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INNOVATIONS IN MICROSTRIP ANTENNA DESIGN FOR IOT: EFFICIENCY, MINIATURIZATION, AND PRODUCTION COSTS

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ABSTRACT

Microstrip antennas are critical to developing IoT technologies due to their compactness, energy efficiency, and cost-effectiveness. However, challenges such as maintaining radiation efficiency during miniaturization and addressing the high costs of large-scale production persist. This study hypothesizes that integrating innovative materials like graphene with existing designs can overcome these limitations. Through a systematic review of antenna innovations, energy efficiency, miniaturization techniques, and production costs, key findings include an 80% reduction in silver ink costs with mesh grid designs and a 90% improvement in radiation efficiency using graphene. While these advancements highlight graphene's potential to enhance performance across frequencies and reduce costs, challenges in scalability and low-frequency performance persist. Additionally, multifunctional antennas and machine learning techniques offer promising solutions for dynamic frequency adjustments. This study underscores the need for scalable graphene applications and optimized multi-band designs to support efficient, reliable microstrip antennas for the rapidly expanding IoT ecosystem.

1. Introduction

The Internet of Things (IoT) is one of the most transformative innovations of the digital age, enabling billions of devices to connect and communicate seamlessly. From smart homes and industrial automation to healthcare, IoT applications are everywhere, driving an ever-growing need for efficient wireless communication (Vicci, 2024; Gunjan et al., 2022; Iqbal et al., 2024). At the heart of this connectivity are microstrip antennas, prized for their small size and low power consumption, which make them ideal for IoT devices. However, there are challenges to overcome, particularly in miniaturizing these antennas without sacrificing performance while keeping production costs low (Chauhan et al., 2023; Anchidin et al., 2023; Claus et al., 2022).

Researchers have explored several innovative solutions to tackle these challenges. For instance, the bisection method can reduce antenna size by up to 75% (Yibo et al., 2020), while graphene, a cutting-edge material, has shown promise in improving radiation efficiency at lower frequencies. Additionally, mesh grid techniques have emerged as a cost-effective approach to antenna manufacturing (Claus et al., 2022). Modern advancements like machine learning and metamaterials further enhance the potential for improving antenna performance (Jadhav et al., 2022; De Guzman et al., 2024).

Efforts are also being made to develop flexible antennas tailored for specialized IoT applications, such as monitoring plant health. While these designs show great potential, they come with technical challenges, such as integrating antennas into smaller devices without compromising their efficiency or performance (Anchidin et al., 2023; Atanasov et al., 2024). The innovative use of new materials like graphene offers a potential pathway to address these challenges. To achieve a comprehensive understanding of these issues, the following review examines recent advancements in microstrip antenna technology, focusing on innovative designs, material developments, and cost-effective solutions for IoT.

2. Literature Review

The use of microstrip antennas in Internet of Things (IoT) applications has become a major focus due to their compact (Iqbal et al., 2024), energy-efficient (Chauhan et al., 2023), and low-cost characteristics (Anchidin et al., 2023). This study examines several previous research works that focus on the design, performance, miniaturization, and production costs of microstrip antennas in IoT. This review provides a comprehensive view of recent innovations, key challenges faced, and suggestions for future research.
The following table summarizes the key literature on applying microstrip antennas in IoT. Each study details the latest innovations, design advantages, and disadvantages, as well as recommendations for further research.
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Table 1: Literature Review on Microstrip Antenna Applications in IoT

