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Design Challenges and Solutions of Multiband MIMO Antenna for 5G/6G Wireless Applications: A Comprehensive Review

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ABSTRACT: A comprehensive review of multiband MIMO antennas designed for wireless applications in the 5th and 6th generation (5G and 6G) networks is presented. The demand for higher data rates and improved spectral efficiency in advanced wireless networks continues growing, and multiband MIMO antenna systems have emerged as a promising solution. This review aims to provide an in-depth analysis of the existing literature on multiband MIMO antennas for 5G and 6G wireless applications. The paper's main objectives are: (1) To emphasize the requisite of MIMO antenna for the sub-6 GHz of 5G/6G wireless communication, (2) To demonstrate various techniques to generate multi-band, (3) To highlight the challenges and their potential solutions to design multiband MIMO for 5G/6G, (4) To investigate the methods to attain circular polarization (CP) and pattern diversity for better system performance. The review critically analyzes the latest advancements, challenges, and future research directions for multiband MIMO antennas in the context of 5G and 6G wireless networks. This comprehensive review serves as a valuable resource for researchers, engineers, and practitioners seeking a deeper understanding of multiband MIMO antennas and their potential to support the demands of the ever-evolving wireless communication technology.

1. INTRODUCTION

The implementation of 5G technology was enabled by a group of technologies such as mm-wave technology, massive multiple-input multiple-output (MIMO), small cell technology, mobile edge computing, non-orthogonal multiple access (NOMA) systems, and beamforming techniques [1]. 5G promised to support large-scale events with thousands of users' vehicular and industrial control, environmental and remote monitoring, smart cities, grids, homes, health, transport, and infrastructure. Various features of 5G are summarized in Figure 1(a). 5G networks will utilize a combination of low, mid, and high-frequency bands to provide various services with different requirements. By supporting multiple bands, the antenna can handle a wide range of frequencies and adapt to different use cases, ensuring optimal connectivity and coverage [2]. To support this wide range of applications which are characterized by high data rates and massive number of users, the implantation of multiband MIMO systems is foreseeable. Virtual reality, artificial intelligence, the Internet of Things (IoT), and 3-dimensional media are emerging technologies leading to rapid advancement in the communication field. This technology demands higher data rates, which eventually need a swift transition from 5G communications to 6G technologies.

6G utilizes the frequency range (0.1–10 THz) primarily for wireless communication [3]. Higher capacity, higher security, broader coverage, and ultra-low latency are the key features offered by 6G to cater wireless industry, health sector, autonomous systems, smart cities, and energy harvesting systems as illustrated in Figure 1(b) [4]. These applications also embrace the integration of GPS, Wi-Fi, Bluetooth, WLAN, etc. to attain miniaturized multi-functional antenna [5]. Several novel approaches and their reviews have been proposed by researchers to meet the current requirements for advancement and development of 5G/6G network [6–10]. Multiband MIMO enables the use of multiple frequency bands simultaneously to cover the desired applications with reduced interference and size as mentioned in Figure 2(a). These antennas can cover a wider range of frequencies, providing flexibility for diverse wireless systems [11]. By supporting multiple bands, multiband antennas allow for more efficient use of the available frequency spectrum, while operating across multiple bands can increase the risk of interference between different frequency bands, requiring careful antenna design and integration considerations [12]. The existing literature discusses wideband antennas, 5G antennas, or MIMO antenna, but multiband MIMO antenna for 5G/6G is inadequately summarized as per authors' knowledge. The paper encompasses all the aspects allied to the multiband MIMO technology for 5G/6G with their applications. The paper organization is mentioned in Figure 2(b). Section 1 discusses the requisite of multiband MIMO antenna for 5G/6G wireless communication. Section 2 introduces several techniques to generate multiple bands with a comprehensive

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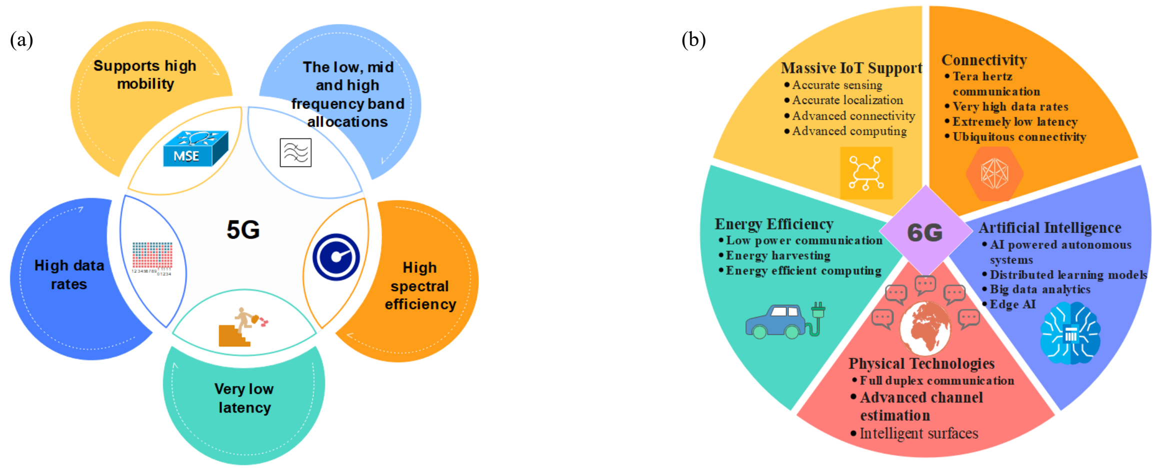


FIGURE 1. Technology key features of (a) 5G, (b) 6G.

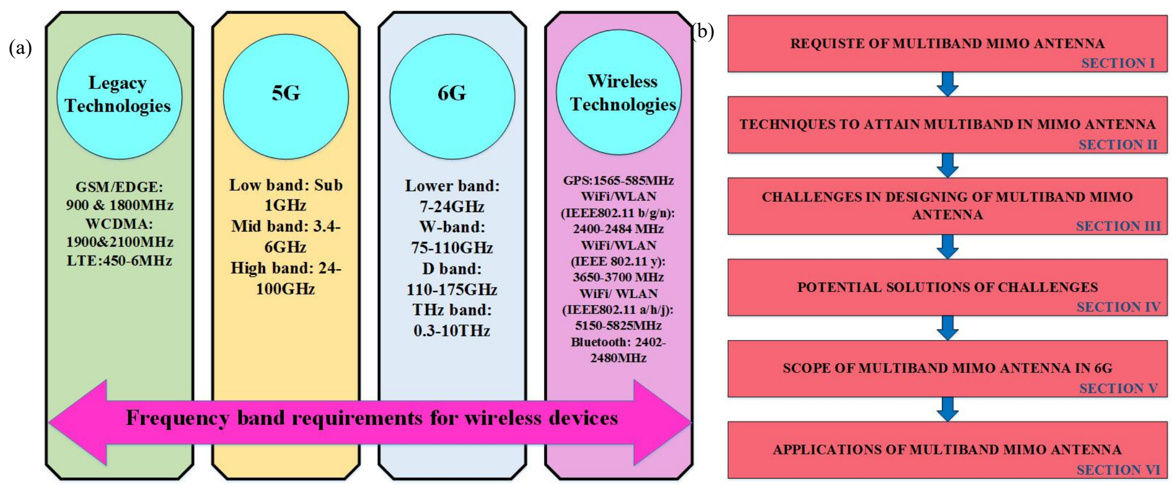


FIGURE 2. (a) Frequency allocation of wireless technologies. (b) Organization of paper.

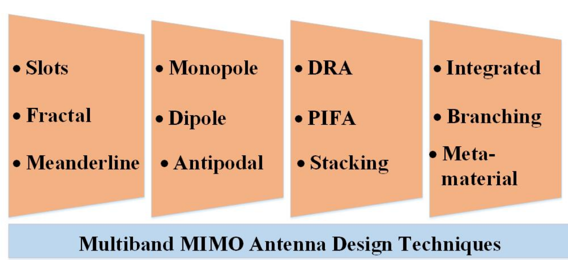


FIGURE 3. Techniques for attaining multiband MIMO antenna.

comparison of existing techniques used in literature through single antenna and MIMO antenna. The design challenges are analyzed and summarized in Section 3. The potential solutions are recommended in detail to tackle mutual coupling, high gain, wide bandwidth, compactness, circular polarization, and diversity in Section 4. The prominent technology used to design a 6G user's antenna is communicated in brief in Section 5. An outlook on popular applications that cater to 5G/6G antennas is mentioned in Section 6. Section 7 concludes the survey and suggests the future scope.

