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A LITERATURE REVIEW ON THE APPLICATIONS OF TRI-BAND MIMO ANTENNAS IN MULTI-STANDARD SUB-6 GHZ SYSTEMS

Mr. Suresh Shripatrao Kambale[1], Dr. Anuradha Deshpande[2]

[1]Research Scholar, Department of Electronics & Telecommunication Engg, JSPM University Pune
Email: sushrikambale@gmail.com
[2]Research Guide, Electronics & Telecommunication Engg, JSPM University Pune
Email: asd.secs@jspmuni.ac.in

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***ABSTRACT*:**

The demand for high-speed, low-latency, and reliable wireless communication has intensified with the rollout of 5G networks. To meet these requirements, Multiple-Input Multiple-Output (MIMO) antennas have become vital, especially in the Sub-6 GHz band due to its favourable balance between coverage and data rate. This study proposes the design and simulation of a compact Tri-band MIMO antenna operating at 2.4–2.5 GHz, 3.4–3.6 GHz, and 4.6–4.8 GHz, targeting Sub-6 GHz applications such as smart cities, IoT, cloud computing, and fixed wireless access. The research addresses challenges like mutual coupling, limited bandwidth, and size constraints in current MIMO antenna systems. Using HFSS software, antenna parameters including return loss, VSWR, channel capacity loss, and isolation loss are optimized. The fabricated prototype on an FR4 substrate is evaluated using a vector network analyser. The expected outcomes include enhanced efficiency, improved isolation (⩾20 dB), and a channel capacity loss below 0.1, contributing significantly to next-generation wireless communication technologies.

The advancement of 5G technology has necessitated the development of compact, high-performance antennas to accommodate the demands for enhanced speed, reliability, and low-latency communications. This paper presents the design, simulation, and analysis of a compact tri-band MIMO antenna targeting the sub-6 GHz spectrum, operating specifically in the 2.4–2.5 GHz, 3.4–3.6 GHz, and 4.6–4.8 GHz frequency bands. The design tackles critical challenges including mutual coupling, limited bandwidth, and size constraints, using HFSS simulation and FR4 substrate fabrication. The proposed antenna demonstrates improved performance parameters including isolation loss >20 dB, VSWR <2, and channel capacity loss <0.1, making it suitable for modern 5G IoT, smart city, and wireless communication systems.

Keywords*: Tri-band MIMO antenna, Sub-6 GHz, 5G communication, Isolation loss, Channel capacity loss, Mutual coupling, HFSS, FR4 substrate, Wireless networks*

INTRODUCTION

The rapid growth in 5G wireless communication technology has placed unprecedented demands on antenna systems for higher data rates, better spectrum efficiency, and ultra-low latency [1]. One of the enabling technologies in this context is the use of Multiple-Input Multiple-Output (MIMO) antennas. MIMO technology allows multiple signals to be transmitted and received simultaneously over the same channel, enhancing throughput and reliability [2].

Particularly important is the Sub-6 GHz frequency spectrum, which offers a good balance between propagation range and bandwidth availability. Frequencies such as 2.4 GHz (Wi-Fi, LTE), 3.4–3.6 GHz (5G NR Band N78), and 4.6–4.8 GHz are critical in 5G deployments globally [3]. However, designing MIMO antennas that can efficiently operate over multiple frequency bands while maintaining compact form, high gain, and strong isolation remains a significant challenge [4].

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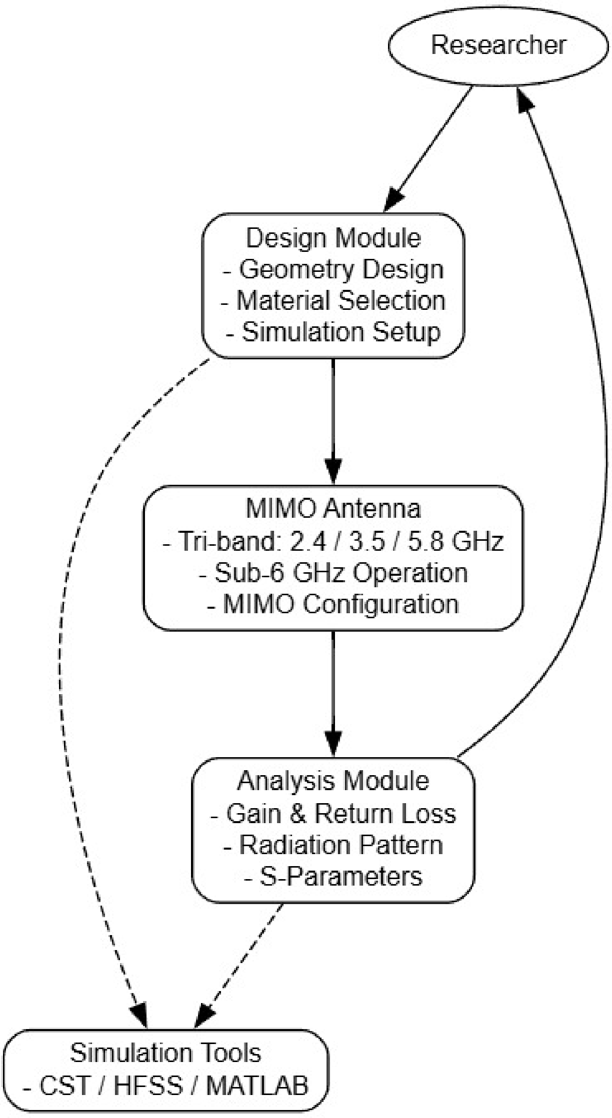

