*Review Article*

Recent Advancement in 5G MIMO Antenna Design and its Performance Optimization Techniques: A Review

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ABSTRACT

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| The extensive demand for high-speed communication and connectivity has triggered the need for research in fifth-generation (5G) of mobile communication. The 5G evolution will not be limited to only mobile phones but also provide seamless connectivity through the internet of Things (IoT) in services like smart cities, smart homes etc. The clear intention of the 5G technology is to provide a vast capacity of network, a higher speed of multiple Gigabits per second, and enhanced dependability with negligible latency and stable radiation. This goal will not be possible without an efficient antenna structure. Numerous 5G antenna designs have been put forth so far by various researchers, but a thorough analysis of the various types of antennas and the techniques of 5G used to improve their performance is required to select an appropriate design for a particular application. The most recent research on the various antenna types and performance improvement methods for 5G technology is presented in this review study. This study is an effort to comprehensively examine the various types of 5G antenna structures, their performance optimization methodologies, comparison, and potential future advancements. |

*Keywords: Antenna design, high-speed communication, Internet of Things (IoT), low latency, network capacity, performance optimization, smart cities, and 5G technology.*

1. INTRODUCTION

The socioeconomic development of any country depends on resource availability and utilization. The rapid transmission of data, termed “data is the new oil,” is vital for progress. In India, the demand for connectivity and data access continues to increase, necessitating advancements in communication technology. The COVID-19 pandemic emphasized the importance of internet connectivity, propelled by 4G advancements. With 5G, humanity seeks further progress, aiming for vast network capacity, ultra-high-speed connectivity, and minimal latency. Significant improvements in antenna structures are needed to realize these objectives. 5G technology supports IoT, causing substantial changes in education, industry, healthcare, and more. It significantly expands the IoT ecosystem, enabling multiple devices to connect efficiently while managing latency, cost, and speed. The Third Generation Partnership Project (3GPP) actively updates 5G standards, aiding researchers in aligning their goals with technological progress. Recent developments have outlined three main use cases for 5G: Enhanced Mobile Broadband (eMBB), Massive Machine Type Communications (mMTC), and Ultra-reliable Low Latency Communications (uRLLC) [1]. eMBB ensures seamless connectivity for high-quality streaming and fast browsing, achieving data rates of up to 20 Gbps indoors. mMTC focuses on low-power communications across devices, enhancing machine-to-machine interactions. For applications needing immediate responsiveness, uRLLC provides reliable, low-latency communication, crucial in scenarios where delays could have serious effects.

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| **Figure 1. Use Cases for 5G**  The fifth generation (5G) technology specifications focus on eight key aspects, utilizing frequency bands below (FR1) and above 6GHz (FR2) for varying applications [2]. The introduction of 30GHz to 300GHz millimeter waves boosts speed, leading to peak data rates of 20 Gbps and average rates exceeding 100 Mbps, significantly surpassing the fourth generation, benefiting video communication and AI services. 5G employs beam division multiple access (BDMA) for enhanced user capacity and filter bank multicarrier (FBMC) for better spectral efficiency. Low latency is ensured via low-density parity check (LDPC) codes, enabling support for mobile stations at speeds over 500 km/h, with an average spectral efficiency density of 9 bit/s/Hz and 1 million connections per square kilometer, ensuring high reliability with a 0.99999 link outage probability.    **Figure 2. 5G Specifications**  The total 5G spectrum comprises two classes as shown in Table 1.: FR1 (under 6GHz) and FR2 (over 6GHz). FR1, or "sub-6 GHz," is used for wider regional connectivity and suits urban and rural deployments due to its balance of coverage and capacity. In contrast, FR2, or "mm-Wave," includes frequencies above 24 GHz (24.25 to 52.6 GHz), and provides higher data rates and capacity. However, FR2 has a shorter operational range and is more susceptible to interference from obstacles.  **Table 1. 5G frequency spectrum details**   |  |  |  |  | | --- | --- | --- | --- | | **#** | **Frequency Band** | **Frequency**  **Range (MHz)** | **Class** | | 1 | n71 | 470-698 | Frequency  Range 1 (FR1) | | 2 | n5, n8, n12, n14, n15, n20, n25, n28, n29, n81 - n83, n89, n91 - n94 | 698-960 | | 3 | n50, n51, n74 - n76, n91 - n94 | 1427-1518 | | 4 | n1 - n3, n34, n39, n65, n66, n70, n84, n86,  n95 | 1710-2025 | | 5 | n65, n66 | 2110-2200 | | 6 | n30, n40 | 2300-2400 | | 7 | n7, n38, n41, n90 | 2500-2690 | | 8 | n77, n78 | 3300-3400 | | 9 | n48, n77, n78 | 3400-3600 | | 10 | n48, n77, n78 | 3600-3700 | | 11 | n77 | 3700-4200 | | 12 | n80 | 4400-4990 | | 13 | n257, n258, n261 | 24250-39500 | Frequency  Range 2 (FR2) | | 14 | n260 | 37000-43500 | | 15 | -- | 45500-47000 | | 16 | -- | 47200-48200 | | 17 | -- | 66000-71000 | |

The success of 5G technology relies on effective antenna design, crucial for signal operation. Antennas are akin to "the pipeline" for data, comparable to how pipelines transport oil. In wireless networks, antennas send and receive data, facilitating its flow to various destinations. They serve as "data conduits" and are essential components of 5G devices, requiring enhanced strength, bandwidth, and reduced radiation losses. The architecture of antennas for 5G is vital to meet communication demands. This paper evaluates various 5G antenna structures, their performance optimization, comparisons, and future developments, guiding researchers toward advancements in antenna design based on practical applications[92].

