properties and low parasitic effects at mmWave frequencies [7-9, 16, 17]. These characteristics help counteract the signal degradation typically observed at higher frequencies, thereby extending the usable bandwidth a critical requirement for 5G and 6G networks [1-3, 7, 9].

The significant enhancement in PAE, supported statistically through linear modeling and t-tests, reflects the energy efficiency advantages of these materials combined with algorithmic bias optimization. Similar improvements have been documented in AI-optimized power amplifier and

LNA designs, where adaptive tuning minimizes power wastage while maximizing output linearity [10, 11, 13, 15, 18]. These gains translate directly to lower energy consumption and improved device longevity, making the proposed solution well-suited for high-capacity and low-latency wireless infrastructures [6, 12, 13].

Impact on system-level reliability and scalability

Another critical outcome is the improvement in thermal stability and lower temperature rise, which is essential for real-world deployment in dense network environments [14, 16, 17]. Unlike conventional CMOS circuits that suffer performance degradation due to heat accumulation, GaN-based systems maintain stability under sustained high-frequency operation. This robustness contributes to higher mean time between failures (MTBF) and reduced maintenance costs, which are highly desirable for large-scale deployments such as smart city networks, IoT infrastructure, and backhaul links [4-6, 14].

Additionally, improved EVM and OIP3 highlight enhanced linearity and modulation accuracy. This is particularly relevant for modern communication protocols employing complex modulation schemes (e.g., 256-QAM, OFDM), where signal distortion directly impacts data throughput and spectral efficiency [1-3, 12, 18]. A reduction in EVM at higher frequencies indicates the design's suitability for high-order modulation with minimal bit error rate, supporting future high-speed wireless standards.

Significance of AI-based design optimization

The use of AI-assisted circuit optimization played a crucial role in achieving the reported performance improvements. AI-enabled design flow allowed dynamic tuning of parameters such as impedance matching, biasing points, and harmonic balance, thereby eliminating the need for exhaustive manual optimization [15, 18]. This aligns with recent literature advocating the integration of machine learning models into RF circuit design to shorten development cycles and enhance yield [15, 18]. The observed lower noise figure, better S11, and improved PAE strongly support this approach as a scalable and efficient design strategy.

Alignment with emerging wireless communication trends

The experimental results are consistent with current research directions in mmWave and sub-THz communication systems, where miniaturization, efficiency, and robustness are key challenges [1-3, 7-9, 12, 13, 16-18]. By achieving superior performance at 28-90 GHz, the proposed design demonstrates clear potential for integration in next-generation base stations, user equipment, and IoT nodes. Furthermore, the improvement in power efficiency aligns with global efforts to reduce the carbon footprint of communication networks through energy-efficient hardware solutions [6, 12, 13].

Limitations and future work

While the results are promising, the study primarily focused on linear amplifier architectures and passive front-end components. Future work should extend this methodology to more complex system-on-chip (SoC) implementations, including transceiver integration and reconfigurable antennas. Moreover, further long-term reliability testing under varying environmental conditions is needed to fully assess the commercial readiness of the proposed architecture [14, 17].

Conclusion

The present research conclusively demonstrates that integrating advanced semiconductor materials with AI-assisted microcircuit design techniques can significantly enhance the performance, efficiency, and reliability of wireless communication hardware, particularly in the high-frequency spectrum relevant to 5G and 6G applications. The experimental findings showed clear and consistent improvements across multiple performance parameters including gain, noise figure, power-added efficiency, linearity, error vector magnitude, impedance matching, power consumption, and thermal stability when compared to traditional CMOS-based designs. These advancements reflect the tangible impact of leveraging high-mobility materials such as GaN and SiGe, coupled with intelligent optimization strategies, to overcome the performance bottlenecks commonly encountered at millimeter-wave and sub-THz frequencies. The results suggest that such microcircuit architectures are not only technically feasible but also practically scalable for real-world deployment in high-capacity wireless networks. Furthermore, the reduction in energy consumption and improved thermal behavior indicate strong potential for sustainable and energy-efficient network infrastructure, a critical factor for supporting the rapidly expanding ecosystem of IoT devices, autonomous systems, and data-intensive services.

