

EQUIVALENT CIRCUIT OF A FREQUENCY RECONFIGURABLE METAMATERIAL MIMO ANTENNA FOR INTERNET OF THINGS APPLICATIONS

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ABSTRACT

This study introduces a metamaterial MIMO antenna design that offers frequency reconfigurability. The antenna is intended for Internet of Things (IoT) applications. It is simulated using an FR4 substrate with dimensions of 1.6mm thickness and 0.025 loss tangent. Based on the proposed design, the MTM MIMO antenna can operate at 2.5GHz & 2.54GHz (WLAN), 4.2GHz, 6.6GHz, 6.64GHz & 7.8GHz (C-Band), and 9.6GHz & 9.7GHz (X-Band). To accomplish this, Two PIN diodes are connected to each gap capacitance of the MTM antenna. The performance enhancement of the reconfigurable MTM MIMO antenna was achieved using a CST microwave solver. The system performance was validated using ADS. Furthermore, the diversity metric conducted on the proposed MTM MIMO antenna revealed that the antenna has a low correlation coefficient (<0.03), total active reflection coefficient ($<0\text{dB}$), and channel capacity loss of ($<0.4\text{bits/sec/Hz}$). The simulated isolation of $<-20\text{dB}$ is noticed for all four states. The antenna peak gain is 3.1 dBi. An MTM MIMO antenna with these characteristics suits many IOT communication systems.

Keywords: Metamaterials, positive intrinsic negative diode, equivalent circuit, multiple-input-multiple-output

1 INTRODUCTION

Internet of things (IoT) refers to a global network of billions of physical objects that gather and transmit information without requiring human-to-human and human-to-computer interactions. There are several fields where IoT is being implemented, including smart homes, medical healthcare facilities, transportation, smart buildings, manufacturing, smart agriculture, and automation, which allows for quick decision-making based on real-time data analysis [1]. IoT applications share the spectrum with Bluetooth and Wi-Fi at 2.4GHz and 5GHz and occupy multiple frequency bands, including 2.6GHz and 3.5GHz [2]. As IoT evolves, reconfigurable antenna hardware has become a desirable option for multiband support. Besides modulating and adjusting the radiation pattern, the polarization, and the frequency of operation of an antenna, they can also change the antenna's shape and size. To provide network

connectivity to this vast number of devices, antennas must be designed to work with IoT applications [7]. The MIMO technique is characterized by multiple antennas on both sides [8]. It is the purpose of the MIMO system to integrate sampled signals in the spatial terrain at both terminals to boost data rate, improve communication quality, and produce concrete multiple parallel spatial information [9]. Adding a non-correlated antenna element will increase the signal-to-noise ratio (SNR) by concentrating the energy in the desired direction; this is called beamforming in the presence of random fading caused by multipath propagation. This is what space diversity is all about. A metamaterial can be thought of as a collection of tiny artificial cells or elements (e.g., scatters or pylons) that are arranged in a uniform pattern across an area of space to achieve desired macroscopic electromagnetic properties that would be hard to achieve with natural materials [10, 11, 12]. MTM antennas play a crucial role in IOT by facilitating the transmission and reception of data between IOT devices. To be effective, IOT antennas must be small, low-cost, and operate efficiently in crowded frequency spectra. Therefore, they must be smart with frequency reconfigurable capabilities. This can be achieved by using a metamaterial to improve the performance of the IOT devices [13]. Reconfiguration techniques include optical techniques [14], mechanical techniques [15], varactor diodes [16], PIN diodes [17], and radio frequency microelectromechanical systems [18]. The narrow open slot LTE MIMO antenna reported in [19] is capable of multiband operation at the lower band of GSM and LTE. The antenna has the disadvantage of low isolation and efficiency. According to [20], parasitic ground structures can be switched over four frequencies using PIN diodes, but the antenna is complex in design. [21] presents a multimode frequency reconfigurable MIMO antenna for sensing and reconfigurable communication modes. Despite its functionality, the antenna has a lower gain of 2.6 dBi and is not compact. A compact reconfigurable MIMO antenna presented in [22] is designed for WLAN and WiMAX band microwave sensing. Employing four PIN diodes for reconfiguration, the antenna has a multiband frequency response yet faces limitations regarding gain and bandwidth. In [23], a reconfigurable MIMO antenna for WLAN and UWB applications has been reported. The gain is relatively high, but the isolation is low. In this study, we propose a 2-MTM MIMO Antenna for IoT Applications. PIN Diodes are utilized to reconfigure different frequency responses. Equivalent circuit model analysis is introduced for more validation of the process. In the rest of the letter, four sections are presented. Section 2 explores the MTM MIMO antenna design process, the suggested geometry, unit cell geometry and equivalent circuit model analysis. In section 3, the simulated results are presented. Section 4 covered the MTM MIMO antenna diversity metrics and a comparison of the suggested antenna with the most recent literature. Section 5 concludes with final remarks.

2 METAMATERIAL MIMO RECONFIGURABLE ANTENNA DESIGN METHODOLOGY

2.1 MTM MIMO Antenna Configuration

The proposed geometry of a frequency-reconfigurable MIMO system is depicted in Figure 1. The W_1 is used to excite the antenna unit cell, which produces multiband characteristics. Two gap capacitances are coupled to unit cell metamaterial via PIN diodes D_1 and D_2 for tuning capability. By modifying the distance and location of the feedline, the proposed antenna is matched to a 50Ω feedline. The MTM MIMO antenna is etched onto the top side of an FR4 substrate with a thickness of 1.6mm, a relative permittivity of 4.3, and a loss tangent 0.025. The optimization and validation of the antenna's performance was carried out using both computer simulation technology (CST) and advanced design systems (ADS). Table 1 displays the optimal parameters of the suggested antenna.

