Hindawi
International Journal of Antennas and Propagation
Volume 2023, Article ID 5906721, 19 pages
https://doi.org/10.1155/2023/5906721

Review Article

Advancing 5G Connectivity: A Comprehensive Review of MIMO Antennas for 5G Applications

Poonam Tiwari,[1] **Vishant Gahlaut**,[1] **Meenu Kaushik**,[2] **Preeti Rani**,[1] **Anshuman Shastri**,[3] **and Bhupender Singh**[4]

[1]*Department of Physical Sciences, Banasthali Vidyapith, Radha Kishnpura, Rajasthan 304022, India*
[2]*School of Automation, Banasthali Vidyapith, Radha Kishnpura, Rajasthan 304022, India*
[3]*Centre for Artificial Intelligence, Banasthali Vidyapith, Radha Kishnpura, Rajasthan 304022, India*
[4]*Department of Water Supply and Environmental Engineering, Arba Minch University, Arba Minch, Ethiopia*

Correspondence should be addressed to Bhupender Singh; bhupender.sandher@amu.edu.et

Received 12 May 2023; Revised 17 August 2023; Accepted 21 August 2023; Published 31 August 2023

Academic Editor: Rakesh Chowdhury

The review focuses on the emergence of 5G wireless communication and the need for multiple-input multiple-output antennas to support high-speed communication systems. The article discusses the advantages of MIMO antennas, including increased channel capacity and the ability to focus radio frequency energy on specific users. However, the challenges of creating compact MIMO antennas with ideal isolation are addressed, including short wavelengths, connection losses, constrained bandwidth, and path losses in the millimeter-wave range. Design techniques and methods to enhance the performance of conventional antennas for 5G applications are discussed, along with potential solutions for upcoming challenges. The article provides an overview of MIMO antennas for 5G applications, covering frequency bands, system architecture, advantages, challenges, advancements, performance enhancement techniques, design techniques, and state-of-the-art developments.

1. Introduction

The fifth generation (5G) of wireless communication technology offers higher data rates, lower latency, increased network capacity, and a better user experience compared to its predecessors (3 G and 4 G). One of the most discussed technologies these days is 5G new radio (NR). Due to the limited bandwidth available in the microwave sector, along with high latency and restricted data rates, there is a rapidly increasing demand for more efficient use of this technology. 5G NR uses millimeter-wave (mm-wave) especially in (24–100 GHz) frequency range. The 5G NR includes smart factories, smart cities, smart homes, factual reality, seamless connectivity in self-driving cars, and telemedicine [1, 2]. 5G·mm-wave wireless channel bandwidths will be ten times larger as compared to today's 4 G long-term evolution (LTE) 20 MHz cellular channels. 5G technologies are reliable with a wide range of antennas to better meet the huge growth in large data rate needs and low-power expenditure devices [3]. Several multiple-input multiple-output (MIMO) antennas that work in the spectrum designated by the Federal Communications Commission (FCC) for 5G communication have recently been proposed [4].

Some of the key features of 5G technologies are as follows:

(i) Increased data rates: 5G provides a peak data rate of 20 GBps, which is 20 times faster than 4 G
(ii) Low latency: 5G has a latency of less than 1 millisecond, which means that there is minimal delay between sending and receiving data
(iii) Massive network capacity: 5G can connect more devices per unit area compared to 4 G, enabling it to support the increasing number of connected devices

(iv) Improved user experience: with higher data rates, lower latency, and greater network capacity, 5G offers a better user experience compared to previous generations of wireless technology

(v) Enhanced security: 5G uses advanced encryption techniques to secure data transmissions, making it more secure than 4 G

(vi) Multigigabit wireless connectivity: 5G enables multigigabit wireless connectivity for devices, making it ideal for applications that require high-speed data transfer, such as virtual reality (VR) and augmented reality (AR)

The 5G technology of wireless networking systems will offer consumers "unlimited" data, improved connections, and speedier surfing. Virtual reality/augmented reality (VR/AR), huge multimedia streaming, user-centric computing, smart transportation, disaster monitoring, private security and public safety, emergency services, etc. are examples of 5G services as shown in Figure 1.

The wireless industry has made revolutionary advancements in which MIMO antenna design has proven to be a leader by offering secure communications. The antenna has been widely incorporated as a custom design used in many commercial, industrial, wireless body area networks (WBANs), satellite communication, military and green radio communications applications, etc. [5]. The antennas are critical for the development and deployment of 5G communication systems. IMO antennas provide a means to achieve high data rates and improved signal quality in dense urban areas, where traditional antennas may not be able to effectively provide coverage due to interference and other factors. Additionally, they are able to support various frequency bands, such as sub-6 GHz (refers to medium and low frequency) and mm-wave frequency bands, utilized in 5G communication systems [6]. Figure 2 depicts a few mm-wave applications. However, there are some challenges associated with using mm-wave frequencies, such as the fact that the signals are highly susceptible to attenuation and can be easily blocked by obstacles such as buildings and trees [7]. To overcome these challenges, MIMO systems operating in the mm-wave band typically use beamforming and other advanced signal processing techniques to improve signal strength and quality. For the invention of brand-new mm-wave signaling protocols (such as air interfaces), precise propagation models are essential [8].

The MIMO system promises exceptionally high spectral efficiency as they deviate in the spatial domain by making equal correspondence channels [9]. For this utilization, microstrip antennas are chosen in light of their advantages such as their minimum expense and simple design. The designing of MIMO antennas poses several challenges that subsequently improve antenna performance [10], the main being the composition of nearly packed antenna elements with high isolation and low mutual coupling. As a result, MIMO antennas are designed in smaller sizes [11]. Antenna elements used in MIMO systems require a minimum bit error rate (BER) and maximum channel capacity to achieve

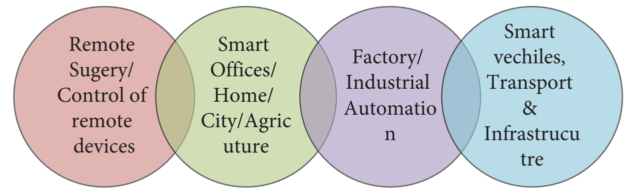


Figure 1: 5G services.

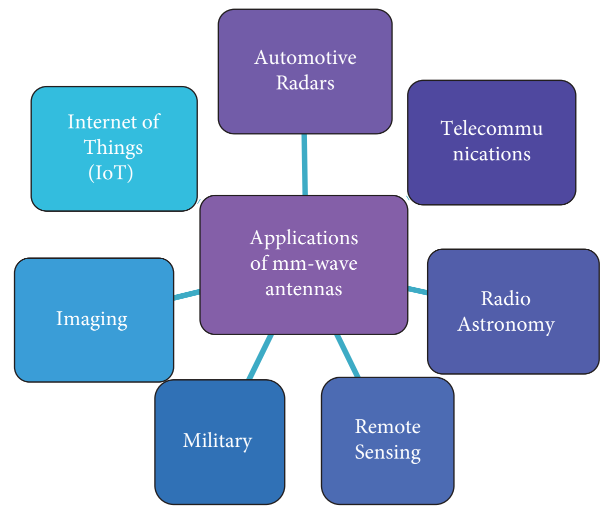


Figure 2: Applications of mm-wave antennas.

wide lobe patterns, high gain, and high separation between antenna elements. MIMO antennas are used to achieve high diversity and overcome the effects of multipath fading. At higher frequency ranges, attenuation and absorption effects become more important [12]. To overcome increased atmospheric attenuations, high gain antennas are required. Planar MIMO designs are popular due to their simple design, compact size, low cost, and ease of fabrication with other high-frequency devices [13].

Recent advancements in wireless communication technologies have aided in the creation of massive MIMO (M-MIMO) scenarios. M-MIMO is a disruptive technology that is more than a decade old and has been incorporated into the 5G standard. Researchers are focusing on new methods to improve the technology and make it a vital part of the next generation of communications networks, such as 6 G [14]. M-MIMO is a key technology in upcoming 5G networks, primarily used to boost spectrum utilization and communication system channel capacity [15]. For example, Bluetooth (2.480 GHz), Worldwide Interoperability for functionalities to support multiple wireless standards in the Microwave Access (Wi-MAX) (3.3–3.7 GHz), Wireless Fidelity (Wi-Fi) (2.4–5 GHz), Wireless Local Area Network (WLAN) (5.1–5.825 GHz), Ka-band (33.4–36.0 GHz), Ultra-Wideband (UWB) (3.1–10.6 GHz), 5G NR N77 (3.3–4.2 GHz), N79 (4.4–5.0 GHz), N78 (3.3–3.8 GHz), Industrial mm-wave radar sensors (IWR6843) (57–64 GHz), IEEE 802.11ad (57–71 GHz) (60 GHz) (V band), and high-speed authorized microwave data links (36–40 GHz) are the various bands utilized [16].

This research paper's innovation comes from a number of significant contributions that set it apart from earlier works on related subjects that have been published. The following novelties are specifically highlighted in this paper.

(i) This review paper offers a thorough analysis of the spectrum of global frequency bands for 5G MIMO antennas. This study presents a global view by analyzing the allocation and utilization of frequency bands for 5G MIMO systems, whereas previous literature may have touched on certain frequency bands. It differs from published articles that are largely focused on regional or particular frequency band considerations due to its global perspective.

(ii) The review paper discusses the most recent developments in performance improvement methods for MIMO antennas in 5G networks. It goes beyond generic conversations by offering a thorough review of cutting-edge techniques. It offers insightful information for academics and practitioners by examining the benefits, drawbacks, and trade-offs related to various strategies.

(iii) This review paper focuses primarily on the establishment and optimization of MIMO antennas in 5G networks, as opposed to other studies that may discuss MIMO antennas in a broader context. It explores the particular difficulties and opportunities of using MIMO antennas in the context of 5G.

(iv) It covers a lot of topics, including design methodologies, performance traits, and applications, and provides a comprehensive explanation of their function in 5G. This enormous overview offers a consolidated viewpoint to scholars and practitioners that has not been fully explored in the previous literature.

