

Enhancement Techniques for Massive MIMO Antenna Arrays in 5G Millimeter Wave Base Stations: A Comprehensive Review

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ABSTRACT

The emergence of 5G technology highlights millimeter-wave (mmWave) communication as a critical enabler due to its ability to handle vast data demands, addressing the exponential growth in wireless services. Massive Multiple-Input Multiple-Output (MIMO) antenna arrays play a pivotal role in mitigating mmWave propagation challenges by compensating for severe path loss, ensuring high capacity, enhanced coverage, and superior spectral efficiency for 5G base stations. This paper provides a comprehensive review of enhancement techniques applied to Massive MIMO antenna arrays in 5G mmWave base stations. It begins with an overview of Massive MIMO and mmWave technologies, discussing their advantages and challenges in practical deployments. Key challenges include significant path loss, beamforming complexities due to beam misalignment, and hardware intricacies arising from the large number of antennas required. The study then explores advanced enhancement techniques designed to address these challenges, detailing their contributions to signal quality, coverage enhancement, and interference mitigation. It also highlights innovative antenna array designs and architectures that optimize gain and radiation patterns for improved base station performance. This survey offers valuable insights into state-of-the-art solutions for Massive MIMO antenna arrays in 5G mmWave systems and underscores their role in advancing wireless communication technologies. The findings aim to inspire further research and innovation to meet the evolving demands of modern wireless networks.

Keywords: MIMO antenna; fifth generation; mm-Wave communication; Massive MIMO Antenna; Millimeter Wave; metamaterial; base station

INTRODUCTION

The exponential growth in user traffic demand necessitates that 5G provides solutions for applications requiring significant bandwidth. Key objectives of 5G include faster connectivity, improved reliability, spectral efficiency, higher data rates, and enhanced energy efficiency. Achieving these goals presents technical challenges, particularly the need for higher data rates compared to previous generations. This necessitates the use of higher frequencies within the millimeter-wave (30-300 GHz) spectrum, which requires many antennas to overcome high path loss and provide sufficient bandwidth. Additionally,

smaller cells must be used to reduce interference by utilizing these many antennas (Busari et al. 2018).

Massive MIMO is designed to address the demands of 5G and future wireless networks. It is an innovative wireless technology that improves MIMO technology by deploying hundreds or thousands of antennas at a central station. This results in enhanced spectral efficiency and faster data transfer speeds. Massive MIMO combines antennas, radio frequency components, and the available spectrum to achieve higher capacity and faster speeds in a 5G network (Rusek et al. 2013). The crucial role of Massive MIMO in the advancement of new wireless standards is due to its capability to enhance throughput and spectral efficiency, primarily by generating substantial

array gain using a considerable number of antennas (Marzetta 2015). Massive MIMO is a crucial technology for 5G and future networks, and it is instrumental in enabling intelligent sensing systems. Traditional multi-access methods are not practical for collecting data from numerous smart sensors as they result in high latency, low data rates, and poor reliability. Massive MIMO can gather data from numerous sensor transmissions with low latency using its substantial multiplexing gain and beamforming capabilities. This results in higher data rates and reliable connectivity, providing sensors with efficient data transmission. This technology plays a vital role in real-time data transmission from smart sensors, with numerous practical applications. Various applications can take advantage of Massive MIMO technology, Examples include self-driving cars, telemedicine, intelligent power grids, advanced antennas, connected roadways, intelligent buildings, and environmental monitoring systems (Chataut & Akl 2020). The evolution of MIMO technology began with diversity systems using two receivers to address signal fading due to multipath effects (Beverage & Peterson 1931; Peterson et al. 1931). Research indicates that MIMO systems, with more complex structures than single-input single-output (SISO) systems, provide multiple additional paths, reducing multipath interference, delays, and packet loss, thereby enhancing various communication methods.

According to Shannon's theorem, channel capacity is influenced by both bandwidth and SNR. MIMO systems can significantly increase data throughput by maintaining fixed bandwidth and transmission power, thanks to their multi-port design (Foschini & Gans 1998; Moghe & Upadhyay 2009).

Millimeter-wave communication systems (mmWave) are essential for 5G wireless technology. The International Telecommunication Union has allocated various frequency bands for 5G, while the Federal Communications Commission has allocated the 27.5-28.35 GHz band (Marcus 2015). 5G systems, compared to 4G, require data rates of several gigabits per second, high data flow with minimal delays, the ability to handle numerous connections, and efficient frequency spectrum usage at controlled costs (Lee et al. 2016). The signal-to-interference-plus-noise ratio (SINR) declines, however, because of the significant free-space loss and also electromagnetic wave obstruction at higher frequencies that are millimeter wave bands (Zhang et al. 2016). Signal interference from other systems on common channels can be reduced by using line-of-sight (LOS) transmission with directional antennas.

Figure 1 shows a typical scenario of a hybrid 5G wireless network. The use of directional antennas helps because transmission based on line-of-sight (LOS) can reduce much of the signal interference coming from other systems on common channels.