Recent advancements in 5G MIMO antenna design have focused on enhancing spectral efficiency, minimizing mutual coupling, and optimizing beamforming capabilities to address the demands of high-speed, low-latency communication[97]. A prominent technique involves the integration of metasurface-based structures to manipulate electromagnetic waves, enabling compact, wideband antennas with improved gain and reduced interference. For instance, reconfigurable MIMO systems using PIN diodes or MEMS switches dynamically adjust operating frequencies or radiation patterns, adapting to varying channel conditions in real time[98]. Decoupling techniques, such as defected ground structures (DGS) and parasitic elements, have been employed to mitigate mutual coupling between closely spaced antenna elements, preserving envelope correlation coefficient (ECC) values below 0.05 for robust spatial diversity[99]. Additionally, substrate-integrated waveguide (SIW) technology has gained traction for its low-loss characteristics at mmWave frequencies (24–40 GHz), facilitating high-efficiency arrays with stable radiation patterns. Machine learning-driven optimization tools, such as genetic algorithms and neural networks, are increasingly used to automate parameter tuning for impedance matching and bandwidth enhancement, reducing design cycles. Material innovations, including liquid crystal polymer (LCP) substrates and 3D-printed dielectric resonators, further enable lightweight, conformal designs suitable for IoT and vehicular applications. However, challenges persist in balancing miniaturization with thermal stability, particularly for high-power scenarios. These advancements collectively aim to meet 5G’s stringent requirements while paving the way for 6G integration [100].

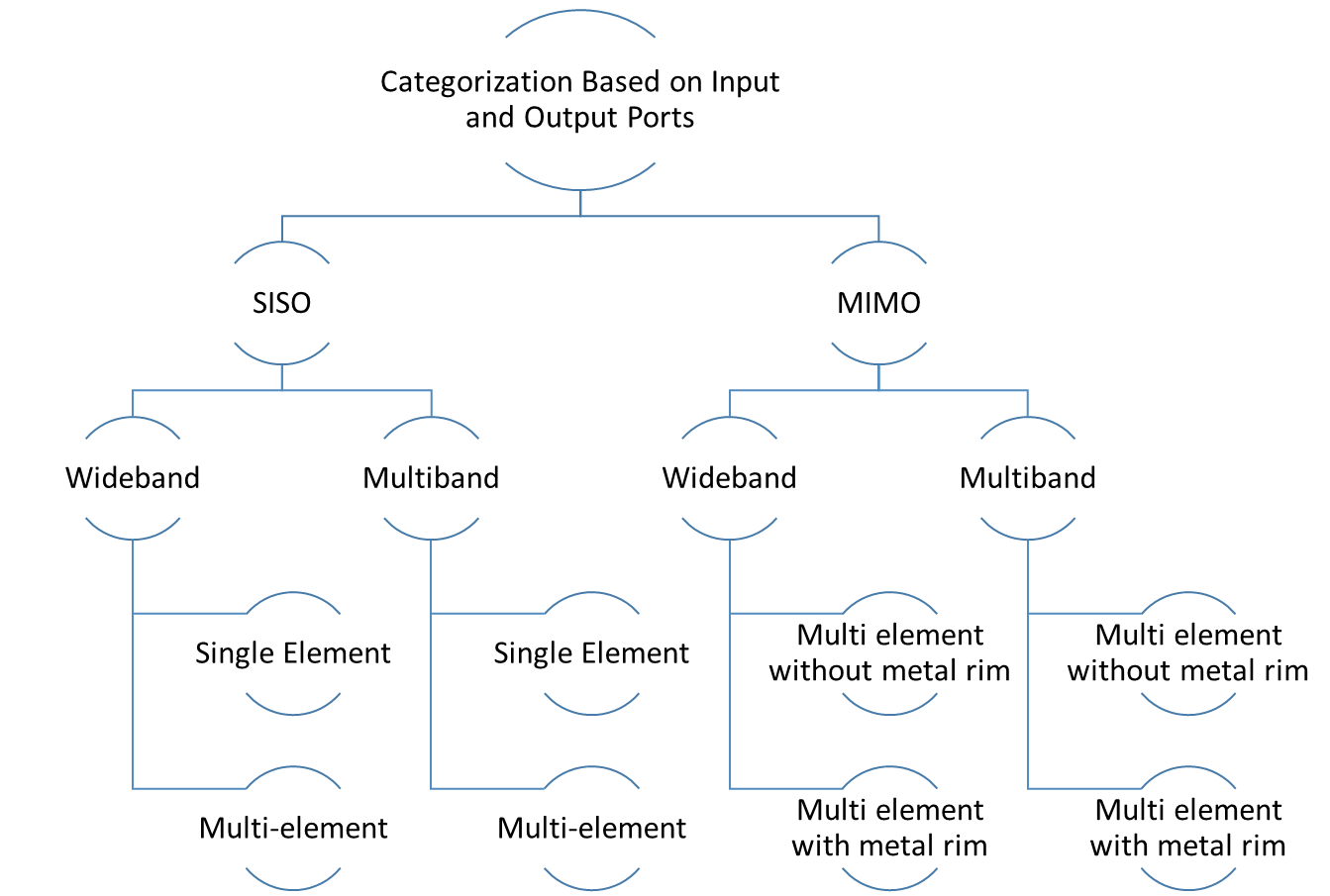
The paper is structured as follows: Section II provides an overview of 5G antennas, detailing their categorization and performance enhancement methods. Section III presents benchmark research on antenna optimization, including a critical review of recent approaches. Section IV summarizes key findings, while Section V concludes the study.

2. 5G antennas: overview, categorization and optimization methods

In 5G networks, antennas are crucial for maintaining reliable connections between devices and the network, utilizing technologies like Beamforming and Massive MIMO for optimization. Efficient antenna design affects coverage area, reach, and signal propagation parameters, such as distance and throughput. Proper deployment enhances user experiences. 5G uses various frequency bands, necessitating antennas that perform well across them for improved spectral efficiency. The design of antennas directly impacts network capacity, data rates, latency, and throughput. Advancement in antenna technologies boosts 5G with enhanced gain, bandwidth, and interference management, delivering faster speeds. Densely deployed small cells with compact antennas are essential for seamless connectivity in high-capacity locations, minimizing interference. The antennas in 5G technology are categorized in two ways one is based on the Input and Output Ports while the other category is based on the types of antenna structure. As shown in figure 3, based on the number of ports at input and output, the antennas are categorized as Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO) [3].

