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Original Article

Remotely Controlled Reconfigurable MIMO Antenna for Wireless Communication Applications

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Abstract *- In this paper, a frequency-reconfigurable dual-element MIMO antenna is designed and developed. The antenna is implemented on the modified FR-4 substrate of size 30×50×1.6 mm³. Resonance and stimulus tuning under the sub-6 GHz working frequencies were also improved using the iterative design process in four phases. The first iteration added a second coupler but did not resonate due to the saturation of the ground plane. In later iterations, slot modifications, half-ground structures, parasitic loops, and Defected Ground Structures (DGS) were introduced with the objectives of achieving better impedance matching and overall frequency response. The result for the last version from a staircase ground plane with a T-shaped stub leaded to resonances at the following frequencies: 3.6, 3.9, 4.8, 5.9 and a broadband response among 6.15 and 6.5 GHz, with return losses from - 14 dB to - 33 dB. The proposed antenna features two PIN diodes for frequency reconfigurability and, therefore, has four operating modes. Depending on the states of the diodes, the antenna actively tunes its resonance frequencies to different bands from 3.72 GHz to 6.35 GHz with desirable return losses. All configurations of the antenna exhibit an omnidirectional radiation pattern with a 5 dBi average gain and an efficiency of 75% in broadside directions. These PIN diodes were wirelessly operated using the Node-MCU module, eliminating the manual tuning. Thus, the suggested MIMO antenna can be a good candidate for future wireless communication systems, which also include applications, such as 5G and sub-6 GHz.*

Keywords *- Defected Ground Structures, MIMO antenna, PIN diodes, FR-4, Reconfigurability of frequency.*

1. Introduction

The swift progress of wireless communication technologies has led to a remarkable escalation in demand for high-performance, tunable, and compact antenna systems. One of the most important advances in radio technology that has emerged is Multi-Input Multi-Output (MIMO) antennas, arisen as a fundamental technology that can overcome the challenges of supporting very high data rates, efficient use of the spectrum and improved reliability of the signal. Antenna is designed in many configurations, but the Patch antenna is a low-profile, easy to fabricate, and integrate with modern communication devices. Typical MIMO patch antennas, on the other hand, are often characterized by their limited reconfigurability and static radiation patterns, which limit their suitability for dynamic wireless environments. In order to overcome these challenges, this article proposes a new Remote-Controlled Reconfigurable Dual-Element MIMO Patch Antenna for wireless communication. The design makes use of reconfigurability to tailor performance to varying environmental and operational conditions. Reconfigurable antennas provide frequency, polarization, and pattern agility, distinguishing them from fixed-geometry counterparts; such agility makes them suitable for modern wireless communication systems, including 5G, cognitive radio, and Internet of Things (IoT) applications [1-2].

MIMO (Multiple-Input Multiple-Output) antennas are a key component in the ability to achieve this reconfiguration, contributing to their inherent opportunistic use case in dynamic wireless telecommunications systems. In contrast, static antennas cannot change parameters (e.g., frequency, radiation pattern, polarization) to improve system performance, while reconfigurable antennas can do it live. This is beneficial in the case of MIMO systems, in which several antennas combine efforts to increase data throughput, minimize interference and increase signal robustness. By supporting dynamic spectrum access, reconfigurable MIMO antennas improve the efficiency of spectrum use and allow for continuous operations over a wide range of frequency bands, which is essential in the establishment of new applications like cognitive radio systems and 5G networks. Additionally, you'll notice that these antennas can reduce multipath fading and interference by manipulating the radiation patterns or polarization, resulting in stable and robust communication links. One additional significant advantage of reconfigurable antennas is the removal of excessive hardware; that is, instead of having multiple fixed antennas for different frequency bands or applications, we potentially only need a single reconfigurable antenna, saving on size and the materials required. In addition, these antennas can provide adaptive beamforming; this enables intelligent beam steering able to optimize signal strength in a particular area, without the need to minimise interference [3, 4]. Various techniques have been used to implement reconfigurable antennas, including PIN diodes, varactors, microelectromechanical systems (MEMS), RF switches, liquid crystal substrates, and metamaterials. These characteristics change periodically depending on external control signals, resulting in adjustable operations for antennas. In terms of the parameter that has been reconfigured, reconfigurable MIMO antennas can fall into four major groups: frequency reconfigurable MIMO antennas, pattern reconfigurable MIMO antennas, polarization reconfigurable MIMO antennas, and compound (hybrid) reconfigurable MIMO antennas [5].

The capability of switching between different operating frequencies within a single antenna is termed frequency reconfigurability, which is especially advantageous for multi-band and wideband applications. This could be realized through embedding tunable elements (PIN diodes, varactors, MEMS-based capacitors) or tunable materials (liquid crystals) in an antenna structure to make such an antenna tunable. Cognitive radio networks, multi-band wireless systems (Wi-Fi, 4G, 5G, IoT), and satellite communication widely utilize frequency reconfigurable antennas. On the other hand, pattern reconfigurability allows antennas to dynamically vary their radiation pattern so as to steer signals towards a target location or to avoid interference. Either varying the elements, reflecting them with some electronic device, or using a phased array, etc., to steer the beam depending on your need. These antennas are commonly used in smart antenna systems, adaptive beamforming, interference mitigation, and directional communication in vehicular and aerospace networks [6-7].