2. TECHNIQUES TO ATTAIN MULTIBAND

Multiband antenna proves to be a boon for the wireless industry as it reduces the need for various antennas to cover different wireless applications simultaneously. However, the design of a multiband antenna starts with a prudent selection of patch followed by numerous iterative simulations and optimization after applying multiple techniques until the desired frequency of operation is attained. Multiple branches are the most frequent method to realize multiband antenna as each branch acts

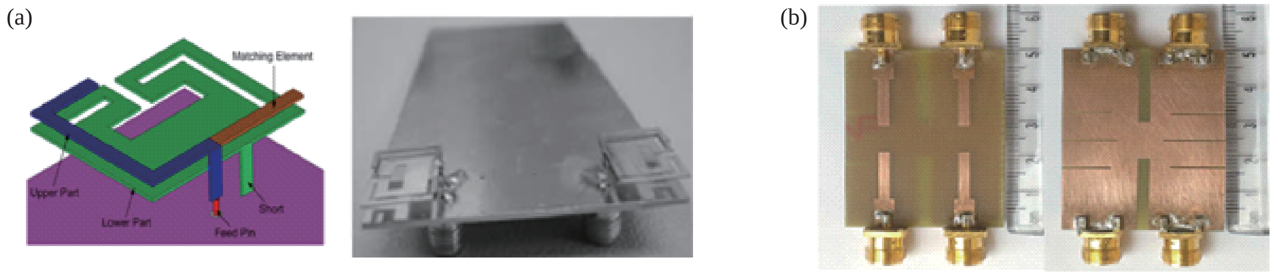


FIGURE 4. (a) Quad-band two-port antenna using PIFA structure [13]. (b) Dual bands self-duplexing four-port antenna using slot technique [15].

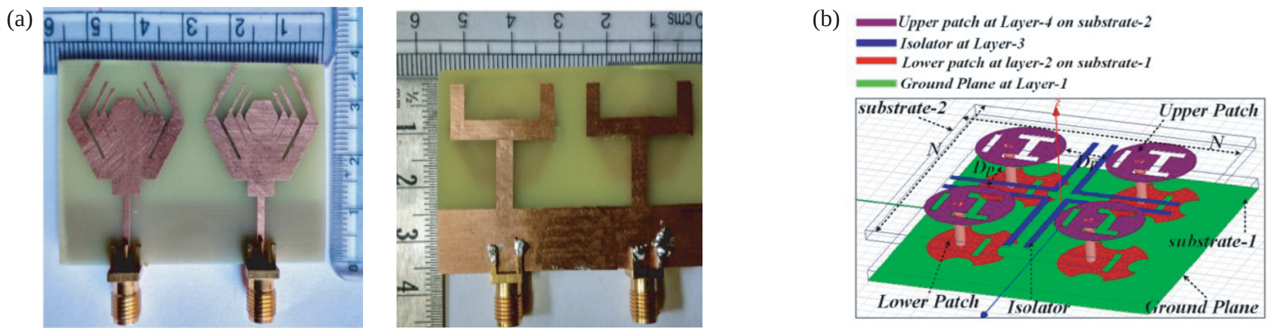


FIGURE 5. (a) Quad-band fractal based hexagon shape two port antenna [16]. (b) Triple band four port MIMO antenna using a stack of 4 layers [19].

as a resonating structure. Several other methods available in the literature to attain multiband are mentioned in Figure 3 and discussed further.

2.1. Planar Inverted-F Antenna (PIFA)

PIFA is a planar antenna that is printed or etched on a printed circuit board (PCB), which comprises a radiating element, a ground plane, and a shorting pin or strip. The radiating plate is shorted with the shorting strip to the ground plane and sourced via a feeding point. The shorting strip/pins are connected at the end which makes it resonant at a quarter-wavelength. The resonant frequency can be tuned by varying the length of the shorting strip, while the distance between the feed and shorting strip varies with the PIFA impedance. Slot and slit techniques are incorporated in the PIFA method to attain quad bands at 2.4/3.5/5.2/5.7 GHz. An additional $\lambda/4$ resonator is integrated with the PIFA antenna to get the fourth band [13] as shown in Figure 4(a).

2.2. Slot Antenna

A slot antenna is designed by etching a circular, rectangular, or desired-shaped slot on a conductive surface. Electromagnetic waves are generated inside the slot, whenever an alternating current is given to the feed line connected to the patch. The slot dimensions determine the operating frequency and radiation characteristics of the antenna. A penta-band MIMO antenna is designed using multiple slots in a square shape patch as discussed in [14]. A self-duplexing based on a slot antenna resonant at dual frequency bands is shown in Figure 4(b). The variation in the length of the slots for different ports results in two different resonant frequencies [15].

2.3. Fractal Antenna

A fractal antenna is an antenna design that incorporates repeated patterns which induce complex arrangements of inductance and capacitance. Thus repeating pattern allows for increased frequency bandwidth and multi-directional radiation patterns. A hexagon slot is etched from the hexagon patch four times to create a spider-shaped fourth iterative fractal antenna to generate four bands at 2.43/3.83/4.4/5.8 GHz [16] as shown in Figure 5(a). The amalgamation of Koch and Minkowski curves is implemented on the boundaries of the rectangle patch which leads to three resonant bands [17].

2.4. Stack Antenna

A stack antenna consists of multiple antennas stacked vertically or horizontally with the same or different substrates to achieve desired radiation characteristics. By combining individual antennas, the stacked antenna can enhance the overall gain, directivity, and bandwidth of the system. Separate resonances are contributed by different layers of stacked and driven patch [18]. A compact structure of four layers by stacking two substrate layers offers triple bands at 2.9 GHz, 5.0 GHz, and 5.9 GHz. Embedding three semicircular slots in the circular patch at layer 2 offers resonance at 5.8 GHz. The H and I shapes in the fourth layer add two more resonant frequencies. Layer 3 adds isolation between different frequency bands obtained as shown in Figure 5(b) [19].

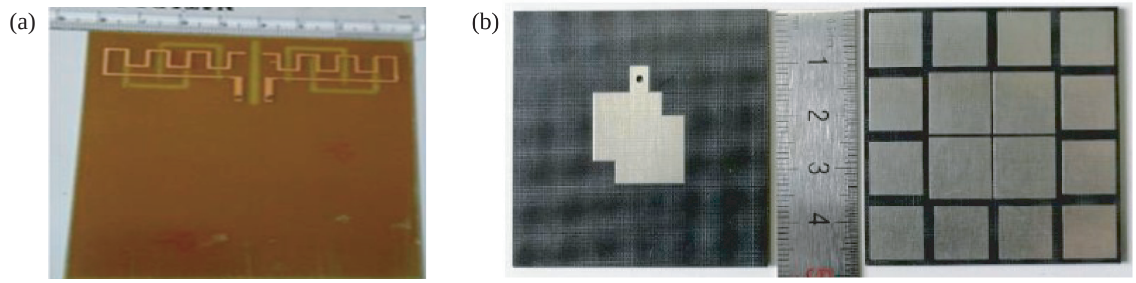


FIGURE 6. (a) Hepta-band two port MIMO antenna using meander line [21]. (b) Triple band antenna with twelve parasitic patches [23].