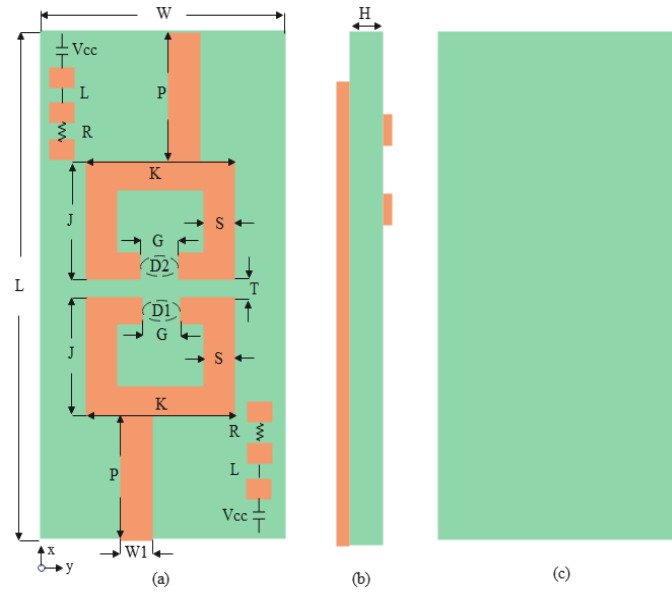


Figure 1. The proposed reconfigurable MTM MIMO antenna's geometry (a) Front view, (b) side view, (c) Back view

Table 1. Dimension of the reconfigurable MTM MIMO antenna

Variables	Size (mm)	Variables	Size (mm)
G	1	P	18
H	1.6	S	2.8
J	14	T	4
K	10	W	20
L	60	W ₁	3.1

2.2 Evolution Steps

The procedures that need to be followed to complete the development of the MTM MIMO antenna are depicted in Figure 2(a). The MTM MIMO antenna was designed to operate in the 1 to 10 GHz frequency range. The S_{11} response of antenna I is not good, as shown in Figure 2(b), due to the port's position. The S_{11} response experiences a further enhancement in multiband characteristics when the position of the feedline has been shifted sideways. The proposed antenna's third step involved adding another element and proper shift of the feeding port. This new arrangement enhances the antenna's capability in terms of matching. To achieve reconfigurable architecture, two PIN diodes are linked to the gap capacitance of each radiator, which can be toggled between "ON" and "OFF" states. A parametric analysis has been carried out for the gap capacitance and position of the feeding port. As depicted in Figure 2(c), a value of 1mm has been chosen for the proposed work. Figure 2(d) shows the various positions of the port concerning S_{11} . A position at 4.2mm is also taken for the proposed MTM MIMO antenna.

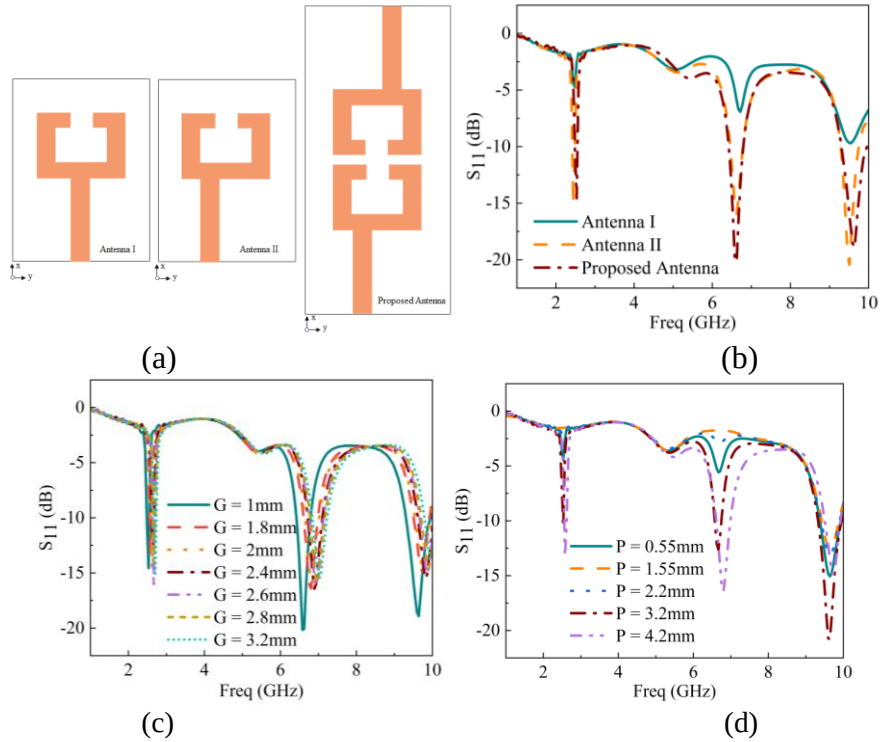


Figure 2. (a) Evolution stages of suggested MTM MIMO antenna, (b) S_{11} response of the various stages, (c) Various distances of the gap capacitance, (d) Position of the feeding port

2.3 Equivalent Circuit Model Analysis

(i) *Equivalent Circuit for Case-00 (off state)*: The model parameters are refined using the gradient optimization technique, keeping each component's values between the designated minimum and maximum ranges [24]. As seen in Figure 3, the equivalent circuit of the suggested MTM MIMO antenna was optimized while it was in its off state using the ADS software. The model consists of connections between the feedline's first parallel LC circuit and an inductor on the left-hand side representing the first port, followed by two cascaded LC circuits with a second inductor for the second port. Two inductors, L3 and L4, in series with two parallel shunt capacitors 0.15pF that represent the two diodes in their off states. A capacitor C3 is between the two parallel LC circuits as the gap capacitor between the two MIMOs. The graphical representation of the S_{11} is illustrated in Figure 4, showcasing a comparison with the full wave CST model, which enables a multiband frequency response of 2.5GHz, 6.6GHz, and 9.6GHz, respectively. The optimized circuit components are given in Table 2.