Polarization reconfigurable antennas are utilized to achieve multiple orthogonal states (i.e., linear, circular, or elliptical) in order to adapt to different environmental conditions and to mitigate polarization mismatch losses. For reconfigurability, these antennas rely on either changing feeding networks with RF switches or PIN diodes, rotating mechanical elements, or employing reconfigurable metasurfaces. Introduction Polarization is an inherent property of an electromagnetic wave and is critical in engineering and applied physics; it is extensively used in satellite communication, radar systems, and MIMO applications in which polarization diversity is utilized to improve the capacity as well as to mitigate fading of the received signals [1, 2]. There are compound or hybrid reconfigurable designs that involve multiple types of reconfigurability incorporated in a single antenna. The simultaneous multi-domain tunability of these antennas (frequency, radiation pattern, and polarization control) provides more operational flexibility. Hybrid reconfigurable antennas utilize different devices such as PIN diodes, varactors, MEMS, tunable metasurfaces, or liquid-crystal-based substrates in combination, endowing them with high flexibility, which allows their use in scenarios like 6G networks, Reconfigurable Intelligent Surfaces (RIS), military applications or other advanced wireless technologies that require extreme adaptability [8-10].

Reconfigurability is a game changer for MIMO systems, leading to enhanced spatial diversity, spectral efficiency, and interference mitigation. They can be implemented through several methods, which include element switching (on/off) for optimum performance or adaptive beamforming, in which case the phase and amplitude of each MIMO element are tuned according to where the beam is being steered.

Load impedance tuning is available as another approach in which tunable impedance networks are used to provide better isolation and reduce mutual coupling among antenna elements, leading to improved system efficiency. Also, diversity techniques based on patterns provide different radiation patterns for several MIMO elements with the goal of wider coverage and link reliability [11-12].

Especially, reconfigurable MIMO antennas are critical components for 5G and beyond-5G (6G) networks with high flexibility in dynamic spectral ferrying, energy-efficient communications, and reliable connection. As smart, intelligent, and adaptive systems whose components reorganise based on environmental changes, they can enable smart cities, self-driving cars, and IoT ecosystems. These antennas can thereby optimize the performance of communication systems, improve the user experience, and facilitate more advanced communication systems, such as those stipulated in 5G requirements, through advanced reconfiguration techniques [13-14].

This writing would be the new piece of this work, specifically the blasting of one remote control structure for the genuine time reconfiguration components on the receiving framework. Your physical access to the device is therefore unnecessary, thanks to both mechanical and conductive tuning and reconfiguration options, which enable dynamic tuning of critical parameters (i.e., operating frequency, radiation pattern, and polarization state) without requiring physical access. It employs electronically tunable switching elements (PIN diodes/varactors) to vary the properties of the antennas according to external control signals. This enables a 2-element MIMO configuration to provide spatial diversity that increases destination performance robustness for use in multipath-rich channels while being compact and maintaining good element-to-element isolation.

Enhanced spectral efficiency, data rates, and link reliability have resulted in the advancement of wireless communication technologies and the development of MIMO (Multiple-Input, Multiple-Output) antennas. Conventional MIMO systems exhibit a rigid structure that prevents them from adapting to dynamically changing environments. Reconfigurable MIMO antennas have been an area of significant research in attempts to address these issues. Antennas can be tunable for frequency, radiation pattern, and polarization. 1 Related Work This section reviews the state of the art in reconfigurable MIMO patch antennas, including the various types of reconfiguration, their control methods and their integration into current wireless communication systems. A frequency reconfigurable MIMO antenna that switches frequency using varactor diodes within the microstrip feedline is proposed in [15]. The design is aimed at wireless hand-held devices and multiband MIMO applications. The antenna covers the frequency range of 1.3-2.6 GHz. The work [16]describes a back-to-back microstrip patch antenna that can take different shapes using PIN diodes. It is simulated at 2.45 GHz with a 180 ° beam switching, which is suitable for beam steering operation in wireless communication systems. Another work [17] presents a frequency-reconfigurable microstrip antenna of compact size by employing PIN diodes to switch back and forth between different frequency bands. Practical results are presented, demonstrating the excellent performance of the proposed antenna.

In [18], a polarization reconfigurable antenna using a PIN diode is reported to switch between linear and circular polarizations. The design, operating at 2.45 GHz, is also particularly suitable for WLAN systems, in which flexibility of the polarization diversity is desired for better signal integrity and dependability under complicated conditions. Another paper [8] introduces a planar reconfigurable antenna, by using PIN diodes to control a new radiation direction, with a frequency is 2.45 GHz. The antenna enables beam steering and is capable of enhancing coverage while minimizing interference for Wi-Fi networks. In [19], a frequency reconfigurable antenna for over the full UWB range is designed by the use of varactor diodes for continuous tuning in the 2.5-4.5 GHz ISM frequency band.

The proposed antenna operating on a low-loss Rogers substrate shows high efficiency and resonant frequency tunability. Its structure is suitable for cognitive radio and multi-band communications. In [20], a compact antenna on a Taconic substrate is presented to achieve frequency reconfigurability using PIN diode switching. The antenna is triband in nature and intended for WiMAX and WLAN applications. Its small size and selective band control enhance spectrum flexibility in modern networks. This antenna [21] facilitates band switching between the ISM and the higher frequency bands in conjunction with the PIN diodes. The FR 4-based platform provides inexpensive realization and reconfigurable frequency operation. It is a good choice for industrial, scientific and medical communication applications.

Hybrid antenna [22] also combines PIN and varactor diodes to realise the frequency reconfigurability in a broad range of 0.9-2.6 GHz. It works with most of the worldwide 5G sub-6 GHz bands, providing flexibility in a range of environments. Fine and coarse tuning are easily adjusted using the dual-diode design. To overcome the above problem, a polarization reconfigurable antenna with the use of PIN diodes [23] is utilized for ISM and GSM bands. Based on Rogers RT5880, and provides high radiation efficiency and low dielectric loss. The antenna can switch between linear and circular polarizations, enhancing signal robustness in wireless systems.

