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A Review on Sub-6GHz Multiband Antennas for 5G-Based IoT Systems

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ABSTRACT:
The fast growth of fifth-generation (5G) networks and Internet of Things (IoT) requires the development of compact high-performance antennas which operate within the sub-6 GHz spectrum. The antennas need to support multiple frequency bands while keeping high efficiency levels and delivering dependable operation for wearable electronics and smart sensors and high-capacity Multiple-Input Multiple-Output (MIMO) systems. This review provides an extensive evaluation of modern sub-6 GHz antenna designs through an examination of four prominent antenna types which include microstrip patch antennas, slot antennas, monopole antennas and Planar Inverted-F Antennas (PIFA). The paper examines multiple advanced enhancement methods which include slot and stub loading together with Defected Ground Structures (DGS) and Metamaterials/Metasurfaces and reconfigurable mechanisms and machine learning-assisted optimization and flexible material utilization. Additionally, the evaluation of selected studies examines key performance parameters which include gain, efficiency, reflection coefficient (S11), Envelope Correlation Coefficient (ECC), mutual coupling, polarization, compactness and Specific Absorption Rate (SAR) are discussed. The analysis of existing literature shows that ECC and SAR and polarization diversity metrics receive insufficient reporting in wearable and MIMO antenna research. Finally, the review paper identifies design limitations for advancing antenna development in 5G-enabled IoT systems.
KEYWORDS: Sub-6 GHz, Multiband Antenna, PIFA, IoT, Slot Antennas

1. INTRODUCTION:

The Internet of Things (IoT) rapid expansion together with fifth-generation (5G) communication systems deployment requires immediate development of high-performance antennas that function optimally in sub-6 GHz spectrum. The sub-6 GHz bands serve as the preferred choice for IoT applications because they offer beneficial propagation properties and reduced signal loss and work well in both indoor and outdoor settings compared to mmWave frequencies [1]. The antennas operating in this spectrum need to fulfill exact requirements for multiband functionality and miniaturization and gain and reliability to support wearable electronics and wireless sensors and massive machine-type communications. The systems require multiband and MIMO antennas as fundamental components to boost data throughput and channel capacity and spectral efficiency [2]. The development of antennas which combine compactness with high isolation and stable gain and low mutual coupling presents a major design challenge. The conventional design process frequently disregards essential performance parameters which include polarization diversity and efficiency and Specific Absorption Rate (SAR) safety constraints [3].The recent literature presents multiple methods to overcome these system limitations. The MIMO system performance has been enhanced through the implementation of defected ground structures (DGS) and metamaterials and slot/stub loading techniques [4]. The use of PIN diodes and tunable components enables reconfigurable antennas which provide adaptive radiation characteristics and frequency agility for dynamic IoT scenarios [5]. The development of wearable and body-centric antenna designs continues for health monitoring and on-body communications applications [6]. The evaluation of recent sub-6 GHz antenna designs for their performance across multiple applications remains incomplete. This paper reviews specific multiband and MIMO antenna studies to evaluate their gain and efficiency and polarization and compactness and isolation features for future 5G-enabled IoT system design guidance.This review examines recent advancements in multiband antenna designs to meet the evolving requirements of efficient antenna systems in 5G sub-6 GHz applications. The review examines essential performance characteristics while discussing the emerging trends and breakthroughs that will define the future of 5G connectivity. The main contributions of this review are summarized as follows:

- Reviews various recent types of multiband antennas for 5G sub-6 GHz applications.
- Discusses key antenna performance parameters such as reflection coefficient, gain, efficiency, and radiation pattern.
- Summarizes various design techniques used to achieve compact, efficient, and multi-frequency operation.
- Highlights challenges and overlooked factors in current antenna research, including polarization and integration issues.

The rest of the paper is structured as follows. Section 2 reviews existing surveys and identifies research gaps. Section 3 explores antenna types used in sub-6 GHz systems. Section 4 discusses performance requirements and design techniques. Finally, Section 5 concludes the paper.