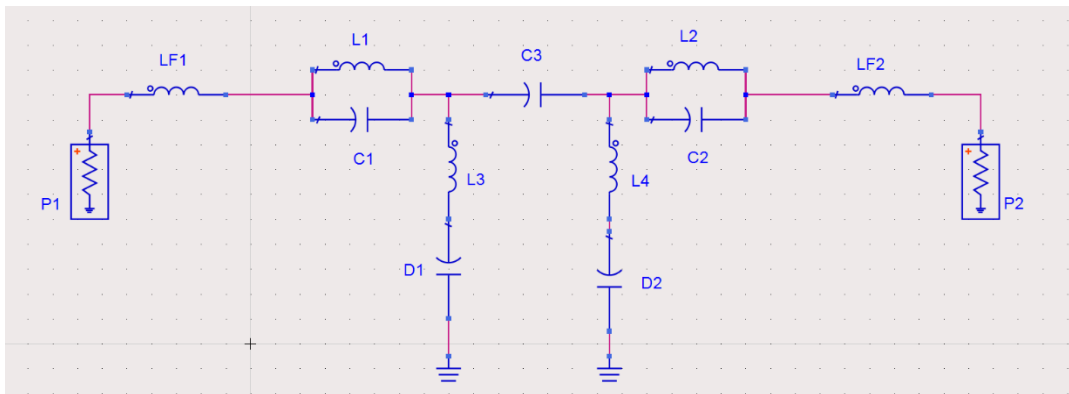


Figure 3. Equivalent circuit model for case-00 (off-state)

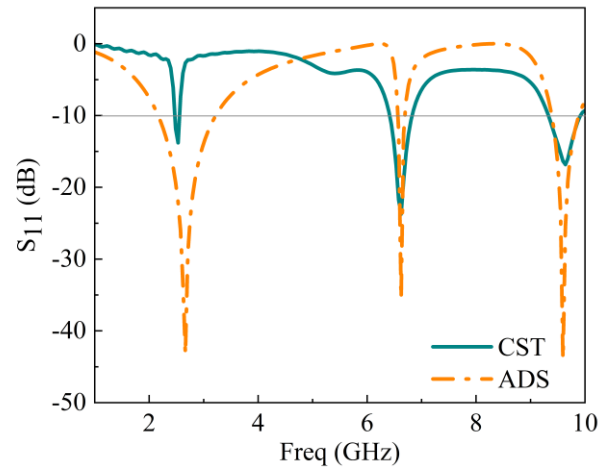


Figure 4. Circuit model S_{11} for case-00 (off state)

Table 2. Components used in case-00 (off-state)

$C_1 = 1.1433\text{pF}$	$D_2 = 0.15\text{pF}$	$L_4 = 0.6\text{nH}$
$C_2 = 470.95\text{fF}$	$L_1 = 2.0658\text{nH}$	$L_{F1} = 569.29\text{pH}$
$C_3 = 0.7626\text{pF}$	$L_2 = 1.0947\text{nH}$	$L_{F2} = 772.87\text{pH}$
$D_1 = 0.15\text{pF}$	$L_3 = 0.6\text{nH}$	-

(ii) *Equivalent Circuit for Case-01 (on the state)*: A similar analysis was performed for a proposed configurable MTM MIMO antenna. The diode is activated, and the two shunt capacitors are replaced with two 4.5Ω resistors. The value of the circuit parameters is re-optimized to produce a different dual-band frequency response of 7.8GHz and 9.6GHz. The circuit configuration and its corresponding S_{11} spectra are depicted in Figures 5 and 6, respectively. The refined parameter values of the circuit components are listed in Table 3.

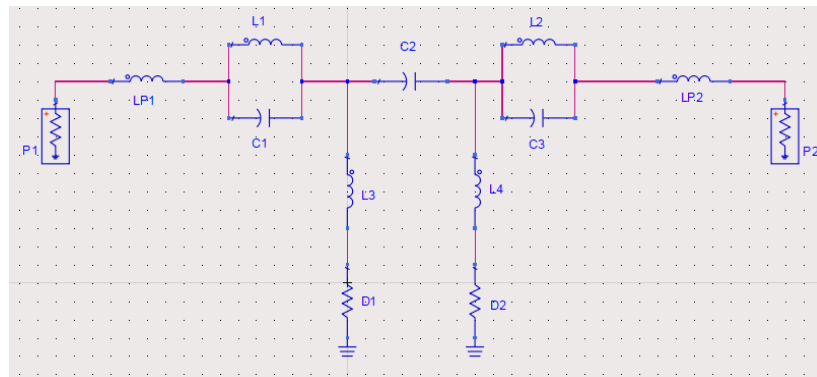


Figure 5. Equivalent circuit model for case-01 (on the state)

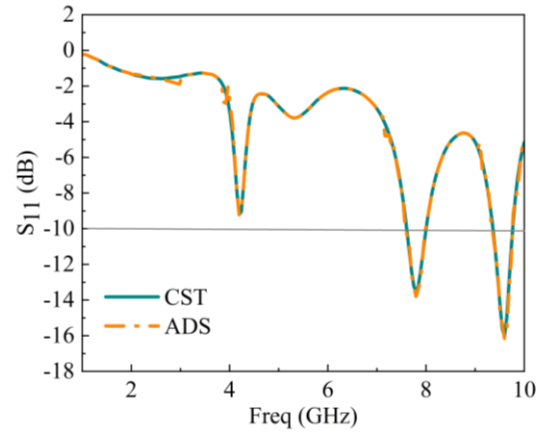


Figure 6. Circuit model S_{11} for case-01 (on state)

Table 3. Components used in case-01 (on state)

$C_1 = 1.8389\text{pF}$	$D_2 = 4.5\Omega$	$L_4 = 0.6\text{nH}$
$C_2 = 466.76\text{fF}$	$L_1 = 479.14\text{pH}$	$L_{P1} = 1.3404\text{nH}$
$C_3 = 2.9175\text{pF}$	$L_2 = 105.89\text{pH}$	$L_{P2} = 276.96\text{pH}$
$D_1 = 4.5\Omega$	$L_3 = 0.6\text{nH}$	-

(iii) *Equivalent Circuit for Case-02 (on, off state)*: Further optimization processes were performed for the third case (on, off), as shown in Figure 7. To see the effect on the S_{11} spectra, the first resistor is replaced with a shunt capacitor in the first diode, representing the “ON and OFF” state, after the two cascaded LC circuits, which produces an additional lower frequency response of 4.2GHz. Figure 8 depicts the MIMO model S_{11} as compared to the CST model. The optimized values of the circuit parameters are given in Table 4.