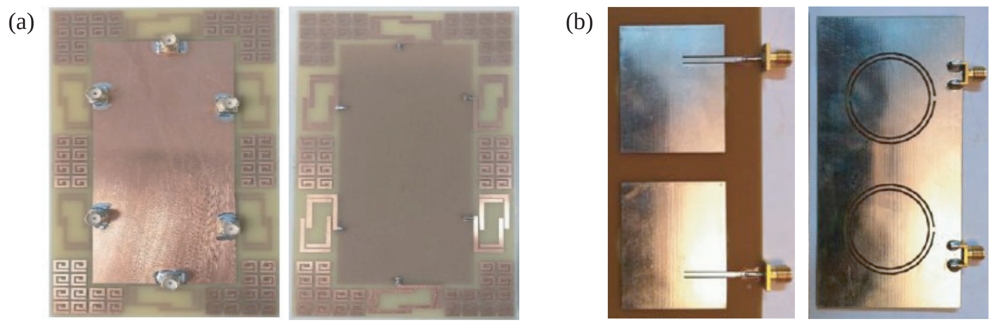


FIGURE 7. (a) 6-port folded dipole antenna [24]. (b) Front and back view of multi-band MIMO antenna using CSRR metamaterial structure [26].

2.5. Meander Line Antenna

A meander line antenna is a type of antenna that utilizes a meandering conductor pattern on a substrate to create a longer physical length of the antenna within a limited space. This elongated conducting pattern acts as an inductor which changes the characteristic impedance of the monopole antenna. This allows for miniaturization with increased efficiency and bandwidth compared to traditional straight-line antennas. To cover frequency less than 1 GHz range is very difficult to attain with small size antenna. However, it is made possible in [20] by using a meandering technique with a monopole element. A hepta-band antenna is proposed in [21] using meander lines connected with L-shape microstrip feed line as shown in Figure 6(a).

2.6. Parasitic Antenna

A parasitic antenna consists of a driven element and one or more passive elements (parasitic elements) positioned in its vicinity. The parasitic elements couple power with the electromagnetic waves radiated by the driven element, resulting in constructive or destructive interference to achieve increased gain and directivity. The parasitic elements can act as a second radiator too and have their modes of resonance depending on the design. Two U-shaped rectangular parasitic elements are placed along the side of the rectangular patch [22]. These parasitic elements excite the higher-order modes which result in triple bands. The resonant frequencies vary with the variation in parasitic element length. A metallic truncated square patch is surrounded by twelve square parasitic patches as depicted in Figure 6(b). The metasurface with the 12 square parasitic patches excites the second and third resonant modes [23].

2.7. Folded Dipole Antenna

A folded dipole antenna is a variant of a dipole antenna where the ends of the antenna element are folded back towards each other. This design increases impedance and bandwidth. When a signal is applied to the folded dipole, it produces a radiating electromagnetic field. The diameter of the folded dipole is directly responsible for variation in 1st-order modes and 3rd-order modes of folded dipole. In [24], wide band from 3 to 5 GHz is investigated using a folded dipole antenna as shown in Figure 7(a).

2.8. Metamaterial Antenna

A metamaterial antenna is an antenna that utilizes artificially engineered materials known as metamaterials to control and manipulate electromagnetic waves. By incorporating metamaterial structures, such as split-ring resonators (SRR) or complementary SRR (CSRR), into the antenna design, unique electromagnetic properties can be achieved, such as negative refraction, multiband, enhanced gain, and increased bandwidth. The multiple resonances are attained by placing SRR on the opposite sides of the patch, which acts as an LC resonator in [25]. In [26], the inductive and capacitive coupling of CSRR with patch is used to lower the resonant frequency and multiple bands as shown in Figure 7(b). The variation in resonant frequency of CSRR is directly proportional to the variation in antenna resonant frequency.

2.9. Reconfigurable Antenna

A reconfigurable antenna is an antenna that can change its operating frequency, radiation pattern, or polarization dynamically.

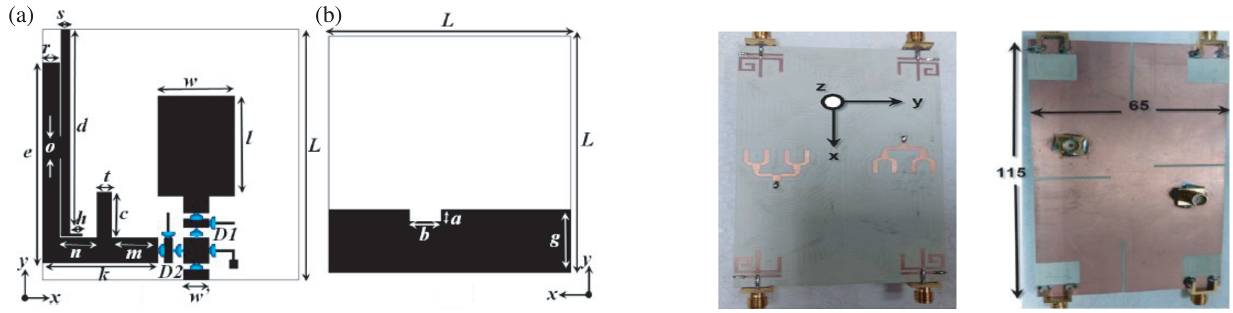


FIGURE 8. (a) Triple band reconfigurable antenna using PIN diode [27]. (b) Dual-band through integrated array and monopole antennas [29].

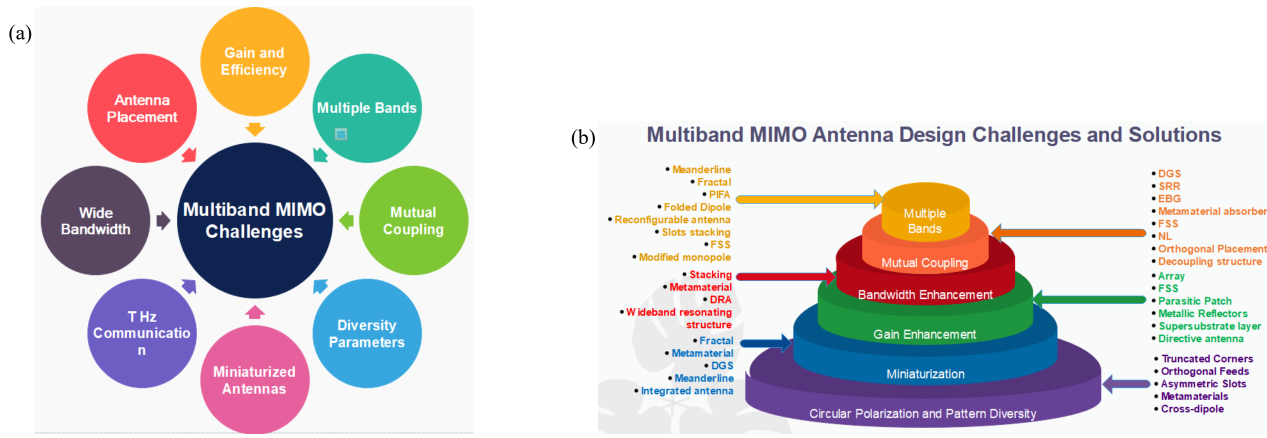


FIGURE 9. (a) Challenges in designing multiband MIMO antenna. (b) Solutions for designing challenges of multiband MIMO antenna.

This is achieved by incorporating tunable or switchable components like PIN diode, varactor diode, etc. into the antenna structure. The reconfigurability allows the antenna to adapt to varying signal conditions, optimize performance, and support multiple communication standards. An integrated antenna connected via two PIN diodes can transit from ultra-wideband (UWB) mode to tripe band mode in [27] for a vehicular network as demonstrated in Figure 8(a). Another triple band resonance is obtained by connecting the triangular parasitic element to the main equilateral triangle through PIN diodes. Eight different combinations of turning ON-OFF PIN diodes alter the path length and current distribution leading to tuning of frequency bands [28].

2.10. Integrated Antenna

Two or more different resonant structures are co-located in the vicinity and results in multiple bands. With the integration of the antenna into the device, the proximity between the antenna and the device's electronic components can be optimized, resulting in improved performance and reduced electromagnetic interference. In [29], four monopole antennas and two linear connected arrays are integrated as shown in Figure 8(b) to attain two bands at 2.4/3.6 GHz and one 5G band at 28 GHz. A four-port MIMO antenna comprises a multipurpose filter to attain three modes of operation-interweave cognitive radio, underlay cognitive radio, and sensing antenna [30].

Researchers are exploring various novel technologies for fulfilling the ever-increasing demands of the digital age. Multiband MIMO technology has a significant future scope in the development of antennas for 5G and 6G networks as it provides faster speeds, higher capacity, better reliability, and enables a variety of future technologies. Table 1 indicates the comparison of multiband techniques used in multiband MIMO antenna by various researchers.