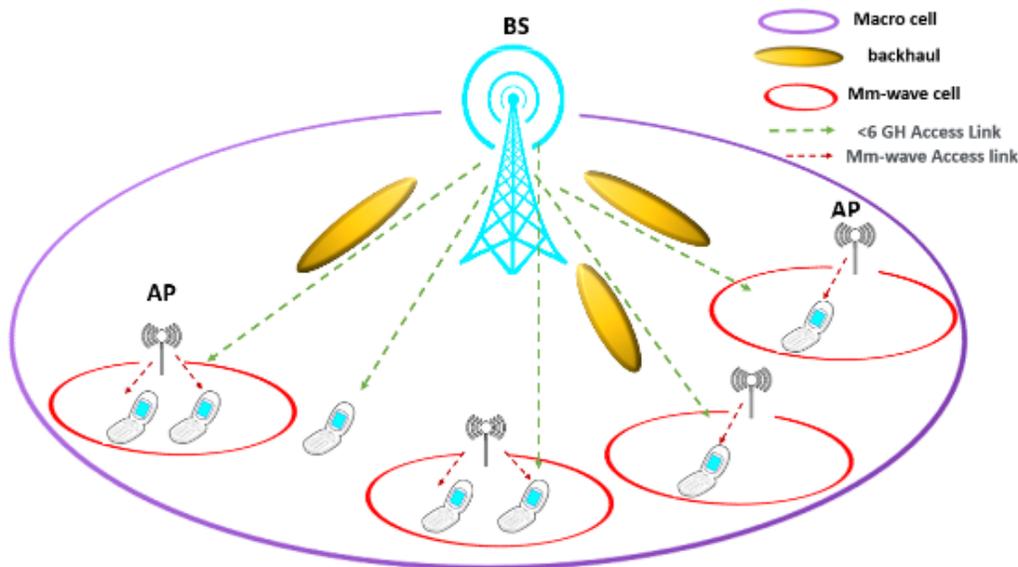


FIGURE 1. Schematic representation of a heterogeneous mobile network scenario of Massive MIMO and mmWave technologies across different cell types in a 5G network.

In long-distance millimeter-wave point-to-point (P2P) communications with direct line-of-sight (LOS) connections, these antennas significantly enhance SINR, thereby improving performance. They also reduce path

loss but are less suitable for multi-user mobile communications due to their narrow beams and limited spatial coverage. For non-line-of-sight (non-LOS) communications, beam direction needs to be managed

electronically or mechanically, which increases cost and reduces performance, posing challenges to the widespread adoption of commercial millimeter-wave technology (Niu et al. 2015; Pi & Khan 2011).

Millimeter waves have long been recognized as beneficial for wireless communication, especially with the advent of 5G networks, which are expected to be 100 times faster than 4G. 5G technology, as shown in Figure 2, supports diverse IoT devices and smart vehicles due to its high data rates (up to 10 Gbps), low latency, and enhanced reliability (Dahlman et al. 2014; Dussopt et al. 2015).

5G technology offers significantly faster data rates of up to 10 Gbps, which is 100 times faster than 4G, and lower latency at 1 ms compared to 4G's 10 ms. It improves signaling efficiency for IoT and M2M communication, enhances spectral and network efficiency by tenfold over 4G, and provides better user experience through advancements in augmented reality, artificial intelligence, and virtual reality. Additionally, 5G is 90% more energy-efficient than 4G, allowing low-powered IoT devices to enjoy extended battery life of up to 10 years (Shaikh et al. 2023). It also supports widespread connection capability, accommodating over 65,000 connections, which is 100 times more than 4G.

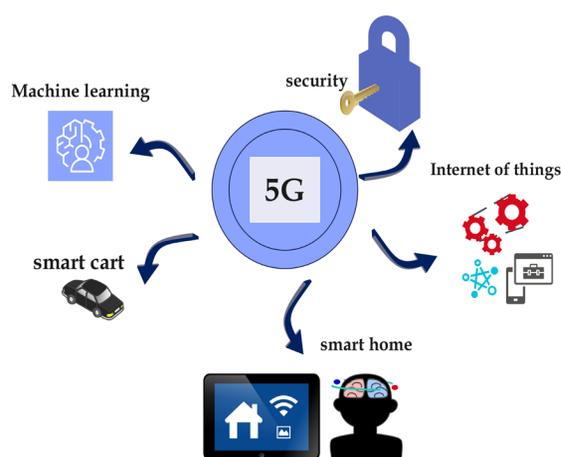


FIGURE 2. Various factors contribute to the significant increase in wireless data traffic.

This comprehensive review paper discusses topics not previously discussed comprehensively, as the authors of the previous paper (Benzaghta & Rabie 2021; Chataut & Akl 2020) discussed Massive MIMO systems for 5G and the challenges without specifying a specific band, while the authors of (Wang et al. 2018) discussed the challenges to do with the use of millimeter waves only. Hence, this article will comprehensively investigate the Massive MIMO antenna array within the 5G millimeter-wave base station. The subsequent sections of this paper are structured

as follows: Section 1 focuses on the Massive MIMO antenna in the base station, as well as the challenges and problems associated with millimeter-waves. Massive MIMO antenna and millimeter-wave advantages are discussed in Section 2. Section 3 focuses on literature survey analysis, MIMO taxonomy analysis, and recently developed technologies. Finally, in Section 4, the conclusion is presented.

MASSIVE MIMO ANTENNA

A massive MIMO antenna enhances spectrum and energy efficiency by using a large number of antenna elements, typically tens to thousands, in a single array. "Massive" refers to the number of antennas, not their size. This technology employs algorithms to combine radiative power from multiple antennas, focusing energy to improve throughput and efficiency. In 5G NR networks, massive MIMO boosts spectral efficiency, network capacity, coverage, and data rates (Hassan & Fernando 2017; Zaidi et al. 2018).

The utilization of MIMO technology in mobile standards has become increasingly prominent ever since Spatial Multiplexing (SM) was introduced in 3GPP (Dreifuerst & Heath Jr 2023). MIMO technology was crucial in advancing High-Speed Packet Access (HSPA). Later, downlink MIMO capabilities were enhanced to 2x2, supporting two users, while uplink remained single user. Additionally, new multi-antenna techniques in various transmission modes were introduced. (Sim et al. 2018)

