

Design and Optimization of Reconfigurable Patch Antenna for Wireless Applications

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1. Title and Abstract

1.1 Title

Design and Optimization of Reconfigurable Patch Antenna for Wireless Applications

1.2 Abstract

As wireless communication standards rapidly evolve toward 5G Sub-6 GHz and Wi-Fi 6E/7 architectures, modern handheld devices must support an increasing number of frequency bands within a physically constrained platform. Traditional "fixed" antennas lead to "Aperture Congestion," where multiple antennas compete for limited space, causing interference and increased device dimensions. This research proposes the design, optimization, and hardware validation of high-order Reconfigurable Patch Antennas that dynamically adapt their electrical characteristics to overcome these limitations. The primary objective of this research is to achieve high-order frequency and pattern agility while maintaining a minimalist switching network to reduce biasing complexity. The work is divided into three distinct phases of design evolution.

In the first phase, a novel frequency-reconfigurable antenna was developed for 5G and WLAN applications. By utilizing only two PIN diodes, the design achieves an unprecedented nine distinct frequency states ranging from 2.83 GHz to 8.47 GHz. This represents a significant advancement over current state-of-the-art designs, which typically require more switches to achieve fewer bands. The second phase focuses on the optimization of a slotted Rectangular Microstrip Antenna (RMSA). This design achieves dual reconfigurability (frequency and pattern) using only a single PIN diode, providing peak gains up to 5.59 dBi. By integrating specific slotting techniques and Defective Ground Structures (DGS), the antenna mitigates the typical gain degradation associated with low-cost FR4 substrates. The final phase involves a slotted Circular Microstrip Antenna (CMSA) utilizing advanced DGS geometries to enhance bandwidth and isolation. This research has resulted in significant intellectual property contributions, including two granted design patents and one pending utility patent.

All designs were modelled and optimized using Ansys HFSS. To validate the simulation, hardware prototypes were fabricated and tested using a Vector Network Analyzer (VNA) and an RF Anechoic Chamber. The measured results demonstrate a high degree of correlation with simulated data in terms of Return Loss ($S_{11} < -10$ dB), VSWR < 2 , and radiation patterns. The research concludes that strategic switch placement and optimized geometries can achieve superior spectral agility, providing a robust solution for next-generation software-defined radio front-ends.

Keywords: Reconfigurable Antenna, 5G Sub-6 GHz, PIN Diodes, Frequency Agility, Pattern Reconfigurability, Patch Antenna, HFSS, DGS.

2. Introduction

In the era of multi-standard wireless communication, modern devices such as smartphones, IoT terminals, and portable gadgets must seamlessly support diverse services including GSM, LTE, 5G Sub-6 GHz, and Wi-Fi 6E/7 within a single compact platform. Traditional fixed-frequency antennas exacerbate the challenge by requiring dedicated apertures for each band, resulting in aperture congestion that inflates device size, escalates RF front-end complexity, and drives up manufacturing costs. As communication systems evolve toward software-defined architectures, the antenna hardware must dynamically adapt its electrical characteristics particularly resonance frequency to align with operational requirements, thereby enabling

frequency agility without additional physical components. This thesis addresses the critical need for reconfigurable antennas that act as intelligent pre-filters, resonating selectively at the frequency of interest to reject out-of-band interference and enhance signal-to-noise ratio (SNR), unlike wideband antennas that capture excessive noise across the spectrum.

Reconfigurable antennas offer a transformative solution by consolidating multiple functionalities into a single aperture, simplifying RF front-ends, reducing the number of physical elements, and achieving high frequency agility without compromising the slim profiles demanded by IoT and portable wireless terminals. Through mechanisms such as PIN diodes, varactors, RF-MEMS, or metamaterials, these antennas dynamically tune their resonance, ensuring optimal performance across standards while minimizing costs and volume. This approach not only mitigates aperture congestion but also improves overall signal integrity in dense spectral environments, paving the way for efficient integration in next-generation devices. By exploring novel reconfigurable architectures, this PhD research aims to deliver practical implementations that balance compactness, cost-efficiency, and superior SNR, ultimately advancing multi-standard wireless technology for real-world applications.

3. A Brief Description of the State of the Art of Research Topic

Modern wireless systems are rapidly evolving toward multi-standard operation, where a single terminal is expected to support services such as 5G sub-6 GHz, Wi-Fi, LTE, IoT, and emerging sensing applications. This evolution has increased the demand for antennas that are not only compact, but also electrically agile enough to adapt to changing frequency and radiation requirements. Traditional fixed patch antennas are limited in this respect because each operating band typically requires a separate resonant structure, which increases device size, causes aperture congestion, and complicates the RF front-end. In contrast, reconfigurable patch antennas offer an adaptive solution by using switching or tunable elements to modify current distribution, resonance, or radiation direction without changing the physical platform. As a result, they are becoming an important research direction for next-generation compact wireless devices.