Figure1.1: Flow work of Diagram

The rapid growth of wireless communication systems has increased the need for compact, high-performance antennas that can support multiple frequency bands with enhanced data throughput and reliability. As 5G and emerging technologies evolve, Multiple Input Multiple Output (MIMO) antenna systems have become crucial for ensuring higher spectral efficiency and improved link quality. The sub-6 GHz frequency band is particularly important for 5G due to its favourable trade-off between coverage and capacity.

Tri-band MIMO antennas have gained attention for their ability to operate across three distinct frequency bands, enabling seamless integration with various wireless standards. This flexibility and backward compatibility are essential for heterogeneous networks. However, key design challenges include maintaining good impedance matching across all targeted frequency bands, ensuring low mutual coupling between antenna elements, and achieving compactness without compromising gain or radiation efficiency. Recent research has explored techniques to address these challenges, including metamaterials, defected ground structures, electromagnetic bandgap structures, and novel radiating element geometries. This paper presents the design and analysis of a compact tri-band MIMO antenna tailored for sub-6 GHz applications, aiming to achieve high isolation between antenna elements, good return loss across the three bands, and satisfactory radiation characteristics.

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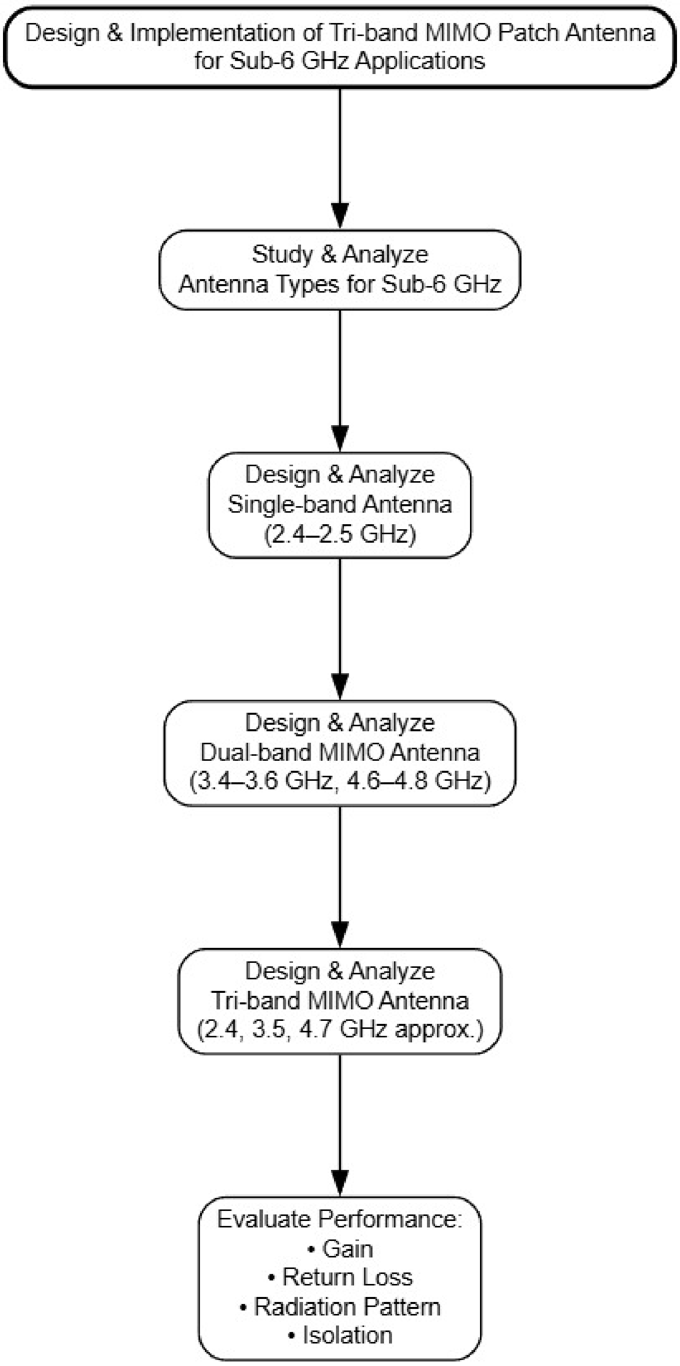

Figure1.2: System Flow

This research focuses on designing a tri-band MIMO antenna for sub-6 GHz applications using a structured approach. The process includes problem definition, analysis, initial antenna design, MIMO configuration design, simulation and parametric analysis, optimization, and prototype fabrication. The antenna is designed using a microstrip patch or planar monopole configuration, with radiator geometry tailored to support resonance at the desired frequency bands. The antenna is extended into a MIMO configuration, with isolation enhancement techniques applied. Full-wave electromagnetic simulations are performed, and parametric sweeps are conducted to study the effect of design variables on performance. Optimization algorithms are employed to fine-tune antenna dimensions for optimal performance. The prototype is fabricated on a low-loss substrate, and measurements are conducted to validate S-parameters. Performance comparisons and benchmarking are conducted to highlight improvements and contributions of the proposed antenna.