(v) The investigation of the state of the art in MIMO antennas for 5G networks is a novel feature of this review paper. This study offers an up-to-date review of the most recent developments and trends in MIMO antenna research and application, even though previous publications may have covered particular topics or methods. A useful starting point for future research and development is provided by this thorough assessment of the state of the art.

These contributions differentiate this review paper from the mentioned published papers.

This article provides an overview of MIMO antennas and their applications in 5G networks. It covers the fundamental concepts of MIMO antennas, design considerations, and performance characteristics. The paper discusses challenges in implementing MIMO antennas in 5G networks, including the need for compact and efficient designs. It also explores recent advancements in MIMO antenna technology and their potential applications in 5G networks.

The article is structured into ten sections, covering topics such as frequency spectrum, MIMO antenna functioning, performance enhancement techniques, mutual coupling reduction, current state of the art, and future challenges and opportunities.

2. Frequency Bands for 5G MIMO Antennas

Worldwide wireless operators use low-, mid-, and high-frequency band spectrum as shown in Figure 3, providing a 5G experience to meet the consumer's demand. 5G uses a combination of these bands to get the benefit of services and executes an important role in determining the speed and extent of coverage [17].

Bands with lower frequencies support longer distances and are less likely to be blocked by substantial objects but this is achieved by trading off speed and capacity. Mid-band spectrum, generally over 3.5 GHz presents a bandwidth of (50–100 MHz) to support high-capacity and low-latency networks. The high-band mm-wave spectrum can exhibit the highest performance of 5G applications with a (24–70 GHz) band [18].

The master international frequency register (MIFR), which falls under the jurisdiction of ITU-R, is a crucial component of international frequency management services [19]. It serves as a permanent database containing spectrum parameters for radio station operations across the globe, providing global acknowledgment and anti-interference protection [20]. Currently, the database holds over 2.6 million frequency allocations for terrestrial services, with over 200,000 new allocations added every year, managed by radio communication bureau (BR). The frequency bands are further divided into licensed and unlicensed bands, with over 40 licensed bands globally for LTE, which is still the industry's primary focus. In addition, the unlicensed spectrum globally is 2.4 GHz/5.9–7.1 GHz [21].

The surrounding environment, including obstructions, wind, and interference sources, has a substantial effect on the propagation characteristics of the various frequency bands in wireless communications. Due to the shorter wavelength, higher frequency bands are more susceptible to attenuation and signal degradation, resulting in a smaller coverage area than lower frequency bands. In addition, signal attenuation is the result of meteorological conditions such as rain, fog, or turbulence, especially at higher frequencies, which affect the effectiveness and dependability of communication systems. Specific frequency bands are also affected by interference from other wireless devices or electromagnetic signals, resulting in signal degradation, increased noise levels, and reduced signal-to-noise ratios. For wireless communications to operate optimally, system architecture, coverage, and overall performance must be understood and addressed [22, 23].

In other words, Figure 4 depicts a comprehensive overview of the frequency allocation of different services across various countries worldwide. This information is essential in ensuring the efficient and effective use of the RF spectrum while minimizing interference between different services [24].

3. MIMO Antenna System

Previously, the term "MIMO" was used to refer to the use of multiple antennas on both the transmitter and receiver. In recent usage, MIMO generally refers to a practical technique

Figure 3: 5G frequency band.

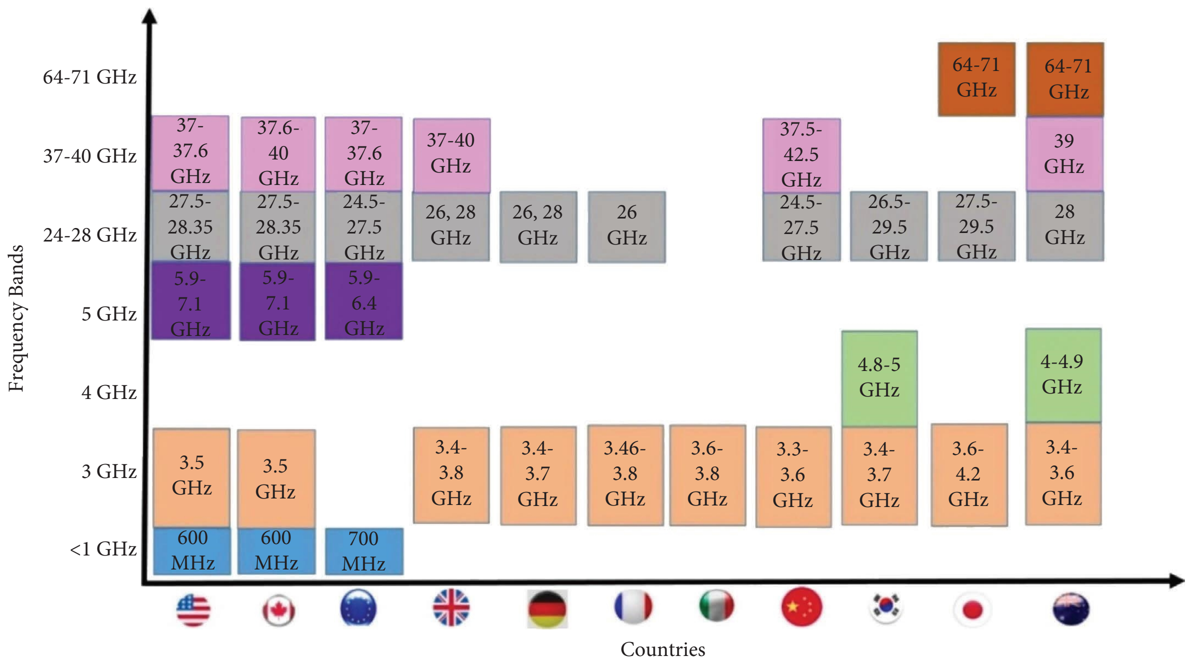


Figure 4: Worldwide frequency spectrum.

for sending and receiving multiple data signals over a single radio channel by means of multipath propagation. MIMO processes can be divided into three main categories—precoding, beam forming, and decoding [25]. A general model of the MIMO system is depicted in Figure 5 where T_x represents multiple transmitting antennas, R_x represents multiple receiving antennas, and H is the channel. The MIMO communication system performs two functions-signal processing and coding at input side whereas signal processing and decoding at output side of the system. MIMO channels include an RF component to improve end-to-end transfer functions. At the transmitter (T_x), data streams transmitted from the transmitting channel (T_xH) are encoded in a discrete-time complex baseband signal that is fed into the beamforming setup [19].

Then, the input signals are distributed in space. The input signal is converted into discrete-time signals in the continuous-time baseband, after which the input signal is fed into a beamforming network on the receiver side [15]. The receiving channel (R_xH) connects the input signal to the receiver (R_x). The signal is then converted into a discrete-time baseband signal, and the signal decoder estimates the transmitted signal stream and receives the output signal [26].

3.1. Massive MIMO Technology. Massive multiple-input multiple-output (massive MIMO) is a wireless communication technology that was proposed by Marzetta in 2010. It was designed to be used in scenarios where time division duplexing (TDD) and multiple cells are present. In massive MIMO, a base station is equipped with a large number of antennas, typically 100 or more, which is significantly more than what is used in current communication systems. This enables higher wireless communication capacity and performance [27]. Mobile terminals in conventional communication networks often employ single-antenna reception, where each terminal has just one antenna for signal reception. While the mobile terminals continue to use a single antenna for reception, the base station in massive MIMO includes numerous antennas for broadcasting and receiving signals. Multiple users can utilize same time-frequency resource at once due to spatial multiplexing, which is made possible by the base station's usage of multiple antennas [28]. This means that the base station can communicate with multiple mobile terminals at the same time, increasing the overall capacity of the system. This has been an active area of research and has shown promising results in various scenarios, including TDD and multicell environments [29]. The core massive MIMO paradigm is shown in Figure 6.

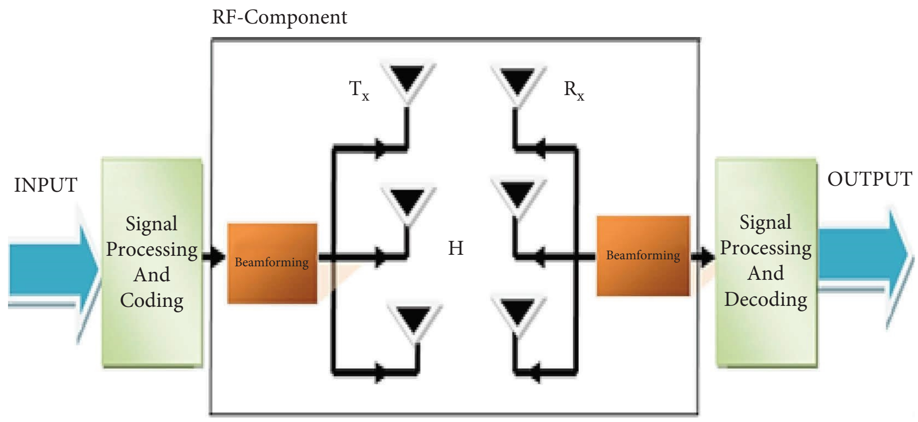


Figure 5: General model of the MIMO system.

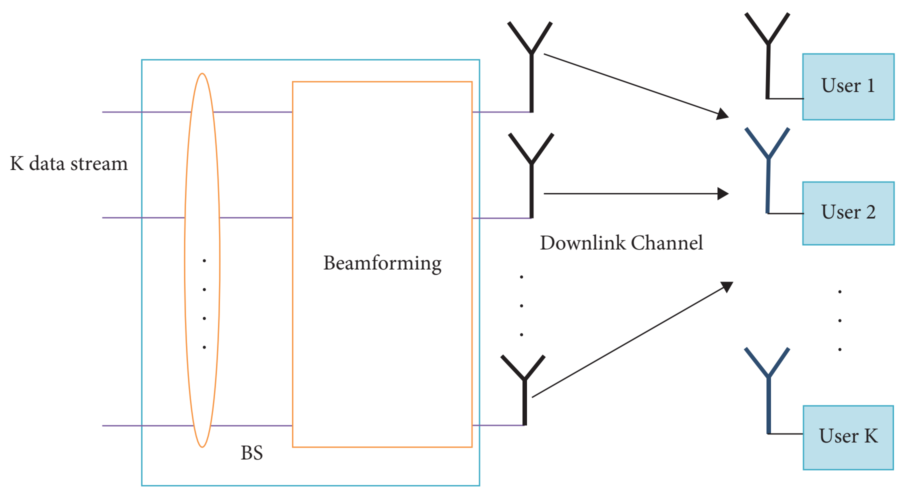


Figure 6: Basic model diagram of massive MIMO.