Various transmission configurations are available, encompassing single-antenna setups, transmit diversity, open-loop SU-MIMO (Single User Multiple Input Multiple Output), closed-loop SU-MIMO, closed-loop rank-1 precoding (beamforming), and MUMIMO (Multi-User MIMO). These configurations are examined or utilized within their respective investigations or analyses. (Choi et al. 2016; Wang et al. 2009), the authors introduced the use of larger array sizes, featuring up to 8 downlink antennas, along with new transmission modes outlined in references (Sim et al. 2018; Wang et al. 2009). In (Son 2024), Antenna arrays were initially structured uniformly, with antennas in columns. Each column and polarization in dual-polarized arrays could be independently controlled for azimuth spatial multiplexing (SM). Elevation angle control was first achieved through mechanical and electrical tilting, but dynamic tilting control later became a widespread standard. The author in (Rebato et al. 2018), Marked a significant advancement by starting a study on full-dimension MIMO (FD-MIMO). This incorporated adjustable elements in azimuth and elevation, enabling three-dimensional

beamforming. It also decoupled the mapping of ports and physical antennas, allowing multiple antennas to be controlled via a single CSI port. This shift from the traditional one-to-one mapping allowed larger, more directional arrays without updating standards or feedback mechanisms. Antennas were “grouped” into subarrays, remaining transparent to the user equipment (UE). This evolution towards massive MIMO (M-MIMO) marked a pivotal moment in antenna technology. There are several common types of antennas that are used in massive MIMO. In (Rahman et al. 2017), Array of rectangular patch microstrip antennas operating in a 2×2 MIMO configuration. The objective of this antenna design is to achieve a small form factor while maximizing gain through an expanded number of radiation elements. This antenna operates effectively within the 28 GHz frequency range (27.5–29.5 GHz) and complies with FCC regulations. The authors in (Senthilkumar et al. 2023), developed a Compact Phased Array Antenna for frequencies below 3 GHz using a 180-degree phase difference at both ports.

5G Massive MIMO antennas come in various configurations to cater to different deployment scenarios and requirements. Here are some common types of 5G Massive MIMO antennas along with details about their characteristics and advantages.

UNIFORM LINEAR ARRAY (ULA)

The ULA is made up of multiple antenna elements that are linearly aligned and provide a simple method for beamforming. It is most commonly utilized in base stations for sector coverage in wireless communication systems, particularly those areas where narrow coverage areas are required. Linear arrangement simplifies beamforming, which makes ULAs perfect for situations that need focused and directed coverage to serve users effectively (Jilani & Alomainy 2018). In (Madhav et al. 2019), The Proposed Array (PA) is an antenna configuration. It is designed to overcome the limitations of the Uniform Linear Array (ULA) that is not uniform in its performance and has difficulty estimating Angle of Arrival (AOA) near end fire angles. The PA increases the ULA by two elements added at the top and bottom of the axis of the array. The paper compares the PA and ULA using algorithms for AOA estimation MUSIC and MVDR. The comparison includes root mean square error (RMSE) analysis under different signal-to-noise ratios (SNR) for improved evaluation. while the reference (Bilal et al. 2022), The paper considers the problem of designing a MIMO system using a uniform circular array (UCA) when applied in line-of-sight (LoS) environments and solves the problem of array misalignment.

The goal is to determine the optimal antenna location on UCAs and develop transceiver architectures that would provide maximum channel capacity without prior knowledge of misalignment. In (Khalid et al. 2020), the same method is discussed.

UNIFORM PLANAR ARRAY (UPA)

A UPA (Uniform Planar Array) as shown in Figure 5(a) is a two-dimensional grid of antenna elements, which provides the capability for both horizontal and vertical beamforming. UPAs offer a higher degree of flexibility in beamforming, allowing better coverage and interference management. They are particularly well-suited for serving users in many different directions within a sector. This flexibility allows network operators to respond to changing situations and channel resources to the needful areas for optimum efficiency, which in turn enhances the overall performance and quality of service in wireless communication systems (Khalid et al. 2020). In (Bhanupriya et al. 2022), The authors explain the effect that various arrangements of antenna arrays have on the propagation environment within a M-MIMO cellular system, with particular attention given to the line-of-sight (LoS) channel. This paper evaluates how effective a Uniform Linear Array (ULA) is in two-dimensional (2D) scenarios and a Uniform Planar Array (UPA) in three-dimensional (3D) scenarios by adopting multi-cell minimum mean squared error (M-MMSE) detection for the uplink scenario. In (Babu & Anuradha 2021), In this paper, the authors investigate how the relationship between beamwidth and received power in mmWave channels is affected when a rectangular uniform planar array (R-UPA) antenna is used instead of a uniform linear array (ULA).

CYLINDRICAL ARRAY

Cylindrical arrays as shown in Figure 3. (b) & (c) consist of antenna elements arranged circularly or cylindrically around a central axis, and they offer unique advantages in wireless communication. These arrays find particular utility in scenarios demanding 360-degree coverage, such as urban environments and stadiums. One of their key strengths is the capability to suppress interference effectively from multiple directions, thereby ensuring reliable and complete signal coverage. This makes cylindrical arrays very good candidates to overcome the problems of complicated network environments filled with interference (Abdullah et al. 2021). In (Dwivedi et al. 2022), the paper proposes a new method for line-of-sight (LOS) MIMO systems using

a uniform circular array (UCA) configuration. The proposed approach introduces a channel-independent beamforming scheme along with fast symbol-wise Maximum Likelihood (ML) detection. A claim is made

that this MIMO system is the first to achieve both N transmit antennas per symbol rate and rapid symbol-wise ML detection.

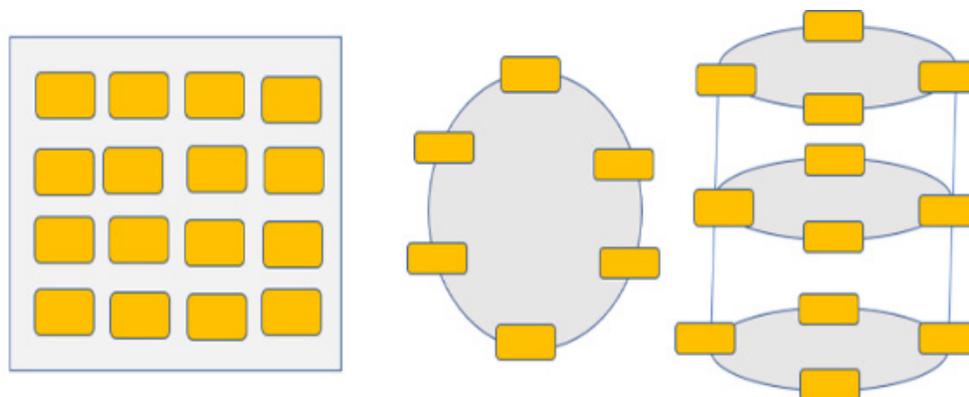


FIGURE 3. From left to right: (a) Planar or Rectangular (b) Circular array (c) Cylindrical array.