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Table 1.1.: Review of Existing Research on MIMO Antenna Design for 5G and Sub-6 GHz Frequencies.

Ref No.	Dimensions (mm)3	Number of Ports	Freq. Bands (GHz)	Isolation	Max. Peak Gain (dBi)	Technique used
[1]	50 ×50 ×1.6	4	2.25–2.4 4.7–6.3	≤−16	4.0	Asymmetric coplanar strip (ACS)
[2]	75 ×66 ×1	2	2.35–2.53 5.23–5.70	≤−1 ≤ 9	3.0	Planar inverted f antenna
[3]	60×120 ×0.76	2	0.66–1.13, 1.4–2.0, 2.42_3.09, 3.18_3.89	≤−13	3.4	Slotted Antenna
[4]	48 ×36 ×1.6	2	3.85–4.25, 4.95–5.1, 6.94–7.35 8–8.3	≤−25	5	Robot character shaped element with slots and stubs
[5]	21 × 90 ×1.6	2	2.22–2.54, 3.14–3.9 5.3–5.7	≤−15	4.3	Quasi-Yagi antenna configuration in a semi-loop mean dered

Ref No.	Dimensions (mm)3	Number of Ports	Freq. Bands (GHz)	Isolation	Max. Peak Gain (dBi)	Technique used
						shape
[6]	120×50 ×1.6	2	1.27–1.43 1.8–2.13	≤−15	4.6	Quasi-Yagi antenna configuration in a semi- loop mean dered shape
[7]	100 × 150 × 18	2	2.6, 3.5	≤ −25	-	U-shape slits Antenna
[8]	70 × 60 × 1.6	2	2.4, 3.4	≤ −24	2.1	T-shape slits and slot
[9]	48 × 31 × 1.6	2	2.4, 3.5, 5.2	≤ −22	2.2	Multiple branches
[10]	50 × 50 × 1.6	2	2.4, 5.5	≤ −19	1.8	L-shaped short strip
[11]	100 × 60 × 1	2	2.4, 5.2, 5.8	≤ −20	-	Slotted Antenna
[12]	60 × 60 × 3.5	2	2.04–2.51, 4.43–5.35 6.76–8.78	≤ −20	-	Two metallic “8”-shaped antenna structures
[13]	30 ×44 ×1.6	1	2.4, 3.5, 5.8,7.9	-	2.9	Frequency selective surface
[14]	55 ×45 ×1.57	2	12.9,13.8, 15.1,18.2, 21.5	≤−23.5	4.2	Log-periodic dipole array
[15]	40 ×25 ×1.6	2	3.8, 5.4, 7.8	≤−29	5.34	Complementary Split Ring Resonator
Ref No.	Dimensions (mm)3	Number of Ports	Freq. Bands (GHz)	Isolation	Max. Peak Gain (dBi)	Technique used
						(CSRR) metamaterial
[16]	54 ×54 ×20	1	2.34,5.32	-	5.1	The artificial Magnetic conductor layer
[19]	32 × 32 × 1.6	4	3.72–3.82,	≤−16	2.5	rectangular- shaped slotted

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			4.65–4.76,			antenna
[20]	42 ×40 ×1.57	2	0.72–1.1, 1.57–1.90, 5.30–6.70	≤−20	2.7	Iterated C- shape Antenna
[21]	50 × 70 × 1.6	4	2.38–2.70, 3.10–3.46	≤−17	-	Ramp-shaped cut at the end of a meandering-shaped patch
[24]	43 × 30 × 1.6	2	2.38–2.70, 3.10–3.46	≤−15	4.0	Monopole radiating units and a metal base with branches and slit slots
[26]	150 × 75× 1.6	2	3.4 -3.6 3.6-3.8	≤−14	4.0	T-shaped element and C-shaped element
[27]	65 × 65× 0.8	4	3.1-3.6 5.9-7.1	≤−14	3.9	monopole antenna is loaded with multiple resonant
Ref No.	Dimensions (mm)3	Number of Ports	Freq. Bands (GHz)	Isolation	Max. Peak Gain (dBi)	Technique used
						Branches
[29]	35 × 30.65 × 1.6	4	3.3–3.8,	≤−14	3.9	Modified Annular Ring Antenna
[30]	120 × 120 × 1.6	4	4.11–4.13 5.18–5.21	≤−17	4.2	defected L- shaped microstrip patch antenna
[31]	27 × 34 × 1.6	2	2.4, 3.5, 5.5	≤−17	5.32	U-shaped rectangular patcharound the inset feed patch, PS Algorithm

MATERIALS AND TOOLS

The proposed tri-band MIMO antenna is fabricated on FR-4, a widely used and cost-effective dielectric substrate in RF and microwave applications. FR-4 is a flame-retardant glass-reinforced epoxy laminate, standardized by NEMA (National Electrical Manufacturers Association).