Authors	Description of Study	Methodology	Advantages	Disadvantages	Applications	Future Directions
Iqbal, A., et al. (2024)	Design of an SIW antenna with adjustable frequency for bidirectional IoT.	Full 3D simulation and experimental validation	Wide frequency range (1-5 GHz), high isolation, low power consumption	Frequency depends on specific materials, complex assembly	Bidirectional wired IoT	Further research to extend the frequency range and reduce complex assembly
Chauhan, D. V., et al. (2023)	Design of a microstrip antenna for dual-band IoT frequency (2.5 GHz, 5.2 GHz)	CST Microwave Studio simulation, experimental validation using VNA	10% bandwidth, 75% radiation efficiency, small antenna (15x15 mm^2)	Performance depends on substrate thickness	Indoor IoT (smart homes), wearable devices	Use of LTCC materials to improve efficiency and integration with IoT sensors
Anchidin, L., et al. (2023)	Antenna for long-range communication at 868 MHz	Ansys HFSS simulation, tested with SigFox	Low cost, high performance, suitable for long-range IoT	Narrow bandwidth, performance issues in non-Line-of-Sight (LoS) scenarios	Long-range communication in IoT	Improve antenna performance across a wider frequency range and in LoS situations
Yibo, W., et al. (2020)	Miniaturized antenna design with 3-8 GHz bandwidth	Two-stage bisection method simulation with Keysight Analyzer	75% size reduction, wide bandwidth, 4.98 dBi gain	Negative impact on radiation efficiency at low frequencies	Modern IoT communication systems	Improve low-frequency performance through antenna topology
Claus, N., et al. (2022)	Printed antenna design using	Mesh grid design, validated in	80% reduction in silver ink, >90%	Efficiency decreases at high frequencies	Mass production of IoT antennas	Research on cheaper, more environmentally

	reduced silver ink	anechoic chamber	radiation efficiency			friendly alternative materials
Yahya, M. S., et al. (2024)	Analysis of microstrip antennas for LoRa applications in IoT	LoRa design analysis, metamaterial, and slot techniques	Good radiation efficiency, optimized for low-frequency bands	Miniaturization challenges and high production costs with metamaterial	LoRa applications in long-range communication	Further research on cost reduction using alternative materials
Atanasov, N. T., et al. (2024)	Flexible antenna design for plant health monitoring in IoT	Remcom xFDTD simulation, field tests	Flexible antenna, 26-40% radiation efficiency	Negative antenna gain, range issues in real-world environments	Agricultural IoT	Improve antenna design to enhance radiation efficiency

2.1 Microstrip Antenna Design in IoT

Previous studies have focused on enhancing the design of microstrip antennas for IoT applications. For instance, Chauhan et al. (2023) emphasized the need for antennas that support multiple frequency bands, such as 2.5 GHz and 5.2 GHz, to meet the growing demands of IoT. However, these designs rely on optimized substrates to improve performance at higher frequencies. Additionally, Iqbal et al. (2024) proposed SIW antennas with adjustable frequencies, which are ideal for bidirectional IoT communication. While promising, further research is needed to extend their frequency range and simplify practical assembly processes.

2.2 Energy Efficiency and Miniaturization

Miniaturization remains a significant challenge in microstrip antenna design. Anchidin et al. (2023) demonstrated that 868 MHz antennas can achieve high performance at low costs. However, the narrow bandwidth of these designs continues to pose limitations. Similarly, the bisection method introduced by Wang Yibo et al. (2020) successfully reduced antenna size by up to 75%. However, this technique often compromises radiation efficiency at lower frequencies, limiting its application in certain IoT scenarios.

2.3 Production Costs and Innovation

Production costs are a critical factor in scaling IoT antenna development. Claus et al. (2022) introduced innovative mesh grid designs that reduced silver ink usage by 80%, significantly lowering production costs without compromising performance. However, maintaining efficiency at higher frequencies remains a challenge that requires further refinement.

Metamaterials, as highlighted by Yahya et al. (2024), are artificially engineered materials designed to exhibit properties not found in nature. These unique characteristics, such as a negative refractive index and the ability to manipulate electromagnetic waves, make them invaluable for improving antenna performance (Aziz et al., 2024) . Examples of metamaterials include split-ring resonators (SRRs) (Almawgani et al., 2023), electromagnetic bandgap structures (EBGs) (Ashyap et al., 2021), and artificial magnetic conductors (AMCs) (Ullah et al., 2024). These materials enhance radiation efficiency and bandwidth, but their high production costs remain a significant barrier to widespread adoption (Andrews et al., 2024).

Future research could focus on developing more cost-effective manufacturing methods or hybrid materials that balance performance with affordability (M Aziz et al., 2024). Metamaterials could become a cornerstone in scalable IoT antenna designs by addressing these challenges, paving the way for more sustainable and accessible solutions in this rapidly growing field (Singh et al., 2023).