2. RELATED WORK AND RESEARCH GAPS:

Multiple review articles have investigated antenna technologies for 5G communication, especially in the sub-6 GHz spectrum. Table 1 summarizes these works, outlining key contributions, performance metrics, and research gaps. While all of the referenced review papers have adequately addressed fundamental parameters such as reflection coefficient (S11) and radiation pattern, our review deliberately focuses on performance aspects that are often underrepresented or inconsistently evaluated such as envelope correlation coefficient (ECC), mutual coupling, SAR compliance, and polarization diversity. These overlooked yet critical parameters are essential for the robust performance of modern antennas in compact, MIMO-enabled, and wearable IoT platforms.

Table 1: Comparison of Antenna Design Features in Existing Review Papers

Ref.	Gain	ECC	Polarization	Mutual Coupling	Compactness	Specific Absorption Rate	Efficiency	5G/IoT Application
[4]	✓	✓	×	✓	×	×	×	✓
[7]	✓	✓	×	×	×	×	×	✓
[8]	✓	✓	×	✓	×	×	✓	×
[9]	×	×	✓	×	✓	✓	✓	✓
[10]	✓	×	×	×	×	×	×	✓
This Work	✓	✓	✓	✓	✓	✓	✓	✓

Jayaraman et al. [4] deliver a comprehensive review of MIMO antenna designs that focuses on methods to increase gain while minimizing mutual coupling. The research examines multiple techniques including metamaterials and defected ground structures (DGS) and parasitic elements and orthogonal placement and frequency selective surfaces (FSS) with an emphasis on compact designs. The paper explains and evaluates performance metrics which include gain and isolation and envelope correlation coefficient (ECC) and total active reflection coefficient (TARC). The review presents tables and figures which compare existing MIMO antennas together with their structural designs and design requirements. The study fails to provide specific information about Specific Absorption Rate (SAR) and polarization performance which are essential for wearable and biomedical IoT applications. The article provides detailed technical information which makes it useful for researchers who focus on sub-6 GHz and beyond 5G communication systems.Chhaule *et al.* [7] present a detailed evaluation of microstrip patch antenna (MPA) designs for 5G systems which includes both traditional optimization methods and machine learning-based optimization techniques. The authors organize antennas through four categories which include patch modifications and slot/stub integration and defected ground structures and multilayer and reconfigurable architectures. The paper examines S11 (reflection coefficient) and gain and efficiency and radiation pattern through design recommendations and performance comparison tables. The authors investigate machine learning models including artificial neural networks (ANN) and radial basis function networks (RBF) to optimize bandwidth and directivity and resonance frequency. The research provides complete coverage of ECC and mutual coupling and polarization aspects for reconfigurable and MIMO antenna arrays. The paper briefly mentions Specific Absorption Rate (SAR) but fails to conduct a thorough analysis of SAR across different design approaches. The review provides an extensive and forward-thinking evaluation of 5G antenna optimization which will be beneficial for researchers who want to use ML-driven design automation. Garcia *et al.* [8] present a detailed assessment of reconfigurable antenna systems for IoT devices by focusing on electrical reconfiguration methods that include PIN diodes, varactors and RF switches. The authors organize reconfiguration techniques into four categories which include electrical, mechanical, optical and material-based approaches while stressing that electrically reconfigurable antennas represent the best choice for small IoT devices that require low power consumption. The study presents radiation pattern and polarization agility through different case examples. The article successfully explains the trade-offs between compactness and efficiency but it fails to provide extensive details about ECC diversity metrics and it does not offer enough comparison of gain between different designs. The study presents S11 characteristics through case illustrations to demonstrate frequency tunability and device adaptability.

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Yahya *et al.* [9] delivered their initial review of LoRa-based microstrip patch antennas (MPAs) which addresses both design challenges and strategies for low-power long-range IoT communication. The authors divide MPAs into five categories which include monopole, PIFA, dipole, Yagi-Uda and wearable formats and explain enhancement techniques through metamaterials, slots and EBG structures. The paper discusses essential antenna performance characteristics including gain and radiation pattern and efficiency and polarization but it fails to address ECC and SAR. The paper presents tabulated performance summaries but it does not provide a complete comparison of mutual coupling and S11 metrics between different designs. The paper functions as a helpful resource for optimizing LoRa-specific antennas yet its absence of standardized evaluation criteria restricts its usefulness for general 5G antenna development. Kirtania *et al.* [10] conduct a detailed analysis of flexible antenna technologies which they focus on wearable and biomedical IoT systems. The research investigates substrate materials and conductive elements such as graphene and PEDOT, PSS and nanowires and production techniques which ensure antenna performance during bending and deformation. The review focuses on SAR requirements and gain maintenance in flexible environments yet it fails to provide systematic evaluations of ECC or mutual coupling and lacks structured S11 or impedance matching analysis across reviewed designs. The paper provides exceptional insights about substrate behavior and conformal deployment and high-frequency application readiness which establishes a solid base for flexible antenna designers working on next-generation wireless systems.