The "FR" indicates flame retardance, compliant with UL94V-0 standards. It has a relative permittivity (εr) of approximately 4.3 and a loss tangent (tanδ) of around 0.02, making it suitable for low to mid-frequency applications such as sub-6 GHz antennas. While not optimal for high-frequency millimetre-wave designs due to its higher dielectric loss, FR-4 remains a practical choice for low-cost MIMO antenna implementations within the 2–6 GHz range.

REVIEW OF PAPERS

Author & Year	Title	Gap Analysis	Remark
Shobhit K. Patel et al., 2025	Design and measurement of a compact MIMO antenna using C-shaped metamaterial for 5G/6G wireless communication circuit	Focuses on GHz and THz regimes with high gain and ultra-wideband; lacks discussion on practical integration in compact or mobile systems.	Innovative use of metamaterials; promising for 6G wearable tech.
Chengzhu Du et al., 2025	Design of tri-band flexible CPW 4-port slot MIMO antenna for conformal 5G, WIFI 6/6E and X-band applications	Strong design for flexibility and conformality, but limited to CPW-fed structure with minimal environmental testing.	Excellent for multi-band wearable uses.
Ming-A Chung et al., 2025	A Compact Multi-Band MIMO Antenna with High Isolation and Low SAR for	Good isolation and low SAR, but limited gain and narrow scope of real-world performance validation.	Scalable design ideal for consumer electronics.

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	LTE and Sub-6 GHz Applications		
Anouar Es-saleh et al., 2025	Design aspects of MIMO antennas and its applications: A comprehensive review	Comprehensive, but lacks quantitative comparative analysis of recent design methods across frequency ranges.	Strong foundation for future design optimization.
Ashish Kumar et al., 2025	Development of semi-circular corner cut MIMO antenna for 5G-advanced and 6G automotive wireless applications	Similar content and challenges as previous review, but lacks distinction in antenna testing for vehicular dynamics.	Application-specific insights for automotive tech.
Noora Salim et al., 2025	Comparative performance analysis of two novel design MIMO antennas for 5G and Wi-Fi 6 applications	Provides direct performance comparison but limited evaluation under dynamic or user interaction conditions.	Useful comparative framework; needs real-world expansion.
Manumula Srinubabu et al., 2025	A compact and highly isolated integrated 8-port MIMO antenna for sub-6 GHz and mm-wave 5G-NR applications	Excellent performance across bands; future work needed on deploy ability and manufacturability.	High potential for infrastructure and mobile device use.
Rakesh N. Tiwari et al., 2025	Triple band lateral 4-port flexible MIMO antenna for millimeter wave applications at 24/28/38 GHz	Promising for wearable biomedical use; lacks exploration of long-term environmental or fatigue effects.	Great for next-gen flexible and wearable mm Wave systems.

LITERATURE REVIEW ON MIMO ANTENNA DESIGNS FOR 5G/6G

- Advanced MIMO Antenna Designs: Shobhit K. Patel and Chengzhu Du propose high-performance antennas for wearable and conformal wireless systems.
- Compact Multi-Band Antennas with High Isolation: Ming-A Chung and Manumula Srinubabu develop antennas optimized for sub-6 GHz and mm Wave applications.
- Comprehensive and Comparative Reviews: Anouar Es-saleh and Ashish Kumar review MIMO antenna technologies.
  Performance Evaluation and Practical Challenges: Noora Salim and Rakesh N. Tiwari analyze novel MIMO antennas.

Author(s) & Year	Title	Gap Analysis	Remark
Youssef Amraoui et al., 2025	High isolation integrated four-port MIMO Antenna for terahertz communication	Limited experimental validation of ANN-assisted design in real-world THz environments	AI-driven optimization offers enhanced THz antenna performance
Rania Hamdy Elabd et al., 2025	Compact Circular MIMO Antenna with DGS for Improved Isolation in 5G sub-6 GHz Systems	Absence of performance testing under real mobile conditions	Excellent isolation and gain for 5G handhelds
Ming-An Chung et al., 2025	A 10×10 Multi-Band MIMO Antenna for LTE, 5G, Wi-Fi 7, and X-Band	Limited practical deployment data; integration challenges in compact devices	Ideal for multifunctional wireless devices
Syed Misbah et al., 2025	High Data-Rate Hilbert-Curved-Shaped MIMO Antenna for Capsule Endoscopy	Still lacks clinical and biomedical certification	Safe, compact, high-data-rate design for WCE
Fatih Özkan Alkurt, 2025	Compact horn antenna design via origami folding for satellite	Lack of structural resilience validation in space conditions	Novel origami method enables compact, high-gain satellite antenna