The literature over the past decade shows a clear progression from simple frequency-agile antennas toward more integrated designs that combine frequency reconfiguration, pattern control, polarization diversity, and multi-mode operation. The 15 papers reviewed in this study reflect that progression. Some works focus on discrete band switching using PIN diodes and slot loading, while others use varactor diodes for continuous tuning or parasitic elements for beam steering. A smaller number of studies attempt hybrid operation, combining frequency and pattern reconfiguration within one platform. Across these works, the main objective remains the same: to achieve high reconfiguration capability while preserving compact size, acceptable gain, stable radiation behavior, and practical manufacturability.

3.1 Types of Reconfigurable Antenna

The reviewed studies can be grouped into three broad categories: frequency-reconfigurable antennas, pattern-reconfigurable antennas, and hybrid reconfigurable antennas. Frequency-reconfigurable antennas form the largest group. These designs change their resonant bands by

altering the effective electrical length of the radiating structure through PIN diodes, varactors, slot perturbation, or defective ground structures. [1] demonstrated a 2×1 array on Rogers 5880 using two PIN diodes and Yagi-Uda parasitic switching to steer the main beam, achieving three states in the 5–6 GHz range with gain between 6.12 and 8.62 dBi. [2] used an F-slot and FRDGS structure on FR4 to obtain six resonant bands from 2.3 to 8.9 GHz, while maintaining a gain of 1.6 to 5.8 dBi. [3] designed a 3×3 metamaterial array on RT Duroid with two PIN diodes to create four switchable mm-wave frequency modes from 25 to 30 GHz, with efficiency reported at 98% but only 1.0 to 4.0 dB gain. Kareem used an octagonal ring MIMO antenna on FR4 with four varactor diodes to achieve dual-band continuous tuning at 4.2 GHz and 4.55–5.56 GHz. [5] proposed an I-shaped monopole on FR4 with one PIN diode that switched between 3.5 and 5.2 GHz while also tilting the beam, but the design was limited to only two states.

Other frequency-agile designs show the same overall strategy but with different trade-offs. Liu developed a circular patch with annular slot on Rogers substrate using four varactors and three feed ports, which supported tuning from 1.17 to 1.62 GHz in the slot region and 2.4 GHz in the patch region, though the feeding arrangement was complex and the footprint was large. Zhao introduced a triangular monopole MIMO with PIN and varactor diodes, creating a three-mode system for UWB sensing, reconfigurable MIMO, and UWB-MIMO operation. [8] combined a CPW-fed monopole with switchable slots to produce four bands at 2.5, 3.5, 5.2, and 7.5 GHz. Singh used a truncated patch with parasitic load and three PIN diodes to realize five closely spaced bands from 3.8 to 6.0 GHz. [10] used a wine-glass patch on Arlon AD250 with two PIN diodes to achieve tri-band agility in a compact LTE/ITS-oriented structure. Li demonstrated a U-slot monopole on Rogers substrate with two PIN diodes, providing UWB operation with switchable notches at 3.5 and 5.5 GHz.

Pattern-reconfigurable antennas are the second important class, and they focus on changing the radiation direction or polarization state rather than the resonant band. Tian proposed a coupled-mode patch on FR4 with one varactor diode that enabled beam scanning from -34 to 34 degrees at a fixed frequency of 2.3 GHz. [13] designed a circular ring antenna on FR4 with two PIN diodes and a reconfigurable feed network to switch among linear, left-hand circular, and right-hand circular polarization states at 2.4 GHz. [14] used a double U-shape patch on FR4 with one PIN diode to toggle between single-band and dual-band resonances, while [15] employed a differentially fed patch with four PIN diodes and an air gap to achieve three frequency states with high gain. Although some of these designs are primarily frequency-reconfigurable, they are important because they demonstrate how structural modification and feed control can be used to influence radiation behaviour, beam shape, or polarization.

3.2 Major findings

PIN diodes are the most practical switching choice for reconfigurable patch antennas because they are low-cost, compact, and easy to integrate into printed structures. Varactor diodes are useful when continuous tuning or beam steering is needed, but they add biasing complexity, linearity concerns, and higher design overhead. Hybrid PIN-varactor designs can expand functionality, yet they also increase circuit complexity and make antenna behavior harder to stabilize. Most reported antennas use FR4 because it is cheap, widely available, and easy to fabricate. However, FR4-based designs often face reduced gain and efficiency compared with Rogers, Duroid, or Arlon-based antennas.

