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Advances in Smart MIMO Antenna Technologies: A Comprehensive Review of Multipath Mitigation and Design Innovations

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ABSTRACT: Smart antennas provide a unique and viable solution to the problem of multipath effects on signal propagation, particularly in the millimeter wave band. Multiple-input multiple-output (MIMO) technology has certain advantages that can prove instrumental in not just eliminating multipath but turning it into an advantage and improving communication link quality. With the use of MIMO and its unique beamforming capabilities, path loss can be significantly reduced, and more efficient use of the communications frequency spectrum can be achieved. MIMO antenna technology consists of a smart antenna array with multiple transmitting inputs and multiple receiving outputs. In this review, we compare some of the latest developments in MIMO technology. It focuses on design techniques, performance parameters, and novel developments. Recent developments include improvements in UWB, multi-band, and smart wear.

1. INTRODUCTION

Smart antennas are one of the major innovations in communication technology of the twentieth century. As consumer demand continues to rise, telecommunications technology is seen forced to improve and evolve. With the advent of 5G, different areas of the frequency spectrum band which have been historically reserved for scientific research are now being used/affected by consumer demand. This is one of the many challenges presented by 5G technology, and new ways of confronting them must be presented and implemented. Smart antennas present a solution to many of these problems, specifically multipath signal loss/path loss for the higher frequencies. Using smart antennas, and multiple-input multiple-output (MIMO) technology in particular, not only can multipath signal loss be mitigated, but much more efficient use of commercial telecommunication frequency bands can be achieved.

The need for development and innovation in telecommunications technology, not just in consumer applications, but also in military, spacecraft, and radioastronomy, is ever increasing. The current trend for commercial antenna technology is toward a smaller, low cost, low profile, and lower noise design [1, 2]. 5G technology has enabled commercial telecommunication technology to tap into the millimeter wave band, which was previously only used for radar and research purposes. This has presented new unforeseen challenges. One such example is how 5G has affected meteorology, particularly since microwave signals in the 23.6 GHz to 24 GHz band are used to measure radiation from water vapor to make weather predictions. This is now more challenging because of out of band noise from 5G signals [3]. Radio frequency interference (RFI) mitigation techniques have been employed to combat this [4], but it would certainly be of help to try to reduce that RFI at the very source. Another significant challenge for the use of millimeter wave bands in 5G technology is path loss and multipath effects [5]. The strength of a signal received by a receptor in free space can be determined by the Friis equation in (1). The graphical representation of the Friis equation is as shown in Figure 1.

$$Pr = \frac{PtGtGr\lambda^2}{(4\pi R)^2} \tag{1}$$

This equation states that the power received by a receptor in free space is directly proportional to the transmitted power, transmitter and receptor gains, and wavelength, while it is inverse-squarely proportional to $4\pi R$, where R is the distance between the transmitting and receiving elements. When antennas are used, signals undergo reflection, diffraction, and scattering causing multiple signal paths (multipath). Such effects can cause fading and increased bit-error rate, thereby severely reducing signal and link quality. The Friis equation serves as a model that approximates the signal strength on a receiving end, but when path loss and multipath effects are too severe, the model falls apart.

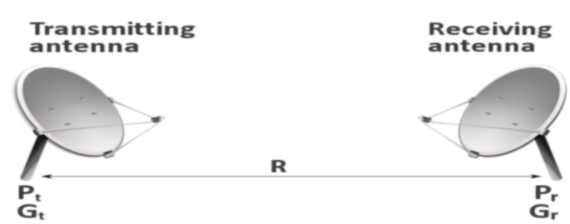

FIGURE 1. Graphical representation of the Friis equation [6].

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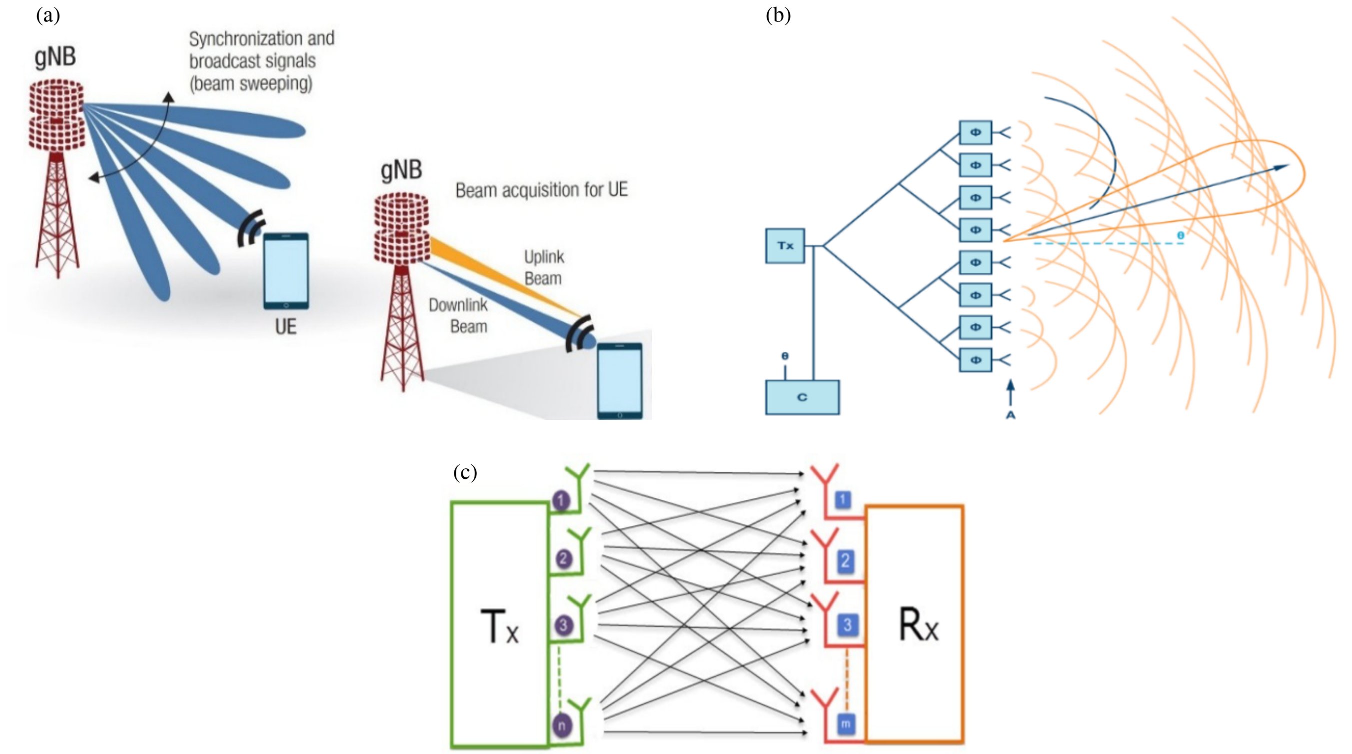


FIGURE 2. (a) switched beam antenna [8], (b) phased array antenna, (c) MIMO system [11].