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David Herraiz et al., 2024	High-Directivity and Low-Loss Couplers via ESICL	Integration of ESICL in compact multi-band circuits not fully explored	Promising alternative to microstrip in RF systems
Widad Faraj A. Mshwat et al., 2024	Compact Reconfigurable MIMO Antenna for 5G/Wi-Fi	Limited reconfigurability modes tested in dynamic environments	Well-suited for adaptive wireless systems
Ayyaz Ali et al., 2024	Compact Tri-Band MIMO Antenna for Sub-6 GHz, Ku, and mm-Wave	Environmental robustness and thermal stability not explored	Strong candidate for multi-band high-speed comms
V. N. Koteswara Rao Devana et al., 2024	Super Wide Band Flower Slotted Microstrip Patch Antenna	Physical size miniaturization for portable devices not addressed	Outstanding bandwidth and spectral efficiency

Author(s) & Year	Title	Gap Analysis	Remark
Islem Bouchachi et al., 2024	Design and performance improvement of UWB antenna with DGS using GWO	Radiation pattern, polarization behavior, and fabrication feasibility not deeply addressed	GWO-enhanced UWB antenna offers wide bandwidth and gain for emerging comm systems
Porchelvi Natarajan et al., 2024	Design of multi-band antenna for terrestrial applications	Real-time environmental performance and SAR analysis not presented	Multi-resonant, compact antenna suitable for future terrestrial networks
Youssef Amraoui et al., 2024	Multiband antenna using photonic crystals and graphene for THz apps	Lacks extensive fabrication feasibility validation	Advanced multiband antenna ideal for THz imaging and security systems
Youssef Amraoui et al., 2024	High isolation MIMO antenna for multiband THz applications	Material innovations and adaptive tuning methods yet to be explored	Efficient compact dual-band THz MIMO array for high-speed imaging
Md Afzalur Rahman et al., 2024	Miniaturized tri-band metamaterial MIMO antenna for 5G IoT	Real-time IoT deployment testing not yet demonstrated	Highly isolated tri-band design for microwave & mmWave IoT systems
Vikash Kumar Jhunjhunwala et al., 2024	Flexible UWB MIMO antenna for wearable applications	Durability under bending and moisture effects untested	Safe, flexible design ideal for wearable healthcare IoT
Christina Josephine Malathi Andrews et al., 2024	Compact Metamaterial antenna for 5G	Limited gain and real-world performance validation	Extremely compact CSRR-based design suitable for embedded 5G modules
Md. Sohel Rana et al., 2024	ML-based patch antenna design for 5G at 28 GHz	Lacks multi-objective optimization and thermal analysis	ML-guided patch design enhances precision and efficiency for 5G antennas

Shobhit K. Patel et al.,2025.[1] This research focuses on designing high-speed communication antennas with ultra-wideband response and high gain. Two MIMO antennas are designed for the GHz and THz regimes. The fractal MIMO antenna, initially designed with four square patches, provides a bandwidth of 5 THz and a gain of 15.1 dBi. The metamaterial effect enhances the antenna's bandwidth and gain, providing 44.8 THz and 25.6 dbi. The design optimizes physical parameters and MIMO performance parameters, making it suitable for wearable applications and 6 G wireless communication devices.

Chengzhu Du et al.,2025.[2] The paper presents a tri-band flexible CPW-fed 4-port slot MIMO antenna designed for emerging wireless systems like 5G, WiFi 6/6E, and X-band satellite communication. The antenna features four orthogonally placed slot elements and high isolation structures. Its compact design and excellent diversity performance make it suitable for wearable 5G and 6G communication applications.

Ming-An Chung et al.,2025.[3] The study presents a multi-band microstrip antenna for MIMO systems in devices like laptops, smartphones, and base stations. It achieves −11 dB isolation, 1.76 dBi peak gain, and an ECC below 0.5. The antenna's simple, robust structure ensures minimal performance impact, making it suitable for scalable integration.

Anouar Es-saleh et al.,2025. [4] This review article provides an in-depth analysis of research on Multiple Input Multiple Output (MIMO) antenna systems, their applications in various technologies. It discusses MIMO fundamentals, performance metrics, and challenges like mutual coupling and size constraints. The article also explores design methodologies like metamaterials, Defected Ground Structures, AI-based optimization, and compact multi-band configurations. It highlights emerging trends and techniques for high isolation, wide bandwidth, and reliable diversity performance. The review concludes that overcoming design trade-offs and technological limitations is crucial for MIMO antennas' transformative impact.

Ashish Kumar et al.,2025.[5] This review article provides an in-depth analysis of research on Multiple Input Multiple Output (MIMO) antenna systems, their applications in various technologies. It discusses MIMO fundamentals, performance metrics, and challenges like mutual coupling and size constraints. The article also explores design methodologies like metamaterials, Defected Ground Structures, AI-based optimization, and compact multi-band configurations. It highlights emerging trends and techniques for high isolation, wide bandwidth, and reliable diversity performance. The review concludes that overcoming design trade-offs and technological limitations is crucial for MIMO antennas' transformative impact.