3. CHALLENGES IN DESIGNING MULTIBAND MIMO ANTENNA

Planar antenna structures, such as microstrip antennas or printed antennas, offer the advantage of being inherently compact and easy to integrate with other components. Planar structures may typically have limited bandwidth and lower gain than three-dimensional antennas. They can also be more prone to coupling and interference between antenna elements. Designing multiband MIMO antennas comes with several challenges that need to be addressed to ensure optimal performance as mentioned in Figure 9(a). Some of these challenges are as follows.

3.1. Mutual Coupling (MC)

When multiple antenna elements are placed close to each other, they have a mutual coupling effect, which can degrade the per-

TABLE 1. Comparison of multiband techniques used by MIMO antennas for advanced wireless communication.

Ref No.	Dimensions (mm)	No. of Ports	Freq. Bands	Technique used	Isolation	Peak Gain (dBi)	Remarks
[31]	$40 \times 40 \times 0.6$	4	1.95–2.5, 3.15–3.85, 5 to 6.55	Meander line monopole with stubs	24, 22, 22.5	1.6, 3.5, 4.4	SRR unit cell acts as a stop-band filter
[32]	$50 \times 50 \times 1.6$	4	2.25–2.4 and 4.7–6.3	Asymmetric coplanar strip (ACS)	≤ -16	≥ 4.0	Stable gain and radiation patterns
[33]	$75 \times 66 \times 1$	2	2.35–2.53 and 5.23–5.70	PIFA	19.74 and 22.98	≥ 3.0	Two-step shape cutout gives pattern diversity
[34]	$60 \times 120 \times 0.76$	2	0.665–1.13, 1.415–2.005, 2.42_3.09, 3.18_3.89	Slot	≤ -13	1.2, 1.8, 2.3, 3.4	Meandered slots with reactive loading via varactor diode is used for compactness
[35]	$48 \times 36 \times 1.6$	2	3.85–4.25, 4.95–5.1, 6.94–7.35 and 8–8.3	Robot character shaped element with slots and stubs	≤ -25	4.1, 4.0, 3.0 and 5	CP at 3.8–4.2, 4.75–5.2, 6.9–7.15, and 8–8.4 GHz, Irregular dotted parasitic element gives isolation
[36]	$21 \times 90 \times 1.6$	2	2.22–2.54, 3.14–3.9 and 5.3–5.7	Complementary open-loop resonator with stub and slots	34.3, 37.37, 34.54	1.35, 1.7 and 3.22	No common ground plane, a large space between two monopoles.
[37]	$120 \times 50 \times 1.6$	2	1.27–1.43 and 1.8–2.133	Quasi-Yagi antenna configuration in a semi-loop meandered shape	≤ -15	4.6	Truncated GND plane acts as a reflector for quasi-Yagi-like antennas

formance of the MIMO system. Mutual coupling can introduce interference between the antenna elements, affecting their radiation patterns and impedance matching [38]. The antenna also needs to be isolated from other nearby antennas so that antenna elements operate independently without affecting each other's performance.

3.2. Multiple Bands at Desired Applications

To cover multiple applications through a multiband antenna is an arduous journey that comprises an amalgamation of multiple techniques, optimization, and perseverance [39]. 5G/6G networks are highly reliant on multiband MIMO systems due to their several merits over the others.

3.3. Antenna Placement

Determining the optimal placement and orientation of the MIMO antenna elements is a challenging task. The placement affects factors such as mutual coupling, signal correlation, radiation pattern, and coverage [40].

3.4. Wide Bandwidth

MIMO systems generally require wide bandwidth to achieve better capacity and improved performance [41]. Designing MIMO antennas that can operate across multiple frequency bands and offer wide bandwidth is challenging due to various design constraints and compromises needed for each frequency band.

3.5. Compact Antenna Designs

In many MIMO applications, especially in consumer devices like smartphones or wearables, there is a need for miniaturized antenna designs with limited space [42]. Designing compact MIMO antennas with acceptable radiation properties and desired performance becomes challenging due to size constraints.

3.6. Antenna Efficiency and Gain

The overall efficiency of MIMO antennas is crucial for optimal system performance. Designing MIMO antennas with high gain and radiation efficiency is challenging, particularly when miniaturization is a requirement [43]. Low efficiency can result in reduced range, decreased data rates, and increased power consumption.

3.7. Diversity Parameters

Designing a circularly polarized MIMO system that generates electromagnetic waves of the same amplitude and 90° phase difference can be challenging, particularly in real-world scenarios where impedance matching and phase control need to be accurate across a wide frequency range [44]. All types of diversity must be incorporated to exploit the MIMO capacity to its fullest.

3.8. 6G Terahertz (THz) Communication

THz signals experience significant absorption and dispersion in the atmosphere, leading to reduced signal range and quality [45]. A large number of small cells and highly dense deployments are needed to achieve coverage in THz communication systems. THz signals are highly directional and require precise beam steering capabilities to establish reliable communication links [46]. Antennas should have the ability to dynamically steer the beam toward the desired direction for efficient signal transmission and reception. This poses a major challenge for long-range communication.

Addressing these challenges requires a systematic design approach, utilizing advanced simulation, optimization, and measurement techniques.

4. POTENTIAL SOLUTIONS FOR DESIGNING MULTIBAND MIMO ANTENNA

Multiband MIMO technology has a significant future scope in the development of antennas for 5G and 6G networks. Some potential solutions to the problems that arise in designing multiband MIMO antenna are exhibited in Figure 9(b).

4.1. Mutual Coupling

Designing the antenna elements to overcome mutual coupling is a prime challenge, where the radiation from one element is effectively decoupled or isolated from the neighboring elements. The simplest way to achieve isolation is by keeping the physical space of more than $\lambda_0/2$ between the antenna elements. Due to size constraints antennas are placed tightly in the MIMO system which may lead to poor isolation, low antenna gain, high correlation between antennas, reduced radiation efficiency, and degradation in diversity performance [47]. Some of the major techniques are as follows:

4.1.1. Orthogonal Placement

By placing the elements in different physical directions, the coupling and interference between them are minimized. A four-port MIMO antenna, resonating at six frequencies between 3 THz and 10.785 THz has its elements placed orthogonally to achieve the isolation of ≤ -15 dB for all the bands [48]. However, this diagonal arrangement wastes a lot of substrate area.

4.1.2. Defected Ground Structure (DGS)

It is the most prominent technique mentioned in the existing literature to enhance the performance of wideband and multiband MIMO antennas. By creating appropriate defects in the ground plane, the surface current is disturbed. Hence, the equivalent impedance changes which cancel out the cross-polarization [49]. DGS implies a reduced front-to-back ratio and a high value of specific absorption rate.

4.1.3. Split Ring Resonators

SRRs are artificially produced metamaterial structures created by nested split square or circular rings. These structures can be designed as band-stop or band-pass filters by controlling the permeability and permittivity of the metamaterial. The antenna presented in [50] is a combination of SRR and CSRR resulting in dual bands at 2.4/3.5 GHz with an isolation of 32 dB. This SRR/CSRR-based isolation technique is successful for the narrow-band antenna.

4.1.4. Electromagnetic Band Gap (EBG)

EBG structures are periodic etched structures that prevent or boost electromagnetic waves in a specific range of frequency [51]. These structures are separated by $\lambda_g/2$ distance that promotes good isolation, high antenna efficiency, and gain by suppressing unwanted waves. The splits on the EBG cell create a fringing effect that suppresses the return current from the ground layer [52].

4.1.5. Parasitic Element

The parasitic elements acting as resonators or reflectors are placed near radiating elements in a MIMO system to overcome the mutual coupling [53]. These parasitic elements are specifically optimized to control the isolation bandwidth. To predict the coupling between the structures accurately and design parasitic elements is quite tedious and requires larger space too.