Most recent works have reported the design and development of reconfigurable MIMO antennas, where the switching elements need to be tuned manually, making it challenging to operate in remote locations. In this work, a complete design and analysis of a frequency-reconfigurable MIMO antenna is presented, where the switching elements (PIN diodes) can be tuned wirelessly using a Node MCU module. This study can enable such infrastructures as MIMO patch antennas that can be reconfigured remotely, and it can make significant contributions to the formation of an intelligent world system in which wearable devices, sensor networks, social networks, and the Internet of Things (IoT) coexist and can share data. The paper is structured as follows: Part II elaborates on the design methodology and working principles of the proposed reconfigurable dual-element MIMO patch antenna. In Section III, we provide the simulation setup and parametric analysis. Performance evaluation and significant results are discussed in Section IV. Finally, Section V delivers the conclusions of this paper and directions for future research.

2. Antenna Design

As illustrated in Figure 1, in iteration 1, a square-shaped patch was tilted 45 degrees around the Z-axis and fed at the bottom corner using the microstrip feed line mechanism. This formed a rhombus-shaped patch with a fully grounded structure. This model resonates frequencies under sub-6 GHz with a lower of -7db return loss. Hence, iteration 2 was performed for better resonating characteristics.

In iteration 2, a rhombus-shaped portion was removed from the inner side of the radiating element, and to change surface current paths, two 2 mm-wide vertical rectangular slots were tilted at 45° and opened on the left and right sides of the grounded rhombus patch. The half-ground structure was introduced in the ground plane as shown in Fig. 1b. This model's resonance frequencies are low because of the small radiating patch. However, this model did not yield satisfactory S-parameter results.

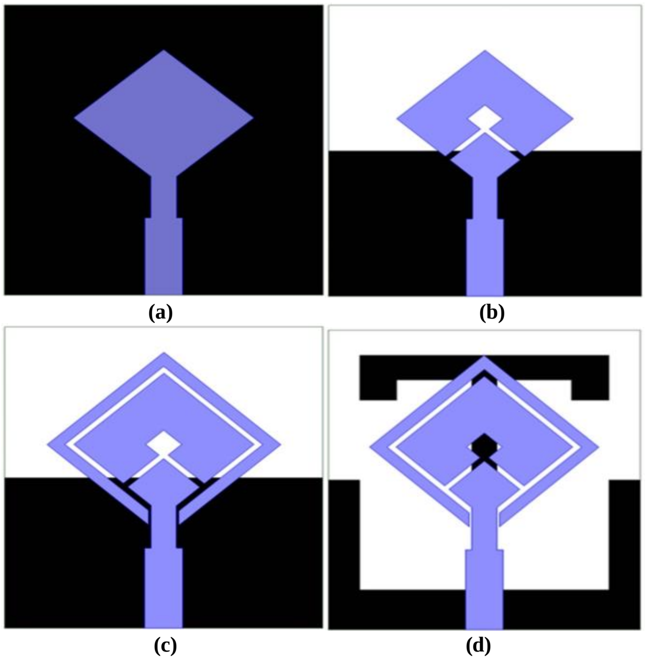


Fig. 1 Illustration of the iterations of the proposed SISO model (a) step-1, (b) Step-2, (c) step-3, (d) step-4.

In iteration 3, depicting a parasitic loop of width 1.5 mm that is introduced surrounding the patch antenna (Figure 1c). This loop helps distribute surface current more uniformly. The distance between the parasitic loop and the inner rhombus-type structure, G1, defines the electromagnetic coupling, and it can be used to optimize it. The design works in a frequency range of 2.5–7.5 GHz with <-5 dB return loss . It was done for further adjustment of the surface currents and to promote resonance at a lower frequency range (iteration 4).

On the ground plane itself, a T-shaped stub is added to the center of it in iteration 4, as shown in Figure 1d. As an additional introduction, a Defected Ground Structure (DGS) is obtained, in which some areas of the ground are removed. The previous iterations of this design did not have a good resonating sub-6 GHz frequency with better reflection coefficient values of -12 dB compared to previous iterations. Hence, the iteration-4 is modified to act as a dual-element MIMO Antenna.

3. The MIMO Antenna Design

By extending the SISO antenna, the MIMO antenna can be designed. While the figures visualize the iterations of a dual-element MIMO antenna. 2. The final specifications of the adapted FR 4 substrate will be 30×50×1.6 mm^3. As shown in Figure 2, the patch antenna design is developed by placing an additional similar radiation element in parallel to the performance of a single-element antenna. 2a relative to the entire ground structure. However, as seen in Figure 3, due to the extensive ground structure, this model does not operate well under sub-6 GHz frequencies.

Use this form of a thin vertical rectangular slot of 2 mm and 1 mm that will be tilted by 45 degrees as an opening at the right edge and the left edges at the bottom of the rhombus-shaped patch in Iteration 2. It modified the ground structure and patch design. A half-ground structure was then proposed with three stubs placed in the middle as well as at the ends of the ground. However, this model was found to have an inefficient return loss of -7.9 dB and a resonant frequency of 4.3 GHz.

In iteration 3, a further parasitic loop was integrated on the opposite side of the patch, along with the modified ground structures, based on iteration 2. The new design operates better than the previous design at 3.72 and 5 GHz with return losses of -13 dB and -7 dB, respectively. The fourth iteration provides the opportunity to further analyze the potential impacts of the Defected Ground Structure (DGS).

At antenna iteration number 4, the transformation of the ground plan was fully dissolved to shape a 3D staircase form on the core ground plane. They planted a cross (T-shaped) at the center. These changes influenced the direction of the surface currents, leading to the resonance at 3.6, 3.9, 4.8, and 5.9 GHz and broadband ranges from 6.15 to 6.5 GHz with return losses of -33, -28, -15.5, -22, and -12 dB, respectively. The overall dimensions of the MIMO antenna are represented in mm as shown in Figure 4 above where G1 = 25, G2 = 9, G3 = 13, G4 = 10, G5 = 4, G6 = 6, G7 = 11, G8 = 2, G9 = 4, G10 = 4, G11 = 25, G12 = 2, H1 = 30, H2 = 2, H3 = 8, H4 = 20, and H5 = 14.