Smart antennas can be instrumental in mitigating multipath effects on signals and maintaining a low bit error rate and high link quality in a communication network operating on 5G millimeter wave bands. There are different types of smart antenna technology, but all of them use the same technique, namely beamforming, to adapt the antenna according to the conditions it is operating under. Beamforming allows the antenna to change the direction of the signal taht it is emitting or change its radiation characteristics depending on the direction of the signal that it is receiving. Additionally, the adjustment of radiation characteristics can improve the signal to noise ratio (SNR) of the smart antenna [7]. Essentially, smart antennas provide one unique solution to the problem of path loss and multipath effects, noise in the microwave/millimeter wave band, and communication link quality. Section 2 discusses smart antennas. Section 3 presents MIMO technology and its comparison. Section 4 outlines the advantages. Section 5 describes challenges and research gaps. Section 6 describes future scope, and Section 7 provides the conclusion.

2. SMART ANTENNAS

Smart antennas have a unique and complex structure and design among antenna configurations. They consist not only of radio frequency (RF) components, but also of a digital signal processor (DSP) to execute its fundamental function. Their design includes an antenna array, which can be aperture, microstrip, or other array designs with multiple elements, phase shifters to control their radiation characteristics, and a DSP that measures the time delay between elements, and essentially serves as the brain of the smart antenna. The DSP uses the measured time delay within the array elements to compute the direction of the signal of interest (SOI) and adjusts the radiation pattern and gain to focus on the SOI. The concept of using antenna arrays and signal processing is not new, but the advent of low cost and high-speed digital signal processors has made this technology not only possible, but also practical in large scale telecommunications for commercial use. Smart antennas are broadly classified into switched beam, adaptive array, and MIMO antennas.

Switched Beam Antennas: A switched beam antenna uses multiple fixed beams to provide directional coverage over different areas. Instead of continuously adjusting the beam's direction as in adaptive or phased-array systems, a switched-beam antenna "switches" between different predefined beam patterns based on the direction of the incoming or outgoing signal. The representation of a switched beam antenna function is shown in Figure 2(a) [8]. The main advantages that switched beam antennas have over adaptive or phased-array antennas are their simplicity and cost effectiveness. Since these systems rely on switching between preexisting fixed beams, they are less complex and computationally intensive. They do not require as much circuitry or fast processing compared to adaptive or phased arrays; thus, they are cheaper to manufacture and implement [9]. The way that it works is that using a digital signal processor, the antenna detects the signal of interest, such as from a mobile device, and then switches to a beam that has the best reception/transmission in the desired direction. The main disadvantage of switched beam antennas is that when a signal of interest is between beams, it will not be able to receive ideal coverage without changing its physical location. It lacks flexibility compared to a phased array.

Adaptive arrays: An adaptive array is a more advanced form of phased array. It can dynamically adjust the radiation pattern of an antenna array to improve the signal reception/transmission and reduce interference in its desired direction. The adjustment of the radiation pattern is achieved through control of the individual array elements' amplitude and phase [10]. In Figure 2(b), it can be observed that by changing the phase of each element in the array, the direction of the radiation pattern's major lobe is adjusted [11]. By adapting to the changing environment, an adaptive array optimizes performance based on the incoming signal conditions, such as multipath interference or the presence of noise. Key characteristics of adaptive arrays include the use of multiple elements arranged in a specific geometry (planar, circular, linear, etc.), real-time adaptation (phase and gain of each antenna element can be adjusted in real time), beamforming to improve signal quality, a signal processing element (usually a DSP in most recent applications), and flexibility and directionality. Unlike switched beam antennas, adaptive arrays can dynamically follow the desired signal, even as the source is moving. Adaptive arrays can also form a null in the direction of unwanted interference to cancel out signals from different directions [12].

MIMO (Multiple Input Multiple Output): There are four main categories of smart MIMO antenna that revolve around the number of inputs and outputs within the antennas as shown in Figure 2(c) [11]. They are single-input single-output (SISO), single-input multiple-output (SIMO), multiple-input single-output (MISO), and multiple-input multiple-output (MIMO) antennas. In this review paper, the focus is on MIMO technology, although each of the technologies has its merits. MIMO has garnered the most attention out of the three main smart antenna configurations due to how well it not only mitigates multipath effects but also turns them into an advantage. In a MIMO system, multiple data streams are transmitted simultaneously over the same frequency channel, exploiting spatial diversity to increase link quality and reduce bit-error rate. This effectively increases the capacity of the communication link without requiring additional frequency bandwidth or power [13]. In addition to using beamforming, MIMO systems use spatial multiplexing. Spatial multiplexing is a technique that increases the data rate in a wireless communication network by transmitting different data streams from each of the transmitting elements to their corresponding receptors. The receiver separates these streams, allowing for an increase in the data rate without requiring additional bandwidth or transmitting power. This technique exploits spatial dimension and the independent fading paths in an environment where the smart antenna undergoes path loss to improve throughput.

3. MIMO ANTENNAS AND ITS COMPARISON

This section compares different MIMO designs and demonstrates MIMO system capabilities in different configurations and conditions. MIMO systems are extremely versatile. Their designs range from having ultra-wideband (UWB) capabilities, multi-band configurations, and even smart-wear/textile implementations. Simulated and measured results show that they can achieve high gain, isolation, and radiation pattern diversity.

Some fundamental metrics for MIMO performance are envelope correlation coefficient (ECC) or isolation, total active reflection coefficient (TARC), MIMO throughput sensitivity (MTS), uplink/downlink throughput, and diversity gain. Diversity gain can be simply described as the improvement in signal reliability and link quality due to the use of multiple antennas. Throughput represents the amount of information that can be transmitted and/or received in a network using multiple antennas. TARC represents the return loss on each port when every port is simultaneously fed. The focus of this comparison will be gain, isolation, and return loss, which are very important metrics in MIMO design.

Sharma et al. in [14] observe that MIMO antennas not only work for 5G networks in urban areas, but also have multiband capabilities, such as for long range communication like for rural monitoring. They can achieve high gain, exceptionally high isolation, and have relatively simple fabrication processes compared to other advanced antenna designs. This compact ultra-wideband MIMO antenna uses an inset coaxial feed for impedance matching and a half disk parasitic patch to increase bandwidth as shown in Figures 3(a) and (b). It offers high bandwidth from 24.25 to 29.5 GHz using an ultra-compact design and is practical for internet of things (IoT) nodes and indoor mm-wave applications. It is used exclusively for 5G FR2 mm-wave bands. The diversity gain of the developed prototype is $\sim$ 10 dB for the entire band with an ECC greater than 23.5 dB as can be observed in Figures 3(c) and (d).