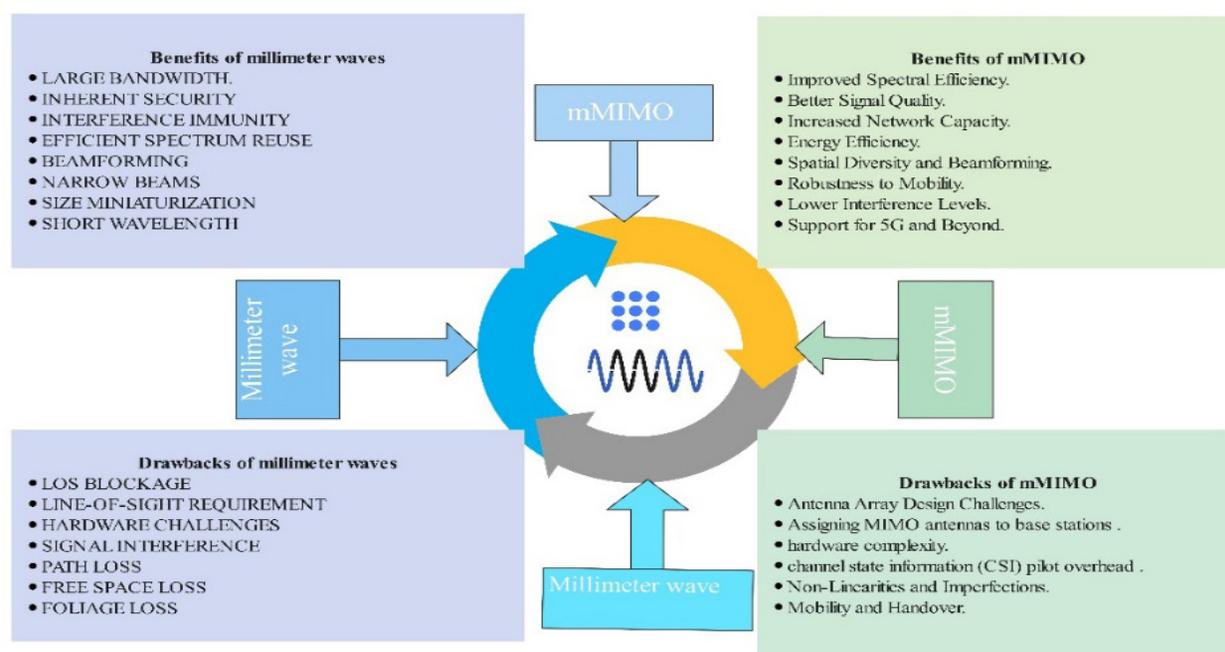


FIGURE 4. Diagram advantages and disadvantages of mMIMO antenna and millimeter wave.

ADVANTAGE AND DISADVANTAGE OF MMIMO

To serve several customers at once, a vast array of antennas must be installed at the base station. Numerous benefits provided by this technology can greatly raise the effectiveness and performance of wireless networks. MIMO offers numerous benefits, as illustrated in Figure 4. Before they can be used in 5G systems, key issues must be addressed. The theoretical basis of the difficulties in

antenna design and channel estimate are discussed in this section of the paper (Chataut & Akl 2020).

MASSIVE MIMO AT MILLIMETER WAVE

Massive MIMO and mmWave communication stand as pivotal technologies within the realm of wireless communication, particularly for advancing wireless networks such as 5G and beyond. Millimeter-wave

communication entails the utilization of higher frequency bands, typically ranging from 30 GHz to 300 GHz, for wireless transmission. These frequencies provide significantly broader bandwidths in contrast to conventional microwave frequencies, thereby facilitating enhanced data rates.

ADVANTAGES OF MM-WAVE COMMUNICATION

The 28 GHz millimeter-wave (mmWave) communication has some great advantages like high bandwidth and low latency which are very important for some applications like the 5G networks that need high data rates and reliable connectivity (Musaed et al. 2024; Rahman et al. 2024; Haque et al. 2024). The band itself has a large amount of available bandwidth, which can allow data rates up to 10 Gbps, much higher than what is possible with lower microwave frequencies. This makes it more attractive for use in high-density urban areas where the capacity of mobile networks can be greatly enhanced (Ashraf et al. 2024; Niu et al. 2015). In order to address problems like oxygen absorption and limited transmission range that are native at high frequencies, advanced technologies such as complementary metal-oxide-semiconductor (CMOS) radio frequency integrated circuits and beamforming are applied. These technologies coupled with large-scale mmWave antenna arrays improve the signal strength and coverage (Rangan et al. 2014; Sanchez 2020).

The directional characteristic of mmWave beams at 28 GHz improve security and reduces interference; thus, it is most suited to applications that demand high precision and high reliability. Techniques such as MIMO and multibeam antennas then go on to better utilize the spectrum and enhance the network's performance by reducing co-channel interference (Elijah et al. 2022; Rehman et al. 2024). The integration of CMOS technology has similarly led to the production of tiny and cheap transceivers that will enable the 28 GHz mmWave communication system to be widely used in different sectors such as mobile networks, vehicular networks, and fronthaul/backhaul links (Hong et al. 2021; Vaigandla et al. 2021). While the challenges are to overcome atmospheric absorption, this is a small issue for the 28 GHz band, given its high directionality (which makes it very useful) and the technological development that can be integrated into it; it is a strong solution for future communication requirements, ensuring increased performance and effective service delivery in many applications (Raj et al. 2023).