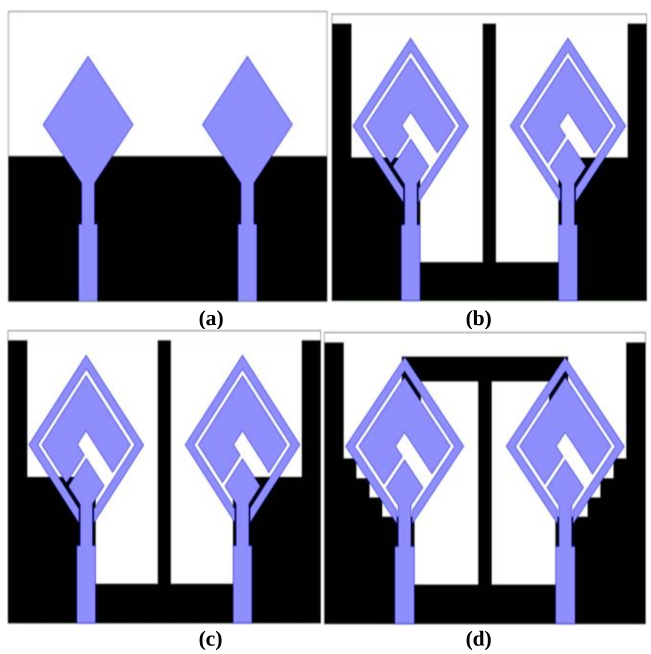


Fig. 2 Iterations of the propounded MIMO model (a) stage-1, (b) stage-2, (c) stage-3, (d) stage-4.

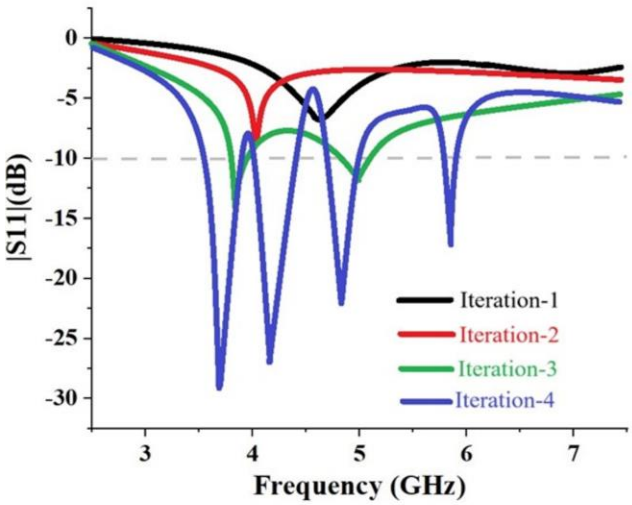


Fig. 3 |S11| Iterations of the proposed MIMO

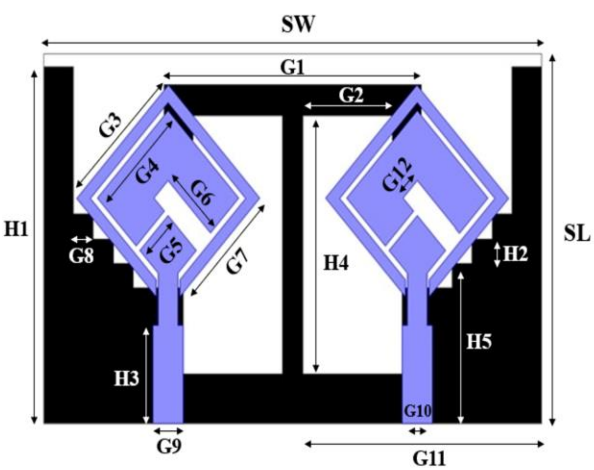
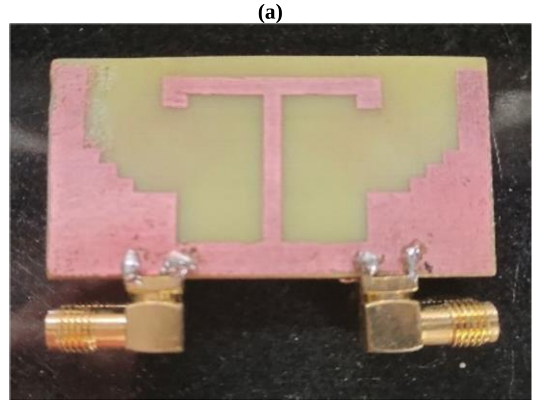


Fig. 4 Dimensions of the proposed MIMO

4. Remotely Controlled Reconfigurability

The frequency reconfigurability of the proposed MIMO antenna is obtained by combining two PIN diodes with the gaps forming between the rhombus patch elements of the proposed antenna, resulting in four different operating modes. As given in the Table 1. The antenna resonates at 3.72, 3.8, 4.9, and 6.15 GHz with return losses of -33, -28.5, -17, and -23 dB when both diodes (D1 and D2) are in the OFF state. When both diodes have the ON state, the working frequencies will be transferred to 5.2 and 6.35 GHz with return losses of -18 and -13 dB, individually. As shown in (b), when setting D1 to be ON and D2 to be OFF, the antenna can achieve coverage of every frequency point for 3.73, 3.8–4.5, 4.9, and 6.15 GHz. Likewise, in the case of D1 OFF and D2 ON, the antenna resonates at a frequency of 3.72 GHz with a reflection coefficient of -13 dB. With this configuration, dynamic frequency tuning is available and makes the antenna suitable for wireless communications in general. Figure 5 shows the fabricated prototype.