3.1.1. *The Benefits of Massive MIMO*

(i) Improved spectral efficiency: by using a large number of antennas, massive MIMO can support a higher number of simultaneous connections and increase the overall data rate

(ii) Enhanced link reliability: spatial diversity provided by multiple antennas helps combat fading and improves the reliability of the wireless link

(iii) Precise beamforming: massive MIMO allows for highly directional beamforming, enabling better signal quality and interference management

(iv) Interference suppression: by spatially separating signals from different users, massive MIMO can mitigate interference and improve system performance

3.2. *Multiuser MIMO (MU-MIMO).*

A wireless communication technique called multiuser MIMO (MU-MIMO) enables numerous users to send and receive data simultaneously over the same frequency channel while utilizing multiple antennas at both the transmitter and receiver. The performance of a single user's transmission is enhanced in classic MIMO systems by using several antennas to increase data throughput, dependability, or coverage. However, MU-MIMO expands on this idea by allowing several users to be serviced simultaneously, considerably enhancing the system's overall spectral efficiency and user capacity [30]. The highlights of several significant benefits are shown in Figure 7.

A strong technique that enables a wireless access point (AP) to broadcast many beams of data to several users concurrently is created when MU-MIMO and multibeam capability are coupled. This is especially beneficial in settings with a high user density, such as public spaces, office buildings, and sports venues [31]. By offering high-speed connectivity to numerous users simultaneously, MU-MIMO and multibeam capability increase the overall performance of wireless networks. In addition, it lessens the interference and signal degradation brought on by overlapping transmissions and improving network dependability and effectiveness [32].

3.2.1. *The Benefits of Multiuser MIMO*

(i) Increased system capacity: MU-MIMO allows the base station to serve multiple users simultaneously, effectively increasing the overall capacity of the wireless system

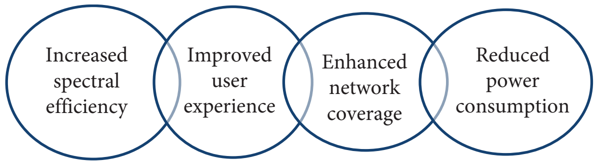


Figure 7: Advantages of the MU-MIMO technology.

(ii) Fair resource allocation: by dividing the available resources among different users, MU-MIMO provides fairness and improves the user experience

(iii) Enhanced network efficiency: MU-MIMO reduces the time required for transmitting data to multiple users, leading to improved network efficiency and reduced latency

Both massive MIMO and multiuser MIMO are key technologies in modern wireless communication systems. They enable higher data rates, increased system capacity, better spectral efficiency, and improved overall performance by leveraging spatial diversity, beamforming, and interference mitigation techniques. Table 1 compares the main distinctions between the three MIMO techniques discussed above.

4. Advantages and Challenges of MIMO Antennas in 5G Applications

Figures 8 and 9 highlight significant benefits and challenges associated with 5G applications, respectively.

4.1. Advantages

(i) MIMO antennas enable faster data transfer rates by transmitting and receiving multiple data streams simultaneously over the same frequency band

(ii) With multiple antennas, they allow multiple users to transmit and receive data simultaneously, increasing the capacity of the wireless network

(iii) These antennas use multiple antennas to mitigate the effects of interference and signal fading, resulting in more reliable communication

(iv) They can improve coverage by using beam-forming techniques to focus the signal in a particular direction

(v) They can provide higher spectral efficiency by using the same frequency band to transmit multiple data streams [33]

4.2. Major Challenges

(i) Designing MIMO antennas with multiple elements that operate in a compact space can be challenging

(ii) These antennas require higher power consumption due to the use of multiple antennas and signal processing techniques [34]

(iii) They can be expensive to design and manufacture due to their complex design and additional components

(iv) These antennas may not be compatible with all devices, and their effectiveness may vary depending on the device's location and orientation

(v) They can experience interference from other wireless devices, which can affect the performance of the wireless network

5. Advancements in MIMO Antennas for 5G

To overcome the challenges associated with MIMO technology in 5G, such as radiation losses, poor efficiency, restricted bandwidth, and low gain, it is essential to develop antennas that fulfill the basic requirements of high gain, broad bandwidth, and high efficiency [35]. Several strategies have been identified to enhance the performance of MIMO antennas, as depicted in Figure 10.

(i) The optimal placement of MIMO antennas is crucial for their performance. To minimize mutual coupling and enhance performance, the antennas should be positioned at a distance greater than half the wavelength of the operating frequency.

(ii) Diversity in MIMO antenna systems enhances reliability and mitigates fading effects by utilizing physically separated antennas with different radiation patterns. This improves link performance and reduces the impact of signal degradation.

(iii) Polarization diversity is a technique that enhances MIMO antenna performance by utilizing antennas with different polarizations, improving connectivity and system performance.

(iv) Beam shaping is a signal processing technique that improves MIMO antenna performance by directing the emission pattern towards a specific direction, thereby enhancing the signal-to-noise ratio and extending the link range.

(v) Interference poses a significant challenge in MIMO antenna systems. Various methods, such as adaptive filtering, antenna selection, and interference cancellation, are employed to mitigate interference and improve system performance.

(vi) Frequency diversity is another approach to enhancing MIMO antenna performance. By utilizing antennas operating at different frequencies, the system can benefit from frequency diversity, resulting in improved link quality and overall system performance.

Combining multiple approaches enhances MIMO antenna performance. Studying and applying these strategies improves system reliability and performance [26, 36, 37].

6. MIMO Antennas: From Inception to the Current Research Scenario

MIMO technology has undergone extensive research and development, encompassing theoretical studies, experiments, standardization efforts, and advanced techniques.

Table 1: Key differences between MIMO, Massive MIMO, and MU-MIMO with multibeam capability.

Features	MIMO	Massive MIMO	MU-MIMO with multibeam capability
Number of antennas	2 or more	Hundreds or more	4 or more
Spatial streams	2 or more	Dozens or more	Up to 8
Interference control	Limited	Good	Excellent
Beamforming	Basic	Yes	Yes
Deployment	Small cell	Large cell	Large cell
Signal range	Short	Long	Long
Spectral efficiency	Moderate	High	Very high
Power consumption	Moderate	High	High

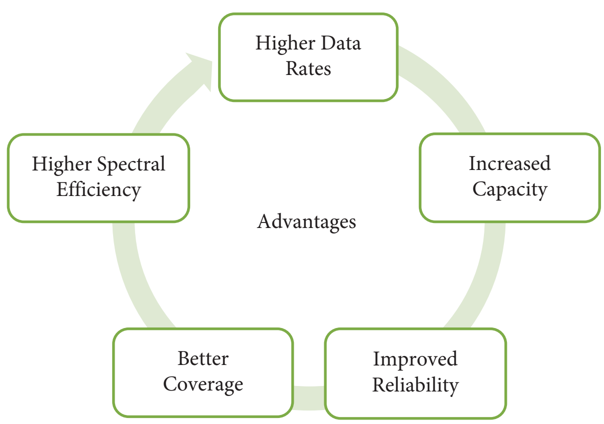


Figure 8: MIMO antennas' advantages in 5G applications.

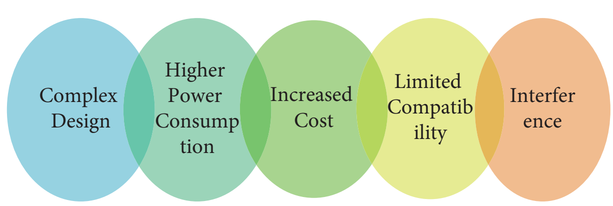


Figure 9: Challenges of MIMO antennas in 5G applications.

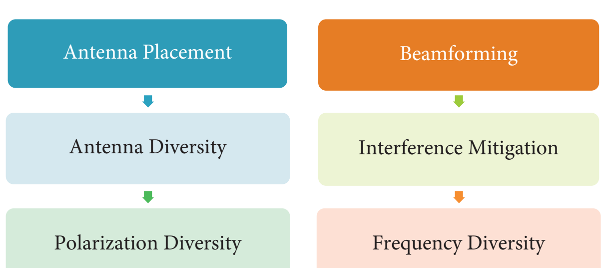


Figure 10: Strategies for enhancing the performance of MIMO antennas.

The evolution of MIMO antennas has led to significant advancements in capacity and performance for wireless communication systems [15, 38].

(i) Early research (late 1970s–1990s): The concept of using multiple antennas for wireless communication was initially proposed in the late 1970s, and early research focused on theoretical studies and simulations. In the 1990s, the idea of spatial multiplexing was introduced, where multiple data streams could be transmitted simultaneously using MIMO antennas, leading to significant improvements in capacity and performance.

(ii) Experimental studies (late 1990s–early 2000s): In the late 1990s and early 2000s, experimental studies were conducted to validate the performance of MIMO antennas in real-world environments. The viability and efficiency of MIMO technology were examined through field trials, channel measurements, and hardware implementations.

(iii) Standardization efforts (early 2000s–mid-2000s): In the early to mid-2000s, standardization efforts began to develop MIMO-based wireless communication standards as the potential of this technology became clear. One example of this is the IEEE 802.11n standard for WLANs, which was introduced in 2009 and included support for MIMO antennas. This standardization effort paved the way for the widespread adoption of MIMO technology in consumer electronics, such as Wi-Fi routers.

(iv) Advanced techniques and algorithms (mid-2000s–2010s): Sophisticated methods and algorithms to improve MIMO antennas' performance were developed. For the purpose of enhancing MIMO performance in diverse wireless communication settings, studies on spatial modulation, hybrid beamforming, precoding, and other signal processing techniques were conducted.