Noora Salim et al.,2025.[6] The study evaluates two advanced 4x4 MIMO antenna designs for 5G and Wi-Fi 6 communications. The CPW-fed antenna achieved a 6 dBi gain, 80% efficiency, and a 2.8 GHz bandwidth, while the spanner-shaped slot antenna had 3.5 dBi gain, 80% efficiency, and a 4.5 GHz bandwidth. Both designs showed low ECC, excellent spatial diversity, and strong isolation. Despite challenges like complex antenna geometry and user interaction, the antennas outperformed conventional ones in frequency coverage, size reduction, and transmission reliability.

Manumula Srinubabu et al.,2025.[7] The article presents a compact 8-port MIMO antenna designed for 5G New Radio applications in sub-6 GHz and mm Wave frequency bands. The antenna features an elliptical-shaped monopole antenna, a Coplanar Waveguide structure, and semi-circular monopole elements. It achieves an impedance bandwidth of 3.15–5.35 GHz for sub-6 GHz and 23.20–29.90 GHz for mm Wave applications. The antenna supports key 5G NR bands, making it suitable for Wi-Fi 6 routers, V2X communication, LTE user equipment, and base stations. Future work could explore manufacturability and performance under real-world deployment scenarios.

Rakesh N. Tiwari et al.,2025. [8] The study presents a triple-band, ultra-thin 4-port MIMO antenna designed for millimeter-wave wearable applications. The antenna, utilizing a flexible Rogers RO3003 substrate, supports three distinct resonance frequencies at 24 GHz, 28 GHz, and 38 GHz. It maintains radiation efficiency and shows gains of 5.96 dBi, 6.62 dBi, and 8.48 dBi. The antenna maintains stable S-parameters under bending radii and meets regulatory safety limits. It is a promising candidate for future wearable mm Wave communication systems, particularly in biomedical and next-generation 5G networks.

Youssef Amraoui et al.,2025.[9] The research introduces a new Artificial Neural Network (ANN)-assisted optimization technique for designing multi-port MIMO antennas for Terahertz communication systems. The ANN model optimizes slot dimensions to enhance performance at 0.445 THz and 0.540 THz frequencies. The ANN is trained using a dataset from simulated antenna designs, and its predictive accuracy is validated using multiple error metrics. The ANN-guided design yields high mutual coupling isolation, broad bandwidth, and peak diversity gain, confirming its feasibility for advanced THz wireless systems.

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Rania Hamdy Elabd et al.,2025.[10] The study presents a compact dual-port circular MIMO antenna designed for sub-6 GHz 5G mobile communication systems. The antenna consists of two radiating elements, circular rings, and side stubs to enhance impedance matching and bandwidth. A partially slotted ground plane with curved cuts suppresses capacitive coupling, while a rectangular Defected Ground Structure minimizes mutual coupling. The antenna achieves a peak gain of 11.5 dBi and a radiation efficiency of up to 95%. It meets international safety standards for handheld 5G devices.

Ming-A Chung et al.,2025.[11] The study presents a compact, multi-band planar MIMO antenna system for modern wireless communication equipment. The antenna operates efficiently over three frequency ranges and features multi-branch microstrip lines and long slot structures. It has a low envelope correlation coefficient and isolation, and its radiation levels remain below international safety thresholds. This antenna is ideal for multifunctional wireless communication systems like smartphones, laptops, and routers.

Syed Misbah et al.,2025.[12]A new ultra-compact circularly polarized (CP) multiple-input multiple-output (MIMO) implantable antenna has been developed for wireless capsule endoscopy (WCE) systems. The antenna uses two Hilbert curve-shaped meandered resonators, enhancing miniaturization and bandwidth up to 250 MHz in the 2.45 GHz ISM band. The symmetry and orthogonal port placement of the antenna achieve high isolation and improved gain. The antenna maintains an axial ratio below 3 dB, ensures excellent decoupling without additional structures, and meets safety standards. It also supports robust data transmission up to 1.8 meters at 78 Mbps. This design is highly effective and safe for next-generation WCE applications.

Fatih Özkan Alkurt,2025.[13] The research presents a novel origami-based horn antenna for satellite communications, designed using aluminum-covered paper sheets folded into a pyramid-like accordion structure. The antenna achieves a wide operational bandwidth and high gain, demonstrating the potential of origami-inspired approaches in advancing horn antenna technology.

David Herraiz et al., 2024.[14] The article discusses the design and implementation of high-directivity, low-loss directional couplers using Empty Substrate Integrated Coaxial Line (ESICL) technology. The couplers use inclined arms, high-isolation sections, and spline-based transitions to optimize performance, reduce return and insertion losses, and stabilize the coupling coefficient. Comparative analysis with microstrip couplers confirms ESICL's potential for compact, high-performance RF applications.

Widad Faraj A. Mshwat et al.,2024.[15] The study presents four compact, miniaturized four-element MIMO antenna designs, each measuring 26 x 26 x 0.8 mm^2. These reconfigurable antennas offer excellent impedance matching, high isolation, low envelope correlation coefficients, diversity gain, peak gains, and radiation efficiencies, making them ideal for modern wireless communication systems.