Khan et al. [15] use an array configuration which characteristically increases gain while also maintaining a compact layout as shown in Figure 4(a). Microstrip feedlines are utilized to facilitate implementation and integration into terminals. It is designed explicitly for mobile terminal integration with high directional gain and has real-world fabrication and measurements to validate its practical feasibility. Quarter-wave transformers are used for impedance matching at the center frequency of the target band at 37 GHz as shown in Figure 4(b). It is implemented as an array to increase gain, and a distance equivalent to a quarter-wavelength is maintained between the elements to achieve a high level of isolation and minimize mutual coupling between the elements. It also stands out because of its excellent radiation efficiency of more than 85%.

Sufian et al. [16] utilize a shared aperture multi-band design, which means that it has one substrate with multiple independent antenna structures and ports for each separate band as shown in Figure 5(a). Television White Space (TVWS) band design consists of circular patches with four rectangular slots to improve gain and bandwidth. What sets this design apart is that it combines multiple bands in just one antenna platform. The purpose of this antenna is to overcome challenges in communications and environmental condition monitoring in rural areas. These scenarios have a unique set of difficulties, and one of them is that usually antenna designs present a tradeoff between frequency and area coverage, so this design helps overcome that boundary. The design has an ECC of 0.0015 and a diversity gain approximately equal to 10 dB.

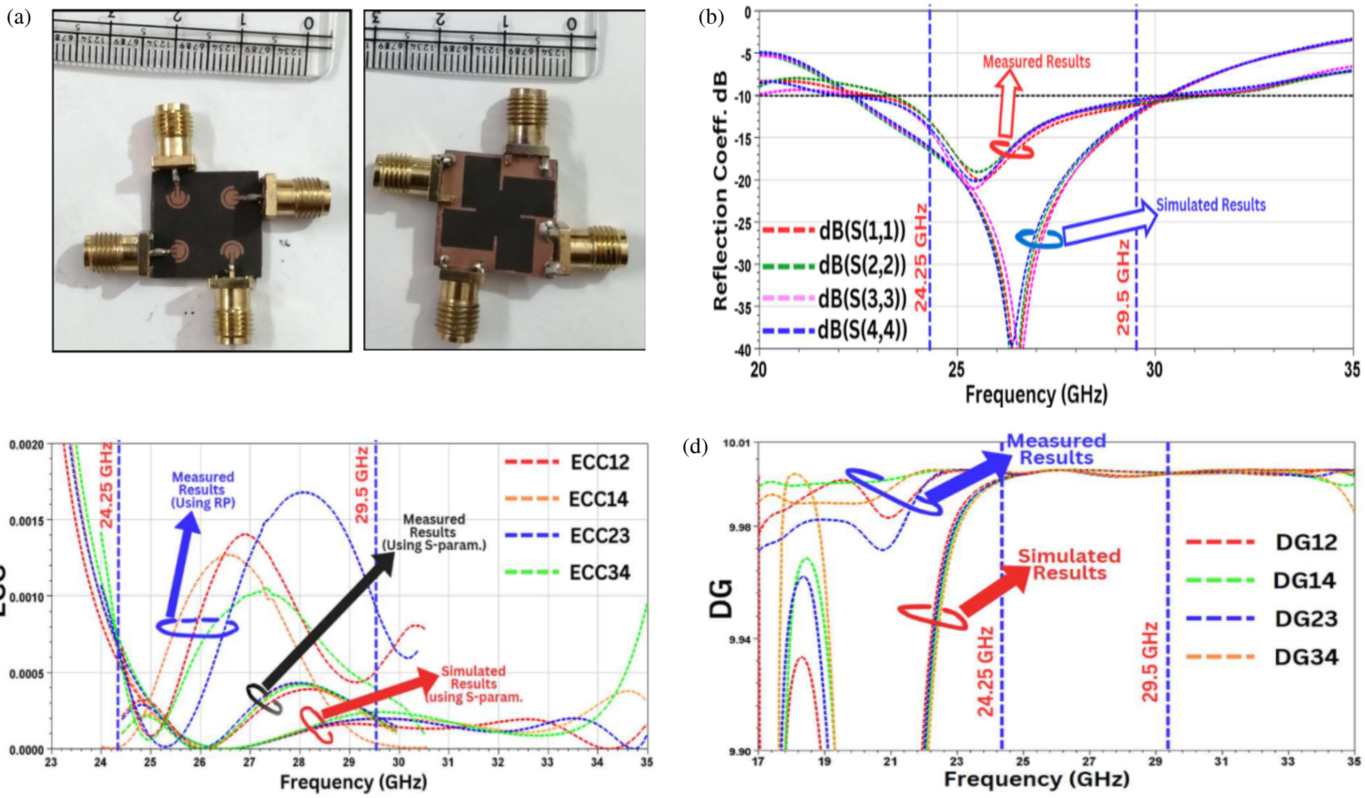


FIGURE 3. (a) Fabricated antenna prototype with front view and back view, (b) S_{11}, (c) ECC/isolation (d) TARC [14].

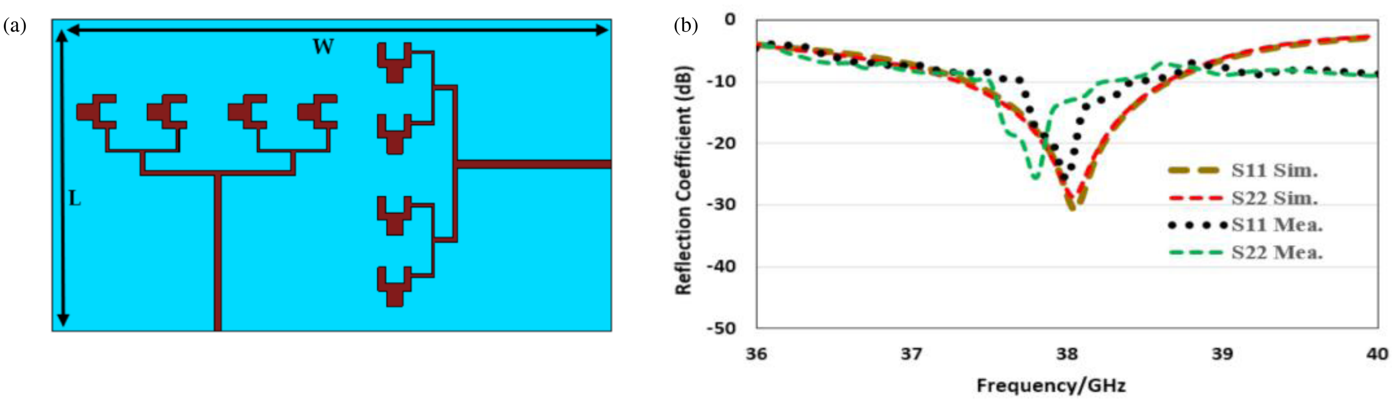


FIGURE 4. (a) Antenna structure, (b) S_{11} [15].