Single Input Single Output (SISO) antennas are fundamental in 5G and other wireless systems. They can be single or multi-element, making them easy and cheap to implement, ideal for constrained devices or budgets. However, as the size of a single element increases for higher gain [4], challenges arise at frequencies above 6 GHz, leading to propagation losses and reduced quality of service. While SISO antennas are simple [5], they are limited compared to more advanced configurations like Multiple Input Multiple Output (MIMO) and Massive MIMO, which use multiple antennas to enhance coverage, capacity, and signal quality, improving overall network performance. Multi-element antennas increase gain but at the cost of greater bulk and complexity [6].

MIMO technology employs multiple antennas at both ends of a communication channel, such as in 5G base stations and smartphones. One key advantage is spatial multiplexing, which enables the simultaneous transmission of multiple data streams, thereby increasing the wireless channel's capacity and data rates. By leveraging multiple antennas, MIMO markedly improves the data speeds, coverage, and overall performance of 5G networks. This leads to higher throughput, enhanced reliability, reduced latency, and better spectral efficiency. MIMO is essential for meeting the demands of 5G, supporting applications such as HD video streaming, virtual reality, and IoT connectivity. By optimizing antenna deployment, MIMO boosts channel capacity through intelligent signal transmission [7]. To minimize antenna numbers, multiband antennas serve various wireless needs. Wideband and multiband MIMO antennas can be categorized by their frequency band and involve configurations with or without metal rims. Metal rim antennas enhance durability and aesthetics for mobile devices.



**Figure 3 : Antenna Categorization based on input and output ports**

Figure 4 shows another popular method for antenna categorization which is based upon the types of antenna.

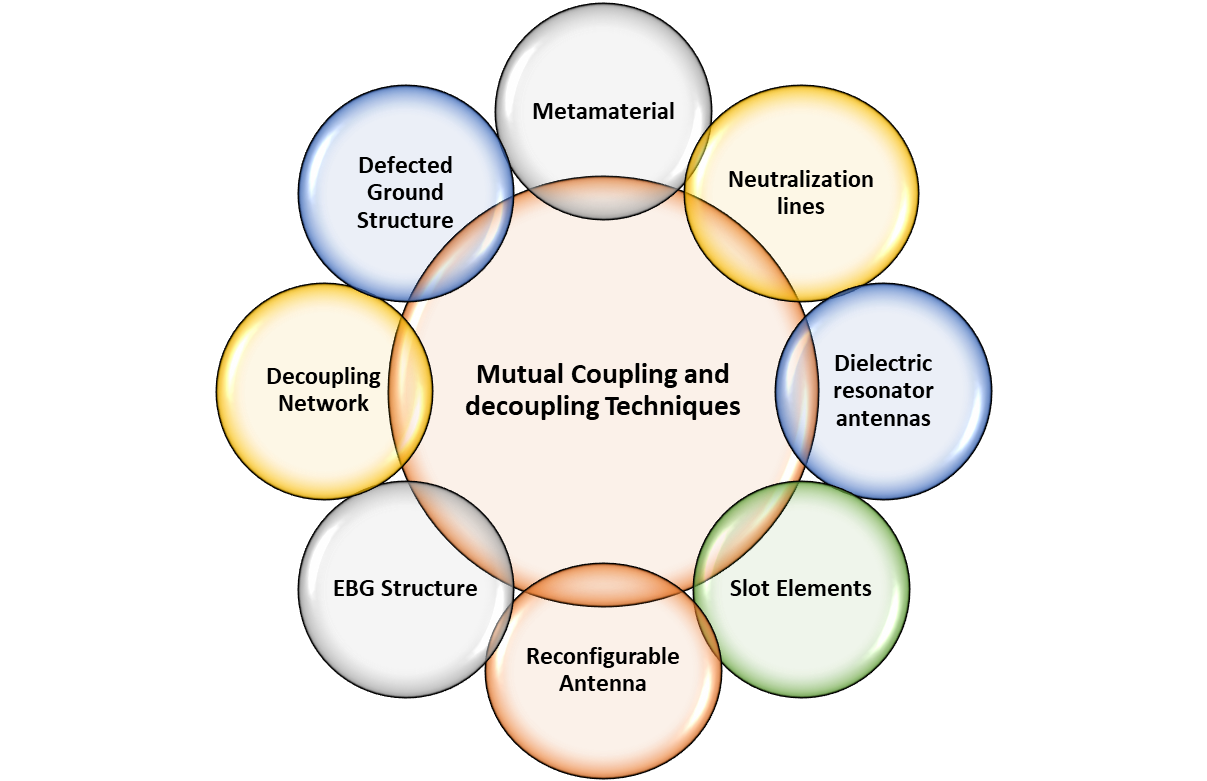
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| **Figure 4: Categorization Based on antenna types** |