2.1 SCOPE OF THE REVIEW: The review evaluates contemporary antenna technology research for sub-6 GHz 5G and Internet of Things (IoT) applications through examinations of multiband, MIMO, reconfigurable, LoRa-based and flexible antenna structures. The review synthesizes findings from leading review articles to assess the coverage and depth of fundamental performance metrics which include gain, radiation pattern, envelope correlation coefficient (ECC), mutual coupling, reflection coefficient (S11), efficiency, polarization, SAR, and compactness. The selected studies span multiple application domains which include high-capacity MIMO systems and machine learning-assisted designs as well as reconfigurable IoT antennas and body-conformal flexible antennas. The review both summarizes current design approaches and reveals research deficiencies which include inconsistent ECC and SAR treatment and insufficient performance metric benchmarking and missing unified design evaluation frameworks. The analysis provides direction for future antenna development which addresses requirements of 5G and wearable and IoT environments.

3. COMMON MULTIBAND ANTENNA TYPES FOR SUB-6 GHZ 5G APPLICATIONS: These four common multiband antenna types are microstrip patch, slot, monopole, and PIFAare widely adopted in sub-6 GHz 5G systems due to their compactness, bandwidth versatility, and suitability for integration in IoT and portable devices. Each design offers unique advantages in performance metrics such as gain, efficiency, and reconfigurability, making them key enablers for next-generation wireless networks.

3.1 MICROSTRIP PATCH ANTENNA: The planar structure and compact size of microstrip patch antennas makes them suitable for IoT and portable wireless applications in sub-6 GHz 5G systems. Recent advancements aim to enhance performance metrics such as gain, bandwidth, and efficiency by introducing techniques like slot loading, parasitic element coupling, and defected ground structures (DGS). Alharthi and Podilchak proposed a compact patch antenna incorporating rectangular and circular slots with parasitic strips, achieving high gain and broad impedance bandwidth in the C-band range [11]. Chhaule et al. conducted a thorough review which demonstrated that patch antennas continue to be the preferred choice for 5G design because of their thin profile and discussed optimization techniques including machine learning-based design and multiband tuning methods [7]. The advancements demonstrate that microstrip patch antennas will continue to serve as fundamental technology for sub-6 GHz 5G communication systems. Their ability to meet current performance requirements makes them essential components for future wireless communication networks.

3.2 SLOT ANTENNA: Sub-6 GHz 5G systems use slot antennas due to their compact size, extensive bandwidth possibilities, and ease of integration with planar circuits. An innovative compact semi-circular slot (SCS) 2 × 2 MIMO antenna design was developed for 5G NR sub-6 GHz applications, achieving high isolation and excellent impedance matching. The antenna exhibited an impedance bandwidth ranging from 5.10 GHz to 5.80 GHz, with a return loss of −39.5 dB, confirming its suitability for sub-6 GHz 5G communication. [12]. A slotted plus-shaped patch antenna (PSPA) including a defective ground structure (DGS) was proposed for 5G Sub-6 GHz and WiMAX applications. The antenna offered a wide bandwidth of 2.56 GHz, ranging from 2.67 GHz to 5.23 GHz, making it suitable for 5G sub-6 GHz applications [13]. The designs illustrate how slot antenna shapes can produce compact, high-performance systems. The integration of MIMO capabilities with effective radiation properties establishes slot antennas as a preferred option for future 5G antenna advancement.