MILLIMETER-WAVE PROBLEM USED IN MIMO ANTENNA IN BASE STATION 5G.

Wireless communication in industrial environments presents unique challenges compared to residential or office settings due to the presence of metal structures, bulky equipment, and moving objects, resulting in complex multi-path environments with abundant scattering (Babu & Anuradha 2021). Blockages caused by humans or obstacles can significantly degrade the performance of mmWave systems, and narrow beam antennas using beamforming may reduce path diversity. Particularly in non-line-of-sight scenarios, necessitating accurate channel models for reliable communication (Abdullah et al. 2021). In the late 1990s, the Local Multipoint Distribution Service (LMDS) planned to use the 28 GHz and 38 GHz bands, offering over 1 GHz of bandwidth. Recent developments challenge the assumption that the mm-wave spectrum is unsuitable for mobile communications due to rain and atmospheric conditions, with urban environments benefiting from mm-wave cellular technology, as it overcomes rain attenuation and atmospheric absorption for small cell sizes (Zhang et al. 2023). Free space loss, a reduction in signal strength as it propagates without obstructions, significantly impacts signal transmission distance in millimeter wave communication. It is influenced by signal frequency, distance between transmitter and receiver, and wavelength. Directional antennas can be used to mitigate free space loss, with the corresponding equation for free space loss in decibels (Sulyman et al. 2016). Foliage loss occurs when millimeter wave signals encounter vegetation during propagation, leading to signal reduction. It depends on signal frequency, foliage type, density, transmitter-receiver distance, and can be calculated using the foliage loss equation (Patel et al. 2022).

IMPROVEMENT TECHNOLOGIES

Numerous researchers have employed diverse methods to improve the performance of antennas as shown in Figure 5. which can enhance one or more parameters such as gain, efficiency, bandwidth, and reduction of mutual coupling, and compact size. Different techniques are available for enhancing and decoupling antennas used in the base station MIMO. The improved parameters resulting from these techniques are also mentioned. This article will explain the various performance enhancements and decoupling techniques for antennas.

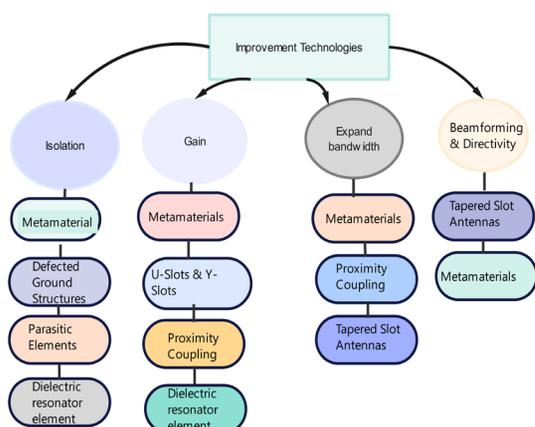


FIGURE 5. Techniques are available for enhancing and decoupling antennas.

METAMATERIALS AND METASURFACE

Metamaterials are artificially structured materials engineered to control electromagnetic waves. By integrating metamaterials with MIMO antennas, enhanced isolation and gain can be achieved through engineered electromagnetic responses that are not possible with natural materials. These materials provide unique solutions to reduce mutual coupling and improve overall antenna performance (Sharma et al. 2024). Metamaterials can be categorized based on their permittivity (ϵ) and permeability (μ) as shown in figure 6. Right-handed materials (RHM) like FR4, Rogers, and Bakelite have positive permittivity and permeability. In contrast, left-handed materials (LHM) possess negative permittivity and permeability, which do not occur naturally. LHMs are classified into three main types: Epsilon Negative (ENG), Mu Negative (MNG), and Double Negative (DNG) materials (Vinodkumar & Sharma).

The design of metamaterials involves creating specific properties and functions by configuring structural units in terms of shape, size, lattice constant, and interatomic interaction. By arranging nano-sized unit cells in particular configurations, the refractive index of metamaterials can be adjusted to exhibit positive, near-zero, or negative values. Veselago introduced the classification of metamaterials based on permittivity and permeability (Shelby et al. 2001; Smith & Kroll 2000; Veselago 1967). Metamaterials can also be categorized by dimensionality: 3D metamaterials have multiple constituent elements in various directions, 2D metamaterials (metafilms or metasurfaces) are thin films, and 1D structures include optical waveguides with nano inclusions, plasmonics, and polaritonic nano-chains (Babicheva 2023).

A novel hybrid decoupling method has been proposed to achieve high isolation between two-element MIMO antennas at the 5G millimeter wave band over 27.5–28.35 GHz. This method employs an electromagnetic bandgap (EBG) structure on stacked dielectric substrates and a hairpin-shaped defected ground structure (DGS). This combination achieves significant isolation improvements, with measured isolation at 71.9 dB, a gain of 9 dBi, and a front-to-back ratio of 19.8 dB (Wu et al. 2024). Recent advancements include a flat multiple-beam lens operating at 28 GHz for spatial MIMO, a large-scale metalens tailored for massive MIMO applications, a three-beam metalens antenna for base stations, and a Huygens' surface-based metalens designed to minimize reflection, As shown in figure 7. These metasurfaces have achieved scanning coverage of $\pm 27^\circ$, gains ranging from 20.5 to 24.2 dBi, and an aperture efficiency of 24.5% (Chen et al. 2021). In Table 1, a comparison with additional previous studies is presented.