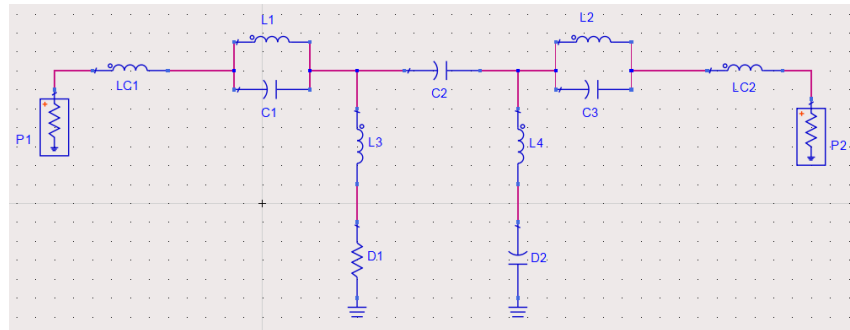


Figure 7. Circuit model for case-02 (on, off state)

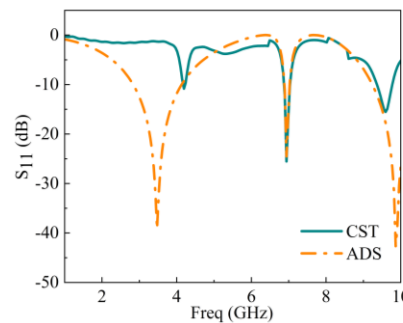


Figure 8. Circuit model S_{11} for case-02 (on, off state)

Table 4. Components used in case-02 (on, off state)

$C_1 = 815.65\text{fF}$	$D_2 = 0.15\text{pF}$	$L_4 = 0.6\text{nH}$
$C_2 = 0.6137\text{pF}$	$L_1 = 527.16\text{pH}$	$L_{C1} = 892.72\text{Ph}$
$C_3 = 869.52\text{fF}$	$L_2 = 715.71\text{pH}$	$L_{C2} = 842.95\text{Ph}$
$D_1 = 4.5\Omega$	$L_3 = 0.6\text{nH}$	-

(iv) *Equivalent Circuit for Case-03 (off, on state)*: The fourth optimization process was also performed on the components shown in Figure 9 to validate the S_{11} spectra. In this state, the first resistor is replaced with a capacitor in the first diode, and then the second diode is replaced with a resistor, representing (an “OFF, ON”) state. This state's triple frequency band is realized at 2.54GHz, 6.64GHz, and 9.7GHz, respectively. Figure 10 shows the MIMO model S_{11} compared to the CST model, and the optimized values of the circuit parameters are given in Table 5.

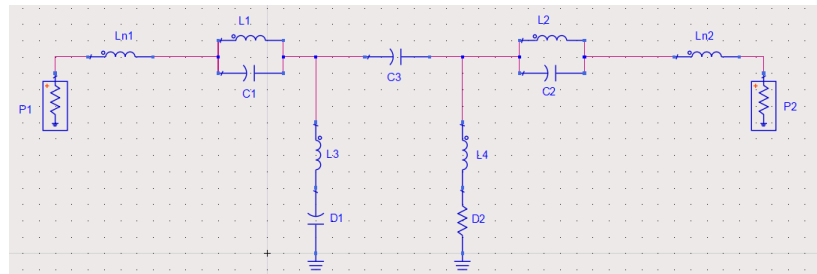


Figure 9. Circuit model for case-03 (off, on state)

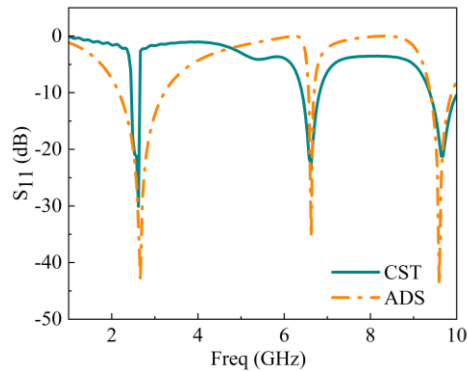


Figure 10. Circuit model S_{11} for case-03 (off, on state)

Table 5. Components used in case-02 (on, off state)

$C1 = 3.7792\text{pH}$	$D2 = 4.5\Omega$	$L4 = 0.6\text{nH}$
$C2 = 1.3195\text{pH}$	$L1 = 703.25\text{nH}$	$Ln1 = 26.112\text{fH}$
$C3 = 1.5\text{pH}$	$L2 = 724.45\text{pH}$	$Ln2 = 53.705\text{fH}$
$D1 = 0.15\text{pF}$	$L3 = 0.6\text{nH}$	-

2.4 Principle of Operation

Two PIN diodes, $D_1 - D_2$, are coupled to two-gap capacitances of the primary radiators; when $D_1 - D_2$ are activated in forward DC bias mode, the two PIN diodes offer different biasing scenarios:

Case-00: In this case, the two diodes are reversed-biased (switched off). Hence, the MTM MIMO antenna radiates at 2.5GHz, 6.6GHz, and 9.6GHz.

Case-01: The two diodes in this instance are forward-biased (switch on), thus connected to the central radiator. This antenna configuration resonates at 7.8GHz and 9.6GHz.

Case-02: Diode D_1 is forward-biased (switch on) in this case, while D_2 is reversed-biased (switch off). In this situation, the antenna radiates at 4.2GHz, 7.8GHz and 9.6GHz.

Case-03: D_1 is reversed-biased (switch off), while D_2 is forward-biased (switch on). In this final stage, the antenna radiates at 2.54GHz, 6.64GHz, and 9.7GHz, respectively.

3 RESULTS AND DISCUSSION

This section demonstrates the simulated results of the proposed reconfigurable MTM MIMO antenna. The RF PIN diode employed in the proposed MIMO antenna's equivalent circuit model is depicted in Figure 11 for both forward-biased (switch-on) and reverse-biased (switch-off) conditions.

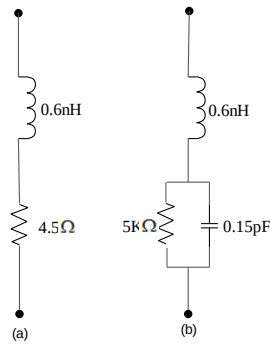


Figure 11. Equivalent circuit for PIN diode (a) Forward biased, (b) Reverse biased

A. Case-00: When both PIN $D_1 - D_2$ are turned off, the S_{11} & S_{21} spectra and realized gain are shown in Figure 12, indicating that the suggested antenna resonates at 2.5GHz, 6.6GHz, and 9.6GHz. The peak realized gain of $>2\text{dBi}$ is realized at 6.3GHz.