3.3 MONOPOLE ANTENNA: The 5G systems that operate in sub-6 GHz frequencies use monopole antennas because they offer compact dimensions and omnidirectional radiation patterns and work well with portable and IoT devices. Iriqat et al. [14] designed a dual-band 2 × 1 monopole antenna array using a rectangular patch with circular and thin slots and a defected ground structure to achieve a wide bandwidth of 2–7.62 GHz and a peak gain of 6.47 dBi which supports WiMAX and sub-6 GHz and sub-7 GHz applications. Askari et al. [15] created a circularly polarized monopole antenna with an artificial magnetic conductor (AMC) as the backing which boosted the gain from 3.3 dBic to 8.7 dBic and widened the axial ratio bandwidth from 27.27% to 51.67% to support the n77/n78/n79 5G bands. The designs prove that monopole antennas remain essential for building multiband and high-performance features in future 5G wireless networks.

3.4 PLANAR INVERTED-F ANTENNA: The Planar Inverted-F Antennas (PIFAs) serve as a popular choice for sub-6 GHz 5G and vehicular-to-everything (V2X) wireless systems because they offer compact dimensions and low profile alongside omnidirectional radiation patterns. The research by Ghosh et al.[16] introduced a wideband low-profile PIFA for vehicular communication which operates from 617 MHz to 6 GHz to support major 5G and V2X frequency bands. The antenna design provided both high efficiency and stable radiation patterns together with compact integration capabilities that made it suitable for automotive platforms. Khan et al. [17] created a frequency reconfigurable compact PIFA using PIN diodes for portable 5G-enabled devices. The antenna system operated through dynamic resonance switching between 3.5 GHz and 4.6 GHz frequencies to support flexible 5G sub-6 GHz band adaptation. The research shows how PIFA structures effectively address wireless devices' dynamic frequency needs and compact integration requirements for next-generation wireless technology. PIFAs represent an ideal solution for 5G IoT applications because they offer tunable or broadband operation with low SAR values and simple structures.

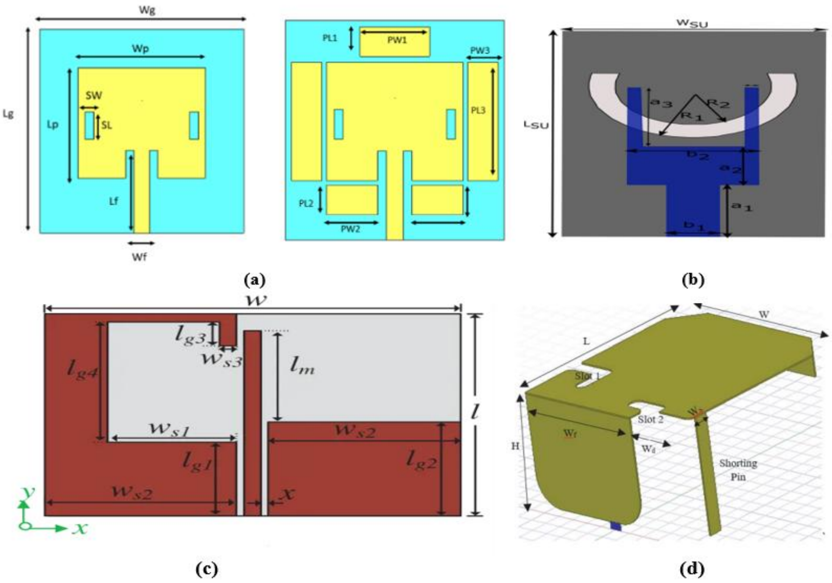

Figure 1: Structural models of typical sub-6 GHz antenna types for 5G communication: (a) microstrip patch (b) slot (c) monopole; and (d) PIFA.

4. ADVANCED TECHNIQUES AND PERFORMANCE METRICS IN 5G ANTENNA DESIGN

The development of fifth-generation wireless communication technology requires antennas to achieve better gain performance and efficiency and compact design and low mutual coupling especially in multiband and MIMO systems. Researchers have developed multiple advanced antenna design techniques which include slot and stub loading and defected ground structures (DGS) and metamaterial integration and reconfigurable mechanisms and machine learning-assisted optimization. These methods enhance fundamental parameters including radiation efficiency and bandwidth while providing dynamic adaptability for integration into compact devices such as IoT sensors and wearable electronics.