(v) Massive MIMO and 5G (2010s–present): Massive MIMO, which uses a lot of antennas at the transmitter and receiver, has attracted a lot of interest recently as a crucial technology for 5G and future wireless communication systems. Massive MIMO may enhance spectral efficiency, coverage, and capacity in upcoming wireless networks, according to research.

(vi) Application-specific MIMO (present): In addition, research on application-specific MIMO has been growing and focusing on designing MIMO antennas tailored for specific use cases, such as Internet of Things (IoT) devices, wearable devices, vehicular communication, and smart antennas for radar and sensing applications.

Table 2: Performance enhancement techniques of MIMO antenna with advantages and disadvantages.

Reference no	Performance enhancement techniques	Advantages	Disadvantages
[39], 2020	Substrate selection	Substrate's low permittivity characteristics offer a wide bandwidth, improved gain, and high efficiency. Having high permittivity increases the return loss value.	Low permittivity substrate is costly and difficult to procure.
[40, 41]	Decoupling/mutual coupling reduction	Optimizes the gain and efficiency while greatly improving the impedance matching. Reduced mutual coupling reduces the decrease in antenna size.	Mutual connection affects antenna design and makes it more complex.
[42, 43]	Multielement	Significantly increases bandwidth, radiation efficiency and return loss. Effectively decreases back-lobe levels effectively reduce side.	The feeding network for such systems is challenging to design and adds a certain amount of complexity.
[16, 44]	Corrugation	Gain, bandwidth, efficiency, and return loss improvements can be made.	Reduces input impedance considerably.
[20, 24]	Dielectric lens	Improved front-to-back ratio increases with stable radiation pattern. Increased gain, improved back-to-back ratio, stability in radiation patterns, and radiation in the front-facing direction.	As antennas expand in size, the price of manufacturing them also raises.

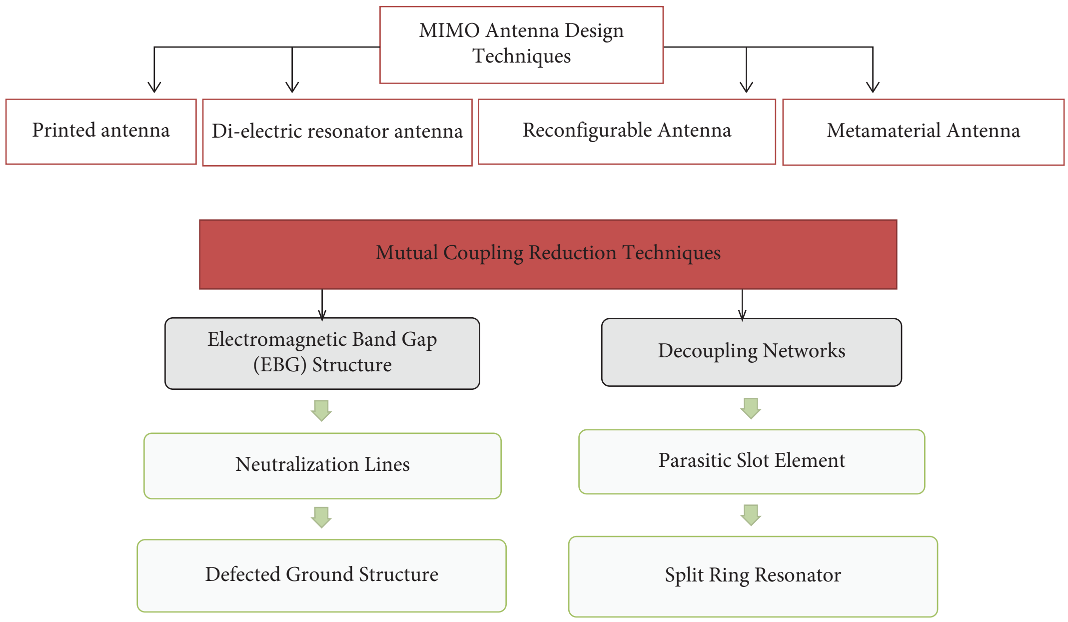


Figure 11: A generic view of designing and reduction techniques for MIMO antennas.

Table 2 presents a summary of different performance enhancement techniques used in antenna design and their respective advantages and disadvantages. This table highlights the trade-offs and complexities involved in each technique, which can aid in making informed decisions during the antenna design process.

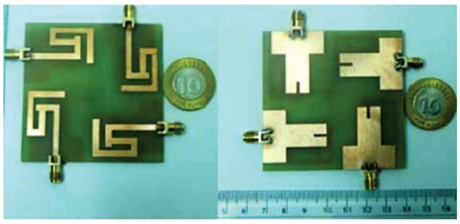
7. MIMO Antenna Design Techniques Based on Mutual Coupling Reduction

Mutual coupling of closely correlated interelements within a MIMO system can have adverse effects on its performance. Consequently, achieving good isolation between closely coordinated elements is imperative for an effective communication system. The effectiveness of an antenna system is significantly impacted by its communication system's capacity gain, and thus mutual coupling reduction is a key consideration in MIMO antenna design, particularly for 5G communication and wide-band applications. Various decoupling and design techniques have been developed and can be effectively employed to achieve superior performance. A summary of MIMO antenna design is available in [45], while specific antenna designs for mutual coupling reduction can be found in [46].

One of the most notable features of a multielement antenna array in the context of MIMO antenna design is the potential influence of antenna elements situated on the printed circuit board (PCB). Thus, careful attention must be paid to the layout of the antenna system, as detailed in Figure 11. By following proper layout techniques, the adverse effects of mutual coupling between closely coordinated elements can be minimized, resulting in improved performance for MIMO communication systems [47].

7.1. Printed Antenna. Microstrip antennas, also known as printed antennas (Figure 12), are a type of antenna that are constructed using a thin conducting metal strip or patch printed on a dielectric substrate. The substrate is typically made of materials such as fiberglass, ceramic, or Teflon, which provide both electrical insulation and mechanical support. The conducting strip is usually made of copper or aluminum and is designed to resonate at a specific frequency. The benefits of microstrip antennas include their durability, flexibility, compactness, and affordability. Due to their flat and low-profile structure, they are easy to integrate into a variety of devices and systems, including portable communication devices and aerospace applications. They can also be easily manufactured using standard printed circuit board (PCB) technology, which makes them a cost-effective choice for both the military and commercial sectors [48].

7.2. Dielectric Resonator Antenna. A dielectric resonator antenna (DRA) is a specialized type of antenna commonly used for microwave and higher-frequency communication. It consists of a ceramic block, known as a dielectric resonator that is positioned on top of a metal ground plane. When radio waves are transmitted through the antenna, they enter the resonator material and cause standing waves to form within its interior, bouncing back and forth against its walls. The energy from these waves can be transmitted into the surrounding space as the walls of the resonator are partially permeable to radio waves. This unique design makes DRA a highly effective and efficient antenna for high-frequency communication applications. For instance, a cylindrical resonator MIMO antenna is depicted in Figure 13 [49].



Front Back

Figure 12: Printed MIMO antenna.

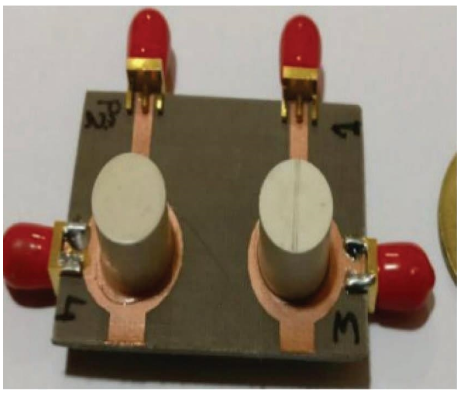


Figure 13: Cylindrical dielectric resonator MIMO antenna.

7.3. Reconfigurable Antenna. An antenna that can continuously, controllably, and irreversibly change its frequency and radiation characteristics is said to be reconfigurable. In terms of operating frequency, beam pattern, polarization, and other features, these antennas may perform a variety of tasks. By regulating a certain switching mechanism by controlling electrical, mechanical, physical, or optical switches, dynamic tuning can be accomplished (Figure 14) [50].

7.4. Metamaterial Antenna. Metamaterial antennas utilize metamaterials to enhance the performance of electrically small or miniaturized antenna systems. These antennas can significantly reduce the size of the antenna while improving other antenna characteristics, such as bandwidth, gain, and multiband frequency functionality. By incorporating metamaterials into the design, they can achieve superior performance compared to traditional antennas. Figure 15 depicts an example of an antenna structure that utilizes metamaterials [51].

7.5. Electromagnetic Band Gap (EBG) Structure. It acts as a conduit for electromagnetic (EM) waves to be transmitted. This structure offers high efficiency and the low mutual coupling [52]. A broadband gap-widening scattering parameter is obtained. It is possible to achieve a far-field gain pattern in the required direction. Figure 16 depicts an antenna utilizing the EBG structure.

7.6. Neutralization Lines. In order to completely decouple or reduce the effects of mutual coupling, neutralization can be used to transmit EM waves utilizing metallic slits or lumped elements between antenna elements. This enhances the antenna's coupling and bandwidth. The neutralization line based on the two-element MIMO antenna example is depicted in Figure 17 [53].

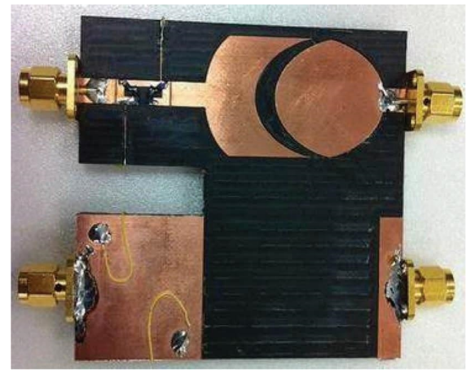


Figure 14: Reconfigurable antenna.