(a)



(b)

Fig. 5 Proposed antennas prototype model (a) Front view (b) Back view.

Table 1. The reconfigurable states of the proposed antenna

Configuration	Diode 1	Diode 2	Operating frequency (GHZ)
A1	OFF	OFF	3.72, 3.8, 4.9, 6.15
A2	ON	OFF	3.73, 3.8-4.5, 4.9, 6.15
A3	OFF	ON	3.72
A4	ON	ON	5.2, 6.35

Combining IoT technology with MIMO antennas, especially through the use of pin diodes for adjusting frequencies, provides an innovative solution for optimizing wireless communication systems. PIN diodes are semiconductor devices known for their variable capacitance, which can be controlled by adjusting the bias voltage across them. By integrating IoT, MIMO antennas with pin diodes can be managed and monitored remotely, allowing for dynamic frequency adjustments to meet changing communication needs and environmental factors. This remote management capability enables real-time optimization of antenna performance, ensuring efficient use of available spectrum resources and minimizing interference.

Furthermore, IoT-driven frequency adjustment enhances the adaptability of MIMO antennas to support various communication standards and frequency bands, addressing the evolving requirements of wireless networks. Additionally, IoT integration enables intelligent decision-making based on data analysis, empowering antennas to anticipate and respond proactively to changes in channel conditions or user needs. Through the utilization of pin diodes for frequency adjustments within an IoT framework, MIMO antennas can achieve improved reliability, throughput, and spectral efficiency in wireless communication, leading to enhanced network capacity and user experience.

Node MCU is a popular open-source firmware and development board grounded on the ESP8266 Wi-Fi module. It is used for structure IoT (Internet of Things) systems, especially those that require wireless communication. The Node MCU board has built-in Wi-Fi connectivity, which allows it to communicate with other devices over a network or the internet. It also has an important microcontroller that can be programmed using Arduino IDE. In the proposed system, the NodeMCU module is used to wirelessly control the switching state of PIN diodes integrated into the MIMO antenna design for frequency reconfiguration. The GPIO pins of the NodeMCU are interfaced with the biasing circuitry of the PIN diodes. The NodeMCU receives wireless control commands via Wi-Fi and accordingly toggles the GPIO outputs to switch the PIN diodes ON or OFF, thereby altering the effective electrical length or geometry of the antenna elements. This dynamic control enables the antenna to operate at different resonant frequencies without any manual intervention. The entire setup is powered through a regulated DC supply or USB, and the firmware running on the NodeMCU processes the control logic and communication protocol, such as HTTP, for remote operation.

As seen in Figure 6, the proposed antenna's PIN diodes are connected to the node MCU to operate them wirelessly anywhere.

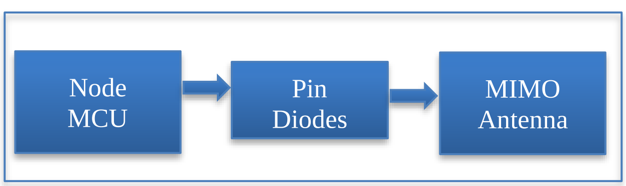


Fig. 6 Illustration of IOT controlled reconfigurable antenna

4.1. Reflection Coefficient

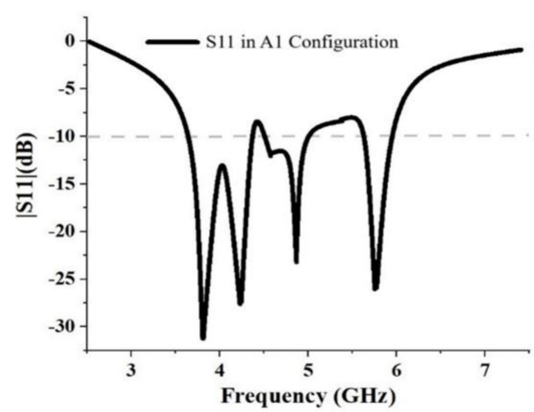
S11, also referred to as the reflection coefficient, is an important parameter in the characterization of MIMO (Multiple Input, Multiple Output) antennas. It indicates the ratio between the incident electromagnetic energy and the energy reflected back from the antenna. MIMO systems utilize multiple antennas for both transmission and reception, and therefore, understanding the S11 characteristics is key to making sure that signals propagate correctly. The S11 parameter is generally correlated and analyzed at different frequencies across the entire operating bandwidth of the antenna. An S11 value that is small means that the antenna is well matched to the transmission line or feeding network and minimizes signal reflection and maximizes power transfer.

Mutual coupling between elements of an array antenna in an MIMO system can degrade the performance, including impedance matching, radiation efficiency, and diversity gain. A number of design techniques are adopted in the design of the proposed frequency-reconfigurable MIMO antenna to achieve low mutual coupling and high isolation between elements. The antenna elements are spaced optimally greater than 0.5λ at the lowest operating frequency to minimize near-field interactions.

A Defected Ground Structure (DGS) is designed to disturb the surface current. Additionally, isolation is further enhanced using decoupling techniques such as parasitic stubs placed between antenna elements to redirect and cancel coupled energy. The use of PIN diodes for frequency reconfiguration not only provides dynamic tuning capability but also reduces active coupling by selectively engaging frequency bands.

As seen in Figure 7, the measured S11 of all four configurations of the proposed antenna was taken inside the anechoic chamber, and it was confirmed that at four different frequencies, the antenna was operating in accordance with the states of the PIN diodes.