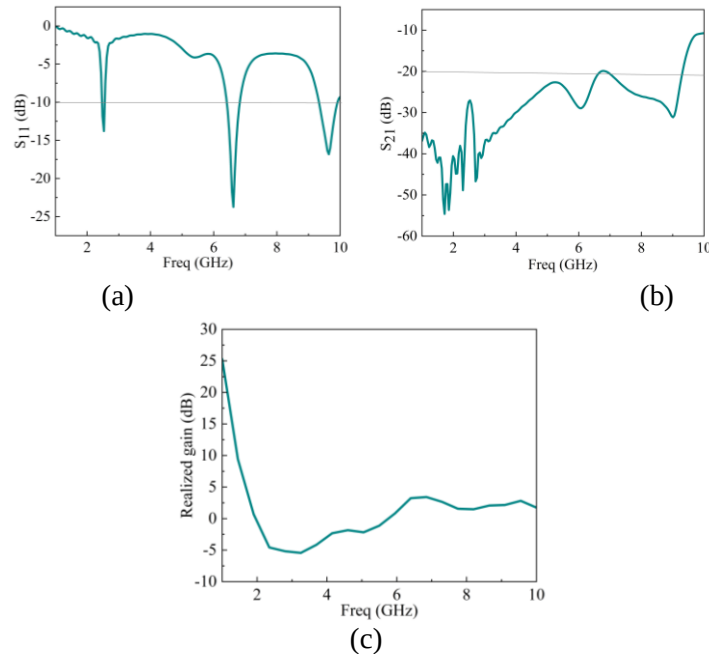


Figure 12. The spectral profiles of (a) S_{11} , (b) S_{21} and (c) peak realized gain for the suggested antenna under reversed biased state (switched off)

B. Case-01: The simulated S_{11} , S_{21} and peak realized gain when D_1 through D_2 are in the ON state is depicted in Figure 13. Dual-band frequencies of 7.8GHz and 9.6GHz have been realized in this configuration mode. The peak realized gain is 3.1dBi at 9.6GHz.

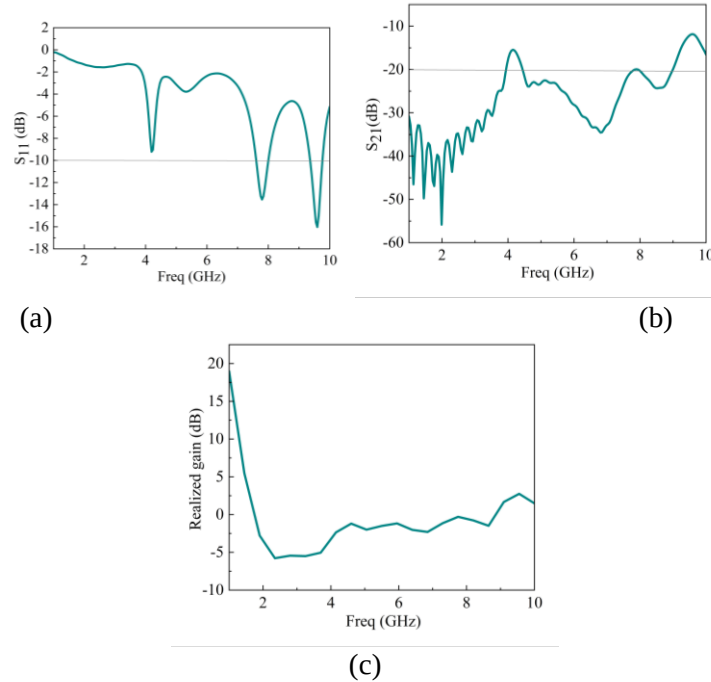


Figure 13. The spectral profiles of (a) S_{11} , (b) S_{21} and (c) peak realized gain for the suggested antenna under forward biased state (switched on)

C. Case-02: In this configuration mode, the first diode is ON while the second diode is off. The proposed antenna resonates at three different frequencies of 4.2GHz, 7.8GHz, and 9.6GHz, as depicted in Figure 14(a). Figures 14 (b) and 14 (c) show the isolation and peak realized gain. The maximum realized gain of 2.5dBi is realized in this state.

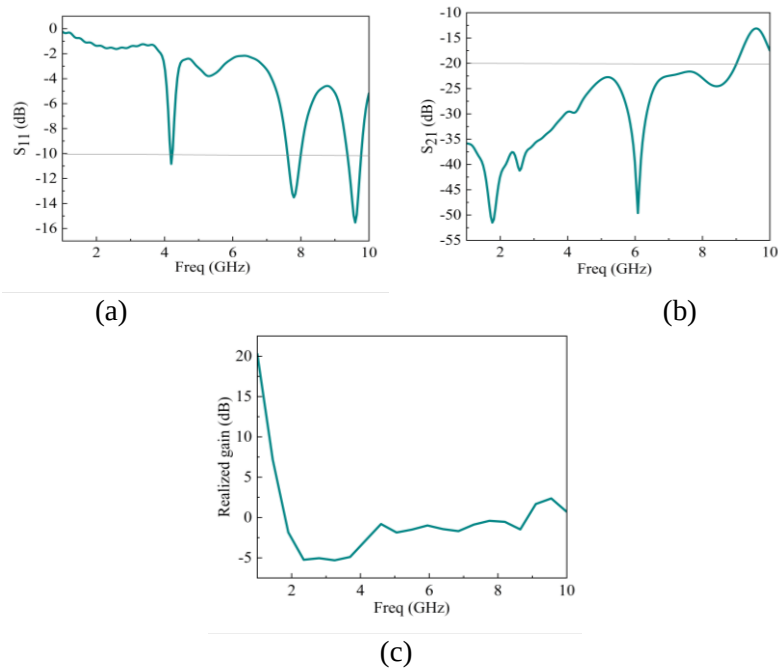


Figure 14. The spectral profiles of (a) S_{11} , (b) S_{21} , and (c) peak realized gain for the suggested antenna when the diodes are in or off state

D. Case-03: This is the final state of the configuration in which D_1 is off while D_2 is on. This configuration mode produces a triple band frequency response of 2.54GHz, 6.64GHz, and 9.7GHz. The

S_{11} , S_{21} and peak realized gain are shown in Figure 15, with a maximum realized gain of 2.4dBi at 6.6GHz. Table 6 summarizes the various PIN diode-switching conditions. It is significant to observe that the antenna consistently upholds strong isolation levels below -20 dB. The information in the Table shows that the antenna offers the advantage of being electronically adjustable to enhance its flexibility and adaptability in IOT applications.