Lai et al. [17] introduce a novel decoupling method using parasitic metal stubs to greatly improve the isolation between MIMO elements. These stubs form a current node at the antenna center, preventing energy coupling between adjacent MIMO elements. This simple technique achieves up to 52 dB of isolation between elements, while being more than 22 dB for the entire band as shown in Figure 6(a). This technique is applicable to multi-element designs and beam-scanning phased arrays. The design covers 25.1–33.3 GHz mm-wave band as shown in Figure 6(b).

Armghan et al. [18] make a design that demonstrates dual-band performance in a low-profile, compact form. They utilize sickle-shaped radiating patches and defective ground structures for their design, including parasitic patches to improve bandwidth and beam steering, and reduce mutual coupling as shown in Figure 7(a). The two design bands are 2.14–3.515 GHz for IoT, Wi-Fi, and marine communication and 5.335–5.585 GHz for aerospace applications. They first develope a single element patch, then optimize a design, and expande it into a 4-element array as shown in Figures 7(a), (b) and (c). Figures 8(a), (c), and (e) present the return loss for the single element, single element with parasitic, and 4-element array respectively, and (b), (d), and (f) present the isolation between ports for each configuration. While the ECC and diversity gain of this design are adequate, optimizing the TARC still represents a significant

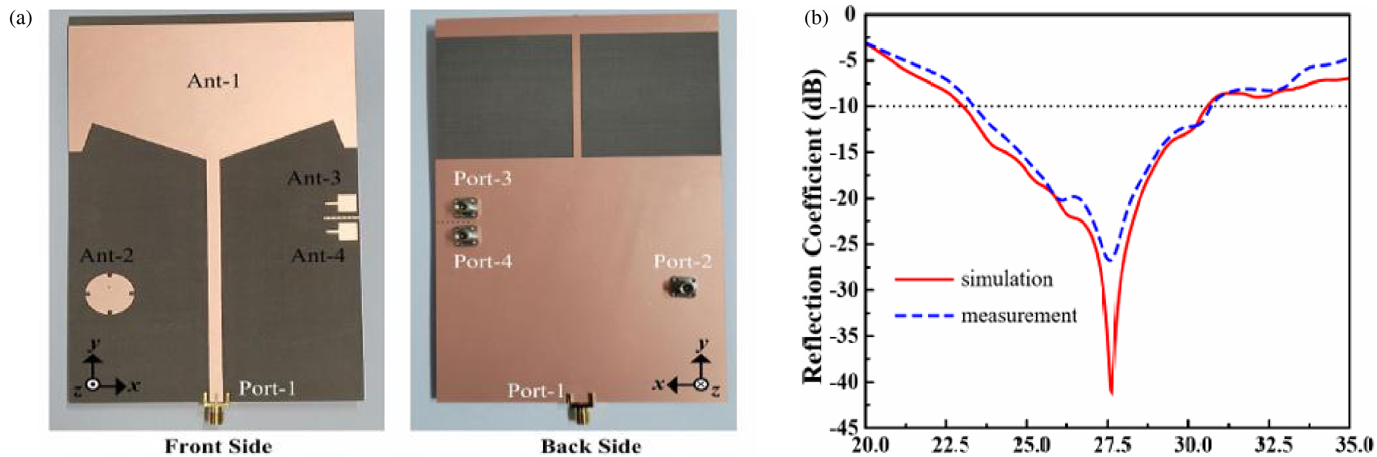


FIGURE 5. (a) Antenna structure, (b) S_{11} [16].

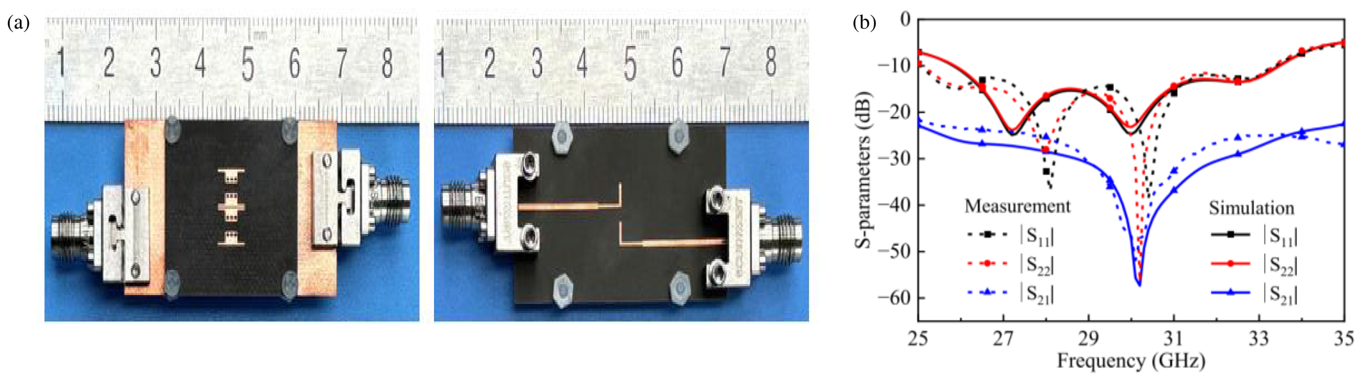


FIGURE 6. (a) Top and bottom views of 1×2 MIMO ME dipole antenna array, (b) S_{11} [17].

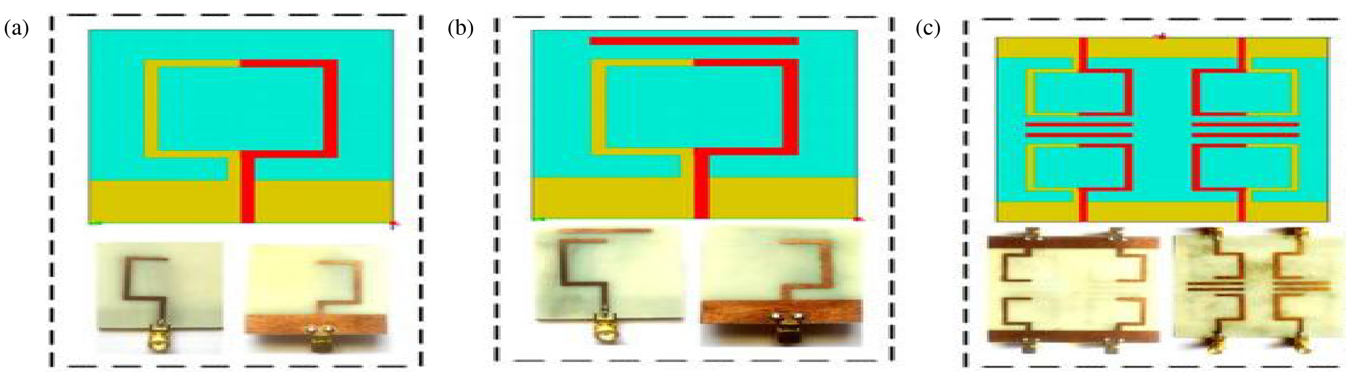


FIGURE 7. (a) Single element, (b) Optimized single element, (c) Proposed 4 element array [18].

challenge, as it remains above -10 dB for a significant portion of the band.