Toggle navigation For both diodes in the OFF state (A1: OFF, OFF), the antenna functions at 3.72, 3.8, 4.9 and 6.15 GHz. With A2 (ON, OFF), it has a wider range, covering 3.73 GHz, a continuous band from 3.8 to 4.5, 4.9, and 6.15 GHz. The antenna functions only at 3.72 GHz in the A3 (OFF, ON) state. Finally, when both diodes are switched ON (A4: ON, ON), the resonance is pulled to 5.2 and 6.35 GHz. This fine-tuning ability adds to the versatility of the antenna in various wireless contexts.



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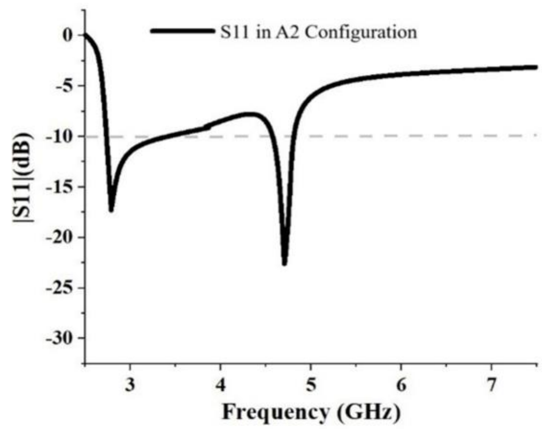

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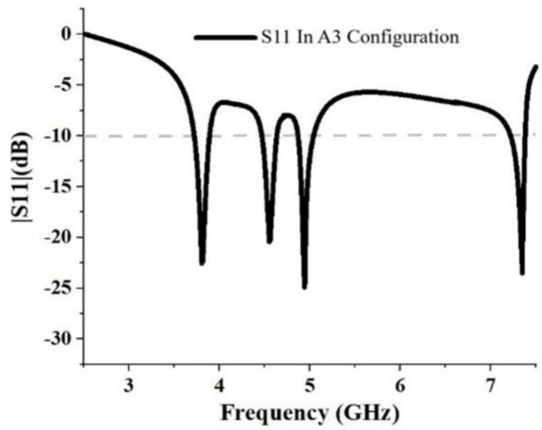

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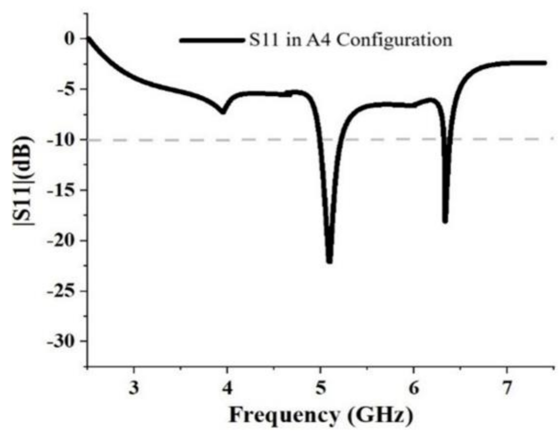
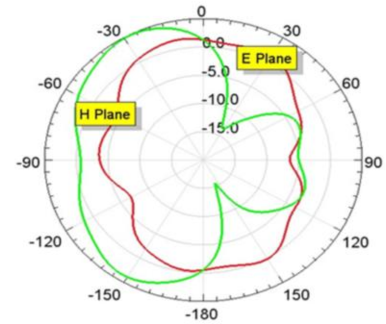


(d)

Fig. 7 |S11| measurement plot in all four states (a) A1, (b) A2, (c) A3, and (d) A4 configuration



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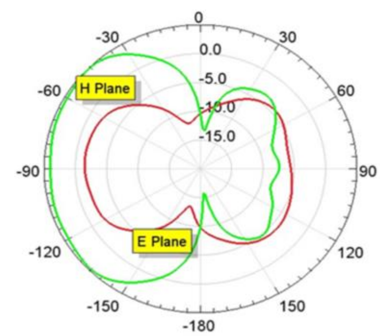

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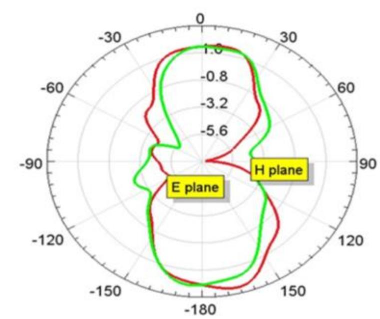

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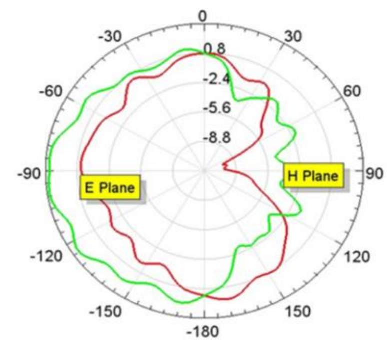
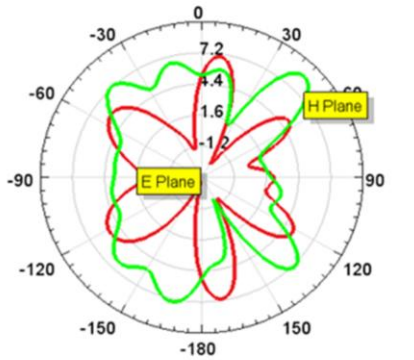


(d)

Fig. 8 Radiation plot in A1 configuration.

4.2. Radiation Pattern

Formed E and H forms of the propounded antenna were obtained in all four geometrically distinct configurations as shown in Figures 8-11. The antenna in all arrangements demonstrated a well-defined and well-behaved radiation pattern, which retained its omnidirectional property across its region of operation, allowing it to be utilized for smooth wireless communication applications.