Another clear trend is that most antennas provide only a few discrete states, usually between two and six. That level of reconfiguration is useful for basic multi-band operation, but it is still

limited for future multi-standard systems. Some compact designs achieve good miniaturization, but their gain or tuning range is modest. In contrast, higher-gain designs often need larger footprints, thicker profiles, or more expensive substrates. Several works also report limitations such as back radiation, gain variation, frequency drift, or structural complexity.

These results show that reconfigurable antenna design is not only about adding switches. It also depends on careful choice of geometry, substrate, feed structure, and switching location. For this reason, the literature still lacks a compact FR4-based patch antenna that uses only one or two PIN diodes yet offers multiple frequency bands and at least one useful pattern-reconfigurable state. That gap is especially important for low-cost, slim wireless devices. Your work fits directly into this gap by targeting compactness, FR4 compatibility, and reduced switching complexity while still supporting multiple frequency bands and one pattern-reconfigurable function.

Ref. No.	Configuration	Observation	Performance (Bands/Gain)	Key Limitation
[1]	2X1 array, 52.5X40.5mm, Rogers 5880 2 PIN diodes	Used Yagi-Uda parasitic switching to steer the main beam	3 States (5-6 GHz); 6.12 – 8.62 dBi	Cost & Scale: Large footprint; relies on expensive low-loss substrate to maintain gain.
[2]	F-slot & FRDGS ; 25x28x1.57mm; FR4 Substrate ; 2 PIN Diodes	Combined patch slots with a Defective Ground Structure (DGS) for wide-band frequency tuning.	6 Resonant Bands (2.3–8.9 GHz); 1.6 – 5.8 dBi Gain	Integration & Stability: DGS can lead to back-radiation; narrowband gain remains low (< 2.5 dBi) in most modes.
[3]	3X3 Metamaterial Array; 30X23x; RT Duroid ; 2 PIN Diodes	Used hexagonal metamaterial unit cells and PIN diodes to create 4 switchable frequency modes.	4 Modes (25–30 GHz); Gain: 1.0 – 4.0 dB; 98% Efficiency	Gain Stability: Significant gain variance between modes; low peak gain for mm-Wave applications.
[4]	Octagonal Ring MIMO; 50 X 50 X1.6 mm ; FR-4; 4 Varactor Diodes	Used varactor-loaded octagonal ring slots in a DGS for continuous dual-band tuning.	Dual-band: 4.2 GHz & 4.55–5.56 GHz; Gain: 2.91–4.76 dBi	Switching Type: Uses varactors which may have higher power consumption and linearity issues compared to PIN diodes.
[5]	I-Shaped Monopole; 25X15X1.6mm FR4 ; 1 PIN Diode	Integrated a PIN diode into an I-shaped patch to switch between 3.5/5.2 GHz while tilting the beam.	2 States (3.5 & 5.2 GHz); Pattern tilt: -170 to 160	Low Agility: Limited to only two frequency bands; gain performance is modest due to extreme miniaturization.