A typical type of antenna found in communication via wireless systems, including 5G networks, is the monopole antenna. A single radiating element plus a ground plane make up the basic and extensively used antenna structure [9]. There are two popular types on monopole antenna configurations based on their length, if the length is one fourth of the wavelength, then it is called a quarter wave monopole while if the length is half of the wavelength, then it refers to have wave monopole antenna. Monopole antennas are suited for a wide range of practical applications due to their simple design, easy installation, and omnidirectional coverage. Several variations were proposed in the literature that modify the fundamental structure into various shapes such as conical, spiral, and others according on the applications and requirements [10]-[11]. Dipole Antenna: Comprising two symmetrical conductive elements (each ~λ/4 long), half-wavelength dipoles resonate at half the operating frequency’s wavelength [12][13]. They radiate omnidirectionally perpendicular to their axis. Variants like folded dipoles enhance impedance matching, while log-periodic arrays (LPDAs) offer wideband coverage. Magneto-Electric (ME) Dipole Antenna: Combines a planar electric dipole with a vertically shorted quarter-wave patch. The magnetic dipole is fed from the substrate’s underside [14]-[17]. Research focuses on height reduction, alternative feeding methods, and polarization diversity. Loop Antenna: A conductive loop (round, square, etc.), sized as a wavelength fraction, radiates omnidirectionally (small loops) or directionally (larger loops) [18][19]. Challenges include lower gain and susceptibility to interference. Antipodal Vivaldi Antenna (AVA):A tapered slot on a dielectric substrate with trapezoidal geometry, fed at the narrow end. Operates across GHz ranges, offering wideband impedance matching, high gain, and directional radiation [6][20]–[23].Fractal Antenna: Uses self-similar fractal patterns for miniaturization, multiband operation, and omnidirectional radiation [24][25]. Design complexity requires optimization via simulations. Inverted F Antenna (IFA): Features vertical and horizontal arms connected to a ground plane. Compact and efficient, it is widely integrated into small wireless devices [26][27]. Planar Inverted F Antenna (PIFA): A planar variant with an F/L-shaped radiator parallel to the ground plane. Offers wideband performance and is common in mobile devices due to its low-profile design [28][29].

**2.1 Performance Enhancement Techniques for 5G Antennas**

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| **Figure 5: Techniques for performance optimization of 5G Antenna** |

Substrate Selection: Substrate material properties (dielectric constant, loss tangent, thickness) critically influence antenna bandwidth, efficiency, and impedance matching [22]. High dielectric constants enable compact designs but reduce bandwidth, while low loss tangents minimize energy dissipation. Optimal thickness improves radiation patterns and frequency tuning. Multi-layer substrates enhance performance [30]. Mechanical durability and environmental resilience are vital for long-term stability. Corrugation: Periodic surface variations improve bandwidth, gain, radiation patterns, cross-polarization suppression, radar cross-section reduction, and frequency selectivity [6]. Design parameters (geometry, dimensions) depend on application needs. Multi-element Structure: Combining elements enhances gain, bandwidth, polarization diversity, and impedance matching beyond single-element limitations [22]. Configurations are optimized via simulations, considering spacing, feeding networks, and frequency range. Dielectric Lens: Adjusts radiation patterns by phase/amplitude modulation, boosting gain, directivity, and side-lobe suppression. Lens geometry, refractive index, and material properties determine effectiveness [22]. Mutual Coupling and Decoupling Techniques: Proximity-induced coupling degrades isolation and efficiency. Mitigation strategies include physical isolation, orthogonal placement, shielding, polarization diversity, and impedance matching [31] (Figure 6). Figure 5 summarizes these techniques



**Figure 6: Mutual Coupling and decoupling Techniques**

Neutralization Lines: Metallic slits/lumped elements between antenna elements reduce mutual coupling and enhance bandwidth. Position-dependent impedance tuning optimizes performance. Electromagnetic bandgap (EBG) structures, with periodic metallic/dielectric arrangements, enable multi-bandgap operation for low coupling and high efficiency [31][22]. Dielectric Resonator Antennas (DRA): High gain, efficiency, and dual-band isolation characterize DRAs. Defected Ground Structures (DGS)—slots in the ground plane—improve bandwidth and reduce mutual coupling [31][22]. Slot Elements: Integrated in ground planes/patches to boost impedance bandwidth and gain. Metamaterial-enhanced slots achieve compact size, low coupling, and wide bandwidth [31][22]. Reconfigurable Antennas: Use p-i-n diodes, MEMS, or varactors for frequency agility, low mutual coupling, and high diversity gain. Complementary Split Ring Resonators (CSRR) enhance isolation and miniaturization [32][33][22]. Decoupling Networks: Passive components (e.g., resonators, transmission lines) between antennas reduce mutual coupling by transforming cross-admittance to imaginary values. Cost-effective for multi-element arrays [31]. Electromagnetic Bandgap (EBG): Periodic structures suppress unwanted frequencies, enhance directivity, reduce back radiation, and improve bandwidth. Mitigate mutual coupling in dense arrays [22]. Defected Ground Structure (DGS): Ground-plane slots/patterns optimize bandwidth, efficiency, and mutual coupling reduction [22].

3. Benchmark research in antenna optimization

This section critically analyzes benchmark research in 5G antenna optimization, focusing on contemporary designs. While not exhaustive, it compares modern SISO (single-element/multi-element) and MIMO (multi-element with/without Metal Rim) antennas, categorized as wideband or narrowband (Figure 3). Key advancements in these configurations are discussed.

**3.1 SISO Wideband Antennas**

Recent studies on SISO antennas focus on optimizing single and multi-element structures for 5G, targeting size, gain, bandwidth, and front-to-back ratio. Single-element antennas are favored for their simplicity, cost-effectiveness, and compact size. Desai et al. proposed a 10 × 12 × 1.48 mm³ transparent antenna covering 23.92-43.8 GHz with 1.94 dBi gain [35]. Zeng et al. introduced a Magneto-Electric Dipole Antenna with 9.2 dBi gain and >50% bandwidth, covering 57-71 GHz [36]. Lei Xi et al. designed a wideband planar filtering dipole for WiMAX and WLAN [37]. Dixit et al. developed an antipodal Vivaldi antenna for 25-29.5 GHz and 31.8-33.4 GHz ranges [23]. Dadgarpour et al. suggested a Quasi-Yagi antenna with a dielectric lens, achieving 14-15 dBi gain and 24-40 GHz bandwidth [38]. Goel et al. used a windmill-shaped antipodal Vivaldi antenna for 10-160 GHz with 8.7 dBi peak gain [20]. A resonance-based reflector antenna with three metallic layers improved FBR bandwidth [39]. A 3D spray-coated antenna was metalized for compactness [40], while a conformal approach enabled smartphone integration with 8-9 dBi gain [41].