Mohamed and Aboualalaa [19] design an ultra-wideband antenna with a bandwidth of nearly 100% from 2.5 to 50 GHz as shown in Figures 9(a) and (b). The proposed antenna functions for both FR1 and FR2 bands within 5G frequencies. The peak gain for this antenna is 9.98 dBi; however, it maintains a gain of at least 3.5 dBi for the entire band that operates. This antenna operates in a remarkable bandwidth, maintaining not only consistent return loss below 10 dB, but also gain above 3.5 dBi and isolation greater than 26 dB. This antenna is particularly attractive for IoT applications and 5G. The curvature incorporated into the antenna's ground plane serves to improve bandwidth by manipulating current distribution.

Tiwari et al. in [20] utilize MIMO technology and 5G bands for biomedical applications. Specifically, the 1×4 array presented is suitable for wearable medical devices and biomedical telemetry due to its flexible characteristics as far as the bands

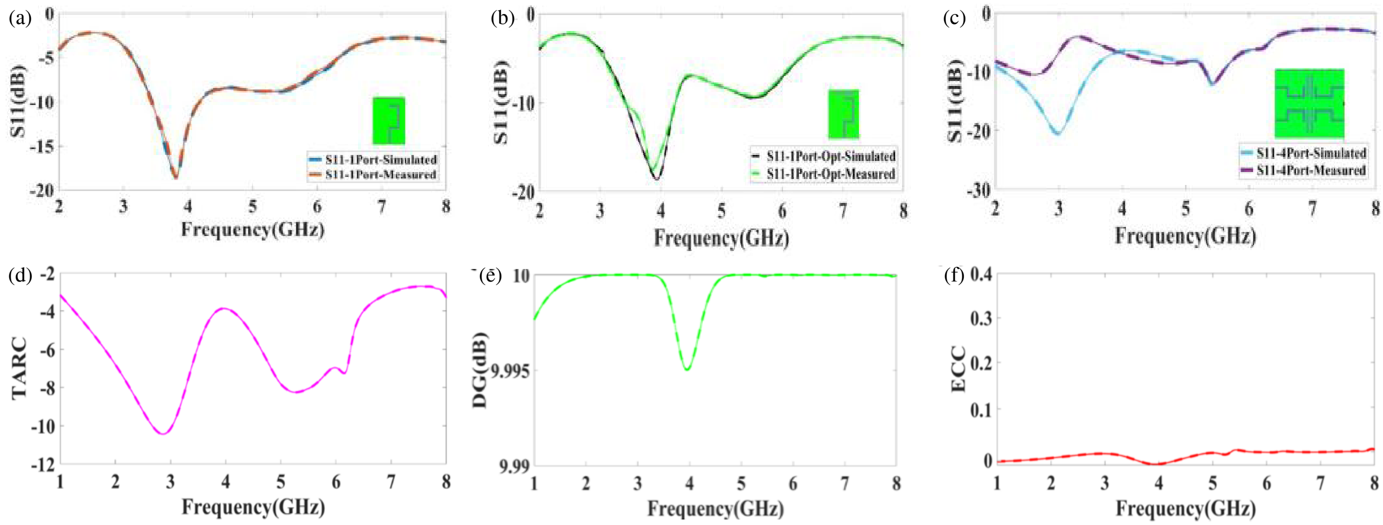


FIGURE 8. (a) Single element return loss, (b) optimized single element return loss, (c) 4-element array, (d) total active reflection coefficient, (e) diversity gain, (f) ECC [18].

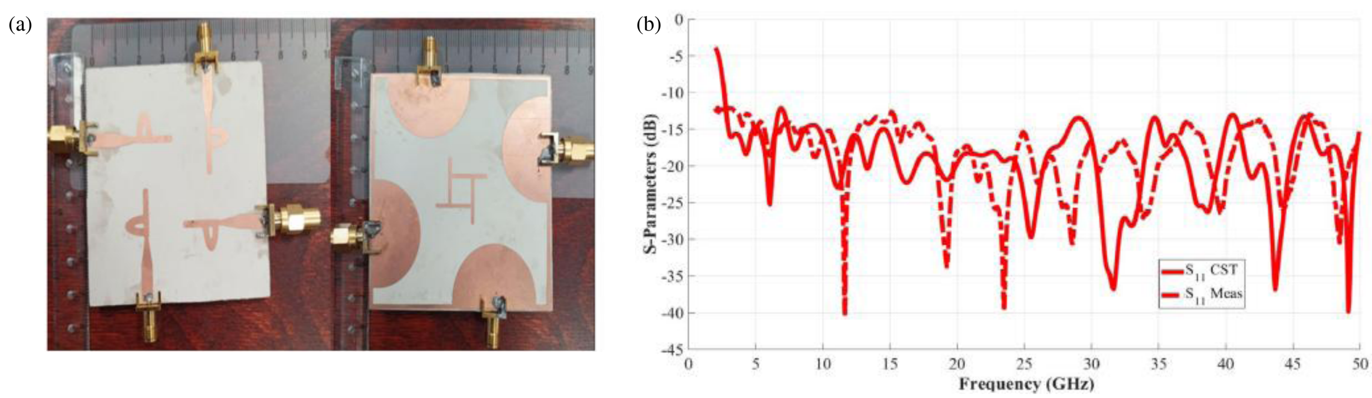


FIGURE 9. (a) 4 element MIMO prototype, (b) S_{11} [19].

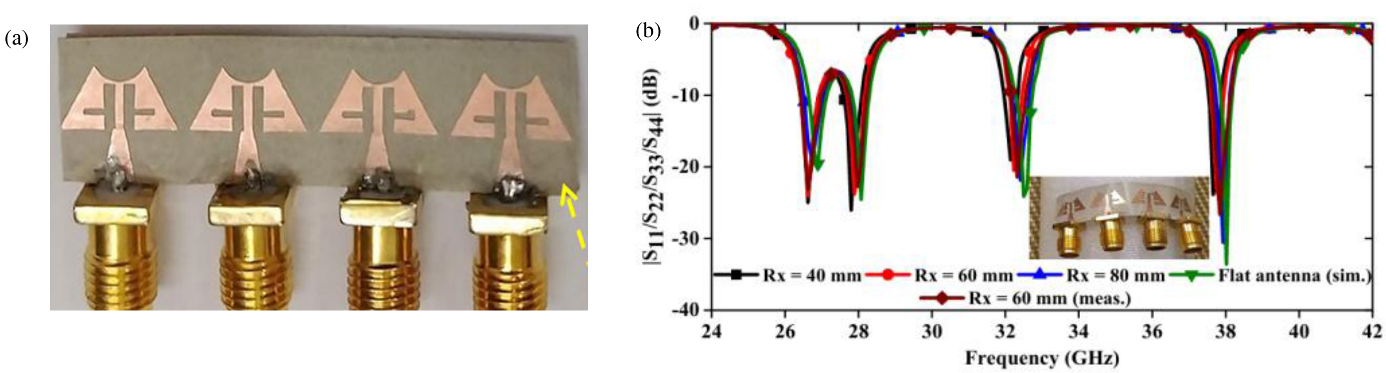


FIGURE 10. (a) MIMO array prototype, (b) simulated and measured return loss [20].

that it operates in, as well as the substrate utilized. The single element design includes a triangular patch with a circular notch and multi-slot ground as shown in Figure 10(a), and the return loss is shown in the graph of Figure 10(b). The ground slots serve to improve bandwidth and add cross polarization. Analysis of the design also includes link budget, link margin, and data rates for the different design bands and different distances.