[6]	Circular Patch w/ Annular Slot; 80x80x7.6mm; 4 Varactors; 3 Ports	Used a slotted patch with shorting posts to excite broadside and conical radiation modes.	Tunable: 1.17–1.62 GHz (Slot) & 2.4 GHz (Patch)	Complex Feeding: Requires 3 feed ports and precise shorting post placement; large footprint.
[7]	Triangular Monopole MIMO; 50x30x1.6mm; FR4 ; PIN + Varactors	Created a 3-mode system: UWB sensing, Reconfigurable MIMO, and UWB-MIMO.	UWB: 3–12 GHz; Reconfigurable: 4.2–6.0 GHz	Hybrid Complexity: Requires complex biasing for both diode types; larger footprint than single-element designs.
[8]	CPW-fed Monopole; 25X30X1.6 mm; FR4 ; 2 PIN Diodes	Combined a modified radiating patch with switchable slots to tune between four distinct bands.	4 Bands (2.5, 3.5, 5.2, 7.5 GHz); Good matching ($S_{11} < -10\text{dB}$)	Limited Agility: Only 4 switching states; lacks high-order frequency granularity compared to multi-switch designs.
[9]	Truncated Patch w/ Parasitic Load; 25x25x1.6 mm; FR4 ; 3 PIN Diodes	Used corner truncation and parasitic strips to create five choice-based optimized frequency responses.	5 Bands (3.8, 4.1, 4.4, 4.9, 6.0 GHz); Compact IoT profile	Granularity: Frequency bands are closely spaced, potentially leading to interference between modes.
[10]	Wine-glass Patch; 30x30x0.762mm Arlon AD250 ; 2 PIN Diodes	Integrated a switchable rectangular ring slot in the ground plane to achieve tri-band agility.	3 States (3.8, 4.5, 5.0, 5.9 GHz); Compact LTE/ITS focus	Agility & Material: Limited to 3 switching states; uses specialized Arlon substrate rather than low-cost FR4.
[11]	U-slot Monopole; 24x32x0.8 mm; Rogers Substrate ; 2 PIN Diodes	Integrated switchable U-slots and open-ended slots to create on-demand single/dual band-notches.	UWB (3.1–10.6 GHz); Notches at 3.5/5.5 GHz; Flat gain profile	Spectral Efficiency: Rejects bands but remains active across the UWB range; lacks discrete frequency agility.
[12]	Coupled-mode Patch; 40x40x1.6mm; FR4 ; 1 Varactor Diode	Loaded a ground-etched slot with a single varactor to perturb cavity modes for beam steering.	Beam Scanning: -34 to 34; Fixed Frequency: 2.3 GHz	Frequency Drift: Steering the beam causes the center frequency to shift (1.7% to 2.1%), which may drop the link in narrow-band systems.

[13]	Circular Ring; 60x60x1.6mm; FR4 ; 2 PIN Diodes	Integrated a reconfigurable feed network at the center of a circular ring to switch polarization states.	3 States (LP, LHCP, RHCP); 2.4 GHz ISM Band; Isolation more than 15 dB	Fixed Frequency: No frequency agility; large footprint compared to modern sub-6 GHz monopoles.
[14]	Double U-shape Patch; 30x38x1.6mm; FR4 ; 1 PIN Diode	Placed a PIN diode across the slot between two U-patches to toggle between single and dual-band resonances.	State 1: 3.5 GHz; State 2: 3.2 & 5.5 GHz; Gain: 2.3–3.9 dBi	Limited States: Can only toggle between two operational modes; modest gain performance.
[15]	Differentially-fed Patch; 50x50x4.1mm; 4 PIN Diodes	Used two layers of substrates with an air gap to switch between three frequency states.	3 States (2.4, 3.5, 4.9 GHz); High Gain: 7.2–8.4 dBi	Structural Complexity: High-profile design (4.1 mm) due to air gap; difficult to integrate into slim mobile devices.

Table-1: State-of-the-Art Works on Spectrum Allocation

3.3 Summary and Research Gap Perspective

The state-of-the-art literature a clear agility bottleneck, with most reconfigurable antennas supporting only 3–6 bands per design. This means current solutions still fall short of the high-frequency flexibility needed in compact multi-standard wireless devices. A second gap is component overload, because higher agility often requires more active elements, which increases DC biasing complexity and integration difficulty. At the same time, many multiband antennas suffer from a gain-agility trade-off, where gain drops below 2 dBi as the number of bands increases. Therefore, the literature still lacks a compact FR4-based design that uses only 1–2 PIN diodes while delivering multiple frequency bands with stable gain and one useful pattern-reconfigurable state.

4. Definition of the Research Problem

- **Aperture Congestion in Modern Terminals:**
 - Integrating multiple dedicated antennas for GSM, LTE, 5G Sub-6GHz, and Wi-Fi within a single device leads to severe space constraints and increased mutual coupling.
- **Hardware-Software Mismatch:**
 - While communication systems are moving toward software-defined architectures, the physical layer (antenna) remains largely static, limiting the overall agility of the RF front-end.

- **Performance vs. Complexity Trade-off:**
 - Existing reconfigurable designs often achieve higher agility only by increasing the number of active switches, which introduces high insertion losses, complex DC biasing, and battery drain.
- **Substrate-Induced Gain Degradation:**
 - Achieving high-order frequency agility (6+ bands) on low-cost substrates like FR4 often results in poor radiation efficiency and inconsistent gain across different operating states.

5. Objectives and Scope of the Work

5.1 Objectives

The major objectives of the present research are as follows:

- To achieve high-order spectral agility (6+ bands) through optimized switching matrices.
- To implement minimalist reconfiguration using low-component counts to reduce biasing complexity.
- To maintain structural miniaturization on a 1.6 mm FR4 profile without compromising peak gain.
- To design antennas for key frequency allocations within the Sub-6 GHz spectrum, ensuring optimized performance along with legacy wireless protocols.