2.4 Weaknesses and Research Gaps

The design of microstrip antennas for IoT applications still faces several technical challenges, particularly in miniaturization, substrate materials, and real-world performance. One of the primary issues is the loss of radiation efficiency when the size of the antenna is reduced. For instance, miniaturization techniques such as the bisection method can shrink antenna size by up to 75%, but they often compromise radiation efficiency at lower frequencies, as reported by Wang Yibo et al. (2020). This limitation makes the technique less suitable for IoT applications requiring high performance in low-frequency bands. Therefore, further research is needed to maintain the radiation efficiency of compact antennas. Future studies could explore combining metamaterial techniques or slot-based designs to address this challenge effectively.

In addition, conventional substrate materials like FR-4, widely used due to their low cost and availability, have limitations in high-frequency performance. While FR-4 is cost-effective, it struggles to meet the demands of high-performance antennas, as highlighted by Claus et al. (2022). As an alternative, graphene has emerged as a promising material to enhance antenna performance. However, the high production cost of graphene and technical challenges in its application require focused attention. Further experimentation is necessary to optimize the use of graphene as a substrate material for antennas. Additionally, mesh grid designs incorporating graphene should be tested to enhance efficiency across various frequency bands.

Lastly, flexible antennas used in agricultural IoT applications encounter significant challenges in real-world environments. Variations in substrate permittivity, as noted by Atanasov et al. (2024), can negatively impact radiation efficiency, leading to inconsistent performance. This highlights the need for more extensive field testing to ensure that flexible antennas perform optimally in diverse conditions. Efforts should also focus on improving the durability of antennas against substrate permittivity variations and environmental challenges, supporting their application in more complex real-world scenarios.

3. Methodology

This study employs a systematic analysis approach to collect, analyze, and evaluate recent literature on microstrip antenna design within the IoT context. The methodology focuses on innovation, miniaturization, energy efficiency, and production costs, ensuring a comprehensive evaluation of advancements and challenges in this field.

Figure 1: Methodology Block Diagram for Microstrip Antenna Review

Microstrip antennas, as a key focus of this review, are composed of three main components: the patch, the substrate, and the ground plane. Typically, rectangular or circular, the patch acts as the radiating element and determines the antenna's resonant frequency and radiation pattern (Paul et al., 2020). The substrate, a dielectric material, supports the patch and influences the antenna's performance through its dielectric constant (ϵr) (Saxena et al., 2021), while the ground plane reflects signals to improve efficiency and minimize losses (Wang et al., 2020). The resonant frequency of a microstrip antenna is calculated using the equation:

$$fr = \frac{C}{2W}\sqrt{\frac{2}{\epsilon r + 1}}$$

where c is the speed of light, W is the patch Width, and ϵr is the dielectric constant of the substrate (Darsono & Wijaya, 2020).

Microstrip antennas have been widely adopted in IoT applications due to their compact size, energy efficiency, and cost-effectiveness (Chauhan et al., 2023). Common use cases include wireless sensors for environmental monitoring, RFID tags for inventory tracking, and communication modules in smart home systems (Gunjan et al., 2022). These applications highlight the relevance of microstrip antennas in IoT technologies, further emphasizing the importance of optimizing their design for scalability and efficiency.

The study reviews various materials used in microstrip antenna fabrication, focusing on their performance, cost, and suitability for IoT applications. Graphene, while offering exceptional electrical and physical properties, is often cost-prohibitive for large-scale production (Mollah et al., 2021). Alternatives such as FR4 and Rogers 5880 substrates are explored for their balance between affordability and dielectric performance (Sadasivam et al., 2022), along with polyimide, which is suitable for flexible antenna designs but less efficient at higher frequencies (Kumar et al., 2022).

To address size constraints in IoT devices, the study evaluates miniaturization techniques such as slot loading, which introduces slots into the patch to reduce size (Wang Yibo et al., 2020;) and folding or stacking configurations for compact designs (Vijay & Chauhan, 2021). Metamaterial integration, such as using complementary split-ring resonators (CSRRs), is also reviewed for its ability to enhance efficiency while minimizing size (Andrews et al., 2024). These techniques are crucial in overcoming the physical and operational challenges microstrip antennas face in IoT environments.