4.1.6. Metamaterial Absorber

Metamaterials are artificially designed materials having negative relative permittivity (ε_r) and permeability (μ_r). This double negative material serves as a black hole where the propagation of electromagnetic (em) waves is not allowed. An ideal absorber needs unity normalized impedance due to equal values of ε_r and μ_r which leads to perfectly matched impedance with free space [54]. The split square rings are rotated in 90° fold symmetry to enhance the coupling of the electromagnetic field between the cells. An isolation of 35 dB is attained by suppressing the surface current through four elements of a flower-shaped metamaterial absorber in the middle of the two antennas [55].

4.1.7. Neutralization Line (NL)

NL is an unconventional technique to reduce mutual coupling by connecting a strip at a minimum impedance of two radiators.

The length of NL is appropriately selected for the phase reversal and cancellation of electromagnetic signal. Isolation ≥ 25 dB is attained over a wide bandwidth through three different NL techniques, which are proposed and verified for three different structures [56].

4.1.8. Frequency Selective Surface (FSS)

An FSS antenna is an antenna that uses a two-dimensional periodic structure to selectively transmit or block certain frequencies. FSS structure acts as a frequency filter by reflecting or absorbing certain frequencies while allowing others to pass through. A 3D multiband MIMO antenna employs FSS as a decoupling structure to reduce the coupling between pairs of antenna operating at 2.4/3.2/3.5/3.8/5.5 GHz [57].

4.1.9. Decoupling Structures

These structures modify the electromagnetic coupling between the elements by creating additional decoupling paths to reduce mutual coupling effects [58]. A decoupling structure comprises slots, metallic strips, and shorting pins to change the electromagnetic distribution for mutual coupling reduction by 32 dB [59]. Shorting pins and vias are one of the best compact methods to attain high isolation in narrow band MIMO antenna without degradation of radiation performance.

4.1.10. Nulling Techniques

Nulling techniques involve adjusting the amplitude and phase of the antenna signals to create nulls in the direction of the interfering signals. This helps reduce interference and improves isolation. Two mutual coupling nulls are formed by path cancellation due to half wavelength strips, and one null is formed due to phase cancellation between the driven element and passive parasitic patch. This decoupling method attains an isolation of 36.5 dB without any enhancement in the profile of the stacked structure [60].

A comprehensive comparison of balance isolation requirements with other design considerations is mentioned in Table 2.

4.2. Bandwidth Enhancement Techniques

Bandwidth is defined as the frequency range over which an antenna radiates or receives properly, while impedance bandwidth considers the frequency range over which return loss is ≤ -10 dB. Conventional microstrip antennas suffer from narrow frequency bandwidth, low gain, and low efficiency. Wideband feeding techniques, such as aperture coupling or balun feeding, can achieve broader bandwidth by efficiently coupling energy to the antenna elements [67]. However, this may require precise design and optimization to achieve the desired bandwidth. Proper impedance matching is also crucial for achieving wider bandwidth in antennas. Here are a few techniques to enhance the bandwidth along with their merits and demerits:

4.2.1. Stacked or Multilayered Structures

Stacking multiple layers of antennas or using multilayered structures can increase the overall bandwidth of the antenna. Each layer operates at a different frequency, allowing for broader frequency coverage. Stacked or multilayered structures can lead to increased complexity in the fabrication process. They may also suffer from increased losses and reduced radiation efficiency due to the presence of additional layers and interconnections. A multilayered structure connected with metalized vias with an array antenna fed by a power divider on two different dielectric substrates enhances the bandwidth by 17.7% [68].

4.2.2. Incorporation of Metamaterials

Metamaterials can be used to enhance the bandwidth of antennas by introducing artificial electromagnetic properties. Implementing metamaterials can be challenging and often involves complex fabrication techniques. An array of 2×2 rectangular patches is loaded with SRR metamaterial to increase the bandwidth by 60% [69].

4.2.3. Wideband Resonating Structures

Wideband resonating structures, such as slot antennas or log-periodic antennas, are designed to exhibit frequency-independent behavior over a wide bandwidth. These structures can provide consistent performance over a broad frequency range. The slot resonance is merged with the stub resonance to widen the bandwidth with suitable impedance matching [70]. They may also have larger physical dimensions than narrowband antennas.

4.2.4. Dielectric Resonator Antenna (DRA)

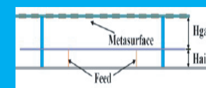
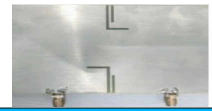
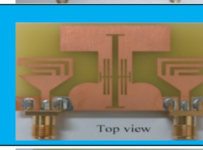
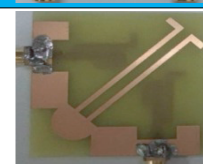
The first DRA made use of high permittivity dielectric material excited by multiple feeds to excite several modes. In general, DRA utilized low-loss dielectric which leads to minimum dielectric losses and hence better radiation efficiency. Cylindrical, triangular, conical, rectangular, etc. shapes are most common for nowadays wireless applications. An elliptical frustum-based asymmetric flared dielectric resonator MIMO antenna attains wide impedance bandwidth and low mutual coupling between them [71].

It should be noted that bandwidth enhancement techniques often involve trade-offs among bandwidth, efficiency, and complexity as mentioned in Table 3. Designers must carefully consider the specific requirements of their application to select the most suitable technique for achieving broadband performance.

4.3. Gain Enhancement Techniques

Gain quantifies the radiation intensity of an antenna in a particular direction compared to the radiation intensity of an isotropic antenna. The higher the number of antenna elements is in the MIMO antenna system, the higher spatial diversity is attained which enhances the received signal strength and helps in

TABLE 2. Comparison of isolation techniques used in multiband MIMO antenna.

Ref No.	Dimensions (mm)	No. of Ports	Freq Bands (GHz)	Multiband Technique	Isolation (dB)	Isolation Technique	Prototype
[61]	$100 \times 150 \times 18$	2	2.6, 3.5	U-shape slits	≤ -25	Metasurface creates shielding zones	
[62]	$70 \times 60 \times 1.6$	2	2.4, 3.4	T-shape slits and slot	-24.998 dB and -29.96 dB	Slots loading of length $\lambda/4$	
[63]	$48 \times 31 \times 1.6$	2	2.4, 3.5, 5.2	Multiple branches	≤ -22	Slotted ground plane in CPW-fed antenna	
[64]	$50 \times 50 \times 1.6$	2	2.4, 5.5	L-shaped short strip	≤ -19	Neutralizing line with inverted L-shaped stubs	
[65]	$100 \times 60 \times 1$	2	2.4, 5.2, 5.8	Slots	≤ -20	meta-inspired decoupling network	
[66]	$60 \times 60 \times 3.5$	2	2.04–2.51, 4.43–5.35 and 6.76–8.78	Two metallic "8"-shaped antenna structures	≤ -20	Stub with three subsections	

achieving gain. The constructive interference between the elements also results in overall antenna gain improvement [78]. To achieve a gain in a multiband antenna, several techniques are incorporated in structures like frequency selective surface (FSS), parasitic patches, superstrate, metallic reflectors, partial substrate removal, and shorting pins.

4.3.1. Array Antenna

Multiple antenna elements are arranged in a specific pattern with a phased array configuration. Phased array systems allow for beamforming, where the antenna elements are individually controlled to steer the radiation pattern toward the desired direction, thereby achieving gain [91]. The gain of 6.7 dBi is enhanced to 12.8 dBi by comprising four elements in each array [79].

4.3.2. Frequency Selective Surface (FSS)

FSS is an array of metallic patch on a dielectric substrate that has the potential to block or pass certain frequency bands. An annular ring unit cell is periodically arranged in a 4×4 configuration and placed beneath the MIMO antenna to improve the gain up to 5.49 dBi [80].

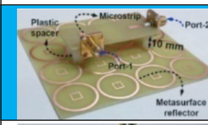
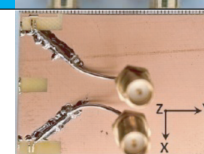
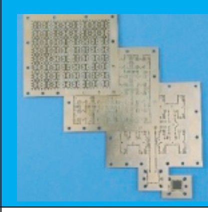
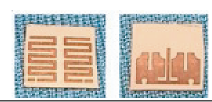
4.3.3. Parasitic Patches

Parasitic patches are placed near radiating elements, but they are electrically disconnected. The energy is transferred through inductive coupled or otherwise. Carefully arranging the position of parasitic elements can result in the enhancement of gain, isolation, and bandwidth. Paper [81] investigates the difference in the effect of E-coupled and H-coupled square-shaped parasitic patches on isolation, gain, and bandwidth.