Multilayer antennas offer higher gain, better radiation control, and frequency selectivity. Park et al. designed a low-profile filtering antenna covering 3.24-3.8 GHz using a nonuniform metasurface [42]. Sun et al. presented a stacked dielectric antenna with 6-9.2 dBi gain for 3.1-5.1 GHz [43]. Hussain et al. proposed a two-layer RT/Duroid 5880 antenna covering 24-34.1 GHz with 9.5-11 dBi gain [44].

Feng et al. designed a five-layer metasurface-based antenna for 2G/3G/LTE/5G bands [45]. Table 2 compares single/multilayer SISO 5G antennas by size, layers, substrate, gain (dBi), and frequency (GHz). Compact, cost-effective FR4-based antennas are reported in [37] and [23], while [41] offers a small antenna with moderate gain. Multilayer designs enhance gain in compact sizes, with [44] achieving the highest gain and smallest size among multilayer antennas.

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| (a) |
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| **Figure 7: (a) Wideband antenna proposed in [43], copyright 2019 Wiley Periodicals, Inc., multilayered antenna proposed in [44]** |

**Table 2: Benchmark research in single element antennas (SISO wideband)**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **S.N.** | **Antenna Structure** | **Substrate Materials** | **No of Substrate layers** | **Size in millimeter** | **Gain (dBi)** | **Frequency Band (GHz)** | **Ref. No.** |
| 1 | Dipole | FR4 | 1 | 40 x 10 x 1 | 2-2.5 | 3.08 to 5.15 | [37] |
| 2 | Antipodal Vivaldi  antenna | FR4 | 1 | 40 x 24 x 1.6 | 5-9.53 | 25 - 33.4 | [23] |
| 3 | Circular slot | Nelco NY9220 | 1 | 20 x 16 x 0.508 | 8 – 9 | 20 – 28 | [41] |
| 4 | Microstrip patch | RO4003C,  Taconic TLX-9 | 2 | 90 x 96 x 2.878 | 8.59-10.43 | 3.24-3.8 | [42] |
| 5 | ME dipole | Arlon 25N | 2 | 40 x 40 x 10.516 | 6-8 | 4.98-6.31 | [17] |
| 6 | Dielectric  resonator antenna | Teflon, ceramic,  Rogers 5880 | 3 | 75 x 75 x 15.428 | 6- 9.2 | 3.1 - 5.1 | [43] |
| 7 | Microstrip patch | RT/Duroid 5880 | 2 | 12 x 12 x 1.02 | 9.5-11 | 24-34.1 | [44] |

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| (a)   |  |  | | --- | --- | | FIGURE 7. | FIGURE 7. | |
| (b) (c) |
| **Figure 8: (a) multilayered antenna proposed in [44], (b) Axial Ratio and Gain with and without Metasurface, (c) S11 with and without Metasurface**  Micromachines 13 01215 g011a 550  Micromachines 13 01215 g011b 550 |
| **Figure 9: Multilayered antenna proposed in [49], (a) Four element array (upper layer), (b) reflector with the frequency-selective surface (lower layer)**  Multi-element SISO antennas enhance gain, directivity, and spatial diversity, improving communication range and reliability compared to single-element designs. A miniaturized antipodal Vivaldi antenna [6] achieves 8.2–13.2 dBi gain (24.04–40.85 GHz) using RT/Duroid 5880 substrate. Ullah et al. proposed single-layer antennas: one covering 23.41–33.92 GHz with 8.5–10.7 dBi gain [46], and a fractal-based design operating at 25.28–29.04 GHz with 7.8–10.9 dBi gain [25]. Table 3 compares wideband 5G multi-element antennas. Multilayer designs in [47]–[49] improve performance but increase size, while [48] prioritizes gain over compactness. Corrugations in [6] enable a compact 1×4 AVA with wide bandwidth. |

**Table 3: Benchmark research in multi-element antennas (SISO wideband)**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **S.N.** | **Antenna Structure** | **Substrate Materials** | **Substrate layers**  **(Numbers)** | **Size**  **in millimeter** | **Gain (dBi)** | **Frequency Band (GHz)** | **Ref. No.** |
| 1 | Antipodal Vivaldi antenna | RT/ Duroid 5880 | 1 | 28.8 x 24 x 0.254 | 8.2 - 13.2 | 24.04 - 40.85 | [6] |
| 2 | Antipodal Vivaldi antenna | RT/ Duroid 5880 | 1 | 40 x 24 x 1.6 | 8.5- 10.7 | 23.41 - 33.92 | [46] |
| 3 | Fractal | RT/ Duroid 5880 | 1 | 32 x 12 x 0.254 | 7.8-10.9 | 25.28 - 29.04 | [25] |
| 4 | Dipole | RT/ Duroid 5880 | 4 | 30 x 35.62 x 4.9 | 10.6 - 12.61 | 27.12 - 29.5 | [47] |
| 5 | Microstrip patch | Taconic TLY-5 | 2 | 96.1 x 50.5 x 1.016 | 13.83 - 14.31 | 26.4 - 28.92 | [48] |
| 6 | Microstrip patch | RT/ Duroid 5880, Acrylic Polymer | 2 | 32.1 x 37.45 x 2.124 | 10 - 12 | 23 – 32 | [49] |

* 1. **SISO Multiband Antennas**

SISO multiband antennas face limited research due to weak bandwidth and performance, making them unsuitable for 5G’s high-speed, low-latency demands. Their low spatial diversity and lack of advanced beamforming hinder MIMO integration critical for 5G efficiency. Deckmyn et al. proposed a dual-band antenna (28/38 GHz, 3.65/2.19 dBi) [27], while Alibakhshi-Kenari’s slotted design achieves triple frequencies with low gain [50]. These limitations highlight SISO multiband antennas as suboptimal for 5G applications.