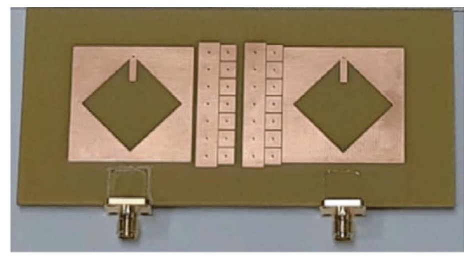


Figure 15: Metamaterial antenna structure.

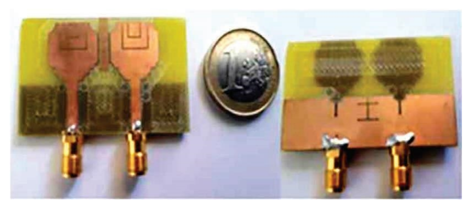


Figure 16: Electromagnetic band gap (EBG) structure.

7.7. Defected Ground Structure. In the antenna ground plane, various geometric features, defects, or slots are consolidated [54]. The highest efficiency is obtained in construction with defective ground and the widest bandwidth with low mutual coupling. Figure 18 depicts an illustration of a patch antenna with a defected ground structure (DGS). The DGS is a design technique used to enhance the performance of the antenna by introducing discontinuities in the ground plane underneath the patch [55].

7.8. Decoupling Networks. By including a discrete component or transmission line, cross-admittance in the decoupling network is changed into a totally fictitious value. This method makes use of a planar decoupling network that behaves like a resonator to lessen the mutual coupling. Decoupling, which can be done by implementing coupled

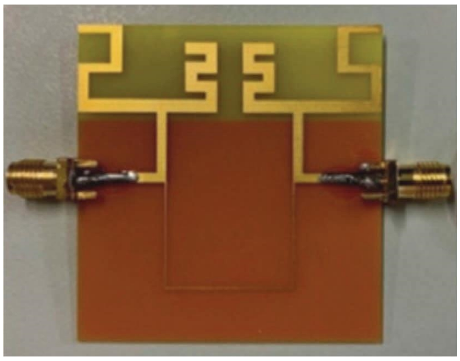


Figure 17: Two-port MIMO antenna with neutralization line.

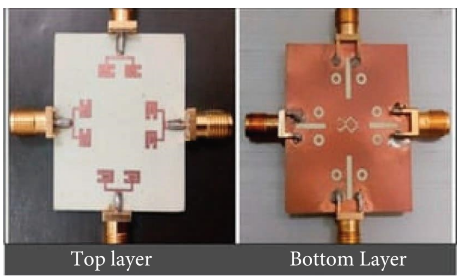


Figure 18: Defected ground structure of the patch antenna.

resonators and dummy loads to improve isolation, can also be used to produce pattern diversity for multielement systems. In Figure 19, an example of a decoupling network for a patch antenna is illustrated [56]. It is designed to reduce the coupling between two adjacent patches in a patch antenna array. The network consists of a series of inductors and capacitors that are strategically placed between the patches to provide a high-impedance path for the unwanted coupling signal. This effectively isolates patches, reducing mutual coupling and improving the performance of the antenna array.

7.9. Parasitic Slot Element. A parasitic element is typically a conductive component, such as a metal rod, that is not electrically connected to any other element in an antenna system. In Figure 20, an example of a printed antenna utilizing a parasitic slot element is depicted [57].

The use of a parasitic slot element in the antenna design offers several benefits. For instance, it can help improve the antenna's directivity, gain, and bandwidth. The parasitic slot element is usually placed near the radiating element and operates by altering the electric field distribution around the radiating element. This alteration results in a change in the radiation pattern of the antenna, thereby enhancing its performance.

7.10. Split-Ring Resonator. Split-ring resonators (SRRs) are created by etching two circular metallic rings onto a dielectric substrate. These rings can be either square or circular and have gaps at their opposing ends. The splits in the rings create structural inhomogeneities that allow the SRRs to

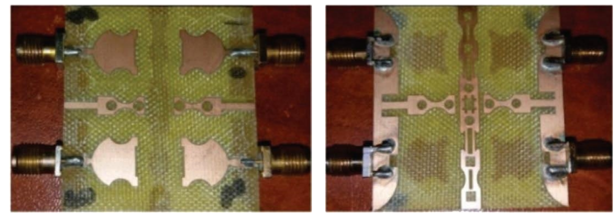


Figure 19: Two-element antennas with decoupling structures.

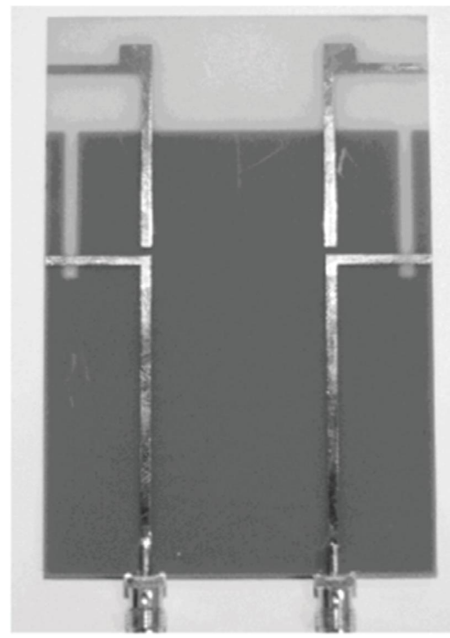


Figure 20: Parasitic slot element-based printed antenna.

accommodate resonant wavelengths that are much longer than the diameter of the rings. The splits in the rings also provide a significant amount of capacitance, which allows the resonator to produce resonance at frequencies much higher than its actual size. This is caused by the inverse connection between capacitance and resonant frequency. The resonant wavelength of SRRs is significantly greater than their physical dimensions due to the interplay between the SRRs' geometry, resonant frequency, and other inherent characteristics. This phenomenon occurs due to the complex nature of the SRRs' interconnections and requires careful consideration when designing and analyzing their behavior. The antenna in Figure 21 is based on SRR [57].

Table 3 contrasts various MIMO antennas based on the methods applied to improve their properties, including, but not limited to, bandwidth, efficiency, isolation, correlation, and diversity. The techniques used to enhance these parameters may include various design elements and configurations, such as antenna size, shape, and number of elements. This table also presents information on the applications of each MIMO antenna, such as cellular communication, Wi-Fi, and satellite communication, among others. By comparing these different MIMO antennas and their characteristics, researchers and engineers may find it

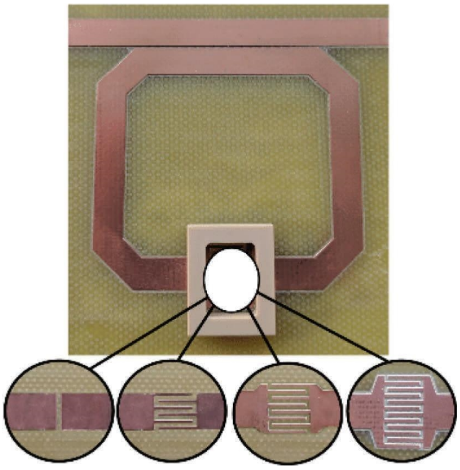


Figure 21: Antenna based on a split-ring resonator.

beneficial to choose the most suitable MIMO antenna for their specific application needs.

It is clear from the literature survey that there is a trade-off between bandwidth and gain. The gain is rather modest for spanning a large bandwidth. Furthermore, the antenna is radiating poorly, resulting in an increase in mutual coupling between distinct MIMO elements. As a result, antenna size must be kept as compact as possible which raises a significant challenge for the antenna designers. Researchers are able to achieve gains of 30–35 dBi, improve bandwidth by 70%, and make several structural changes by utilizing newer technologies.

8. State of the Art

The development of MIMO technology began in 1996, when it was discovered that colocated antennas could increase the capacity of wireless communication systems through multidimensional signal processing and natural multipath propagation. This discovery led to the development of MIMO orthogonal frequency division multiplexing (OFDM) fixed wireless links, which demonstrated error-free operation over six miles with only 1 watt of transmitted power. This breakthrough paved the way for MIMO-based cellular wireless technologies, which were later adopted by LTE mobile networks and Wi-MAX [71].

MIMO technology has been a game-changer in the world of wireless communication. It was developed in the late 1990s and early 2000s by several companies, including Airgo Networks, which was acquired by Qualcomm in 2006 [72]. In 2004, this company unveiled True MIMO, the first MIMO-enabled Wi-Fi device on the market. This was a pioneer in the development of MIMO technology for wireless networking. They used spatial multiplexing, which increases data speeds and reliability by allowing many data streams to be broadcast concurrently across a single-frequency band.

Other businesses have also created MIMO antennas for 5G devices with great performance, capacity, and coverage, including Laird Connectivity, Kathrein, Rosenberger, CommScope, TESSCO, ZTE Corporation, PCTEL, Wilson Electronics, Taoglas, and Qorivo.

The first commercial MIMO system was developed by Iospan Wireless Inc. in 2001, and since then, several companies such as Intel and Broadcom have been introducing novel communication techniques based on MIMO technology to enhance the performance of wireless LAN networks [72].

The development of MIMO systems was driven by the need to improve wireless communication performance by exploiting the spatial diversity and multipath propagation characteristics of radio waves. To achieve this, specialized companies such as Shenzhen VLG Wireless Technology Co. Ltd. [73] specializes in the design and production of antennas for various applications, including MIMO antennas, GNSS antennas, IoT antennas, combo antennas, and antenna accessories.

Chinmore Industry Co., Ltd. focuses on R&D, production, and marketing of MIMO antennas, cable assemblies, and RF connections [74]. REMO electronics offers a diverse range of indoor antennas, including MIMO antennas, for various wireless networks such as GSM, LTE, 4G, 3G, CDMA, and 5G [75].

Airgain, Inc. is a leading supplier of advanced antenna systems to consumers, businesses, and the automotive industries [76]. Their objective is to provide a minimum 30% over-the-air (OTA) throughput boost over rival antenna systems by collaborating with reputable original equipment manufacturers (OEMs) and original design manufacturers (ODMs) to enhance their industrial Internet of Things (IoT) experience. As a leading MIMO antenna manufacturer, Airspan Networks Inc. designs, develops, and manufactures a wide range of MIMO antennas for various wireless communication applications, including fixed wireless access (FWA), mobile broadband, smart cities, IoT, and more. Their MIMO antennas are used by wireless operators, service providers, enterprises, and governments around the world [77].