4.3.4. Superstrate Layer

Superstrate layer comprises the matrix configuration of the metamaterial unit cell with varied shapes and separation from radiating elements. Sometimes layers are used in correlation with several resonant frequencies. Besides the structure shape, the gap between two dielectric layers affects the reflection and transmission coefficients of the complete structure. The measured gain reaches 8.6 dBi by integrating a superstrate layer

TABLE 3. Comparison of bandwidth enhancement techniques used in Multiband/Wideband antenna.

Ref No.	Dimensions (mm)	No. of Ports	Freq. Bands (GHz)	Efficiency (%)	Isolation (dB)	BW enhancement Technique	Prototype
[72]	$22 \times 22 \times 1.6$	2	2.4, 3.4, 5.5	≥ 68.9	17, 18, 32	Metasurface reflector	
[73]	65×65	2	3.1–17.5	≥ 72	≤ -20	Small rectangular notch at the ground plane	
[74]	$27 \times 17 \times 1.6$	2	1–30	≥ 80	≤ -17	DGS	
[75]	10.5×4	2	2.36–2.63, 4.76–8	64, 84	22 and 17	Parasitic resonator	
[76]	$96 \times 96 \times 2$	8×8 array	22.3–32.1	Not reported	≤ -17	Slot-fed by two vias residing on the opposite sides of a dumbbell-shaped aperture	
[77]	$5 \times 4.2 \times 0.12\,\text{mm}$	2	2.15–2.77	≥ 74	≤ -32	DGS, T and I-shaped stubs in the ground	

formed from an array of 4×3 unit cells which highly reflect the signal at 6 GHz frequency [82].

4.3.5. Metallic Reflectors

A complete metallic surface is placed beneath the radiating element which acts as a reflector. The reflector is placed generally at a height half of the wavelength below the radiating element. If the phase difference between the reflected and radiated waves is equal to $2N\pi$, the gain will be enhanced. The height of the reflector and microstrip antenna is chosen appropriately to enhance the gain equal to 9.2 dBi due to the generation of in-phase constructive reflection with the antenna's radiation [83].

4.3.6. Directive Antenna Structures

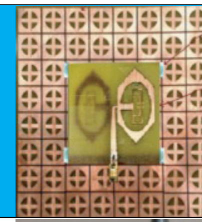
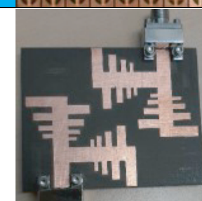
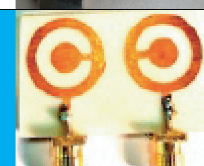
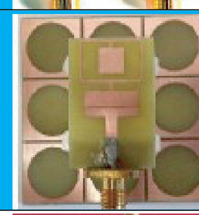
Some antenna structures have inherently high gain, such as horn antennas, parabolic reflector antennas, or Yagi-Uda antennas. These structures have a specific shape and design that focuses the radiated energy in a particular direction to achieve higher gain. Four directive slot antennas are positioned in orthogonal patterns to present high isolation and gain in the azimuthal plane [84]. Directional antennas can be configured with gains up to more than 20 dB.

It is important to note that each of these techniques comes with its own set of design challenges and trade-offs as enlisted in Table 4.

4.4. Mechanism for Compact Antenna

The conventional microstrip antenna size is taken up in the manner of half a wavelength for adequate performance. The latest advent of technology leads to the requirement of compact antennas for handheld devices. Compact antenna designs focus on reducing the physical size of the antenna while maintaining adequate performance. Techniques like the use of high dielectric constant, slots, and slits, DGS, shorting, reshaping, meander lines, fractal, metamaterials, etc. can help in achieving miniaturization. However, compact antennas may suffer from reduced bandwidth or lower radiation efficiency than their larger counterparts. Table 5 tabulates the techniques used by the researchers to achieve miniaturization of MIMO antennas. Here are a few popular techniques to attain miniaturization are discussed in detail.

TABLE 4. Comparison of gain enhancement techniques used in multiband MIMO antenna.

Ref No.	Dimensions (mm)	No. of Ports	Freq Bands (GHz)	Gain	Isolation (dB)	Gain enhancement Technique	Prototype
[85]	$30 \times 44 \times 1.6$	1	2.4, 3.5, 5.8, 7.9	2.63, 2.58, 2.82, 2.99	NA	FSS	
[86]	$55 \times 45 \times 1.57$	2	12.9, 13.8, 15.1, 18.2, 21.5	4.2–10.7	≤ -23.5	Log-periodic dipole array	
[87]	$40 \times 25 \times 1.6$	2	3.8, 5.4, 7.8	5.34	≤ -29	CSRR	
[88]	$54 \times 54 \times 20$	1	2.34, 5.32	5.5, 7.1	NA	The artificial magnetic conductor layer	
[89]	$67 \times 67 \times 12$	3	7.29–9.7	8.93	≤ -17	Loaded on hybrid metasurface layer	

4.4.1. Fractal Antennas

Fractal antennas can provide increased bandwidth with miniaturization. The complexity of the antenna design and fabrication increases with fractal or multi-resonant designs. 42% compactness is attained through a swastika arm structure with the Quadric-Koch fractal technique in a two-port hepta-band MIMO antenna [90]. It may be challenging to achieve high radiation efficiencies and maintain pattern diversity with these antennas.

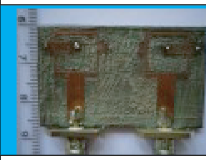
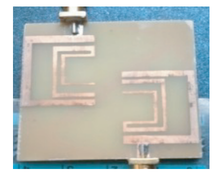
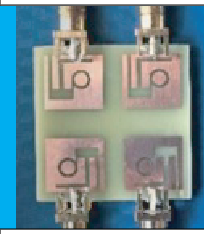
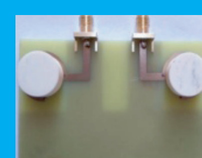
4.4.2. Metamaterial-Based Antennas

Metamaterials enable the design of antennas with unconventional electromagnetic properties and sub-wavelength dimensions. Through carefully engineered structures, they offer the potential for compact and high-performance MIMO antennas. Implementing metamaterial-based antennas can involve complex and non-standard fabrication techniques. The incorporation of metamaterials may also introduce additional losses and narrow bandwidth. A miniaturization of 73% by employing CSRR under the patch is proposed in [91].

4.4.3. DGS

The defects due to etched regions (slots) in the metallic ground plane are referred to as defective ground structures. These slots are excited through coupling from transmission lines just placed above them. A different structure like circular, rectangular, meander line, dumbbell shape, etc. acts as a tuned circuit of parallel L-C circuit whose equivalent value corresponds to the dimensions of the slot. The trapezoidal shape is etched out from the ground plane to suppress the cross-polarization and lower the resonant frequency in turn to attain 22.9% compactness [48]. The implementation of DGS is easy, and the structure is compact which results in the fast evolvement of various shapes and applications for wireless and microwave applications.

TABLE 5. Comparison of miniaturization techniques used for designing multiband MIMO .

Ref No.	Dimensions (mm)	No. of Ports	Freq. Bands (GHz)	Remarks	Isolation (dB)	Miniaturization Technique	Prototype
[94]	$45 \times 25 \times 1.57$	2	2.37–2.64, 3.39–3.58 and 4.86–6.98	First two bands are created by loading the CRLH unit cell	≤ -15	Modified square loop antenna with CRLH unit cell	
[95]	$42 \times 40 \times 1.57$	2	0.72–1.1, 1.57–1.90, 2.19–4.90, 5.30–6.70	Independent tuning, CP bands at 0.9 GHz, 1.8 GHz, and 5.8	-30, -30, -22, -36	Iterated C-shape	
[96]	$32 \times 32 \times 1.6$	4	3.72–3.82, 4.65–4.76, 6.16–6.46	No extra isolation element	≤ -16	Circular and rectangular slot cuts	
[97]	$60 \times 80 \times 0.8$	2	0.89–0.96, 1.7–1.8, 2.3–2.37, 2.5–26	The neutralizing line gives high-isolation	≤ -30	Folded monopole with meander line	
[98]	$48 \times 70 \times 10.1$	2	1.86–2.60, 3.3–3.64 and 4.42–6.75	C-shaped printed line behaves as a magnetic dipole and produces two different radiating modes in CDRA	≤ -20	C-shaped printed lines and cylindrical dielectric resonator	

4.4.4. Antenna Integration Techniques

Integrating antenna elements with other components or structures, such as printed circuit boards and device enclosures like metal frame antenna, PIFA, etc. can help achieve miniaturization without compromising performance. PIFA usually fits inside handheld devices whose backside acts as a ground plane. The metal frame MIMO antennas are placed on opposite edges/corners of the backplane generally without incorporating a decoupling structure. A metal frame quad-band antenna to cover 2G/3G/4G is proposed in [92] without any need for a decoupling technique.