5.2 Scope of the Work

The scope of the research is defined as follows:

- The study is limited to the design and optimization of reconfigurable Microstrip patch antennas operating within the Sub-6 GHz spectrum (2.4 GHz to 8.5 GHz).
- Multi-standard scenarios involving LTE/4G, 5G NR, WiMAX, and INSAT C-Band/X-Band applications are considered for high-order spectral agility.
- The work focuses on electronic reconfiguration using PIN diodes and Defective Ground Structures (DGS) to achieve up to nine distinct operating states.
- Performance evaluation is carried out using Ansys HFSS for electromagnetic modelling and validated through hardware measurements using a 10 GHz Vector Network Analyzer.
- Issues related to alternative switching technologies (RF-MEMS, Varactors), high-power base station requirements, and protocol-layer standardization are beyond the scope of this work.

6. Original Contribution by the Thesis

- Engineered a novel antenna configuration that successfully achieves **9 distinct frequency bands** across 4 operational modes. This work transcends the common 3–6 band limitation currently found in hardware-validated reconfigurable antenna literature.

- Designed a hardware-efficient switching matrix utilizing an extremely low component count (only **1 to 2 PIN diodes**). This approach achieves high-order tuning while significantly reducing biasing circuit complexity and minimizing RF insertion losses.
- Successfully maintained a slim **1.6 mm FR4 profile** while achieving a peak gain of **5.59 dBi**. The design mitigates the gain and bandwidth degradation typically associated with tunable antennas on low-cost, lossy substrates.
- Developed a systematic and manufacturable design methodology specifically targeting **LTE, WLAN, and 5G NR** allocations. The research provides a robust solution for high-traffic Sub-6 GHz applications within a single, compact footprint.
- The originality of these designs is further validated by **two granted design patents** and a high degree of correlation between HFSS electromagnetic simulations and measured results from a 10 GHz VNA and Anechoic Chamber.

7. Methodology of Research, Results/Comparison

7.1 A Multi-Mode Frequency Reconfigurable Antenna for 5G and WLAN Applications

The proposed antenna's geometry is shown in Figure 1. The 30 mm by 20 mm antenna is designed on an FR-4 substrate with 1.6mm height. The substrate is supported by a reduced size metal ground plane for improved gain and directivity. The substrate possesses a relative permittivity of 4.3 and exhibits a loss tangent of 0.025. To accommodate the pin diodes between the strips, a 1 mm gap was created. The antenna is fed by a Microstrip line that is 3 mm wide and 50 ohms in resistance. The antenna was designed and simulated with the calculated parameters using Ansys HFSS, a FEM-based electromagnetic program.

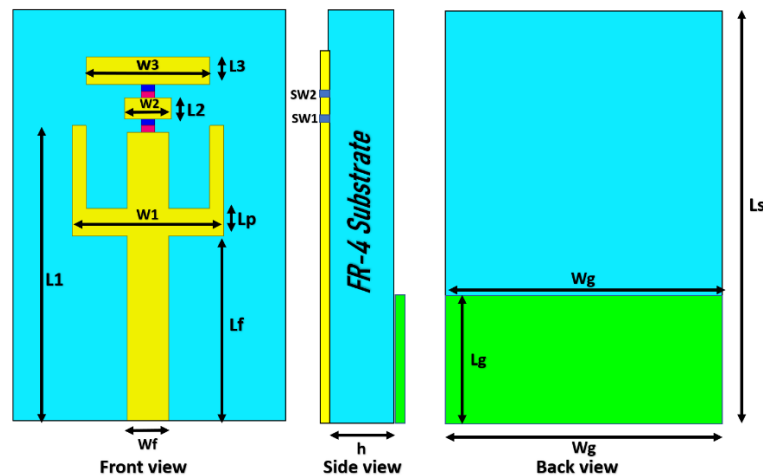


Figure 1. The geometry of proposed antenna

The various evolution phases of the proposed design are shown in figure 2. The strips of width w_2 and w_3 are added to get the desired bands and better impedance matching.