Huawei, a transnational Chinese company, is a world leader in 5G antenna technology [78]. They offer a broad portfolio of multiband antennas, multibeam antennas, smart antennas, combined amplifiers, and other supporting components for electronics and telecom infrastructure.

Taoglas Limited, located in Ireland, is a top provider of custom antenna design, device configuration optimization, and car antennas for IoT. They offer mm-wave and sub-6 GHz 5G antennas for both indoor and outdoor applications in a range of form factors [79].

Panorama Antennas Ltd., situated in the UK, manufactures wireless antennas from 2 G to 5G frequencies, including indoor 5G antenna options, multipurpose, wideband, and MIMO directional antennas [80].

Ericsson is a Swedish multinational networking and telecommunications company that provides a range of products and services for 5G networks. Their massive MIMO antenna is designed to improve network capacity and coverage. Their antenna supports frequency ranges from 1.7 to 2.7 GHz and is designed to support both 4G and 5G networks [81].

Table 3: Comparison of existing MIMO antennas with respect to design techniques, specifications, and applications.

Reference nos.	Types of antenna	Techniques to enhance bandwidth/isolation	Feeding method	Design parameters	Applications
[58]	Meander line monopoles	Decoupling technique	Coaxial feed	(i) Resonant frequency: 2.6 GHz (ii) BW: 2.5–2.7 GHz (iii) Isolation >8 dB (iv) Dimension: 10 mm × 20 mm (v) Envelope correction coefficient (ECC): 0.025	(i) USB dongles design (ii) Wireless communication
[59]	Planar-monopole antennas	Protruding ground stubs	Microstrip-feed	(i) Resonant frequency: 3.1-10.6 GHz (ii) BW: ≥10 dB(wideband) (iii) Isolation >15 dB (iv) Dimension: 26 mm × 40 mm (v) Gain: 0.9–6.5 dBi (vi) ECC: 0.025	(i) Portable UWB applications
[60]	S-shaped monopole antenna	Neutralization line and decoupling	Microstrip-feed	(i) Resonant frequency: 1.62-2.92 GHz (ii) BW: 1.3 GHz (iii) Isolation: >40 dB (iv) Dimension: 100 mm × 60 mm (v) Gain: 5 dBi (vi) ECC: 0.009	(i) Mobile terminals (ii) GSM1900, (iii) GSM1800, (iv) UMTS, (v) LTE2500, (vi) LTE2300 and 2.4 GHz, (vii) WLAN
[61]	Rectangular and circular patch antenna	Radiator strip and ground plane	Coaxial-feed	(i) Resonance frequency: multiband between 1.5 and 2.7 GHz (ii) Isolation: >13 dB (iii) Gain: 6.622 dBi 6.01 dBi at 28 GHz (iv) 7.35 dBi, and 2.2 GHz, and 1.5 GHz (v) SAR: 1.5 G Hz value is 0.205 W/kg, 2.2 GHz it is 0.471 W/kg	(i) GSM, LTE, mm wave bands (ii) 5G mobile applications
[62]	Circular monopole and quarter loop	Pattern diversity	Microstrip-feed	(i) Resonance frequency: 2–9.5 GHz (ii) BW: 7.5 GHz (iii) Isolation: >40 dB (iv) Total efficiency: 70% (v) Dimension: 110 mm × 60 mm (vi) Gain: 1.5 dBi (vii) ECC: 0.03	(i) Mobile applications
[63]	Counter facing F-shaped monopole antenna	Elliptical slot and parasitic strip	Microstrip-feed	(i) Resonance frequency: (5.7 – 6.2 GHz) and (3.2–3.8 GHz), (ii) BW: 5.2–5.4 GHz (iii) Isolation: >20 dB (iv) Dimension: 30 mm × 26 mm (v) Gain: 1.5 and 2.8 dBi (vi) ECC: 0.03	(i) Wi-MAX (ii) WLAN (iii) Applications

Table 3: Continued.

Reference nos.	Types of antenna	Techniques to enhance bandwidth/isolation	Feeding method	Design parameters	Applications
[64]	Circular disk monopole	Rectangular ground surface	Coplanar waveguide feed	(i) Resonance frequency: (3.01 –12.5 GHz) (ii) BW: 3.03–10.74 GHz (iii) Isolation: >20 dB (iv) Dimension: 81 mm × 87 mm × 1.6 mm (v) Gain: 5 to 9 dBi (vi) ECC: <0.1	(i) Mobile communication
[65]	Patch antenna	I-shape DGS and T-shape DGS	Coaxial-feed	(i) Resonance frequency: 5.25–5.3 GHz (ii) BW: 0.5 GHz (iii) Isolation: >25 dB (iv) Dimension: 60 mm × 50 mm × 1.46 mm (v) Gain: 7.88 dBi (vi) ECC: 0.03	(i) WiMAX (ii) Wi-Fi (iii) 5G services
[66]	T-shape antenna	T-shape slot	Coaxial probe feed	(i) Resonance frequency: 2.4 GHz (ii) BW: 2.3–2.6 GHz (iii) Isolation: >25 dB (iv) Dimension: 35 mm × 45 mm	(i) ISM band
[67]	F-shape monopole antenna radiators	Folded U-shaped slot and mushroom type EBG structure	Microstrip-feed	(i) Resonance frequency: 7.3 GHz and 8.2 GHz (ii) BW: (5.2–6 GHz), (7.9–8.2 GHz) (dual band) (iii) Isolation: >25 dB (iv) Dimension: 20.8 mm × 20.8 mm × 19 mm (v) Gain: 7 dBi (vi) ECC: >0.5	(i) UWB applications (ii) X-band uplink/downlink satellite communications
[68]	Olympeak-shaped structure	Partial ground with bent corners and a square slot on the middle in ground	Microstrip-feed	(i) Resonance frequency: 4.4 GHz (ii) BW: 23–33 GHz and 37.75–41 GHz (iii) Isolation: >20 dB (iv) Dimension: 48 mm × 12 mm × 0.8 mm (v) Gain: 5.7 dBi	(i) 5G applications
[69]	Fractal-based patch antenna	Sierpiński triangle fractal	Open-circuited feed line through a coplanar waveguide	(i) BW: 1.95 and 2.7 GHz and 4.2–4.3 GHz (ii) Isolation: >10 dB (iii) Dimension: 40 mm × 30 mm × 1.67 mm (iv) Gain: 5.5 dBi	(i) 5G applications

Table 3: Continued.

Reference nos.	Types of antenna	Techniques to enhance bandwidth/isolation	Feeding method	Design parameters	Applications
[70]	Crescent-shape patch	DGS with circular slot	Inset-feed	(i) Resonance frequency: 28 GHz and 38 GHz (ii) BW: 3.05GHz and 2.41 GHz (iii) Isolation: >30 dB (iv) Dimension: 33 mm × 33 mm × 0.203 mm (v) Gain: 8.14 dB and 8.04 dB at 28 GHz and 38 GHz	(i) 5G millimeter-wave applications

ZTE is a Chinese multinational telecommunications equipment and systems company that provides products and services for 5G networks. Their massive MIMO antenna is designed to improve network capacity and coverage. Their antenna supports frequency ranges from 1.8 to 2.6 GHz and is designed to support both 4G and 5G networks [82].

9. Future Opportunities and Challenges

MIMO systems offer a variety of advantages, including cochannel interference reduction, diversity gain, and array gain. Array gain boosts coverage and quality of service (QoS), while diversity gain, multiplexing gain, and cochannel interference reduction increase spectral efficiency and cellular capacity, respectively. Above all, the MIMO system demonstrated itself to be the finest future technology for LTE systems when combined with OFDM technology [83]. The MIMO technology can greatly improve network capacity and coverage in indoor environments, such as shopping malls, airports, and stadiums. They can also be used to provide high-quality video streaming services, such as 4K and 8K video, to mobile devices. The use of massive MIMO technology can enable the deployment of 5G networks in rural and remote areas where it is not economically feasible to build wired infrastructure [84]. MIMO can be applied in smart cities, where it can facilitate the deployment of various IoT applications, such as smart parking, smart lighting, and smart waste management. MIMO can also be used in drone communication and control systems, enabling high-bandwidth communication and real-time control [85]. For MIMO and mm-wave channel measurements, antennas hold significant challenges to deal with certain parameters such as a multitude of scenarios, wider bandwidth, high-frequency band, gain, and efficiency [86]. These technologies can greatly enhance wireless access and throughput in various 5G scenarios including high-speed train (HST) and vehicle-to-vehicle (V2V) communication. Thus, sixth-generation (6 G) MIMO antennas in wireless communications are predicted to come on the scene in the future. MIMO antennas will be used in IoT, M2M communications, and network-enabled cars, healthcare, smart utilities, etc.

In the future, the requirements for higher data rates will rise, and this demand can be overcome by MIMO technology that will provide higher data rates for consumers, possibly 10 times higher than 4G and 5G capabilities.

(i) Integration with other 5G technologies: MIMO antennas are just one component of the larger 5G communication system. In the future, how to optimize MIMO antenna design to work seamlessly with other 5G technologies, such as beamforming and massive MIMO may be investigated.

(ii) Miniaturization and cost reduction: While MIMO antennas can offer significant benefits to 5G communications, their size and cost may make them impractical in some situations. Some different ways may be looked at for miniaturizing MIMO antenna designs while maintaining or improving their performance and reducing the cost of MIMO antenna manufacturing.

(iii) Enhancing performance: While MIMO antennas can improve 5G communication, there is always room for improvement. Research is always open to investigate how to further enhance the performance of MIMO antennas by improving their efficiency or reducing their mutual coupling.

(iv) Compatibility with new frequency bands: As 5G develops further, other frequency bands might be added. It might be worth looking into how MIMO antennas can be made functional in these new frequency ranges while still performing satisfactorily.

(v) Regulatory challenges: Regulatory issues, particularly those involving spectrum allotment and interference, may affect the adoption of 5G and MIMO antennas. It may be worth looking into ways to overcome these obstacles, such as by developing MIMO antennas that are less susceptible to interference or by developing better interference mitigation strategies.