4.4.5. Meander Line

The physical length of the antenna can be reduced by incorporating the meander technique as it utilizes multiple folds in the conducting patch [12]. The overall required dimension needed for a resonant frequency is $\lambda_g/2$, which can be attained in a compact form by attaining 30–80% miniaturization using a meander line. Three separate arms comprise meander lines of different lengths resulting in three different resonance frequencies with a compact size of $45 \times 30\,\text{mm}^2$ [93]. Designers must carefully consider the application requirements and constraints to select the most appropriate miniaturization technique.

4.5. Polarization Purity

Polarization determines the geometrical orientation of the transverse wave radiated by an antenna. If an antenna radiates electromagnetic waves in a single plane with the direction of propagation, then it is linearly polarized. The direction of the electric field differentiates the antenna as vertically polarized and horizontally polarized due to the movement towards the vertical plane and horizontal plane, respectively. The antenna radiating em waves in two planes simultaneously with equal amplitude and 90° phase variation is known as a circularly polarized antenna [99]. However, if the amplitudes of the em waves radiated in two planes by the antenna are different while the phase variation is 90°, or if the relative phase varies with an angle other than 90°, it is known as an elliptical polarized antenna. The direction of the electric vector turns in a clockwise direction in right-hand circular polarization (RHCP) and anti-clockwise direction giving left-hand circular polarization (LHCP). Axial ratio assesses CP through the ratio of the major axis to the minimum axis. An ideal CP wave is achieved for the value of $AR = 0\,\text{dB}$, which is not feasible. So an $AR \leq 3\,\text{dB}$ is considered as a practical CP wave [100]. Here are some commonly techniques used to attain CP:

4.5.1. Truncated Corner

The truncation is usually done on opposite corners of an antenna. The electromagnetic fields break apart into orthogonal modes having the same amplitude with 90° phase variation due to truncated corners [101].

4.5.2. Stacked Patches with Different Feed Phases

By stacking multiple patches with different feed phases, circular polarization can be achieved in MIMO antennas. The patches are fed with different signals that have a specific phase relationship, resulting in circular polarization [102].

4.5.3. Orthogonal Feeding Networks

Using orthogonal feeding networks, where the signals to each MIMO antenna element are fed with different phase shifts, can help achieve circular polarization. The orthogonal feeding networks properly excite the antenna elements to generate circularly polarized radiation [103].

4.5.4. Asymmetric Slots/Slits

Circular polarization can be attained by adding slots of varying sizes and asymmetric cuts in opposite directions of an antenna [104]. This result in two orthogonal modes generation at 45° to the feed location with similar amplitude, but these excited modes are 90° out of phase.

4.5.5. Crossed Dipole or Bowtie Antennas

Crossed dipole or bowtie antennas are inherently circularly polarized [105]. By utilizing crossed-dipole or bowtie elements as the antenna elements in a MIMO configuration, circular polarization can be achieved.

4.5.6. Orthogonal Placement/Crossed Configuration

The patch is placed in a crossed configuration to attain higher mutual coupling and wider CP. Some phenomena like unequal dipole length, tunable width/radius, and phase delay circuit are added to get 90 out-of-phase signals which results in CP [106].

4.5.7. Metamaterial Surfaces

Incorporating metamaterial surfaces with specially designed sub-wavelength structures can modify the polarization of the radiated waves [107]. These metamaterial surfaces can be placed near the MIMO antenna elements to achieve circular polarization.

It is worth noting that the specific techniques used to achieve circular polarization in MIMO antennas depend on the antenna geometry, frequency band, and other design constraints. A comparison table listing different techniques to attain circular polarization is demonstrated in Table 6.

4.6. Diversity

The technique to mitigate the fading effect and enhance the performance of the system is known as diversity. Several diversity parameters are commonly considered in MIMO antenna systems. These parameters help improve the performance and reliability of MIMO systems by reducing the effects of fading and interference [114]. Some of the key diversity parameters in MIMO antenna systems are discussed as follows.

4.6.1. Spatial Diversity

Spatial diversity refers to the use of multiple antenna elements that are physically separated in space. The channel capacity can be optimized by choosing adequate element spacing, the appropriate number of elements, and essential topology. The incompetent spacing between antennas results in mutual coupling, which further leads to variations in input impedance and distorted radiation patterns [115].

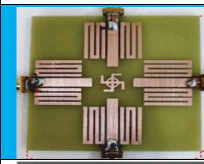
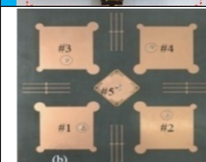
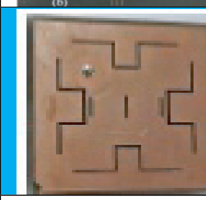
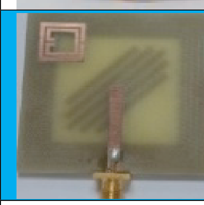
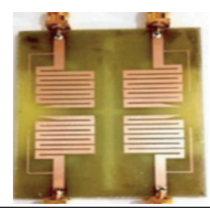
4.6.2. Polarization Diversity

Polarization diversity utilizes different polarization states for the antenna elements to provide a full-rank MIMO system. By having antenna elements with different polarizations (e.g., vertical, horizontal, or circular), polarization diversity helps reduce the effects of polarization mismatch and also reduces mutual coupling. The circular polarization diversity can be incorporated with minimum spacing, low spatial correlation, and high isolation yield by different orientations of polarization [116].

4.6.3. Pattern Diversity

Pattern diversity consists of multiple co-located antennas having the same radiation pattern, but directed to different directions and opposite front-to-back ratio of nearly 4 dB [117]. Usually, directional antennas which are physically separated by a small distance are utilized. By collectively employing these directional antennas discriminate a large area of angle space with higher gain than a single omnidirectional antenna. The correlation effect can be minimized by choosing the angle spacing of signals. Antenna designs with pattern diversity, polarization diversity, or any combination of the three diversity techniques were adopted to overcome the mutual coupling effect and improve MIMO channel capacity and bandwidth performance. Massive MIMO systems with pattern diversity are a

TABLE 6. Comparison of techniques to achieve CP in multiband MIMO antenna.

Ref No.	Dimensions (mm)	No. of Ports	Freq. Bands (GHz)	ARBW	Isolation (dB)	CP Technique	Prototype
[108]	$54 \times 54 \times 1.5$	4	9.82–10.16	9.59–9.69	≤ -40	Slow-wave structure	
[109]	$200 \times 200 \times 6$	4	1.22–1.32	1.26–1.27	≤ -28	Four round disks with different radii	
[110]	$51 \times 52 \times 1.6$	1	1.16–1.20, 1.86–1.92, 2.29–2.38	1.17–1.18, 2.30–2.34	NA	Vertical hat-shaped slits	
[111]	$15 \times 15 \times 15$	4	2.3–2.9, 5.5–6.8	2.2–3.0	≤ -32	Orthogonal placement in 3D cubic antenna	
[112]	$50 \times 50 \times 1.56$	1	1.78–1.87, 2.38–2.71 and 3.21–3.4	1.77 GHz–1.85 GHz, 2.4 GHz–2.7, 3.04 GHz–3.15	NA	Combination of the SRR and strip-slot	
[113]	$50 \times 70 \times 1.6$	4	2.18–2.24, 2.38–2.46, 2.65–2.70, 3.10–3.32, 3.38–3.46	2.18–2.20, 2.39–2.41	≤ -17	Ramp-shaped cut at the end of a meandering-shaped patch	

convincible solution for communication in a real environment, RF harvesting, the Internet of Things, and 5G/6G devices. A comparison table listing different techniques to attain pattern diversity is shown in Table 7.