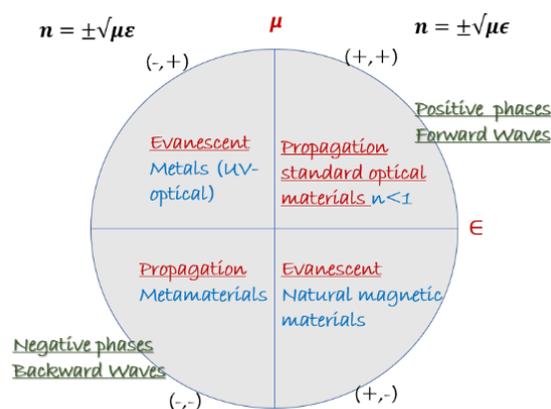


FIGURE 6. Metamaterials can be categorized based on their permittivity(ϵ) characteristics and permeability (μ).

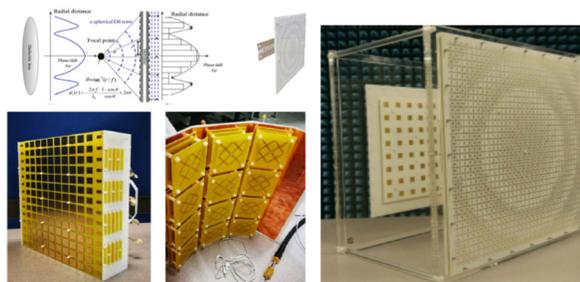


FIGURE 7. Traditional dielectric lens, arrangement of an 8×8 flat wide-scan dual-polarized massive (Chen et al. 2021).

DEFECTED GROUND STRUCTURES (DGS)

Defected Ground Structures (DGS) are etched patterns on the ground plane of microstrip antennas, creating band-stop filters that suppress specific frequency ranges. This suppression reduces surface wave propagation and enhances isolation between MIMO antenna elements (Sheriff et al. 2023). Studies have shown that incorporating DGS can increase isolation by up to 7 dB and reduce mutual coupling to -34.2 dB, significantly improving overall antenna performance (Guler & Bayer Keskin 2023). DGS is a type of electromagnetic structure, as shown in figure 8. used in microwave and radio frequency (RF) circuits, often involving a periodic pattern etched in the ground plane to create a band-stop filter by suppressing electromagnetic waves at certain frequencies (Khandelwal et al. 2017). In MIMO antennas, where elements are placed close to each other, DGS helps to mitigate mutual interference by reducing surface waves and cross-polarization levels, resulting in improved isolation and reduced mutual coupling (Anitha et al. 2014).

The presented work aims at designing a new millimeter-wave (mmW) antenna for MIMO applications in 5G wireless communications using defected ground

structure (DGS) technique to achieve compactness, high bandwidth, and low complexity as in Figure 9. The antenna is designed to cover the frequency band from 25.1 to 37.5 GHz, having a maximum gain of 10.6 dBi at 36 GHz, and efficiency above 80% for the whole band (Jilani & Alomainy 2018). In another study, a vehicular setting demonstrated minimal mutual coupling of -89.5 dB and an envelope correlation coefficient (ECC) below 0.01 for the following: 24.6-42.1 GHz and 50.1-52.5 GHz, with a T-stub loaded into the two-element MIMO antenna (Madhav et al. 2019). A 4-port MIMO antenna design incorporating DGS to enhance performance for 5G mm-wave applications demonstrated broad impedance bandwidths and improved radiation characteristics. This design operates within the frequency span of 25.5 to 29.6 GHz, delivering a bandwidth of 4.1 GHz and achieving a maximum gain of 8.3 dBi (Khalid et al. 2020). Another design using rectangular, circular, and zigzag-shaped slotted structures, to improved antenna performance, achieving low ECC and high isolation (Bilal et al. 2022).

A novel 4-port dual-band printed MIMO antenna array designed for 5G communication operates at both 28 GHz and 38 GHz. Utilizing a cross-shaped DGS and various slots, this design achieved good performance in terms of gain and bandwidth, although its sensitivity to environmental variations was noted (Aghoutane et al. 2022).

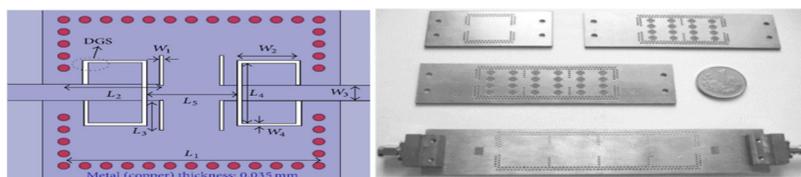


FIGURE 8. Coplanar waveguide integrated with Substrate Integrated Waveguide technology incorporating Defected Ground Structure (Khandelwal et al. 2017).

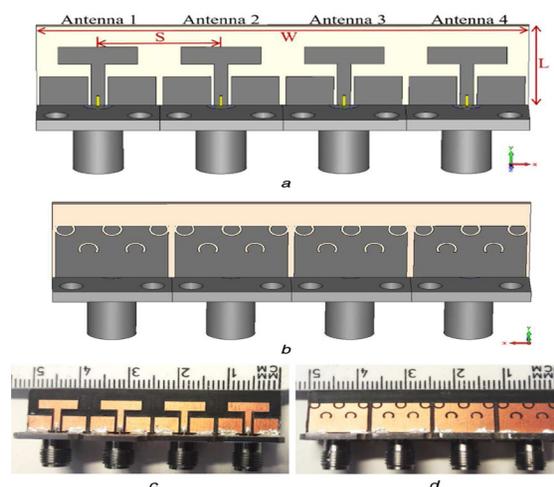


FIGURE 9. Fabricated Prototype of the Proposed MM Antenna with DGS: (a) Front View - Simulated, (b) Back View - Simulated, (c) Front View - Prototype, (d) Back View - Prototype (Jilani & Alomainy 2018)

PARASITIC ELEMENTS

Passive elements, or parasitic elements, are the basic components in antenna design for radiation efficiency and directivity enhancement (Kalis et al. 2014). These elements rely on the feed of a primary driven element and do not have independent feeds. Parasitic elements can be in the form of slots, strips, and so on, positioned within the induction field of the driven element. Contributing indirectly to radiation enhancement by helping to create a better coupling between both elements (Celebi 2015). In different antenna setups, recent works have examined the advantages and usefulness of parasitic components, especially in enhancing multiple-input multiple-output (MIMO) systems for the wireless communications of today.