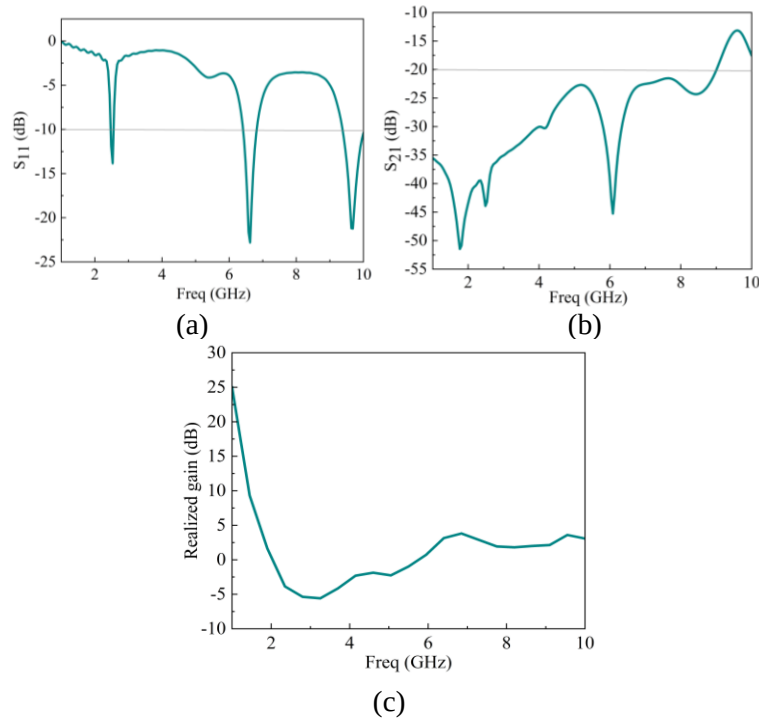


Figure 15. The spectral profiles of (a) S_{11} , (b) S_{21} , and (c) peak realized gain for the suggested antenna when the diodes are in on the state

Table 6. Performance of an antenna when subjected to different switching scenarios involving PIN diodes

Case	Mode of operation	Band (GHz)	Peak gain (dBi)
00	Multiband	2.5, 6.6, 9.6	2
01	Dual-band	7.8, 9.6	3.1
02	Multiband	4.2, 7.8, 9.6	2.5
03	Multiband	2.54, 6.64, 9.7	2.4

E Far-field Pattern and Surface Current Distribution

The configuration's simulated E and H plane operating at different frequencies is displayed in Figures 16a through 16n. The pattern exhibits omnidirectionality at low frequencies, but it begins to degrade at higher frequencies. The surface current density is shown in Figure 17 at respective frequencies of 2.5GHz, 2.54GHz, 4.2GHz, 6.6GHz, 6.64GHz, 7.8GHz, 9.6GHz, and 9.7GHz. The amount of current in an exciting port is higher.

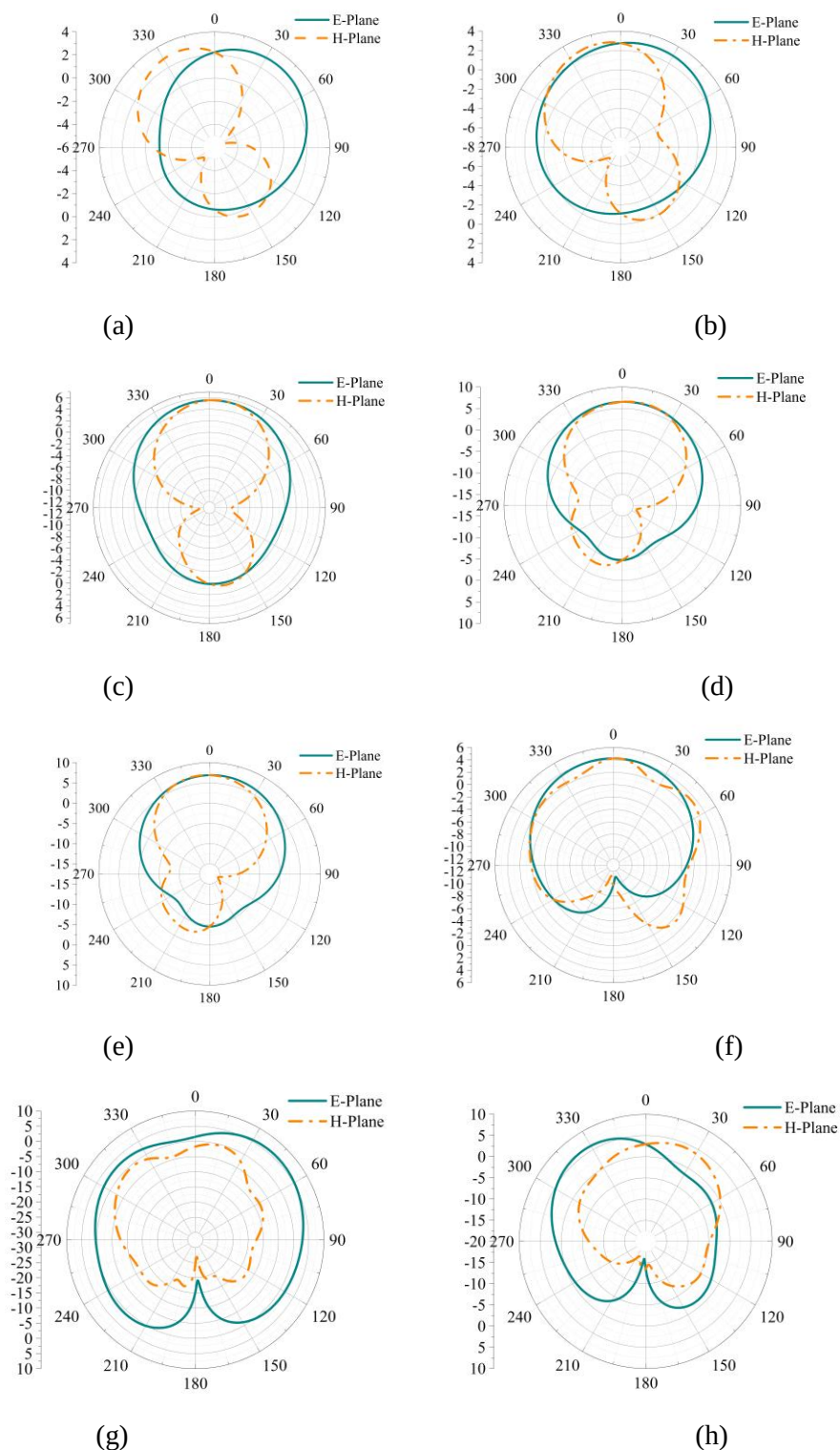


Figure 16. Far-field pattern at (a) 2.5GHz, (b) 2.54GHz, (c) 4.2GHz, (d) 6.6GHz, (e) 6.64GHz, (f) 7.8GHz, (g) 9.6GHz, (h) 9.8GHz