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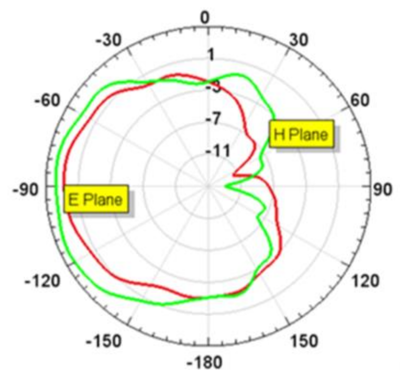
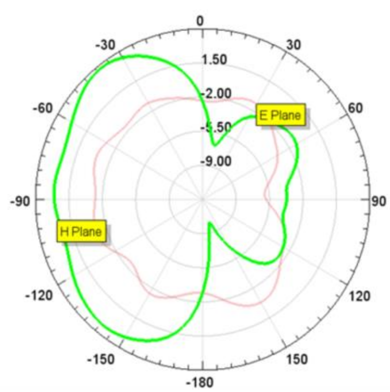


(b)

Fig. 9 Radiation plot in A2 configuration.



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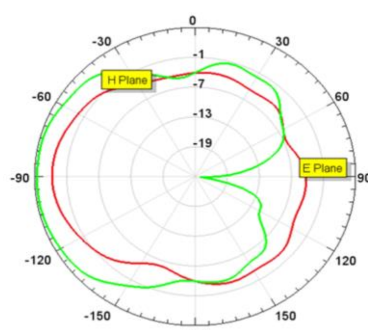

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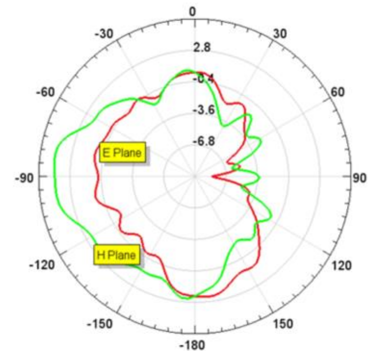
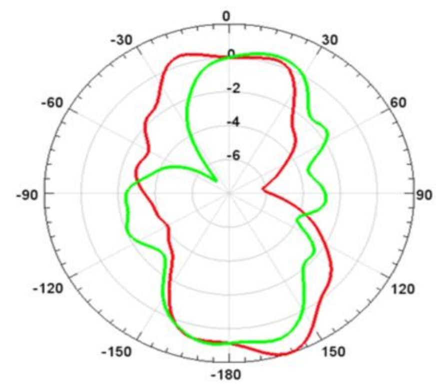
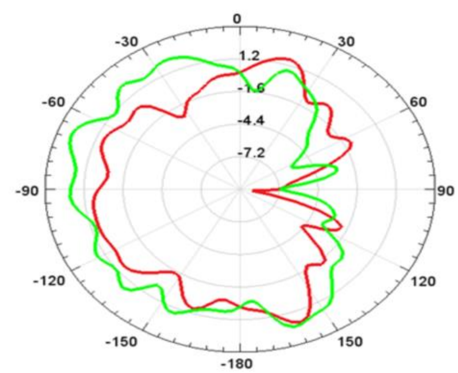


(c)

Fig. 10 Radiation plot in A3 configuration.



(a)



(b)

Fig. 11 Radiation plot in A4 configuration.

4.3. Gain

Gain is an indicator of the antenna's ability to radiate Radio Frequency (RF) power from an antenna in a confined direction. Put simply, how well an antenna transmits/receives signals in a specific direction. Afforded by the antenna with positive gain is increased efficiency compared to an isotropic radiator in that direction. Similar trends are observed in all four configurations, as depicted in Figure 12. With a measured gain of around 5 dBi across all operating frequencies, the proposed antenna was able to achieve that [12]. It demonstrates the efficiency and reliability of the proposed model's applicability in various wireless communication applications.