One of the major advantages in using parasitic elements is that they can reshape the radiation pattern of antennas. The radiation characteristics of dipole or slot antennas can be modified by designers by placing parasitic strips or slots around them in a strategic manner. In study (Komolafe et al. 2021), It has been shown that the inclusion of short parasitic directors on either side of the dipole antenna modifies the radiation pattern of the third resonant mode, leading to a better directivity and gain. The

results of this experiment showed an increase in gain up to 2 dBi, which demonstrated the efficiency of parasitic elements in providing the necessary radiation properties.

Mutual coupling between antenna elements can significantly lower performance in densely packed MIMO arrays, as shown in Figure 10. MIMO systems: In improving isolation between antenna elements, the use of parasitic elements has equally gained a wider reputation. In (Singh & Parihar 2019), In their study, it was found that by placing the parasitic slots between the antenna elements isolation improved by 10 dB, reducing mutual coupling to below -20 dB. This improvement of isolation directly translated into better overall system performance, with a 15 dB observed increase in signal-to-noise ratio (SNR).

The use of parasitic elements in antenna design has been shown to reduce the overall size of the antenna without compromising performance, as shown in Figure 11. The authors of compact MIMO antenna array for portable devices incorporated parasitic strips and slots to achieve high performance with a smaller overall antenna size. The compact design realized 30% reduction in total antenna size while still obtaining the gain of 8 dBi and isolation -25 dB, which is suitable for integration within small form-factor devices (Ravi & Kumar 2022).

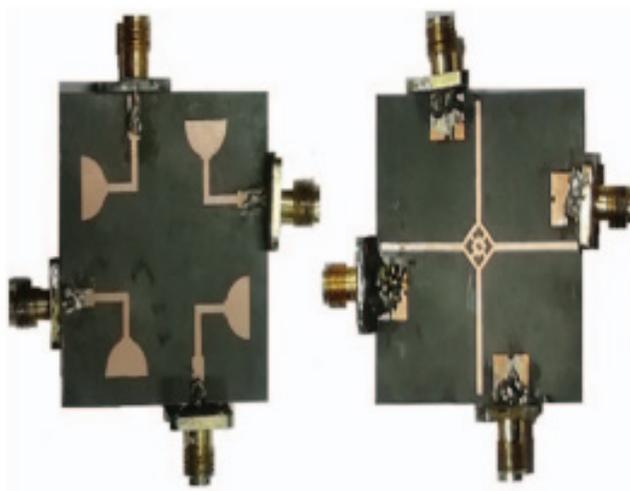


FIGURE 10. Fabricated MIMO Antenna (Singh & Parihar 2019)



FIGURE 11. Fabricated prototype of the proposed antenna (Ravi & Kumar 2022).

DIELECTRIC RESONATOR ELEMENT (DRE)

A dielectric resonator antenna (DRA) is well known to be an antenna that employs a dielectric resonator as its operating part. It has many advantages in performance, such as high gain, high radiation efficiency, and low loss. Dual-band operation with DRAs offering excellent isolation between the bands can also be obtained easily. For contemporary applications like 5G, WiGig, and other commercial mm-wave technologies, effective wideband antennas are vital with the increasing demand (Nadeem & Choi 2018). A dielectric resonator element is a small cylindrical or rectangular shaped device made of dielectric material to resonate at a particular frequency or range of frequencies. It is used in the design of antennas and other microwave circuitry which can be helpful in improving the efficiency and performance of the device. Much work has been done in this regard (Alanazi & Khamas 2022; Baldazzi et al. 2020; Kowalewski et al. 2020; Rajat

Girjashankar & Upadhyaya 2021; Sani et al. 2020; Sharawi et al. 2017).

Alanazi, M.D et al. (2021) Introduced a cylindrical DRA array with a hybrid feeding structure, providing an impedance bandwidth of 24.01% and a high gain of 7.6 dBi, essential for mmWave communications (Alanazi & Khamas 2022). In Nadeem & Choi (2018), polymer-based DRAs with precise cavities in acrylic templates and composite materials were developed, achieving a 12% impedance bandwidth and a 10.5-dBi gain at 60 GHz. The study (Sharawi et al. 2017), presented two linear arrays with four cylindrical DR antennas as shown in Figure 12, the operating at 30 GHz, achieving field correlation below 0.002, gains over 7 dBi, and high radiation efficiency.

In Table 2, a comparison with additional previous studies is presented. There are additional methods discussed in the following studies (Jabber & Thaher 2021), such as Reconfigurable MIMO, which can assist in achieving isolation.