Ayyaz Ali et al.,2024. [16] The paper presents a tri-band 2x2 MIMO antenna for next-generation wireless applications. It operates in 5.2-5.7 GHz, 11.8-17.3 GHz, and 23.4-37.3 GHz frequency ranges. The antenna uses a passive decoupling mechanism and thin microstrip lines for isolation. It achieves peak gains and radiation efficiency, with excellent diversity and isolation characteristics. It's a strong candidate for high-speed wireless communication systems.

V N Koneswaran Rao Devana et al.,2024.[17] The research presents a compact Super Wide Band Flower Slotted Microstrip Patch Antenna (SWB-FSMPA) with a 50 Ω tapered microstrip feed line and rectangular bevelled defected ground structure. It supports various applications, including WiMAX, 5G, WLAN, UWB, and millimeter-wave bands. The antenna achieves a bandwidth ratio of 29.1:1 and a bandwidth dimension ratio of 5284, demonstrating high spectral efficiency. It's a promising candidate for next-generation wideband and millimeter-wave applications.

Islem Bouchachi et al.,2024.[18] The study presents a compact Ultra-Wideband antenna designed for both conventional and emerging millimeter-wave communication systems, including 5G technologies. The antenna, with a compact size and high gain, is optimized using Complementary Split Ring Resonators (CSRRs) to enhance bandwidth performance. The antenna's design balances compact size, ultra-wide bandwidth, and high gain, making it suitable for WiMAX, WLAN, ISM, and millimeter-wave applications. However, factors like radiation pattern fidelity, polarization, fabrication feasibility, and cost considerations are not thoroughly explored.

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Porchelvi Natarajan et al., 2024.[19] The research presents a compact multi-band antenna for terrestrial applications above 5 GHz, featuring Split Ring Resonators (SRRs) and a "C" ring resonator structure. The antenna achieves five resonant frequencies and improves gain and bandwidth with the introduction of the C-shaped SRR. It offers excellent performance compared to traditional multiband antennas and is 30% more miniaturized than standard quadrilateral patch designs. The design is highly reliable and feasible for next-generation communication systems.

Amraoui Youssef et al.,2024.[20] The paper presents a graphene-loaded multiband antenna designed to operate within the terahertz spectrum, overcoming limitations in bandwidth and power efficiency. The antenna features air-hole arrays within a polyimide substrate and has impressive performance metrics, including reflection coefficients, bandwidths, gains, and radiation efficiencies. The design is promising for THz imaging systems, particularly in security screening and biomedical imaging. Challenges like fabrication precision and material compatibility can be mitigated with advanced manufacturing techniques.

Youssef Amraoui et al.,2024.[21] The study presents a compact dual-band MIMO antenna designed for terahertz frequencies, specifically 128 GHz and 178 GHz, to enhance high-speed wireless communication and imaging applications. The antenna uses a defected ground structure and dual linear array configuration, achieving high gains and radiation efficiency. Its small size makes it suitable for terahertz imaging applications, such as security scanning and medical diagnostics. Future directions include expanding the operational range, integrating machine learning-based design optimization, and incorporating novel materials and fabrication methods.

Md Afzalur Rahman et al.,2024.[22] The paper presents a tri-band MIMO antenna designed for simultaneous operation in microwave and millimeter-wave frequency bands. The antenna uses Rogers RT-5880 substrate and incorporates metamaterial components, improving key performance metrics. The antenna offers enhanced gain, increased isolation between ports, and excellent diversity performance, making it suitable for 5G IoT applications, WiMAX, sub-6 GHz, V2X, and mm Wave communications. The use of metamaterials and meta surfaces sets a new benchmark in antenna performance and design.

Vikash Kumar Jhunjhunwala et al.,2024.[23] The article presents a flexible four-port UWB MIMO antenna design for wearable IoT applications, using Polydimethylsiloxane (PDMS) as the substrate. The antenna features a modified circular radiator, elliptical slot, and partial ground plane, offering a wide operational bandwidth and 4.3 dBi peak gain. The Defective Ground Structure ensures high port isolation and low Specific Absorption Rate, ensuring user safety. This antenna is suitable for next-generation wearable electronics and smart IoT sensors, particularly in healthcare monitoring and communication systems.

Christina Josephine Malathi Andrews et al., 2024.[24] The study presents a compact antenna for 5G communication systems using Complementary Split-Ring Resonator (CSRR) metamaterials on an FR4-epoxy substrate. The antenna has a 92% size reduction and a bandwidth of 200 MHz, with a return loss of -20.41 dB and a gain of -3.7 dBi. The CSRR metamaterials contribute to its negative permeability and refractive index, making it suitable for space-constrained IoT or mobile device environments.

Md. Sohel Rana et al.,2024.[25] The study focuses on designing a rectangular patch antenna using two different substrate materials, Rogers RT5880 (Design-I) and FR-4 (Design-II), to investigate their influence on key antenna parameters. Design-I outperformed Design-II, with a return loss of -57.289 dB, VSWR of 1.0023, gain of 7.63 dBi, directivity of 8.51 dBi, and efficiency of 89.66%. The study also integrates machine learning techniques to develop predictive models for return loss, bandwidth, and VSWR, enabling rapid parameter estimation without extensive physical testing.