Chung et al. [21] make a design specifically for applications on smart eyewear, so the goal is to make the design have good gain and bandwidth, while also being as compact and low profile as possible. The 4×4 MIMO design is $50\,\text{mm} \times 9\,\text{mm} \times$

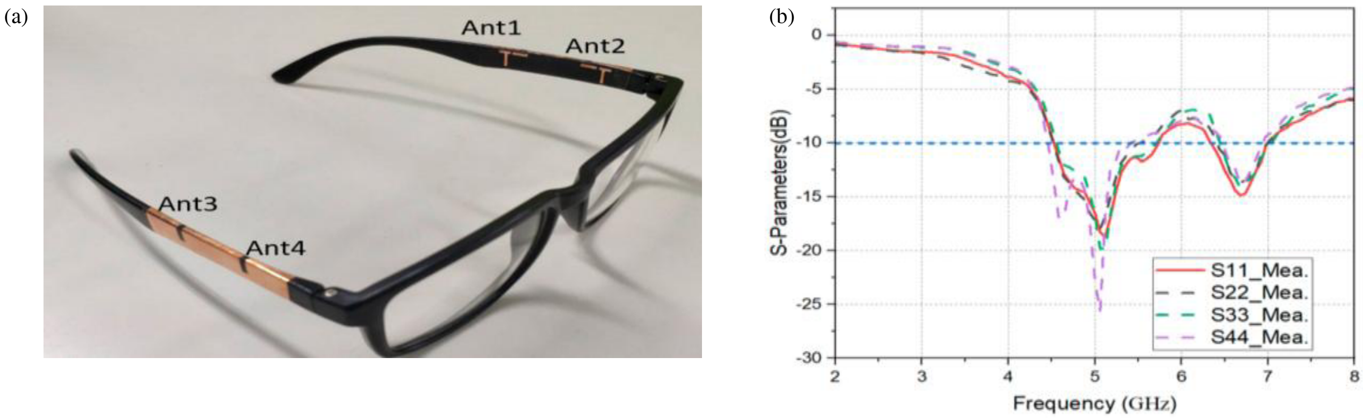


FIGURE 11. (a) 4×4 MIMO antenna in eyeglasses, (b) measured S-parameters of four antennas [21].

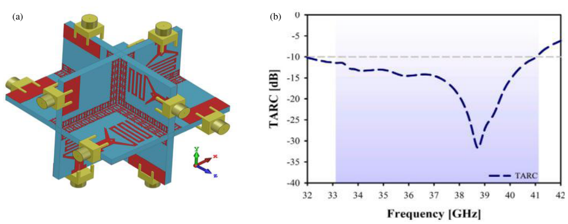


FIGURE 12. (a) 12 port MIMO system. (b) Total active reflection coefficient (TARC) [22].

2.7 mm in dimensions and radiates energy through the slot in the ground plane of a sputtered copper layer outside the temple as shown in Figure 11(a), and the measured S parameter of the four-antenna is shown in Figure 11(b). The results of the designed prototype indicate that smart eyewear devices can be implemented in 5G frequencies, albeit at relatively low gain for now. Two symmetrical antennas and slots on the same temple and series capacitive elements enhance the isolation between the two antenna ports on either side of the glasses. Some interesting techniques used were slot and an inverted-F antenna design, series capacitors to tune frequency and improve isolation, and use of laser direct structuring (LDS) for metal deposition.

Saha et al. [22] implement a design that uses metamaterial-based decoupling (double-negative DNG) and folded monopole design to enhance gain and isolation. It consists of a compact 12-element array architecture as shown in Figure 12(a). The design is proposed for applications in IoT and vehicular networks. The design is unique in that it has 360-degree pattern diversity while maintaining a compact architecture, despite having 12 elements. TARC of the 12-port 12-element antenna is shown in Figure 12(b). It is mentioned that the high throughput and spatial diversity of this 12-port MIMO system is advantageous, but managing multiple data streams in a congested network adds computational complexity, which is one of the major challenges presented by the expansion of IoT.

Bilal et al. [23] implemente a 4-port low profile MIMO configuration antenna for 5G mm-wave applications as shown in Figure 13(a). The design uses a slotted zigzag decoupler to reduce coupling and significantly increase the isolation between elements. The defected ground structure (DGS) serves to increase isolation and improve impedance matching. The antenna is optimized specifically for the mm-wave 28 GHz band as shown in Figure 13(b). The design is remarkable in that it uses no metamaterials or multilayer substrates, and it is simple and easily fabricated. This paper also provides the antenna's throughput capacity for its resonating frequency, rated at 0.4 bits/Hz for a frequency of 28 GHz, a total of 11.2 Gbps.

Govindan et al. [24] explore MIMO applications when it comes to smart clothing and ultra-wideband performance, so it has emphasis on being flexible and low-profile structure as shown in Figure 14(a), and the S parameter graph is shown in Figure 14(b). A novel technique implemented into the device is the use of an artificial magnetic conductor on the backside to suppress surface currents and enhance front radiation, thus improving isolation and gain. An electromagnetic bandgap is integrated near the feed and elements to filter unwanted modes and reduce mutual coupling. The radiating elements are compact coplanar waveguide fed elliptical patches, which serve to achieve ultra-wideband performance. It is fully planar, flexible, and textile conformable. This wideband design is especially remarkable because it not only is successfully implemented using a textile substrate, but also achieves an adequate ECC and a TARC below -10 dB for the full band.

Abbas et al. [25] present a rectangularly notched UWB antenna with an isolator in the center, which is achieved by truncating the corners of the patch as shown in Figure 15(b). The electromagnetic bandgap structures on the back of the antenna serve to implement a notch band for WLAN (5.25–5.85 GHz) rejection. The stubs that extend outwards from the center serve to steer currents and reduce interference between radiating elements. The design also achieves a remarkably low ECC (0.001) and diversity gain of 9.99 dB, which indicates stable MIMO performance for the proposed antenna application.

The different MIMO antenna techniques and characteristics are given in Table 1.

4. ADVANTAGES OF USING MIMO IN MITIGATING MULTIPATH EFFECTS

MIMO technology has high reliability in networks that undergo multipath effects. Since there are multiple paths through which

TABLE 1. Comparison of MIMO antenna characteristics.