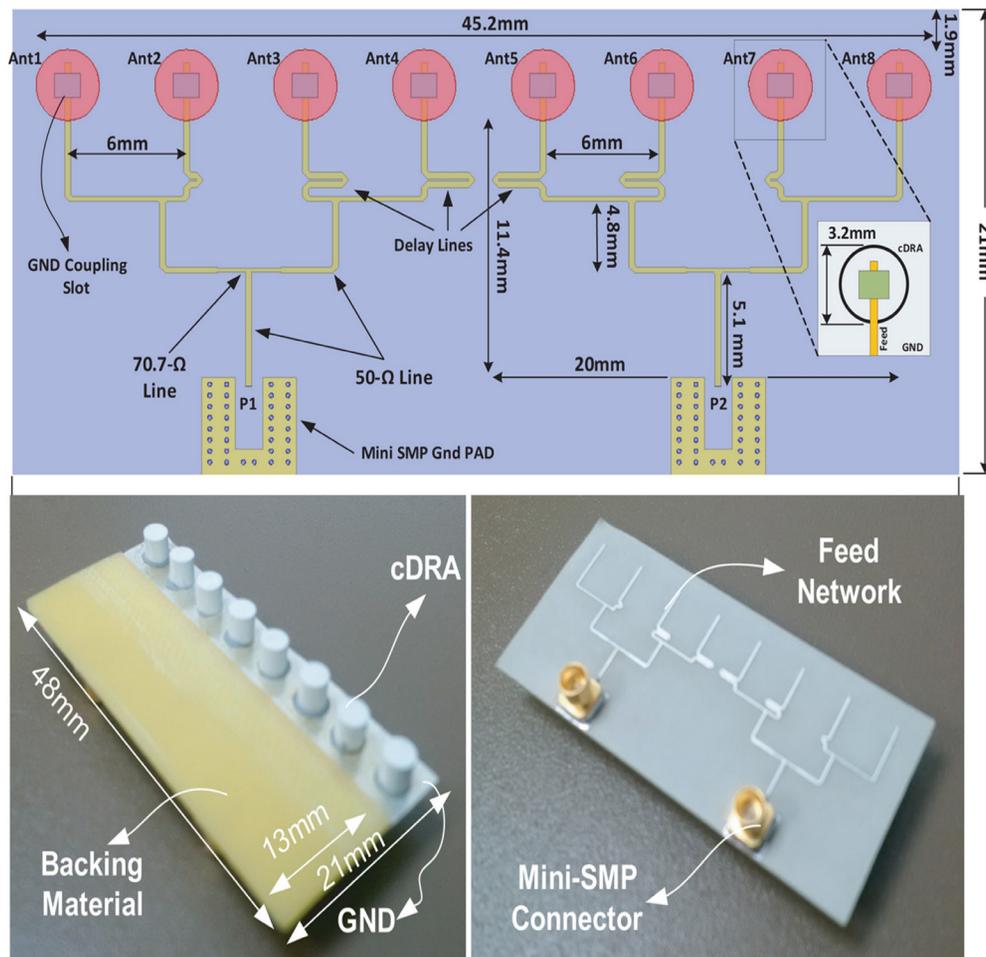


FIGURE 12. Fabricated mm-wave cDRA array based MIMO antenna system(Sharawi et al. 2017).

TABLE 1. Summarization of previous studies and a comparison between the performance of each article

Ref	Tech	Antenna type	Array Size	No. port	Frq (GHz)	B.W (GHz)	Isolation (dB)	Gain (dBi)	Size (mm ²)	Design challenges	Results Approach
(Chen et al. 2021)	MTM	flat lens	1×4	NA	27.8	2.3	-22.3	20.5–24.2	500×500	fabrication difficulties	Small dimensions, lightweight, seamless integration with other circuits.
(Tariq et al. 2021)	MTM	Patch	2×1	4	26	1.95	-38	10.27	30×43	High coupling	Enhance isolation, (ECC), (CCL), (DG), (MEG).
(Hussain et al. 2020)	MTM	Patch	4	4	29	6	-30	11	20.4×20.4	Low gain, narrow band width	high radiation efficiency >95%, gain of 11 dBi, improving isolation
(Jiang et al. 2019)	MTM	bowtie antenna	1	1	26	3.25	NA	7.4	30×10	path loss, multipath fading, interference effect.	High gain, dual beam.
(Sehrai et al. 2021)	MTM	Patch+	4	4	26	5.9	-20	10.44	24 × 24	fabrication difficulties, low gain	Improve gain, total efficiency.
(Dadgarpour et al. 2016)	MTM	Bowtie antenna	1	1	60	10	NA	11.4	NA	Signal is degraded by atmospheric.	improve the gain, reduce the sidelobe level (SLL), increase a bandwidth of 20%.

TABLE 2. Summary and Comparative Analysis of Dielectric Resonator Element (DRE) Performance Across Previous Studies.

Ref	DRA shape	No. of elements	No. of ports	Frequency (GHz)	Dimensions (mm ³)	substrate	B.W (GHz)	Isolation (dB)	Gain (dBi)	Experiment
(Qureshi et al. 2017)	rectangular	4	4	60	5.3×5.3×0.5	acrylic templates, monolithic	7	NA	10.5	Measured
(Sharawi et al. 2017)	cylindrical	8	4	30	10 × 45 × 3.1	Polymer-based DRA	1	≥-10	>7	Simulated
(Kowalewski et al. 2020)	cylindrical	16	2	25,28,30,35,38	NA	RO3003 substrate with $\epsilon_r=3$, $\tan \delta=0.001$	NA	≥-20	10.4	Measured
(Niayesh & Kouki 2021)	cylindrical	16	1	24.50- 27.5 & 33-37	46 × 46×0.508	substrate integrated waveguide (SIW)	9.8	22 & 17 dB	9.9	Measured

CONCLUSION

In this comprehensive review, enhancement techniques for Massive MIMO antenna arrays in 5G millimeter-wave base stations are explored, with key challenges addressed and effective solutions highlighted. The integration of advanced technologies such as beamforming, metamaterials, and hybrid decoupling methods has proven instrumental in overcoming obstacles related to high path loss, beam misalignment, and hardware complexity. These innovations not only improve signal quality and coverage but also enhance spectral efficiency and reduce interference, thereby supporting the robust performance of 5G networks in diverse real-world scenarios. Furthermore, novel antenna designs that incorporate defected ground structures and parasitic elements are pivotal in optimizing performance for 5G applications. As the global demand for high-speed, reliable wireless communication intensifies, the ongoing research and development in this field will be vital for the successful deployment and operation of 5G networks. Future research should focus on further refining these enhancement techniques, exploring innovative materials and designs, and evaluating their practical applications in real-world settings to meet the evolving requirements of next-generation wireless systems.

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DECLARATION OF COMPETING INTEREST

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