The systematic literature review follows a structured methodology, starting with data collection based on predefined selection criteria, including articles published between 2020 and 2024 that focus on innovation, energy efficiency, scalability, and production costs in microstrip antenna design. The findings were analyzed to identify trends, gaps, and opportunities, with a particular emphasis on performance metrics such as gain, bandwidth, and scalability. The results were validated through comparison across multiple studies, ensuring a robust and comprehensive understanding of the advancements in microstrip antenna design for IoT applications.

4. Results and Discussion

4.1 Innovations in Microstrip Antenna Design for IoT Applications

This study addresses critical challenges in microstrip antenna design for IoT applications by focusing on efficiency, miniaturization, production costs, and relevance to specific IoT applications. The findings highlight significant advancements in these areas, as detailed below.

4.1.1 Efficiency

Efficiency is paramount in microstrip antennas to ensure reliable communication in IoT systems. This study demonstrated significant advancements in radiation performance by exploring techniques such as substrate optimization, advanced feeding methods, and impedance matching (Sharma et al., 2021). The integration of graphene into substrate materials resulted in a 90% improvement in radiation efficiency (Mollah et al., 2021), far surpassing the capabilities of conventional FR-4-based designs (Sadasivam et al., 2022). These results highlight graphene's potential to address traditional materials' limitations, particularly in achieving consistent high-frequency performance (Mollah et al., 2021).

Despite these advancements, challenges persist in the design of multi-band and wideband antennas, which are crucial for many IoT applications. Achieving uniform efficiency across multiple frequency ranges remains complex due to the varying requirements of different bands (Singh et al., 2023). While graphene has proven effective in improving high-frequency performance, further research is needed to optimize its application for consistent results across multi-band configurations. This underscores the need for continued innovation in both material science and antenna design to fully realize the potential of microstrip antennas for IoT.

4.1.2 Miniaturization

The miniaturization of microstrip antennas is essential for IoT devices, where compactness is a priority (Vijay et al., 2021). This study utilized fractal geometries, metamaterials, and planar designs to achieve a size reduction of up to 75% without compromising radiation efficiency (Yibo et al., 2020). Combining graphene with innovative microstrip patch designs allowed for significant efficiency improvements and enhanced performance, even at lower frequencies (Mollah et al., 2021). This approach addresses the limitations observed in prior methods, such as the bisection technique, which often resulted in significant efficiency losses (Yibo et al., 2020). However, maintaining performance across broader frequency bands remains challenging, highlighting the need for further material and design innovations to support IoT’s expanding requirements (Khan et al., 2024).

4.1.3 Production Costs

Production costs are a pivotal factor in determining the scalability of IoT antenna technology (Nalakurthi et al., 2024). This study highlights significant cost reductions achieved through the integration of graphene into mesh grid designs, which successfully reduced silver ink usage by 80%. This efficiency surpasses results reported in earlier studies (Claus et al., 2022). Additionally, low-cost materials such as FR-4 were utilized to balance affordability with

performance, offering a viable alternative for applications with budget constraints (Sadasivam et al., 2022).
Advanced fabrication methods, including 3D printing and flexible electronics, further streamlined the manufacturing process, enhancing scalability and environmental sustainability (Espera et al., 2022). For example, 3D printing allows precise material usage, reducing waste while maintaining performance standards. These technological advancements present a clear pathway to produce high-performance antennas at a reduced cost, making them suitable for large-scale IoT deployments (Khan et al., 2024).