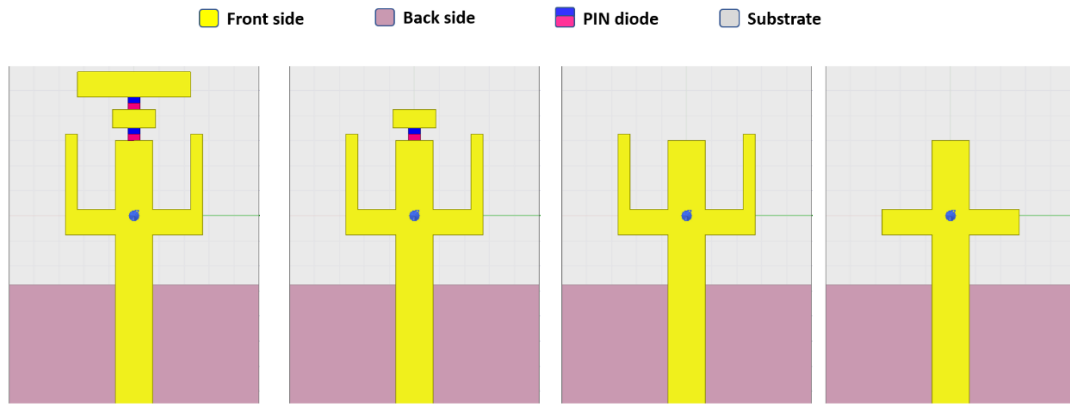


Figure 2. Different phases of the proposed antenna geometry

The comparison of the return loss of the proposed antenna at various design stages is shown in figure 3 and the dimensions of this antenna are summarized in Table I.

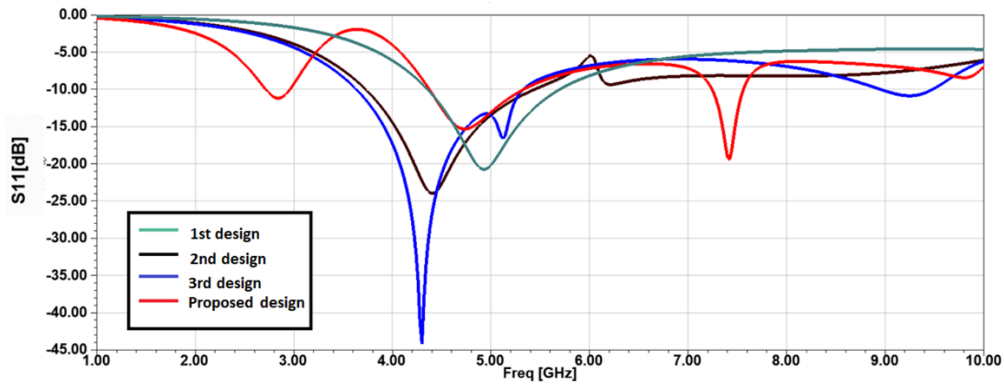


Figure 3. Comparison of S_{11} (dB) for the different design stages

Parameter	Dimensions (mm)
W_s	30
L_s	20
W_g	30
L_g	9.5
W_f	3
L_p	2
L_f	13.5
L_1	21
L_2	1.5
L_3	2
W_1	11
W_2	3.4
W_3	9
H	1.6

Table 2. Dimensions of the proposed antenna

The antenna operates in four distinct modes depending on the switching conditions of both the PIN diodes. The simulated return loss of all 4 modes is shown in figure 4.

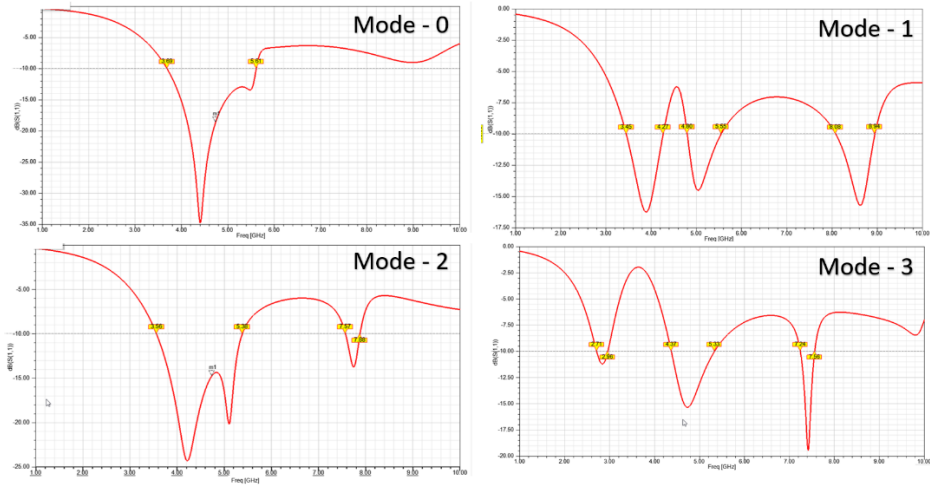


Figure 4. Simulated return loss of all modes

In Mode 0, it functions as a single-band entity spanning 3.69-5.61 GHz, with an average gain of 1.9 and a return loss of -35 dB. Transitioning to Mode 1, it morphs into a tri-band configuration covering 3.45-4.27 GHz, 4.80-5.55 GHz, and 8-8.94 GHz, offering an average gain of 0.85 and return losses of -16 dB, -14.5 dB, and -15.25 dB respectively.