**3.3 MIMO Wideband Antennas**

MIMO wideband antennas without metal rims are implemented as dual- or multi-element configurations. Isolation enhancement is critical for MIMO systems, achieved via surface walls [51], FSS [52], metasurfaces [53][54], metal strips [55], decoupling [27][56], or neutralization lines [57][58]. Zhang et al. designed a dielectric resonator antenna with 24 dB isolation (27.25–28.59 GHz) and 9.9 dBi gain [55]. Wen et al. achieved 33.3 dB isolation using a dual-polarized square loop patch [60]. Hassan et al. developed a dual-element, four-port inverted-F antenna with 92% efficiency and 3 dBi gain [28]. Yang et al. proposed magneto-electric dipoles with 25 dB isolation and 8.2 dBi gain [61]. Key dual-element benchmarks are summarized in Table 4.

**Table 4: Benchmark research in Dual Element Antenna without Metal Rim**

**(MIMO wideband)**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **S.N.** | **Antenna Structure** | **Isolation (dB)** | **Efficiency** | **Size In millimeter** | **Gain (dBi)** | **Frequency Band (GHz)** | **Ref. No.** |
| 1 | Dielectric Resonator Antenna | 24 | Not provided | 20x20x 2.54 | 9.9 | 27.25 - 28.59 | [55] |
| 2 | Monopole | 17 | 58% | 150x75x0.8 | Not provided | 3.4 - 3.6 | [59] |
| 3 | PIFA | 25 | 80%-92% | 50x100x3 | 3 | 2.7 - 3.6 | [28] |
| 4 | ME dipole | 25 | 89.5% | 60x60x8 | 8.2 | 3.3 - 4.36 | [61] |

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| FIGURE 2. - Fabricated four-port, two-element antenna (a) 3D view and (b) bottom view.  (a) | FIGURE 2. - Fabricated four-port, two-element antenna (a) 3D view and (b) bottom view.  (b) |
| **Figure 10 : Duel elements antenna with four ports proposed in [28], (a) Proposed Structure, (b) View from bottom** | |

Multi-element antennas without metal rims outperform dual-element designs in spatial diversity, beamforming, and MIMO efficiency. Wong et al. proposed a 3-monopole Y-shaped MIMO antenna with 15 dB isolation and 0.1 ECC (3.3–4.2 GHz) [62]. Alam et al. designed a 4-port CR-MIMO system with 15 dB isolation (2.5–4.2 GHz) using a multipurpose filter [63]. Abdullah et al. achieved >10 dB isolation (3.4–3.6 GHz) and 35–38 bps/Hz channel capacity with an 8-element array [64]. A compact 4-monopole band-stop filter antenna (50 × 39.8 mm²) achieved >17 dB isolation (2.7–5.1 GHz, 5.9–12 GHz) [65]. Yang Li et al. developed an 8-antenna array with 12.5 dB isolation (2.55–2.65 GHz) and a 12-antenna MIMO array (3.4–3.6 GHz, 0.2 ECC) [66]. Yixin Li et al. achieved 17.5 dB isolation and 40.8 bps/Hz capacity using polarization diversity [67]. Sim et al. proposed an 8-antenna array with wideband inverted-F elements [68]. Khalily et al. designed a 16-element array with 19.88 dB isolation (24.35–31.13 GHz) [68]. Key benchmarks are listed in Table 5.

**Table 5: Benchmark research in Multi Element Antenna without Metal Rim**

**(MIMO wideband)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **S.N.** | **Antenna Structure** | **Isolation (dB)** | **Frequency Band (GHz)** | **Channel Capacity (bps/Hz)** | **Envelope Correlation Coefficient (ECC)** | **Ref. No.** |
| 1 | Monopole | 15 | 3.3 - 4.2 | 16.5 | 0.1 | [62] |
| 2 | Filtenna | 15 | 2.5 - 4.2 | Not Given | Less than 0.5 | [63] |
| 3 | Monopole | 10 | 3.4-3.6 | 35 to 38 | 0.2 | [64] |
| 4 | Monopole | 17 | 5.1-5.9 | Not Given | 0.01 | [65] |
| 5 | Monopole | 12.5 | 2.55-2.65 | 38 to 40 | 0.15 | [69] |
| 6 | SIW Antenna | 12.5 | 3.4-3.6 | 57 | 0.2 | [66] |
| 7 | Slot | 17.5 | 3.4-3.6 | 40.8 | 0.05 | [70] |
| 8 | Inverted F | 17 | 2.5-7.0 | 39 | 0.1 | [67] |
| 9 | Microstrip Patch | 19.88 | 24.35-31.13 | Not Given | Not Given | [68] |

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| **Figure 11: - MIMO antenna array proposed in [66]** |

Multi-element antennas with metal rims offer enhanced stability and reduced interference. Fixed designs are simple and cost-effective for static environments, while reconfigurable antennas adapt dynamically via radiation/frequency/polarization tuning [71][72]. Cai et al. designed an 8-antenna MIMO array (3.3–7.1 GHz) with >11 dB isolation, 47% efficiency, and 0.09 ECC [71]. Sun et al. proposed an 8×8 MIMO system using orthogonal-mode pairs (3.3–5 GHz) with >21 dB isolation and <0.02 ECC [72]. Chang et al. developed 4-/8-element antennas covering 35.2–64.7 GHz with >12.7 dB isolation [73]. Huang et al. demonstrated open/closed slot arrays (3.4–3.6 GHz) with >42% efficiency and >13 dB isolation [73]. Key benchmarks are compared in Table 6.

**Table 6: Benchmark research in Multi Element Antenna with Metal Rim**

**(MIMO wideband)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **S.N.** | **Antenna Type** | **Isolation (dB)** | **Envelope Correlation Coefficient (ECC)** | **Frequency Band (GHz)** | **Efficiency (%)** | **Ref. No.** |
| 1 | Hybrid IFA | > 11 | < 0.09 | 3.3 to 7.1 | 47 to 70 | [71] |
| 2 | Monopole | > 12 | < 0.11 | 3.3 to 5 | 57.8 to 74.7 | [72] |
| 3 | Slot | > 12.7 | < 0.13 | 3.4 to 3.6 | 35.2 to 64.7 | [74] |
| 4 | Slot | > 13 dB | < 0.15 | 3.4 to 3.6 | > 42 | [73] |

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| **Figure 12 : Slot antenna with eight elements in [73] with dimensions in mm, Copyright 2019 Wiley Periodicals, Inc.** |

**3.4 MIMO Multi-band Antennas**

MIMO multiband antennas enhance modern wireless systems by boosting spectral efficiency, data rates, and reliability through multi-frequency operation. They exploit spectrum efficiently, mitigate multipath effects via spatial diversity, and enable simultaneous multi-protocol support. Their ability to generate multiple beams and handle concurrent data streams ensures high-capacity, seamless connectivity for high-speed applications.