5. 6G ANTENNAS

Antenna designers are exploring various novel technologies, such as metamaterials, phased array antennas, reconfigurable intelligent surface, super massive MIMO, cognitive radio, and integrated systems to meet the demands of 6G THz wireless communications. A graphene substrate-based microstrip antenna resonates at 1.96 THz and 4.83 THz by incorporating slots in radiating elements [123]. Another quad-band antenna resonates at 1.57 THz, 2.08 THz, 3.32 THz, and 4.43 THz with a series-fed patch using a branch structure modeled on a polymide substrate with graphene material on the top layer [124]. The combination of multiband MIMO and massive MIMO can further enhance network capacity, coverage, and energy efficiency.

5.1. Reconfigurable Intelligent Surfaces (RIS)

RIS refers to metasurfaces that can manipulate and reconfigure the signal propagation environment. RIS elements are composed of a large number of subwavelength elements that can reflect, refract, or absorb electromagnetic waves [125]. In 6G, RIS can also assist in beamforming, interference management, and localization, enabling highly efficient and adaptable wireless networks.

TABLE 7. Comparison of pattern diversity techniques practiced in multiband MIMO antenna.

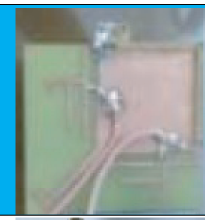
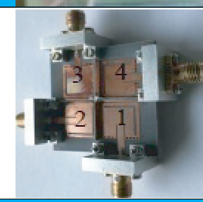
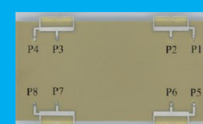
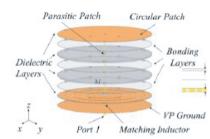
Ref No.	Dimensions (mm)	No. of Ports	Freq. Bands (GHz)	Circular Polarization	Isolation (dB)	Pattern diversity Technique	Prototype
[118]	$120 \times 65 \times 4.8$	3	1.35–2.75, 0.786–0.807, 2.64–2.75, 4.45–4.7	786.7–807, 1.47–2.55	≤ -13.4	Orthogonal mirrored tri-branch	
[119]	$36 \times 36 \times 1.6$	2	3.471–3.529, 5.678–5.721	3.4–3.5, 5.6–5.7	-18.4, -22.7	Metal walls act as reflectors	
[120]	$140 \times 70 \times 1.6$	8	3.06–3.81, 3.33–3.67	NR	≤ -14	Two elements fed by in-phase and 180° out-of-phase excitations	
[121]	$10.9 \times 12.8 \times 9.45$	3	2.35–2.45, 5.75–5.83	2.35–2.45, 5.75–5.83	≤ -15	Artificial transmission line (ATL) cells are structured into a multi-layer architecture	
[122]	$41.05 \times 21.1 \times 1.6$	2	2.56–2.73, 3.15–3.72, 4.67–5.8	NR	≤ -15	Opposite directions placement	

TABLE 8. Applications of 5G/6G multiband MIMO antenna.

References	Applications	Multiband technique
[130]	Rooftop antenna with shark fin shape for vehicular application	Folded 3-dimensional branch structure
[131]	Handheld mobile devices	Minkowski island curve and Koch curve fractals
[132]	5G Laptop devices	Reconfigurability using PIN diodes
[133]	Wireless routers	Meander line
[97]	GSM, LTE ,WLAN, WiMAX and DCS for Smart phone	Folded monopole
[134]	5G IOT	CSRR and DGS
[135]	Broadcasting and telecommunication services	Cylindrical helix with meander loop
[136]	Cognitive radio, RFID bands, 5G	Sensing antenna with slot and meander line
[137]	Biomedical application for high data rate	Shorting pin and arc slots
[138]	Wearable button antenna for 5G	SRR structure
[139]	Wireless access point	Arrow shape dipole with ring structure
[140]	Smart watch	Stacked layer

5.2. Cognitive Radio

Cognitive Radio (CR) is a technology that allows dynamic spectrum access by intelligently exploiting the underutilized or unused frequency bands. CR devices can sense the spectrum in real time, identify the available frequency bands, and opportunistically access them. In 6G, CR can play a vital role in optimizing spectrum allocation, especially in the THz frequency range. By utilizing cognitive capabilities, 6G networks can efficiently allocate spectrum resources, enhance spectrum efficiency, and enable seamless connectivity in dynamic and heterogeneous wireless environments [126].

5.3. Massive MIMO

Massive Multiple-Input Multiple-Output (MIMO) refers to the use of a massive number of antennas at the transmitter and/or receiver. It significantly increases spectral efficiency and capacity, and improves link reliability through spatial multiplexing and interference suppression techniques. In 6G, Massive MIMO can be further enhanced to support even higher number of antennas, enabling extremely high data rates and low-latency communications. Massive MIMO can also be combined with beamforming and advanced signal processing techniques, making it a key technology for achieving the ambitious goals of 6G, such as terabit-per-second data rates and massive connectivity [127].

5.4. Integrating Systems

Automated systems like machine learning and artificial intelligence are adequately developed to fulfill critical real-time applications using infrastructure based on 5G and 6G [128]. The applications and network infrastructure are strongly dependent on 6G to witness the network convergence. A planar, reconfigurable, multi-band, graphene-based antenna incorporates a deep neural network to investigate the radiation characteristics and predicts the return loss and realized gain [129].

The above-said solutions address the unique challenges posed by the THz frequency range, support dynamic spectrum access, and optimize radio resource allocation while providing robust and reliable wireless connectivity. By leveraging these techniques, 6G wireless applications will offer enhanced user experiences, support a wide range of emerging technologies, and pave the way for advanced use cases, including massive IoT, holographic communications, augmented and virtual reality, and beyond.

6. APPLICATIONS

Nowadays, multiband techniques are prominently used in various fields of applications to cater to multiband simultaneously. Slot antennas are typically used in microwave and high-frequency applications. Fractal antennas are known for their compact size, wideband performance, and multiband capabilities. These antennas are commonly used in wireless communication systems, RFID tags, and other applications where size and bandwidth are important factors. Stack antennas are commonly used in radar systems, satellite communication, and wireless networks to communication applications due to their wide bandwidth and compact size. FSS antennas are commonly used in satellite communications, radars, and wireless systems to control or enhance specific frequency bands. PIFA antennas are commonly used in mobile devices, such as smartphones and tablets, due to their small size, omnidirectional radiation pattern, and easy integration with PCBs. Metal-rimmed antennas are commonly found in smartphones and other handheld devices where the metal casing or frame can serve as a useful component of the antenna system. Excellent mechanical strength and aesthetic appearance are provided by implementing metal rim antennas in mobile phones. Table 8 enlists vast applications of 5G/6G MIMO antenna targeted by researchers.

7. CONCLUSION AND FUTURE SCOPE

This paper presents an extensive report on design challenges and their potential solution for multiband MIMO antenna for 5G/6G wireless applications. The multiple techniques to obtain multi-resonant bands are described in detail with their merits and limitations. However, most multiband antennas are larger, low gain, narrowband, and linearly polarized. This yields an opportunity for research for possible performance enhancement of multiband MIMO antennas. The review shows that multiband MIMO antennas are the evident options for antenna engineers to target miniaturized multifunctional systems. A special effort is made to explore the possible means to target the solution for achieving miniaturization, multiband, wide bandwidth, high gain, pattern diversity, and circularly polarized antennas. The paper tries to give a complete solution by concluding with various applications of multiband MIMO antennas. The multiband MIMO for 5G and 6G antennas results in enhanced data throughput, spectrum utilization, beamforming, seamless handovers, diversity, reliability, and support for multiple use. As 5G and 6G networks continue to evolve and accommodate new applications and services, multiband MIMO will play a crucial role in meeting the increasing demands for high-speed, low-latency, and reliable wireless communication.

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