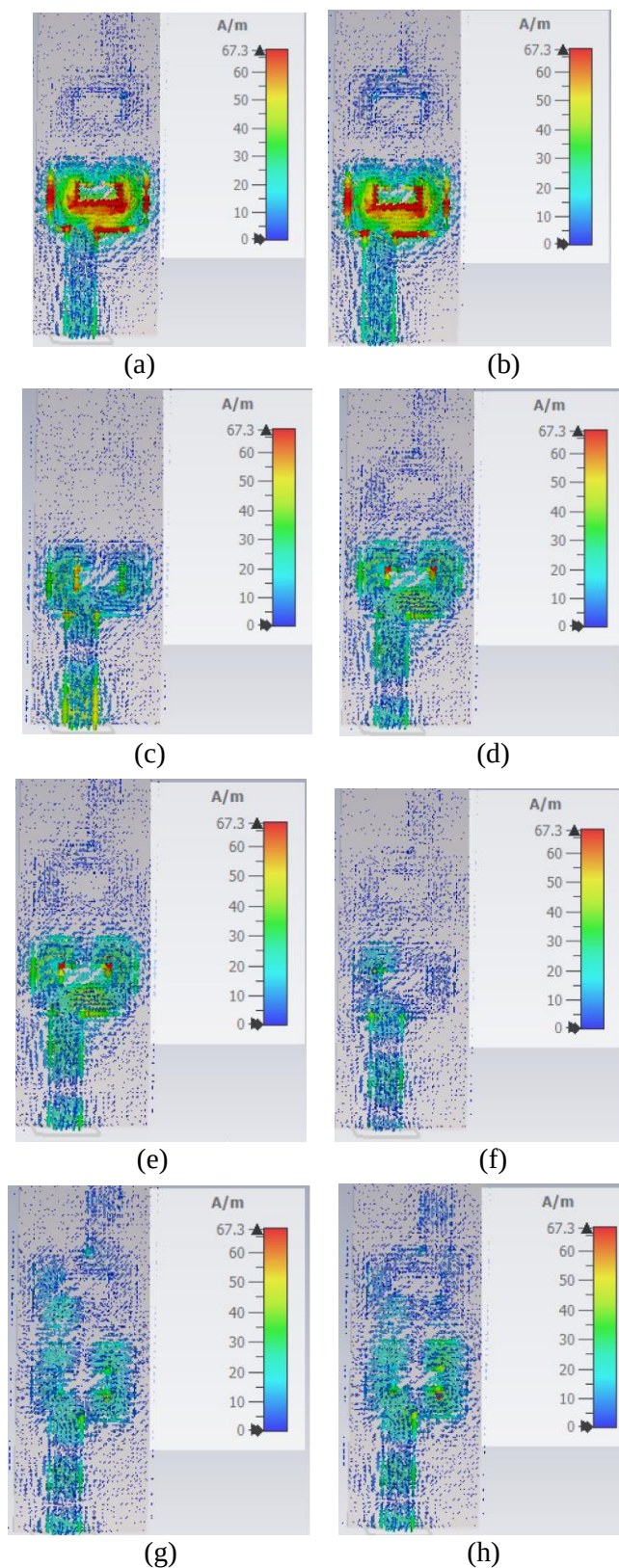


Figure 17. Current distribution at (a) 2.5GHz, (b) 2.54GHz, (c) 4.2GHz, (d) 6.6GHz, (e) 6.64GHz, (f) 7.8GHz, (g) 9.6GHz, and (h) 9.7GHz when port 1 is excited

4 RECONFIGURABLE MTM MIMO ANTENNA DIVERSITY ANALYSIS

This section analyses and discusses the MIMO metric performance of the suggested antenna. A decoupling network has not been integrated because there is a quadrature phase shift of the two antenna orientations. There are several ways to quantify the performance of the antenna, including the total active reflection coefficient (TARC), the channel capacity loss (CCL), The envelope correlation coefficient (ECC), diversity gain (DG), and mean effective gain (MEG). TARC measures the interference between MIMO channels in signals. The following equation (1) was used to calculate it [25].

$$TARC = \frac{\sum_{n=1}^N |b_i|^2}{\sum_{n=1}^N |a_i|^2} = \sqrt{\frac{(s_{ii}-s_{ij})^2 (s_{jj}-s_{ji})^2}{n}} \quad (1)$$

Where a_i stands for the incident wave from port to patch and b_i signifies the waves reflected from patch to port. The variable n indicates the count of MIMO elements engaged in transmission or reception. The simulated TARC shown in Figure 18 is below -10dB, in compliance with established norms. The MIMO system's channel capacity is influenced by a factor called ECC. The standard value of ECC should be below 0.1, as indicated in references [26, 27]. It can be evaluated using equation (2) below.

$$\rho e = \frac{|\iint_{4\pi} [\vec{F}_1(\theta, \varphi) \times \vec{F}_2(\theta, \varphi)] d\Omega|^2}{\iint_{4\pi} [\vec{F}_1(\theta, \varphi)]^2 d\Omega \iint_{4\pi} [\vec{F}_2(\theta, \varphi)]^2 d\Omega} \quad (2)$$

Where F stands for far-fields of the two MIMO antennas, θ , φ , and Ω signifies the elevation, azimuth, and solid angle respectively. The variation of ECC with frequency is shown in Figure 19 with a simulated value of 0.03.