Reconfigurable antennas adapt to dynamic environments by adjusting radiation patterns, frequency, or polarization, enhancing signal quality, reducing interference, and simplifying device design. Nie et al. designed a dual-polarized antenna using a U-shaped structure and PIN diode, achieving 25 dB isolation, 6.86–8.14 dB gain (3.24–5.77 GHz) [32]. Abbas et al. achieved 90% efficiency and ECC <0.001 via tapered slots [75]. Fakih et al. proposed PIFAs for 4G/LTE/5G with 20–35 dB isolation and 80% efficiency (2.5–3.6 GHz) [76]. Liu et al. used metasurfaces for 25 dB isolation and 7.8–8.6 dB gain (2.5–3.6 GHz) [77]. Saleem et al. employed FSS for 30 dB isolation and 55–65% efficiency in multi-band applications [78]. Liu et al. suppressed ground plane currents using a vertical metallic patch with PIFA, achieving 4.3–5.7 dB gain and 55% efficiency [29]. Teng Li et al. integrated metasurface, and PRS for 70 dB isolation, 10.4 dB gain, and 61% efficiency (3.2–4.05 GHz) [79]. Key dual-element benchmarks are summarized in Table 7.

**Table 7: Benchmark research in Dual Element Antenna without Metal Rim**

**(MIMO multiband)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **S.N.** | **Antenna Type** | **Isolation (dB)** | **Frequency Band (GHz)** | **Gain (dB)** | **Efficiency (%)** | **Ref. No.** |
| 1 | Dipole | 25 | 3.24 to 4.03  4.44 to 5.77 | 6.86  8.14 | Not provided | [32] |
| 2 | Tapered Slot | 16  25 | 1.8 to 2.6  27.5 to 40 | 3  7 | 70 to 90  60 to 85 | [75] |
| 3 | PIFA | 20  35 | 2.5 to 2.7  3.4 to 3.6 | 4.8  3.9 | 80 | [76] |
| 4 | Microstrip patch | 25 | 2.5 to 2.7  3.4 to 3.6 | 7.8  8.6 | Not provided | [77] |
| 5 | Folded Monopole | 30 | 2.4 to 2.48  2.91 to 3.49  3.27 to 3.97  3.4 to 3.8  5.15 to 5.86 | 9  7.5  6.5  4  7 | 55 to 65 | [78] |
| 6 | PIFA | Not Provided | 2.5 to 2.7  4.85 to 5.15 | 4.3  5.7 | 55 | [29] |
| 7 | Fabry- Perot resonator antenna (FPRA) | 70  21.5 | 3.2 to 4.05  26.8 to 29.55 | 7.3 to 10.4  11.8 to 14.6 | 61 | [79] |

Multi-element antennas without metal rims support multi-band operation for Bluetooth/Wi-Fi/GSM/5G. Yang et al. [80] designed a 2-element MIMO antenna for GSM/DCS/LTE bands (900–2600 MHz) using neutralizing lines to reduce coupling. Sun et al. proposed a U-shaped slot array for LTE/GSM/UMTS [81]. Dong et al. used slotted structures and protruded ground to achieve >10 dB isolation, 0.5 ECC, and 67.5% efficiency [82]. Yixin Li et al. developed a 10-element array with spatial/polarization diversity, achieving 11 dB isolation and 42–62% efficiency [83]. Liu et al. created a dual-band PIFA with 10 dB isolation and 0.2 ECC [29]. Qin et al. proposed an 8-element PIFA array with 10 dB isolation and 0.1 ECC [84]. Yixin Li et al. designed a 12-port MIMO array for LTE bands 42/43/46 with 12 dB isolation and 82% efficiency [85]. Key benchmarks are listed in Table 8.

|  |  |  |
| --- | --- | --- |
|  |  |  |
| (a) | (b) | (c) |
| **Figure 13: MIMO antenna with Frequency Selective Surface in [78], (a) Radiator structures, (b) Ground plane, (c) Final Structure of MIMO antenna with FSS** | | |

**Table 8: Benchmark research in Multi-Element Antenna without Metal Rim (MIMO multiband)**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **S. N.** | **Antenna Type** | **Size(mm3)** | **Isolation (dB)** | **Frequency Band (GHz)** | **Envelope Correlation Coefficient (ECC)** | **Efficiency (%)** | **Ref. No.** |
| 1 | Microstrip Patch | 95 x 60 x 0.8 | 10 | 0.740-0.965  1.380-2.703 | 0.5 | 40 to 67.5 | [82] |
| 2 | Slot | 150 x 80 x 0.8 | 11 | 3.4-3.8  5.15-5.925 | 0.15 | 42 to 62 | [83] |
| 3 | PIFA | 17.30 x 5.76 x 4.61 | 10 | 2.6  5.0 | 0.2 | Not Provided | [29] |
| 4 | PIFA | 136 x 68.8 x 1 | 10 | 1.88-1.92  2.3-2 | 0.1 | 40 to 65 | [84] |
| 5 | Slot | 150 x 80 x 0.8 | 12 | 3.4-3.8  5.15-5.925 | 0.15 | 41 to 82 | [85] |