Reference and Design Type	Gain	Isolation/ ECC	Unique Contribution	Substrate	Bands covered
[14] Compact UWB MIMO	6 dBi	> 23.5 dB	Ultra-compact, simple, high isolation	Rogers RT5880	24.25 GHz–29.5 GHz
[15] mm Wave MIMO Array	12.8 dBi	> 40 dB	High-gain, dual-array for mobile terminals	Rogers RT5880	37 GHz
[16] Shared-Aperture Antenna	3.14 dBi (TVWS), 6.76 dBi (ISM), 7.68 dBi (5G mm-Wave)	> 26.4 dB	TVWS, ISM, and mm-Wave bands for a unified antenna platform	Taconic TLY-5	470 MHz–780 MHz (TVWS), 5.8 GHz (ISM), 23 GHz–30 GHz (5G mm-Wave)
[17] Decoupling method for wideband MIMO array	10.9–13.4 dBi	> 29 dB	Applicability to multi-element and beam-scanning phased arrays	Rogers RT5880	25.1 GHz–33.3 GHz
[18] Sickle-shaped four port MIMO antenna	Peak gain ~ 15.93 dB	> 16 dB	Dual-band performance, high gain, low-profile, compact form	FR4	2.14 GHz–3.515 GHz and 5.335 GHz–5.585 GHz
[19] A low profile Super UWB-MIMO antenna	9.98 dBi	> 26 dB	Covers entire UWB, 5G, SAT bands	Rogers RT/Duroid 3003	2.5 GHz–50 GHz
[20] Quad-band 1×4 linear MIMO antenna	6.12–8.58 dBi	> 24 dB	Quad-band, wearable stability	Rogers 3003	26.3 GHz–39.5 GHz
[21] 4×4 MIMO antenna for smart eyewear	4.3/3.3 dBi	10 dB	Smart wearable integration	Polycarbonate	4.58 GHz–5.72 GHz & 6.38 GHz–7.0 GHz
[22] Super low profile 5G mm Wave highly isolated MIMO	9.99 dBi	> 10 dB or greater	DNG metamaterial integration, Smart city IoT and vehicular use	Rogers RT-5880	33.1 GHz–41.1 GHz
[23] High-Isolation MIMO Antenna for 5G	12.02 dBi	> 40 dB	High gain & isolation at mm Wave	Rogers RT5880	27.5 GHz–28.5 GHz
[24] UWB MIMO for Smart Textile use	4.5 dBi	> 17 dB	Flexible for smart fabric	Cotton Textile	2.9 GHz–12 GHz
[25] Rectangular Notch UWB-MIMO Antenna	6.94 dBi	> 21 dB (max 50 dB)	Simple + effective UWB with notch	Taconic TLY-5	3 GHz–12.8 GHz, 5.25 GHz–5.85 GHz notch

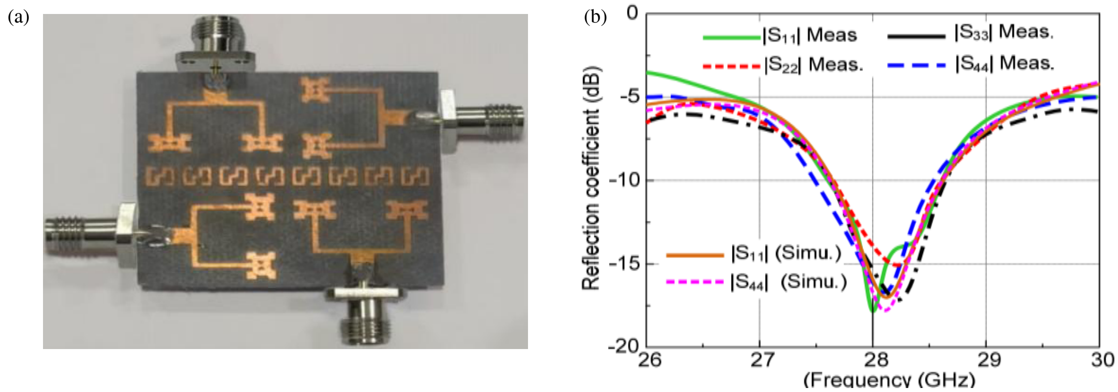


FIGURE 13. (a) Fabricated prototype, (b) measured reflection coefficient [23].

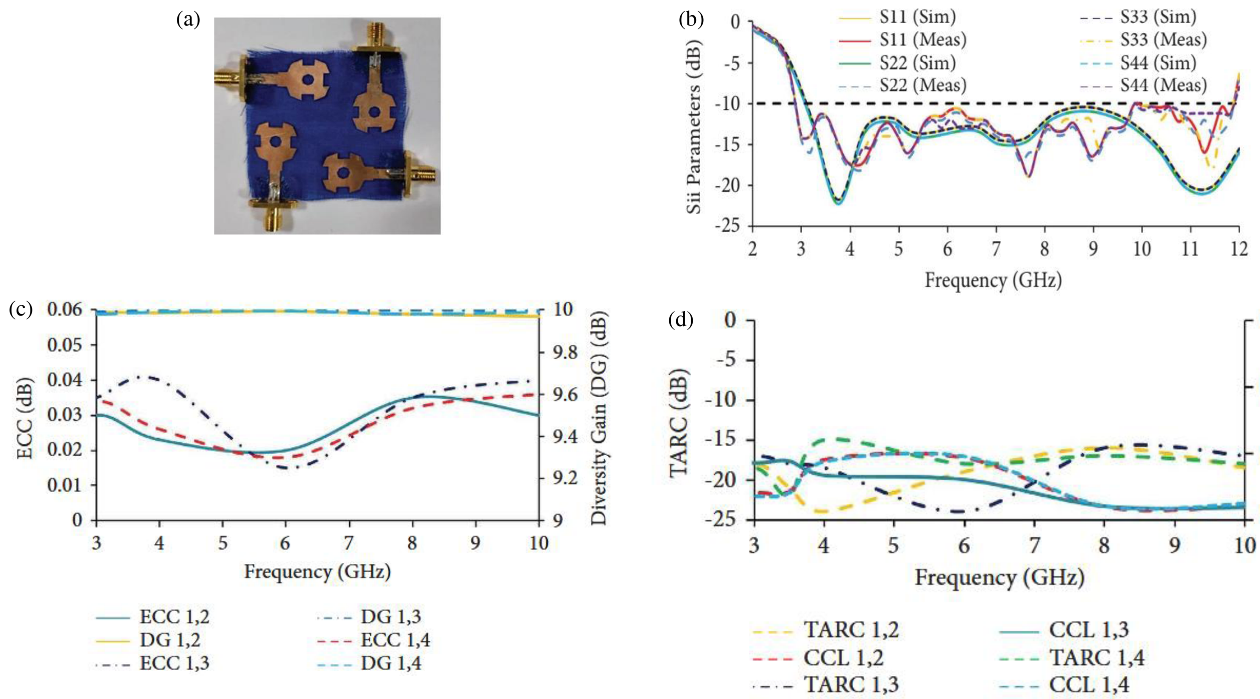
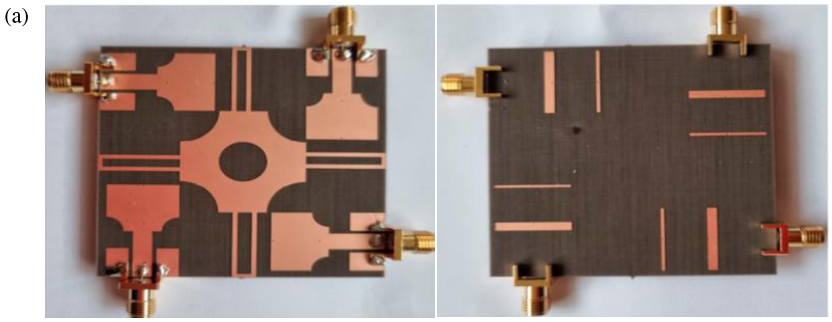