The prospective outlook for MIMO antennas in the context of 5G communication appears highly promising but there are still many challenges that need to be addressed. Research in this area will likely continue for many years to come. One of the challenges in MIMO technology is the need for accurate channel state information (CSI), which can be difficult to obtain in a dynamic wireless environment. MIMO systems also require a significant amount of processing power and memory, which can be a challenge for low-cost and low-power devices [87]. The high density of antennas in massive MIMO systems can lead to increased power consumption and thermal management issues. MIMO systems can also suffer from intersymbol interference (ISI), which occurs when signals from different antennas interfere with each other. In mm-wave frequencies, the attenuation and signal blockage due to obstacles and atmospheric conditions can significantly affect the performance of MIMO systems [88].

10. Conclusion

MIMO, massive MIMO, and MU-MIMO with multibeam capability are essential for 5G communication systems, offering advantages such as increased spectral efficiency, improved capacity, and higher data rates. However, they also face challenges such as high-power consumption, mutual coupling, and interference, which can be overcomed with various strategies such as antenna decoupling and adaptive modulation. MIMO antenna design techniques based on mutual coupling reduction are crucial for improving antenna performance. The state of the art in MIMO antennas for 5G communication is rapidly evolving, and future research should focus on developing low-cost, compact MIMO antennas that exhibit good radiation and electromagnetic properties and can cover the entire 5G frequency range. Miniaturization of antenna arrays is also necessary to improve isolation and reduce multipath interference.

Overall, the development of advanced MIMO antenna technologies is critical for achieving the full potential of 5G wireless communication systems.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

References

[1] N. Ojaroudi Parchin, H. JahanbakhshBasherlou, Y. I. Al-Yasir, A. Ullah, R. A. Abd-Alhameed, and J. M. Noras, "Multi-band MIMO antenna design with user-impact investigation for 4G and 5G mobile terminals," *Sensors*, vol. 19, no. 3, p. 456, 2019.

[2] K. S. Min, D. J. Kim, and Y. M. Moon, "Improved MIMO antenna by mutual coupling suppression between elements," in *Proceedings of the The European Conference on Wireless Technology*, pp. 125–128, Paris, France, October 2005.

[3] L. Malviya, R. K. Panigrahi, and M. V. Kartikeyan, "Four element planar MIMO antenna design for long-term evolution operation," *IETE Journal of Research*, vol. 64, no. 3, pp. 367–373, 2018.

[4] L. H. Brandenburg and A. D. Wyner, "Capacity of the Gaussian channel with memory: the multivariate case," *Bell System Technical Journal*, vol. 53, no. 5, pp. 745–778, 1974.

[5] S. Soltani and R. D. Murch, "A compact planar printed MIMO antenna design," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 3, pp. 1140–1149, 2015.

[6] T. E. Alharbi, A. Shastri, O. A. Alzahrani, and B. Sanz-Izquierdo, "Evaluation of a wideband monopole antenna with tunable stop notches," in *Proceedings of the Antennas and Propagation Conference*, pp. 1–4, Birmingham, UK, November 2019.

[7] P. Rani, P. Tiwari, T. Singh, and V. Gahlaut, "A compact ground fed UWB antenna with single band notch characteristics," in *Proceedings of the IEEE International Conference on Smart Electronics and Communication (ICOSEC)*, pp. 435–440, Trichy, India, December 2021.

[8] O. H. Koymen, A. Partyka, S. Subramanian, and J. Li, "Indoor mm-Wave channel measurements: comparative study of 2.9 GHz and 29 GHz," in *Proceedings of the IEEE Global Communications Conference (GLOBECOM)*, pp. 1–6, San Diego, CA, USA, December 2015.

[9] S. Iffat Naqvi, N. Hussain, A. Iqbal et al., "Integrated LTE and millimeter-wave 5G MIMO antenna system for 4G/5G wireless terminals," *Sensors*, vol. 20, no. 14, p. 3926, 2020.

[10] S. F. Jilani, A. Rahimian, Y. Alfadhl, and A. Alomainy, "Low-profile flexible frequency-reconfigurable millimetre-wave antenna for 5G applications," *Flexible and Printed Electronics*, vol. 3, no. 3, Article ID 035003, 2018.

[11] A. Shastri, I. Ullah, and B. Sanz-Izquierdo, "Alternating current sensing slot antenna," *IEEE Sensors Journal*, vol. 21, no. 7, pp. 9484–9491, 2021.

[12] P. Tiwari, M. Kaushik, A. Shastri, and V. Gahlaut, "Two element microstrip-fed slot loaded millimeter wave MIMO antenna," *IEEE International Conference for Advancement in Technology (ICONAT)*, pp. 1–5, Goa, India, January 2023.

[13] P. Tiwari, M. Kaushik, A. Shastri, J. K. Rai, and V. Gahlaut, "Simulated Design and Analysis of Highly Isolated 5G Millimeter-Waves MIMO Antenna with Wideband Characteristic," in *Proceedings of the IEEE First International Conference on Microwave, Antenna and Communication (MAC)*, pp. 1–6, Prayagraj, India, August 2023.

[14] I. Ahmad, H. Sun, U. Rafique, and Z. Yi, "Triangular slot-loaded wideband planar rectangular antenna array for millimeter-wave 5G applications," *Electronics*, vol. 10, no. 7, p. 778, 2021.

[15] W. A. Ali and A. A. Ibrahim, "A compact double-sided MIMO antenna with an improved isolation for UWB applications," *AEU-International Journal of Electronics and Communications*, vol. 82, pp. 7–13, 2017.

[16] A. Patil and R. S. Bhadade, *A Literature Survey on MIMO Antenna*, Elsevier, Amsterdam, Netherlands, 2021.

[17] A. Ghasemi and E. S. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environments," in *Proceedings of the First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, pp. 131–136, Baltimore, MD, USA, November 2005.

[18] A. Morita and J. T. Hynes, "A theoretical analysis of the sum frequency generation spectrum of the water surface," *Chemical Physics*, vol. 258, no. 2-3, pp. 371–390, 2000.

[19] J. Kowalewski, J. Eisenbeis, A. Jauch, J. Mayer, M. Kretschmann, and T. Zwick, "A mmW broadband dual-polarized dielectric resonator antenna based on hybrid modes," *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 7, pp. 1068–1072, 2020.

[20] M. N. Srifi and M. Essaaidi, "Ultra-wideband printed antennas design," *Ultra-Wideband Communications: Novel Trends-Antennas and Propagation*, Intechopen, New York, NY, USA, 2011.

[21] Y. Li, M. Chiani, and H. V. Poor, "Spatial modulation for MIMO communications: high-rate detection algorithms, channel capacity, and optimization aspects," *IEEE Transactions on Wireless Communications*, vol. 7, no. 12, pp. 5066–5077, 2019.

[22] X. Gao, L. Dai, S. Han, Z. Wang, and R. W. Heath, "Energy-efficient hybrid analog and digital precoding for mmWave MIMO systems with large antenna arrays," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 998–1009, 2016.

[23] L. Dai, B. Wang, Y. Yuan, S. Han, I. Chih-lin, and Z. Wang, "Non-orthogonal multiple access for 5G: solutions, challenges, opportunities, and future research trends," *IEEE Communications Magazine*, vol. 53, no. 9, pp. 74–81, 2015.

[24] R. Chowdhury, N. Mishra, M. M. Sani, and R. K. Chaudhary, "Analysis of a wideband circularly polarized cylindrical dielectric resonator antenna with broadside radiation coupled with simple microstrip feeding," *IEEE Access*, vol. 5, pp. 19478–19485, 2017.

[25] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Transactions on Wireless Communications*, vol. 9, no. 11, pp. 3590–3600, 2010.

[26] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 186–195, 2014.

[27] E. Björnson, E. G. Larsson, and T. L. Marzetta, "Massive MIMO: ten myths and one critical question," *IEEE Communications Magazine*, vol. 54, no. 2, pp. 114–123, 2016.

[28] B. Yang, Z. Yu, Y. Dong, J. Zhou, and W. Hong, "Compact tapered slot antenna array for 5G millimeter-wave massive MIMO systems," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6721–6727, Dec. 2017.

[29] H. Holma and A. Toskala, *LTE for UMTS: Evolution to LTE-Advanced*, John Wiley & Sons, New York, NY, USA, 2011.

[30] N. Parrish, L. Tracy, S. Roy, P. Arabshahi, and W. L. Fox, "System design considerations for undersea networks: link and multiple access protocols," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 9, pp. 1720–1730, 2008.

[31] S. Sun, T. S. Rappaport, R. W. Heath, A. Nix, and S. Rangan, "MIMO for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?" *IEEE Communications Magazine*, vol. 52, no. 12, pp. 110–121, 2014.

[32] G. L. Stüber and G. L. Steuber, *Principles of mobile communication*, Kluwer academic, Boston, MA, USA, 2001.

[33] D. Wang, Z. W. Yin, C. X. Wang, X. You, J. Wang, and I. Chih-Lin, "On a collection of batraxis reitter (Coleoptera: staphylinidae: pselaphinae) from hainan island, southern China," *Zootaxa*, vol. 4109, no. 1, pp. 1–15, 2016.

[34] J. Li and G. L. Stuber, "MIMO-OFDM with adaptive modulation for next-generation wireless systems," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 5, pp. 1085–1095, 2002.

[35] L. Chen and Q. Wang, "Polarization diversity techniques for improved MIMO antenna performance," *Journal of Signal Processing*, vol. 25, no. 4, pp. 110–123, 2020.

[36] C. Lee and D. Kim, "Beam shaping for enhanced MIMO antenna performance," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 8, pp. 3421–3434, 2021.

[37] J. G. Andrews, S. Buzzi, W. Choi et al., "What will 5G be?" *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, 2014.

[38] W. Jiang, B. Liu, Y. Cui, and W. Hu, "High-isolation eight-element MIMO array for 5G smartphone applications," *IEEE Access*, vol. 7, pp. 34104–34112, 2019.