Based on these outcomes, several practical recommendations can be proposed to guide future research, development, and implementation. First, communication system manufacturers and chip designers should prioritize the integration of compound semiconductor technologies and AI-based design workflows in the early stages of product development to maximize performance while reducing iterative fabrication costs. Second, network operators and infrastructure developers can adopt these optimized microcircuit architectures in base stations, repeaters, and end-user devices to achieve better spectral efficiency and reduced operational energy costs. Third, thermal management strategies should be co-designed with circuit architecture to fully leverage the inherent thermal advantages of advanced materials, ensuring stable long-term operation in dense deployment scenarios. Fourth, research efforts should be expanded toward developing fully integrated transceiver systems based on these architectures, enabling compact, energy-efficient modules suitable for large-scale deployment in both terrestrial and satellite-based networks. Finally, industry-academia collaborations should focus on standardizing testing and verification protocols for AI-optimized RF components to accelerate their transition from laboratory prototypes to mass-market adoption. In conclusion, the research provides a strong technical foundation and a set of actionable strategies that can accelerate the evolution of next-generation wireless communication systems, enabling more reliable, efficient, and scalable global connectivity.

References

1. Rappaport TS, Sun S, Mayzus R, *et al*. Millimeter wave mobile communications for 5G cellular: It will work! IEEE Access. 2013;1:335-349.

2. Andrews JG, Buzzi S, Choi W, *et al*. What will 5G be? IEEE J Sel Areas Commun. 2014;32(6):1065-1082.
3. Akyildiz IF, Kak A, Nie S. 6G and beyond: The future of wireless communications systems. IEEE Access. 2020;8:133995-134030.
4. Li S, Xu L, Zhao S. The internet of things: a survey. Inf Syst Front. 2015;17(2):243-259.
5. Lin X, Andrews JG, Ghosh A, Ratasuk R. An overview of 3GPP LTE enhancements on machine to machine communications. IEEE Commun Mag. 2014;50(7):40-47.
6. Ding Z, Poor HV. Energy harvesting wireless communications: a review of recent advances. IEEE Commun Mag. 2015;53(6):102-108.
7. Lee C, Han S, Lee J, Kim D. CMOS RF circuit challenges for 5G communication systems. IEEE Trans Microw Theory Tech. 2017;65(5):1823-1835.
8. Ooi B, Lim K, Lee J. Design of compact microstrip circuits for mmWave applications. IEEE Microw Wirel Compon Lett. 2016;26(10):791-793.
9. Wu Y, Cao Y, Yang L. Design trends in miniaturized microwave circuits. Prog Electromagn Res. 2018;78:1-13.
10. Sharma S, Gupta N, Saxena M. Thermal noise analysis in high-frequency circuits. J Semicond Technol Sci. 2019;19(4):312-321.
11. Chen W, Yang J. Low-noise amplifier designs for mmWave communication. IEEE Microw Mag. 2020;21(3):48-57.
12. Zhang J, Xu W, Wang H. Interference mitigation in next-generation wireless systems. IEEE Commun Surv Tutor. 2019;21(3):2065-2088.
13. Park S, Lee J, Kim H. Dynamic power allocation techniques for 6G networks. IEEE Access. 2021;9:78310-78321.
14. Hasan S, Yilmaz F, Ozkaya A. High frequency circuit stability in harsh environments. Microelectron Reliab. 2022;130:114431.
15. Tanaka T, Watanabe H. AI-assisted circuit optimization for next-generation wireless systems. IEEE Trans Circuits Syst. 2022;69(8):3085-3096.
16. Hu Q, Liu X. Novel semiconductor materials for high-performance microcircuits. Nat Electron. 2023;6(2):124-133.
17. Song H, Kim J. Advanced fabrication processes for ultra-compact RF circuits. IEEE Electron Device Lett. 2023;44(5):701-704.
18. Zhang X, Wang Y. Intelligent microcircuit design for 6G communication networks. IEEE Commun Mag. 2024;62(1):84-91.