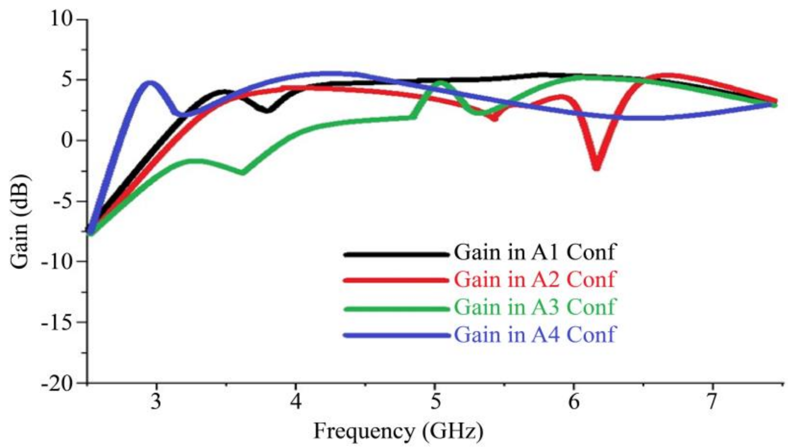


Fig. 12 Measured gain plots in all 4 configurations

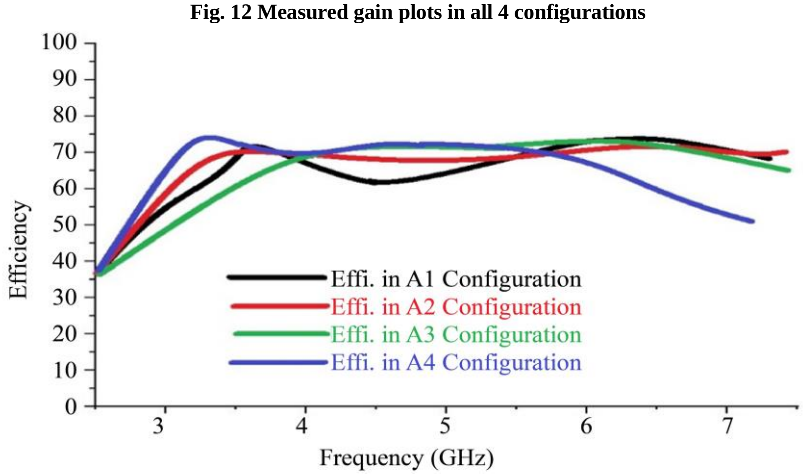


Fig. 13 Measured efficiency plots in all 4 configurations

4.4. Efficiency

Efficiency in MIMO (Multiple Input, Multiple Output) antennas is the fastest-growing parameter that determines how well the antenna system transforms the input power into useful radiated power level. (c) This is a crucially significant performance metric that refers to the proportion of power that is radiated to the total power that is delivered to the input of the antenna. Higher efficiency implies that a smaller chunk of the input power is not lost and is instead useful for the transmission of the actual electromagnetics. Antenna efficiency depends on numerous factors, such as antenna design, material used, impedance matching, and radiation pattern. MIMO systems are used extensively in various applications and environments, making antenna efficiency optimization essential for maximizing signal transmission range, minimizing power consumption, and ensuring robust wireless communication. Greater system performance and data throughput, and overall system reliability are achieved with comprehensive MIMO antennas. All four configurations exhibited around 75% measured efficiency at all operational frequencies, which can be seen in Figure 13. Having the performance there all the time suggests that the suggested method truly is productive and dependable and fit for brewing remote correspondence applications.

4.5. Surface Current Density

Mutual coupling refers to the unwanted electromagnetic coupling of near components, causing distortion, interference, or crosstalk. This is solved by employing various techniques like Defective Ground Structure (DGS), etc. As a practical design, we can employ DGS structures and place a T-shaped structure between two antennas and get a better mutual coupling reduction, as shown in Figure 14. The proposed antenna is compared with the literature and presented in Table 2.

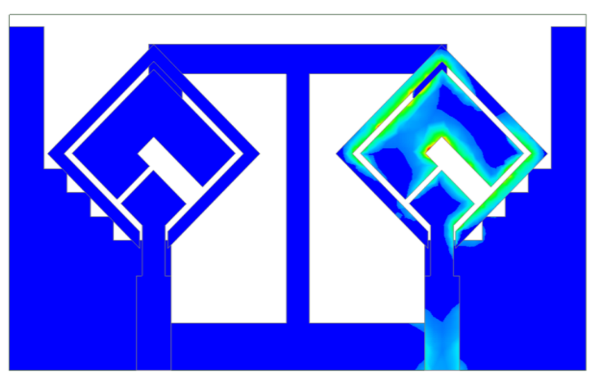


Fig. 14 Surface currents distribution plot of the proposed antenna

Table 2. The proposed antenna is compared with the literature

Ref.no	substrate	Antenna Size(mm^2)	Reconfigurability	Switching element	Operating frequency	Operating Bands	Wireless operation using IOT
15	FR4	120 × 60	Frequency reconfigurable	Varactor diodes	1.3 to 2.6 GHz	WiMAX, LTE	No
16	FR4	98 × 60	Pattern reconfigurable	Pin diodes	2.45 GHz	Wi-fi	No
17	FR4	44 × 44	Frequency reconfigurable	Pin diodes	3.5 GHz and 2.6 GHz	LTE and	No
18	Taconic RF35	90 × 90	Polarization reconfigurable	PIN diodes	2.45GHz	WLAN	No
19	FR4	120 × 60	Pattern reconfigurable	Pin Diodes	2.45 GHz	Wi-fi	No
20	Roger	40 × 100	Frequency reconfigurable	varactor diodes	2.5 – 4.5 GHz	WLAN, WiMAX	No
21	Taconic	13 × 50	Frequency reconfigurable	Pin Diodes	3.963 GHz, 3.074 GHz and 2.95 GHz	WiMAX, WLAN	No
22	FR4	75 × 150	Frequency reconfigurable	Pin Diodes	2.4-2.8 GHz to 3-4 GHz	ISM	No
23	FR4	60 × 120	Frequency reconfigurable	Pin Diodes & varactor diode	0.9 to 2.6 GHz	5G	No
24	Rogers RT5880	80 × 140	Polarization reconfigurable	Pin Diodes	2.3 to 2.6 GHz	ISM, GSM	No
Present model	FR4	30 × 50	Frequency reconfigurable	Pin Diodes	3.72 / 3.73 GHz, 3.8–4.5 GHz, 4.9 GHz, 5.9 GHz and a broadband Response between 6.15 GHz and 6.5 GHz	WiMAX, 5G NR (n77/n78), 5G NR, Wi-Fi (U-NII-1), Wi-Fi 6E/7, 6 GHz Unlicensed	YES

5. Conclusion

In this proposed work, a frequency-reconfigurable dual-element MIMO antenna was successfully implemented and optimized for sub-6 GHz applications. The iterative design method led to a significant improvement in both impedance matching as well as resonating properties as the shape of the ground structure, patch geometry and addition of parasitic elements were modified. Real-time frequency tuning was conducted using PIN diodes in order to achieve four-use modes, and antenna capacity for various types of wireless communications was enhanced. The NodeMCU module was also deployed to facilitate remote reconfigurability for controlling antennas' operating frequencies over wireless communication. This function expands the range of applications of the antenna and benefits real-time adaptation applications such as cognitive radio and intelligent wireless networks. It achieved 75% in all setups while not giving up omnidirectional characteristics with 5 dBi average gain uniformly distributed over the number of antennae. The wireless operation of the switching mechanism enables dynamic tuning of the antenna, allowing it to operate efficiently across multiple frequency bands and support multifunctional wireless applications of WiMAX, 5G NR (n77/n78), 5G NR, Wi-Fi (U-NII-1), Wi-Fi 6E/7, 6 GHz Unlicensed.

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