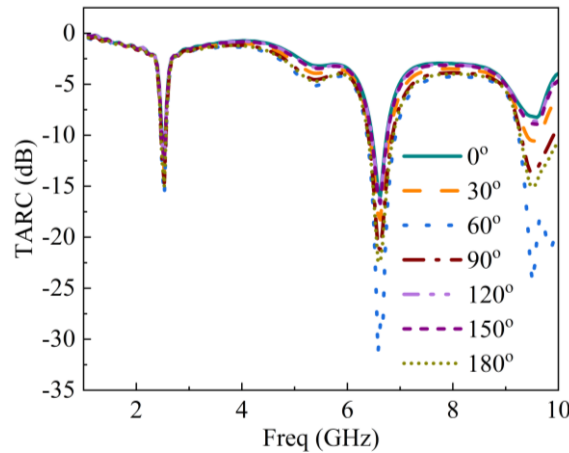


Figure 18. TARC of the MIMO system

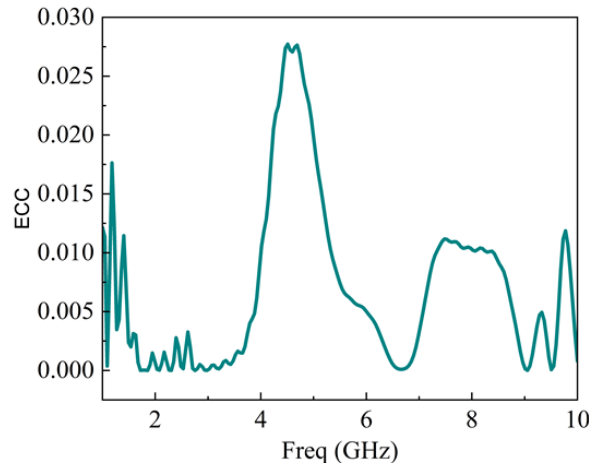


Figure 19. Simulated ECC of the MIMO system

The diversity gain is an additional performance measure to confirm the extent of power reduction in transmission. It is calculated based on the ECC using the approach outlined in reference [28]. As seen in Figure 20, the antenna's diversity gain is nearly 10 dB.

$$DG = 10 \times \sqrt{1 - \rho e^2} \quad (3)$$

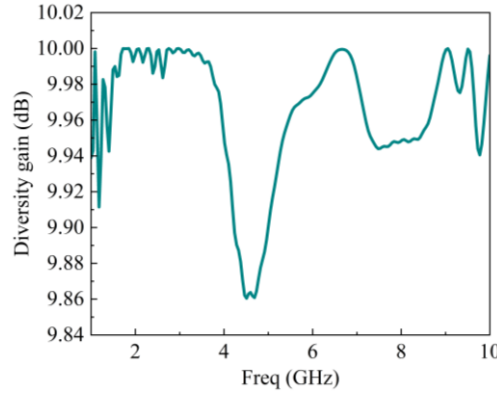


Figure 20. The diversity gain of the MTM MIMO antenna

Increasing the number of antenna elements results in a linear reduction of channel capacity. MIMO systems benefit from more antenna elements to effectively accommodate actual data rates, resulting in improved channel capacity and a crucially desired decrease in channel capacity loss (CCL). This relationship is depicted in Figure 21 and can be evaluated through the method described in [29].

$$CCL = -\log_2(A^\rho) \quad (4)$$

Where A^ρ is the correlation matrix of receiving antenna and it can be defined as:

$$A^\rho = \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix} \quad (5)$$

A metric known as the effective gain compares the power received through the diversity antenna to the total average power received through the isotropic antenna [30]. The computation of the MEG employs the method detailed in [30].

$$MEG = 0.5 \left[1 - \sum_{j=1}^N |S_{ij}|^2 \right] \quad (6)$$

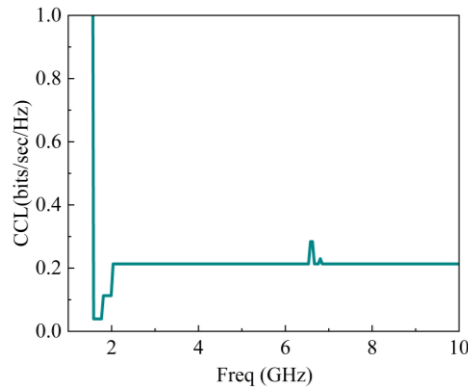


Figure 21. Channel capacity loss of the system

N denotes the count of antennas with (i) indicating the input port. The MEG is graphically presented in Figure 22. The proposed MTM MIMO antenna has been compared to other related literature in various aspects, and the comparison is summarized in Table 7. It shows that our proposed antenna is compact, simple and has a higher gain than some reported ones [30].

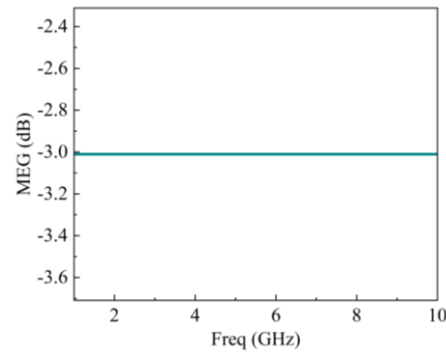


Figure 22. The mean effective gain of the MIMO system

Table 7. Comparison of reported frequency reconfigurable MIMO antenna

Ref.	Size (mm)	Bands	Methods	Isolation (dB)	Peak gain
[17]	52 x 52	UWB	PIN diodes	15.5	NA
[26]	36 x 19	WLAN, ITU	PIN diodes	20	NA
[27]	140 x 70	LTE	Varactors	13	4
[28]	20 x 32	UWB	PIN diodes	22	NA
[29]	120 x 60	GSM, LTE, WiMAX	PIN/Varactors	NA	3
This work	60 x 20	WLAN, C-BAND, X-BAND	PIN diodes	20	3.1

5 CONCLUSIONS

In this study, an equivalent circuit and frequency reconfigurable MTM MIMO antenna is designed and simulated for IOT applications while operating in different frequency bands. Two gap capacitances are coupled to a metamaterial radiator via diodes $D_1 - D_2$. The MTM MIMO antenna can tune eight frequency bands, including WLAN, C- Band, and X-Band. The proposed antenna has a maximum realized gain of 3.1dBi, which shows good MIMO performance and can be used in IOT communication systems.

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