FIGURE 14. (a) prototype of MIMO antenna. (b) Measured vs simulated return loss. (c) ECC and diversity gain. (d) TARC [24].

the signal in a MIMO system is delivered, if one or more of the paths experiences fading, the signal can still be received through one of the other paths, thereby maintaining link quality in a network. The usage of spatial multiplexing allows multiple data streams to be transmitted simultaneously, which increases channel capacity. With increased channel capacity, it is possible for communication systems to limit their band usage such that they do not encroach on bands important for research, which would reduce adjacent band noise on frequencies critical for meteorology and radioastronomy. MIMO technology uses beamforming to steer the major radiation lobe in specific directions, which would focus the receptor on the signal of interest, or the transmission in the desired direction, such that interference from other users or devices is minimized. This reduces the possibility of multipath interference and improves link quality.

In environments or areas where single antennas would undergo the effects of path loss and multipath signal degradation, a MIMO system would in theory be able to exploit multipath propagation and improve network coverage. MIMO systems make more efficient use of the available frequency spectrum through effective use of spatial channels. This is especially useful in crowded wireless environments, like urban areas since they would usually be more susceptible to signal interference. One such example of an environment where antenna receivers would be subject to severe performance issues due to multipath effects is indoors, for both 5G service and Wi-Fi [26]. Other technologies, such as global navigation satellite systems (GNSS) and global positioning systems (GPS), require a direct line of sight to the user to function, but with Wi-Fi and cell service systems, and this is often not possible. With MIMO technology and the utilization of digital beamforming, a direct



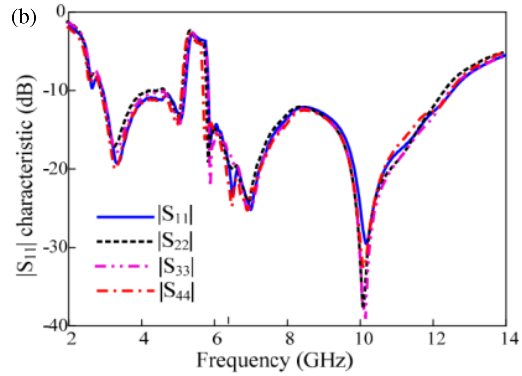


FIGURE 15. (a) Antenna prototype with front and back view. (b) Measured return loss.

line of sight to the signal of interest would potentially not even be required [27]. Another major advantage of this technique is the use of MATLAB simulations to test and optimize the technology based on multiple different environmental scenarios.

5. RESEARCH GAPS AND CHALLENGES

Despite some of the new developments in MIMO technology presented in previous sections, MIMO design still faces significant challenges. When dealing with microstrip array designs, antenna elements get closer together as frequency increases. It leads to increased mutual coupling, which can reduce diversity gain, element isolation, and increase ECC. Some solutions to this issue are parasitic stubs and defected ground structures; however, they are usually band limited and bulky. More wideband and scalable decoupling techniques would be a significant advancement in MIMO technology. While many devices and applications require miniaturized antennas, it usually comes with a tradeoff. Reducing antenna size typically reduces bandwidth, gain, and efficiency, so a compromise must be reached depending on design requirements. There is still a distinct lack of design techniques to balance design compactness with multiband coverage, isolation, and gain.

Flexible and wearable antennas of this nature are a novel concept with a lot of promise; however, as they are a novel concept, they present challenges of their own. The most glaring challenge is the need for lightweight, flexible, and low loss substrates. Substrates with stable permittivity and low loss tangents under stretching/bending conditions are still very limited. While MIMO design is advancing fast, design techniques to achieve the sweet spot that perfectly balances compactness, wide/multi-band operation, high isolation, and real-world reliability are still limited.

6. FUTURE SCOPE

While it is difficult to pinpoint where MIMO technology development will be, say, 10 years from now, certain trends can be observed, and we can make general predictions. The first trend that we can observe is compactness. MIMO designs are becoming increasingly miniaturized. In the future, MIMO systems will rely on compact, integrated layouts. This also goes hand in hand with emerging developments on MIMO applications for wearable technology. Another major development is high element count arrays with high radiation pattern diversity. MIMO arrays will scale up (16, 32, 64 + ports) with high gain and diversity in both polarization and radiation patterns. Pattern-diverse, multi-element MIMO arrays will enable massive MIMO, beamforming, and spatial multiplexing in real-world environments. This development in particular highlights the potential for MIMO to turn multipath effects into an advantage and improve link quality in a communication network. The implementation of metamaterials, artificial surface integration, and simple decoupling structures like stubs, parasitic elements, and defected ground structures will continue to be instrumental in enhancing the performance for MIMO systems, at least until more wideband and scalable decoupling techniques are developed.

7. CONCLUSION

Smart antennas are a powerful tool in modern communication systems. Low-cost DSPs have made these systems more accessible and feasible and have opened the door for these systems to be used more widely in wireless communication systems. The use of these systems can help overcome many of the greatest challenges that modern telecommunications technology faces. It is possible that by increasing channel capacity and reducing signal interference through beam steering, the more efficient use of frequency band can be achieved. Problems like spurious noise in frequency bands can be reduced, simplified, and eventually solved. MIMO technology represents one of the most promising prospects in smart antenna development. Apart from having higher cost since a system with more than one transmitting and receiving element is necessarily more complex, it has all the advantages that other smart antenna systems present and more. Further development and implementation of this technology would result in a more robust telecommunication infrastructure, more reliable signal coverage for commercial use, and a reduction in RFI affecting research frequency bands.

A review on MIMO designs with a broad range of applications is presented in this paper. The comparison of various designs and achievements from different applications presented provides a general sense of what MIMO technology is capable of today and how it will progress in the near future. This includes techniques used to improve performance, such as isolation, gain, wide/multi-band, as well as other novel developments. Prototypes for applications in UWB communications and smart wear have already been developed, and it can be surmised that this technology will see more applications outside the research sector in the coming years.

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