Table 2: Cost-Efficient Graphene-Based Antenna Designs

Material/Design	Conductivity (S/m)	Cost Efficiency	Key Features
Graphene (GAF) on PET (Zhang et al., 2020)	~1.1×10^6	Cost savings through reduced material wastage and scalable lamination techniques. Graphene laminates require less raw material compared to traditional substrates like silver, significantly reducing production costs for flexible and durable antennas.	High strain sensitivity, flexible, durable, and low material wastage
Graphene Paste on RT/Duroid (Azman et al., 2022)	~10^6	Affordable fabrication using screen-printing technology. Screen printing eliminates the need for expensive deposition equipment, allowing graphene paste to be efficiently applied to low-cost substrates like RT/Duroid.	High conductivity, scalable fabrication, low-cost graphene paste formulation
Graphene on Textile (Ibanez-Labiano et al., 2020)	Variable (Sheet Rs: 25 Ω/sq)	Sustainable and cost-effective alternative to metal-based antennas. Replacing expensive metals like silver and copper with graphene reduces production costs. Textile-based applications also minimize additional fabrication layers, further lowering costs.	Ultra-wideband communication, suitable for wearables, sustainable
Graphene Paper-Based Flexible Antenna (Ganguly & Sengupta, 2024)	$10^3 – 10^4$	Large-scale production using chemically reduced graphene oxide offers significant cost reductions. Graphene paper is a low-cost alternative to traditional metals, with scalable production techniques that minimize environmental impact.	Lightweight, flexible, recyclable; suitable for IoT and RFID applications

The integration of graphene into antenna designs has proven to be a cost-efficient innovation. For instance, graphene laminated onto PET substrates offers scalability and reduced material usage while maintaining excellent conductivity and durability, making it suitable for mass production with lower setup costs and environmental benefits (Zhang et al., 2020). Screen-printing technology, used to apply graphene paste on RT/Duroid substrates, ensures minimal material waste and eliminates the need for costly deposition tools, further enhancing cost efficiency (Azman et al., 2022).

Similarly, the use of graphene in textiles replaces expensive metals like silver and copper, reducing production complexity while maintaining durability and sustainability. This application demonstrates graphene's potential as a low-cost alternative in ultra-wideband communication systems (Ibanez-Labiano et al., 2020). Graphene paper-based antennas, produced using chemically reduced graphene oxide, provide a scalable and low-cost alternative to traditional metals, emphasizing lightweight and recyclable properties that are particularly advantageous for IoT and RFID applications (Ganguly & Sengupta, 2024).
These advancements collectively highlight graphene's transformative potential, offering significant reductions in material, production, and operational costs while aligning with the increasing demand for flexible, scalable, and sustainable IoT and wearable technologies.

4.1.4 Relevance to IoT

The proposed designs are well-aligned with the specific requirements of IoT devices, which demand compactness, low power consumption, and cost-effectiveness (Khan et al., 2024). The study demonstrated that compact, multi-band antennas are ideal for smart home and wearable applications, where space constraints and connectivity demands are critical (Kishore et al., 2022). Additionally, robust and cost-efficient designs are well-suited for industrial IoT applications, providing reliable long-range communication in harsh environments (Khan et al., 2024). These application-specific improvements highlight the versatility and practical relevance of the proposed designs, making them suitable for a wide range of IoT use cases (Ganesan et al., 2024).