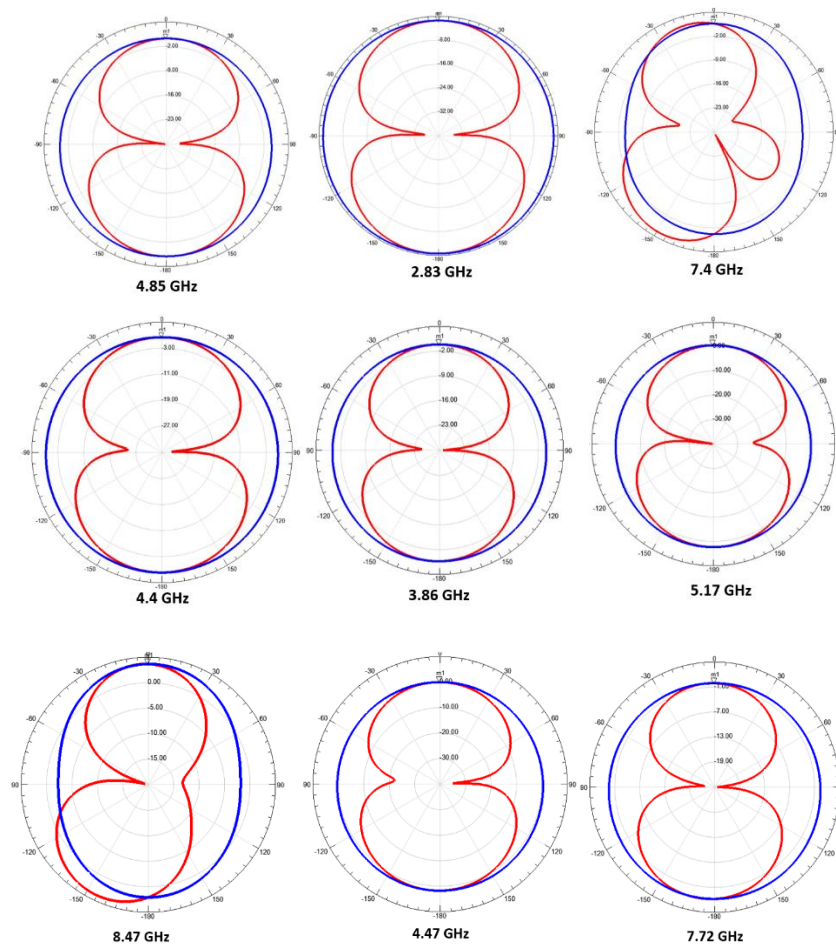


Figure 5. Polar gain plots in E and H planes for various frequencies in different switching modes

In Mode 2, it operates as a dual-band setup covering 3.56-5.38 GHz and 7.57-7.88 GHz, delivering an average gain of 1.67 and return losses of -24 dB and -14 dB respectively. In mode 4, the antenna transitions into a tri-band configuration encompassing the frequency bands of 2.71-2.96 GHz, 4.37-5.33 GHz, and 7.24-7.56 GHz. This mode delivers an average gain of 1.55 and exhibits return losses of -11.2 dB, -15.5 dB, and -19.5 dB for each respective band.

The designed planar and multi-band monopole antenna's E and H plane directivity patterns across various frequency bands are displayed in figure 6. The antenna design proposed in this study is more compact in size compared to the antennas discussed in the comparative analysis. This newly designed antenna exhibits an impedance bandwidth (BW) that spans from 300 to 1920 MHz, providing a broader bandwidth than the antennas developed in previous studies [16–22]. A detailed comparison is presented in Table 3.