Multi-element antennas with metal rims offer enhanced mechanical stability and radiation efficiency, leveraging the rim as a ground plane for reliable multi-band 5G operation. Zhang et al. designed a dual-loop antenna (FR4) with <18 dB isolation, ECC <0.11, and 38–69% efficiency [86]. Stanley et al. proposed a reconfigurable slot antenna covering 698–2690 MHz with >50% efficiency [87]. Chen et al. achieved >13 dB isolation, ECC <0.07, and 75–90% efficiency using Taconic RF-30 substrate [88]. Zi-Qiang Xu et al. developed a 4-loop antenna (FR4) with <17 dB isolation, 43–72% efficiency, and ECC 0.02–0.4 [89]. Kurvinen et al. addressed metal interference via L-shaped slots (FR4), achieving <12 dB isolation and 20–60% efficiency [90]. Yixin Li et al. integrated an 8-element MIMO array (FR4) into a metal frame, achieving 10 dB isolation, 44–66% efficiency, and ECC <0.2 [91]. Table 9 highlights that fixed designs [86] yield lower efficiency, while reconfigurable approaches [88]-[91] enhance performance.

|  |
| --- |
|  |
| **Figure 14: MIMO with twelve elements in [85], (a) final structure, (b) Inverted π Shape, (c) Longer inverted L shape, (d) Shorter inverted L shape.**  **Table 9: Benchmark research in Multi-Element Antenna with Metal Rim**  **(MIMO multiband)**   |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | **S.N.** | **Antenna type** | **Substrate** | **Isolation (dB)** | **Frequency Band (MHz)** | **Efficiency (%)** | **ECC** | **Ref. No.** | | 1 | Loop | FR4 substrate | 18 | LB: 824-960, HB:1710-2690 | LB: 31-38, HB: 42-69 | < 0.11 | [86] | | 2 | Slot | FR4 substrate | 14 | LB: 698-960, HB: 1710-2690 | above 50 | LB< 0.15, HB< 0.05 | [87] | | 3 | Loop | Taconic RF-30 | 13 | 4G: 698-960 and 1710-2690  5G: 3400-3600 | 4G: 40-90, 5G: 60-75 | < 0.07 | [88] | | 4 | Loop | FR4 substrate | 17 | LB: 824-960, HB: 1710-2690 | LB: above 43, HB: 59-72 | LB< 0.02, HB< 0.4 | [89] | | 5 | Slot | FR4 substrate | 12 | LB: 704-960, HB: 5150-5875 | 20-60 | LB < 0.4, HB < 0.1 | [90] | | 6 | Monopole | FR4 substrate | 10 | 2496-2690, 3400-3800 | LB: 48-66, HB: 44-59 | LB < 0.2, HB < 0.05 | [91] |     **Figure 15: 8 element array integrated with metal case in [91], (A) complete structure, (B) close up view, copyright 2018 Wiley Periodicals, Inc.**  **3.5 Challenges in Implementation** |

Implementing antenna designs in real-world scenarios presents multifaceted challenges, often stemming from environmental, material, and operational constraints. Environmental factors such as physical obstructions, multipath interference, and dynamic weather conditions can degrade signal integrity, particularly in urban or indoor settings where reflections and absorptions from buildings or foliage disrupt propagation patterns[93]. Additionally, miniaturization demands for compact devices, such as IoT sensors or wearables, necessitate trade-offs between antenna size, bandwidth, and efficiency, often leading to compromised performance[94]. Material limitations further complicate design optimization, as substrate losses and manufacturing tolerances impact radiation efficiency, especially at higher frequencies like mmWave for 5G/6G applications. Real-world deployment also faces challenges in power handling and thermal management, particularly in high-power systems like radar or satellite communications, where heat dissipation must align with mechanical and electrical stability[95]. Regulatory compliance with regional electromagnetic standards (e.g., FCC, ETSI) adds complexity, requiring iterative testing to meet emission limits without sacrificing functionality[95]. Moreover, integration with existing RF front-end components, such as amplifiers and filters, introduces impedance mismatches and coupling issues, necessitating advanced co-simulation tools. Finally, cost and scalability pressures drive the need for low-cost, mass-producible designs, often conflicting with performance targets. Addressing these challenges requires a multidisciplinary approach, combining computational electromagnetics, material science, and system-level optimization to balance theoretical models with practical feasibility.

4. DISCUSSION AND Conclusion

Single-element SISO antennas are compact and simple but offer limited gain and bandwidth. Enhancements like multilayer designs, corrugations, or transitioning to multi-element SISO structures improve gain, bandwidth, and radiation patterns, though feeding network complexity complicates impedance matching. MIMO dual-element designs (without metal rim) achieve high efficiency but require complex engineering. Techniques like shared grounds, dielectric resonators, or monopole antennas simplify design, while orthogonal polarization enhances isolation and channel capacity. Multi-element MIMO (without rim) further boosts performance but faces impedance challenges. MIMO with metal rim enables compact wideband operation via reactance loading and impedance matching, improving isolation and miniaturization. However, efficiency suffers from environmental interference. Dual-element MIMO (without rim) balances size and performance but struggles with dual-polarization feeding networks. Multiband MIMO (without rim) suits compact applications but suffers from poor isolation and ECC, mitigated via slotted grounds or polarization diversity. Reconfigurable MIMO (with rim) employs switching elements like varactors for agility, complicating design, while carrier aggregation optimizes data speeds.

This study provides a complete assessment of several 5G antennas, as well as a comparative and critical analysis of their performance enhancing approaches. The detailed categorization of antennas proposed for fifth generation technology and their types along with optimization techniques are elaborated in depth. These enhancing approaches have a significant impact on the electric and physical characteristics of an antenna, which improves its overall performance. Multiband antenna structures with multiple inputs and multiple outputs are appropriate for 5G mobile sets but implementing these designs within small space of mobile handset is the area in which work can be done in future. 5G enabled IOT is also an area with significant scope for research work, lack of a standard platform, protocol, and coding language are the main obstacles to the successful adoption of IoT. This review will help the researchers working in the domain of 5G antenna for selection of proper design based on the application requirement and also will play important role in optimizing the performance parameters of the selected antenna configuration.

**Data Availability Statement**

The data will be made available at a reasonable request to the corresponding author.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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