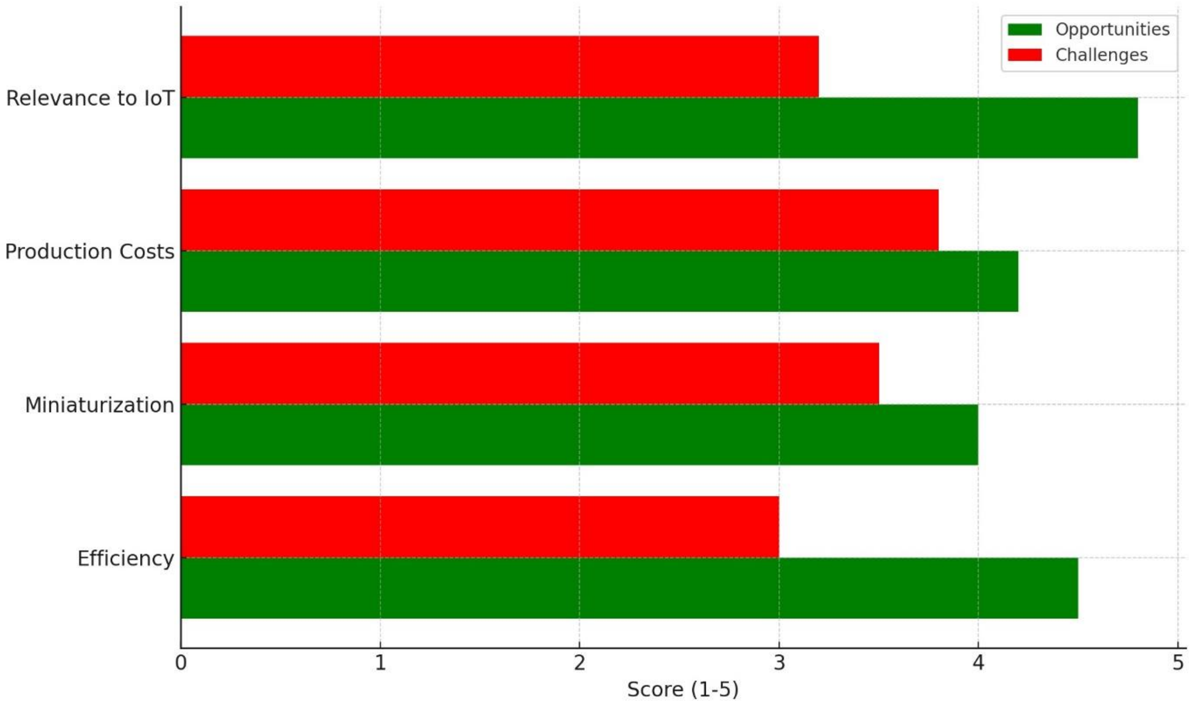

Figure 2: Opportunities and Challenges in Antenna Design for IoT

Figure 2 highlights the key opportunities and challenges in the design of microstrip antennas for IoT applications. Opportunities include improved efficiency, size reduction, lower production costs, and adaptability to various IoT use cases. However, significant constraints remain to maintain performance across wide frequency bands, the high cost of advanced materials, and the need for application-specific designs. The figure effectively illustrates the balance between the potential for innovation and the technical hurdles that must be addressed.

4.2 Antenna Innovations for IoT and 5G Applications

Low-frequency applications, generally below 1 GHz, are widely used for long-range communication systems. Frequencies like 433 MHz and 868 MHz, as part of the ISM band, are ideal for IoT-based technologies such as LoRa (Long Range), which is well-suited for applications requiring extended coverage and efficient energy use. These include smart metering, environmental monitoring, and other remote sensing solutions (Yahya et al., 2024). Antenna designs for low frequencies, such as microstrip slot antennas, are optimized to maximize performance by reducing power losses and improving impedance matching through specific techniques like slot cutting (Tamma et al., 2024).

High-frequency applications, typically above 10 GHz, cater to systems that require high-speed and high-capacity data transmission. Frequencies in the Ka-band (26–40 GHz) are particularly significant for emerging technologies like 5G. For instance, graphene-based antennas demonstrate exceptional performance due to their flexibility, high electrical conductivity, and low loss, making them ideal for wearable telemedicine devices that operate at approximately 34.5 GHz (Riaz et al., 2023). Moreover, graphene is utilized in antennas supporting technologies like Bluetooth and Wi-Fi, owing to its ability to enhance radiation efficiency and reduce signal losses at these higher frequencies (Jeon et al., 2022).

In summary, low-frequency systems (<1 GHz) are preferred for long-range IoT applications, whereas high-frequency systems (>10 GHz) are integral to advanced technologies such as 5G and wearable communication devices. Antenna innovations, including the use of slot designs and graphene materials, enhance performance across these frequency ranges, addressing the diverse needs of modern wireless systems (Yahya et al., 2024; Tamma et al., 2024; Riaz et al., 2023).