[39] R. Liu, X. An, H. Zheng, M. Wang, Z. Gao, and E. Li, "Neutralization line decoupling tri-band multiple-input multiple-output antenna design," *IEEE Access*, vol. 8, pp. 27018–27026, 2020.

[40] Z. Nie, H. Zhai, L. Liu, J. Li, D. Hu, and J. Shi, "A dual-polarized frequency-reconfigurable low-profile antenna with harmonic suppression for 5G application," *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 6, pp. 1228–1232, 2019.

[41] M. Ikram, N. Nguyen-Trong, and A. Abbosh, "A simple single-layered continuous frequency and polarization-reconfigurable patch antenna array," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 6, pp. 4991–4996, 2020.

[42] G. Jin, C. Deng, Y. Xu, J. Yang, and S. Liao, "Differential frequency-reconfigurable antenna based on dipoles for sub-6 GHz 5G and WLAN applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 3, pp. 472–476, 2020.

[43] K. Sulonen, P. Suvikunnas, L. Vuokko, J. Kivinen, and P. Vainikainen, "Comparison of MIMO antenna configurations in picocell and microcell environments," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 5, pp. 703–712, 2003.

[44] N. Ojaroudi Parchin, Y. Al-Yasir, A. M. Abdulkhaleq et al., "Frequency reconfigurable antenna array for mm-Wave 5G mobile handsets," in *International Conference on Broadband Communications, Networks and Systems*, pp. 438–445, Springe, Cham, Switzerland, 2018.

[45] L. Malviya, R. K. Panigrahi, and M. V. Kartikeyan, "A 2× 2 dual-band MIMO antenna with polarization diversity for wireless applications," *Progress in Electromagnetics Research C*, vol. 61, pp. 91–103, 2016.

[46] S. Pahadsingh and S. Sahu, "Four port MIMO integrated antenna system with DRA for cognitive radio platforms," *AEU-International Journal of Electronics and Communications*, vol. 92, pp. 98–110, 2018.

[47] Y. Sun, M. Tian, and G. S. Cheng, "Characteristic mode-based neutralization line design for MIMO antenna," *International Journal of Antennas and Propagation*, vol. 2022, Article ID 9669114, 14 pages, 2022.

[48] H. Sakli, C. Abdelhamid, C. Essid, and N. Sakli, "Metamaterial-based antenna performance enhancement for MIMO system applications," *IEEE Access*, vol. 9, pp. 38546–38556, 2021.

[49] O. Sokunbi and H. Attia, "Dual-layer dual-patch EBG structure for isolation enhancement and correlation reduction in MIMO antenna arrays," *Progress in Electromagnetics Research C*, vol. 100, pp. 233–245, 2020.

[50] T. Reinecke, J. G. Walter, T. Kobelt, A. Ahrens, T. Scheper, and S. Zimmermann, "Design and evaluation of split-ring resonators for aptamer-based biosensors," *Journal of Sensors and Sensor Systems*, vol. 7, no. 1, pp. 101–111, 2018.

[51] M. Khalid, S. Iffat Naqvi, N. Hussain et al., "4-Port MIMO antenna with defected ground structure for 5G millimeter wave applications," *Electronics*, vol. 9, p. 71, 2020.

[52] Y. Wang and Z. Du, "A wideband printed dual-antenna with three neutralization lines for mobile terminals," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 3, pp. 1495–1500, 2014.

[53] Z. Li, Z. Du, and K. Gong, *A Dual-Slot Diversity Antenna with Isolation Enhancement Using Parasitic Elements for mobile Handsets*, Asia Pacific Microwave Conference, Singapore, 2021.

[54] T. Thomas, K. Veeraswamy, and G. Charishma, "MM wave MIMO antenna system for UE of 5G mobile communication: design," in *In Proceedings of the Annual IEEE India Conference (INDICON)*, New Delhi, India, December 2015.

[55] X. Zhao, S. P. Yeo, and L. C. Ong, "Planar UWB MIMO antenna with pattern diversity and isolation improvement for mobile platform based on the theory of characteristic modes," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 1, pp. 420–425, 2018.

[56] T. Agrawal and S. Srivastava, "Compact MIMO antenna for multiband mobile applications," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, vol. 16, no. 2, pp. 542–552, 2017.

[57] M. S. Sharawi, M. Ikram, and A. Shamim, "A two concentric slot loop based connected array MIMO antenna system for 4G/5G terminals," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6679–6686, 2017.

[58] P. C. Nirmal, A. Nandgaonkar, S. L. Nalbalwar, and R. K. Gupta, "A compact dual band MIMO antenna with improved isolation for Wi-Max and WLAN applications," *Progress in Electromagnetics Research M*, vol. 68, pp. 69–77, 2018.

[59] N. O. Parchin, Y. I. A. Al-Yasir, A. H. Ali et al., "Eight-element dual-polarized MIMO slot antenna system for 5G smartphone applications," *IEEE Access*, vol. 7, pp. 15612–15622, 2019.

[60] I. Aggarwal, S. Pandey, M. R. Tripathy, and A. Mittal, "Design and analysis of metamaterial-based SWB-MIMO antenna," *IETE Journal of Research*, vol. 70, pp. 1–14, 2022.

[61] A. A. Ibrahim and W. A. Ali, "High isolation 4-element ACS-fed MIMO antenna with band notched feature for UWB communications," *International Journal of Microwave and Wireless Technologies*, vol. 14, no. 1, pp. 54–64, 2022.

[62] A. M. Ibrahim, I. M. Ibrahim, and N. A. Shairi, "Compact MIMO antenna with high isolation for 5G smartphone applications," *Journal of Engineering Science and Technology Review*, vol. 12, no. 6, pp. 121–125, 2019.

[63] A. M. Al-Juboori and M. A. Matin, "MIMO antenna systems for 5G applications: a review," *Journal of Communication Engineering*, vol. 7, no. 2, pp. 93–105, 2019.

[64] K. Wang, X. Zhang, and P. Cheng, "MIMO antennas for 5G communication: a review," *IEEE Antennas and Propagation Magazine*, vol. 60, no. 2, pp. 142–153, 2018.

[65] S. H. Ghadeer, S. K. Rahim, M. Alibakhshikenari et al., "An innovative fractal monopole MIMO antenna for modern 5G applications," *AEU-International Journal of Electronics and Communications*, vol. 159, p. 154480, 2003.

[66] K. Cuneray, N. Akcam, and T. Okan, "28/38 GHz dual-band MIMO antenna with wideband and high gain properties for 5G applications," *AEU-International Journal of Electronics and Communications*, vol. 162, p. 154553.

[67] Y. Zhang, J. Mao, and Z. N. Chen, "Design and optimization of MIMO antennas for 5G applications: a review," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 9, pp. 6065–6082, 2019.

[68] S. Morris, "Airgo Networks Claims Wireless Breakthrough," 2004, https://www.computerworld.com/article/2562913/airgo-networks-claims-wireless-breakthrough.html.

[69] D. Law, "Airgo's True MIMO: Breakthrough or Hype? Wi-Fi Planet," 2005.

[70] https://www.wi-fiplanet.com/news/article.php/3519661/Airgos-True-MIMO-Breakthrough-or-Hype.htm.

[71] Qualcomm, "Wireless Technology & Innovation | Mobile Technology," Qualcomm, Chennai, india, 2022.

[72] NIHF, "Inductee Arogyaswami Paulraj Invented MIMO Technology," 2020, https://www.invent.org/blog/inventors/Arogyaswami-Paulraj.

[73] Shenzhen VLG wireless technology Co Ltd, "Shenzhen VLG wireless technology Co. Ltd," 2023, https://www.vlgcom.com/.

[74] Chinmore industry Co Ltd, "Chinmore industry Co. Ltd," 2023, http://www.chinmore.com.tw/.

[75] REMO electronics, "REMO electronics," 2023, https://www.remotek.com/.

[76] Airgain, "Airgain, Inc," 2023, https://www.airgain.com/.

[77] Airspan networks 5G solutions, "Airspan networks 5G solutions," 2023, https://www.airspan.com/products/5g-solutions/.

[78] Huawei 5G antenna portfolio, "Huawei 5G antenna portfolio," 2023, https://www.huawei.com/en/products/wireless/antennas.

[79] Taoglas 5G antennas, "Taoglas 5G antennas," 2023, https://www.taoglas.com/products-category/5g-antennas/.

[80] Panorama antennas 5G antennas, "Panorama antennas 5G antennas," 2023, https://www.panorama-antennas.com/products/5g-antennas.

[81] Ericsson massive MIMO antenna, "Ericsson massive MIMO antenna," 2023, https://www.ericsson.com/en/press-releases/2018/1/ericsson-massive-mimo-now-shipping-to-customers.

[82] ZTE, "ZTE Massive MIMO antenna," 2023, https://www.zte.com.cn/global/solutions/5g/201812251711/201812251712.

[83] R. W. Bauml, R. F. H. Fischer, and J. B. Huber, "Systematic design of transmitter precoding matrices for spatial multiplexing systems," *IEEE Transactions on Information Theory*, vol. 50, no. 5, pp. 849–864, 2004.

[84] Y. Zhang and Z. N. Chen, "MIMO antennas for 5G mobile terminals: a review," *IEEE Access*, vol. 6, pp. 20394–20407, 2018.

[85] V. Viikari, "5G antenna challenges and opportunities," *IEEE-International Symposium on Wireless Communication Systems (ISWCS)*, vol. 50, pp. 330–334, 2019.

[86] M. J. Riaz, A. Sultan, M. Zahid, A. Javed, Y. Amin, and J. Loo, "MIMO Antennas for Future 5G Communications," in *Proceedings of the IEEE- International Multitopic Conference (INMIC)*, pp. 1–4, Bahawalpur, Pakistan, January 2020.

[87] T. S. Rappaport, J. N. Murdock, and F. Gutierrez, "State of the art in 60-GHz integrated circuits and systems for wireless communications," *Proceedings of the IEEE*, vol. 99, no. 8, pp. 1390–1436, 2011.

[88] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of things: a survey on enabling technologies, protocols, and applications," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 2347–2376, 2015.