GAP OF RESEARCH

Despite significant advancements in antenna design for modern wireless communication systems, there remains a noticeable gap in developing compact, high-isolation tri-band MIMO antennas specifically optimized for sub-6 GHz applications. Existing designs often face challenges such as poor mutual coupling between elements, limited bandwidth, and increased antenna size, which make them less suitable for integration into portable and compact 5G-enabled devices. Moreover, many studies focus on single-band or dual-band antennas, with fewer efforts dedicated to tri-band performance in a MIMO configuration. Additionally, some techniques used to improve isolation or bandwidth—such as complex metamaterials or bulky decoupling structures—result in increased

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design complexity and cost. Therefore, there is a need for a simplified, low-profile, and efficient tri-band MIMO antenna that offers high isolation, better gain, and wide bandwidth across the sub-6 GHz bands.

RESEARCH GAP

- Limited availability of compact tri-band MIMO antennas tailored for sub-6 GHz applications.
- Most existing designs focus on single or dual-band operation, not tri-band with MIMO.
- Mutual coupling between MIMO elements remains a significant challenge in compact layouts.
- Available tri-band antennas often suffer from narrow bandwidth and suboptimal gain.
- Use of complex or costly decoupling structures increases fabrication difficulty and design cost.
- Lack of efficient, low-profile antennas that balance size, performance, and manufacturability.
- Insufficient experimental validation in many reported designs for real-world 5G scenarios.

APPLICATION OF TRI BAND

Tri-band MIMO antennas play a crucial role in modern wireless communication systems, especially within the Sub-6 GHz spectrum, where a variety of wireless standards such as 4G LTE, 5G NR, Wi-Fi, and IoT protocols coexist. These antennas support simultaneous operation across three frequency bands, which makes them ideal for environments requiring high-speed, reliable, and interference-resistant communication. In multi-standard systems, the ability of Tri-band MIMO antennas to support different technologies enables seamless connectivity, improved data throughput, and better spatial diversity. Their deployment spans across mobile networks, smart homes, connected vehicles, industrial IoT setups, and mission-critical communication systems.

1. 5G and 4G Mobile Communication

- Enables simultaneous support for LTE (e.g., 1.8 GHz), 5G NR (e.g., 3.5 GHz), and other sub-6 GHz bands.
- Improves signal reliability, data rates, and spectral efficiency.
- Provides multi-band carrier aggregation and MIMO diversity.

2. Smart Homes and IoT

- Supports communication protocols like Wi-Fi (2.4/5 GHz), ZigBee, and LoRa.
- Enhances connectivity for smart appliances, sensors, and home automation systems.
- Reduces need for multiple antennas, simplifying device design.

3. Automotive and V2X Communication

- Used in connected vehicles to support V2V (Vehicle-to-Vehicle) and V2I (Vehicle-to-Infrastructure) communication.
- Supports bands like LTE Band 28, 5G NR, and DSRC/C-V2X at 5.9 GHz.
- Facilitates real-time updates, collision avoidance, and navigation systems.

4. Wireless Access Points & Routers

- Powers multi-band enterprise routers and small cell base stations.
- Supports multiple standards like Wi-Fi 6, LTE, and 5G on the same hardware.
- Increases coverage, bandwidth sharing, and network flexibility.

5. Industrial IoT and Smart Manufacturing

- Supports robust wireless links for machine-to-machine (M2M) communication.
- Enables real-time monitoring and control over industrial automation systems.
- Ensures connectivity even in harsh or interference-prone environments.

6. Public Safety & Mission-Critical Systems

- Facilitates emergency communications across legacy LTE (e.g., Band 14) and 5G.
- Ensures high-availability, multi-band access for police, firefighters, and disaster management teams.
- Improves coverage and interoperability across agencies.

CONCLUSION

In this study, a compact multi-band MIMO antenna integrated with a defected ground structure (DGS) has been successfully designed and analyzed for Sub-6 GHz communication applications. The use of DGS has significantly improved key performance parameters such as bandwidth, gain, and isolation between antenna elements. The proposed antenna supports multiple frequency bands within the Sub-6 GHz spectrum, making it suitable for modern wireless standards including 4G LTE, 5G NR (New Radio), and Wi-Fi 6.

The simulation and performance validation demonstrate that the antenna exhibits low mutual coupling, stable radiation patterns, and adequate envelope correlation coefficient (ECC), confirming its effectiveness in MIMO configurations. Overall, the design offers a promising solution for space-constrained wireless devices requiring high-performance multi-band operation in the Sub-6 GHz range.

- A compact multi-band MIMO antenna was designed using a defected ground structure (DGS) for Sub-6 GHz applications.
- The incorporation of DGS improved bandwidth, gain, and isolation between antenna elements.
- The antenna supports multiple bands within the Sub-6 GHz range, suitable for 4G, 5G NR, and Wi-Fi 6.
- Simulation results confirmed low mutual coupling and good impedance matching across all operating bands.
- The antenna maintained stable radiation patterns and high diversity performance.
- The design offers a compact and efficient solution for next-generation wireless communication systems.
- Overall, the proposed antenna meets the performance requirements of Sub-6 GHz multi-band MIMO applications.

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