Table 2: Comparative Table of Advanced Antenna Performance Enhancement Techniques with Quantitative Metrics

References	Techniques	Description	Performance Metrics Improvement
[18]	Slot and Stub Loading	This study presents a compact PIFA using stub and slot loading techniques to achieve miniaturization. The approach effectively reduces antenna size while maintaining acceptable radiation performance, making it suitable for wireless devices where limited space is a key constraint.	Size reduced by 30%, gain approximately -2 dB, bandwidth around 4%, improved compactness.
[19]	Defected Ground Structure (DGS)	This study investigates the use of DGS in a microstrip patch MIMO antenna to improve radiation characteristics. The DGS pattern alters the current distribution, leading to enhanced gain, reduced mutual coupling, and high radiation efficiency. It is particularly effective in compact MIMO systems for WLAN applications.	Gain increased to approximately 9.5 dBi, mutual coupling reduced to below -20 dB, radiation efficiency improved to 93%.
[20]	Metamaterials/Metasurfaces	This 2024 study presents a microstrip patch antenna array enhanced with a single-layer metamaterial superstrate made of circular ring elements. The structure improves electromagnetic wave focusing and impedance matching, resulting in higher gain and efficiency for X-band applications.	Gain enhanced by ~2 dB (27.38%), efficiency improved to ~79.11%, reflection coefficient improved from -48.6 dB to -58.1 dB, operating at 10 GHz.
[21]	Reconfigurable techniques	This 2025 study introduces a compact Reuleaux-triangle-shaped monopole antenna featuring PIN diodes for switching between UWB and Ku bands. Rectangular slits and DGS enhance return loss and bandwidth, making it suitable for 5G, aerospace, and satellite systems.	Frequency bands reconfigured between 2.68–8.55 GHz (UWB) and 12.7–15.65 GHz (Ku), gain improved up to 3.85 dBi, antenna size 20 × 30 mm
[22]	ML-Assisted Optimization	This study presents a triangular microstrip patch antenna optimized using an ELM-based CryStAl algorithm for C-band applications. The approach enhances gain and return loss while maintaining a compact design, demonstrating the effectiveness of ML-assisted optimization in antenna performance enhancement.	Gain increased to 5.09 dB, return loss improved to -32.71 dB, VSWR reduced to 1.2
[23]	Flexible Materials	This study analyzes a Wi-Fi microstrip patch antenna operating at 2.4 GHz using flexible substrates like leather, fleece, and felt. It examines the antenna's performance under various bending conditions to assess suitability for wearable applications.	Maintained return loss below -15 dB, bandwidth exceeding 4%, gain over 5 dB, and VSWR under 2.5 across bending angles up to 17°.
[24]	Parasitic/Decoupling Element	This study presents a dual-band PIFA design employing LPEs and a BL to achieve low mutual coupling and dual-band operation. The approach effectively reduces antenna size while maintaining acceptable radiation performance, making it suitable for space-constrained wireless applications	Isolation improved to below -20 dB, dual-band operation at 2.0 GHz and 2.4 GHz, compact design
[25]	Orthogonal Polarization	This study proposes a dual-band 4-element MIMO microstrip antenna with orthogonal circular polarization for Sub-6 GHz 5G systems. The use of elliptical ring slots and asymmetric feed lines achieves improved isolation, diversity, and reduced coupling in a compact layout.	Isolation greater than 15 dB, ECC less than 0.04, simulated gain of 4 dBic and 5 dBic in respective bands, enhanced diversity and polarization performance

5. CONCLUSION:

The fast adoption of IoT devices with 5G networks creates a growing need for small high-performance multiband antenna systems that operate within the sub-6 GHz spectrum. This review examined recent advancements in sub-6 GHz antenna design through evaluations of microstrip patch, slot, monopole and PIFA structures and emerging technologies including metamaterials and reconfigurable mechanisms and machine learning-assisted optimization. The review evaluated selected papers based on performance metrics which included gain, efficiency, mutual coupling, reflection coefficient (S11), ECC, polarization, compactness and SAR to identify strengths and gaps and trends. Several studies focused on gain and compactness but failed to address essential parameters such as SAR and ECC which are crucial for wearable and MIMO-enabled devices. The review emphasized the requirement for standardized benchmarking systems and complete trade-off evaluations between design parameters. Future antenna research must focus on developing adaptable low-profile designs which meet performance requirements and regulatory standards and integration needs. This research provides essential guidance to researchers and engineers who want to create optimized antennas for the developing 5G-enabled IoT environment.

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