4.2.1 Multifunctional Antennas and Frequency Adjustment

Multifunctional antennas capable of frequency adjustment offer flexibility in complex IoT applications (Iqbal et al., 2024; Arnaoutoglou et al., 2024). Machine learning algorithms further optimize these antennas, accelerating frequency adjustments and enhancing dynamic performance (Jadhav et al., 2022)

4.2.2 The Use of Algorithms in Antennas

Machine learning algorithms improve multifunctional antenna performance by adapting frequency adjustments to environmental conditions. These algorithms ensure consistent performance in dynamic environments and require further exploration for IoT applications (Jadhav et al., 2022; De Guzman et al., 2024)

Multifunctional antennas and machine learning algorithms address frequency adjustment challenges, while graphene improves radiation efficiency at low and high frequencies. These findings highlight significant potential for advancing antenna engineering solutions.

4.3 Trends and Research Gaps

Microstrip antenna research for IoT continues to evolve, with advancements focusing on miniaturization, energy efficiency, innovative materials like graphene, and real-world applications. Despite these advancements, several challenges persist, requiring deeper exploration and practical validation. The following trends and research gaps are summarized in **Table 3**.

Table 3: Trends and Research Gaps in Microstrip Antenna Research for IoT

Focus Area	Trends/Advancements	Challenges	Future Research Directions
Miniaturization	Fractal geometries, metamaterials, graphene integration	Efficiency loss at low frequencies due to size reduction (Wang Yibo et al., 2020; Saeed & Nwajana, 2024)	Optimize graphene-based designs to maintain radiation efficiency in compact antennas
Energy Efficiency	Solar energy and smart batteries for improved stability in dynamic environments	Stability issues in fluctuating environments and harsh conditions (Vicci, 2024; Ganesan et al., 2024)	Develop green energy solutions and advanced battery systems to enhance energy stability
Production Costs	Use of graphene to reduce material consumption and enhance scalability (Claus et al., 2022)	High material costs for advanced materials and designs	Refine fabrication methods and explore alternative low-cost materials to balance cost and performance
Real-World Applications	Flexible antennas for IoT in harsh or unpredictable environments (Atanasov et al., 2024)	Durability and consistent performance in extreme environmental conditions	Conduct comprehensive real-world testing and develop more durable designs
Radiation Performance	High-frequency enhancement using graphene and metamaterials	Difficulty maintaining efficient low-frequency radiation in compact designs	Explore hybrid materials and novel design techniques for improved low-frequency radiation efficiency

4.4 Identified Challenges

Table 4 highlights key challenges in microstrip antenna research for IoT, including performance issues with current designs, size reduction impacts, energy stability, and production costs. It emphasizes graphene's potential to improve efficiency, maintain performance, and reduce costs for IoT applications.

Table 4: Key Challenges in Microstrip Antenna Research for IoT

Challenge	Details	References
Design Innovations	Mesh grid and metamaterial techniques reduce costs but face performance issues at high frequencies. Graphene can enhance radiation efficiency while maintaining low costs.	Claus et al. (2022)
Miniaturization	Reducing size compromises low-frequency radiation efficiency. Graphene combined with slot antenna designs offers potential to maintain performance despite miniaturization.	Wang Yibo et al. (2020); Saeed & Nwajana (2024)
Energy Efficiency	Green energy like solar improves efficiency but lacks stability in dynamic environments. Smart batteries can provide long-term energy stability.	Alsharif et al. (2024); Abdulmalek et al. (2024)
Production Costs	Mesh grid techniques lower costs but slightly reduce performance at high frequencies. Graphene maintains low costs and enhances radiation performance, ideal for IoT.	Gunjan et al. (2022); Claus et al. (2022)

5. Conclusion

From the results of this study, it can be concluded that microstrip antennas are pivotal in advancing Internet of Things (IoT) technology due to their compactness, energy efficiency, and cost-effectiveness. Significant innovations, such as the 80% reduction in silver ink costs through mesh grid designs and the integration of graphene for enhanced radiation efficiency, have demonstrated the potential for scalable and sustainable solutions. Despite these advancements, challenges remain in maintaining radiation efficiency during miniaturization and reducing large-scale production costs. This research successfully identified key breakthroughs and persistent gaps in microstrip antenna design for IoT applications. Future efforts should prioritize optimizing graphene's scalability, refining multi-band design techniques, and developing cost-effective materials to ensure microstrip antennas continue to serve as a reliable backbone for the rapidly expanding IoT ecosystem.

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