Ref.	Size (mm ³)	PIN diodes	No. of bands	Freq. Bands (GHz)	-10dB BW (MHz)	Peak gain
[16]	40 x 35 x 1.6	1	3	2.45, 3.5, 5.4	490-1360	1.92-3.02
[17]	60 x 60 x 1.6	3	5	2.4, 4.26, 4.32, 4.58, 5.76	60-170	1.31-2.77
[18]	53 x 35 x 1.6	1	3	2.45, 3.50, 5.20	147-1820	1-7-3.4
[19]	40 x 22 x 1.6	1	4	2.45, 5.13, 3.49, 5.81	750-1260	1.72-2.96
[20]	39 x 37 x 1.6	1	3	2.4, 5.4, 3	550-1220	1.27-3.8
[21]	37 x 35 x 1.6	2	4	2, 3.4, 2.4, 3.1	200-960	1.76-1.98
[22]	40 x 35 x 1.6	1	3	2.45, 3.5, 5.2	330-1250	1.48-3.26
This work	30 x 20 x 1.6	2	9	2.83, 3.86, 4.41, 4.47, 4.85, 5.17, 7.4, 7.73, 8.47	300-1920	0.85-1.9

Table 3. Comparison of the proposed antenna with other reported work

The purpose of this study is to design a small, flexible antenna with four distinct operating modes and support for nine operating bands. The status of the integrated switches governs this antenna's ability to operate over a variety of frequency bands, making it special. It performs admirably at frequencies between 300 and 1920 MHz, making it appropriate for both narrowband and wideband applications. The antenna has a virtually omnidirectional design that exhibits excellent directivity and a peak gain that ranges from 0.85 to 1.9, making it appropriate for a number of wireless applications. Its small size does not sacrifice performance, either. To validate the computational findings, a cost-effective prototype of the suggested frequency reconfigurable antenna can be created.

7.2 Reliable Single Diode Patch Antenna with Dual Mode Frequency and Pattern Reconfigurability with Compliance Analysis

The development of the reconfigurable antenna starts by constructing a conventional rectangular Microstrip patch on an FR4 substrate with dimensions of 55.2 mm by 50.8 mm. The FR4 material, characterized by a dielectric constant $\epsilon_r = 4.4$, is selected for its affordability and widespread availability in printed circuit board (PCB) fabrication. Despite its higher dielectric losses compared to specialized microwave substrates, FR4 offers a practical trade-off between performance and cost for prototyping and compact device integration.

The initial antenna structure (Antenna 1) consists of an outer patch measuring 36 mm $\times$ 25.2 mm, excited through a 20 mm $\times$ 3 mm inset Microstrip feed line designed to achieve impedance matching. This arrangement yields a single resonant frequency at 5.58 GHz, as illustrated in Figure 1. The corresponding simulated S_{11} response in Figure 2 indicates a return loss below 10 dB, confirming good impedance matching and establishing a solid baseline for reconfigurable enhancements.

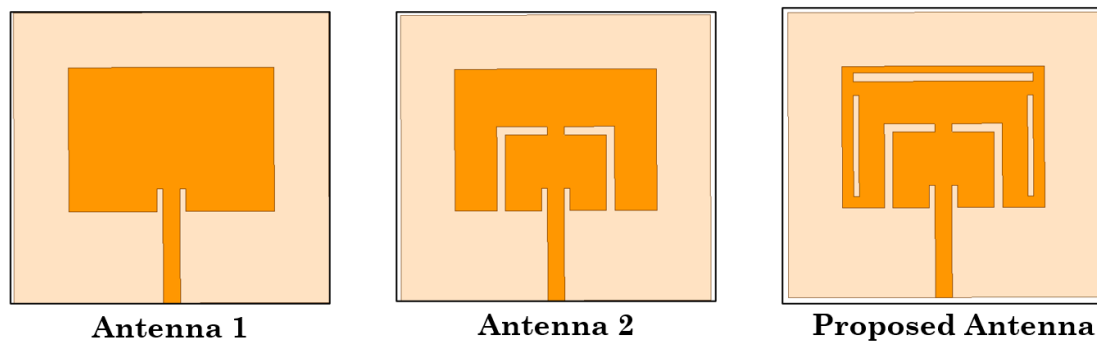


Figure 6. Evolution steps of proposed frequency and pattern reconfigurable antenna

An inverted U-shaped slot of width 2 mm is incorporated into the outer patch of Antenna 2 to enable frequency reconfigurability, enclosing a 21 $\times$ 15 mm inner patch. A single PIN diode integrated within the slot, controlled by a DC bias, switches between two states: ON, electrically connecting the patches and resonating at 3.88 GHz, and OFF, isolating them and resonating at 2.4 GHz. Simulated S_{11} results in Figure 7 confirm dual-band performance with return losses below -10 dB, demonstrating efficient frequency agility and compact design.

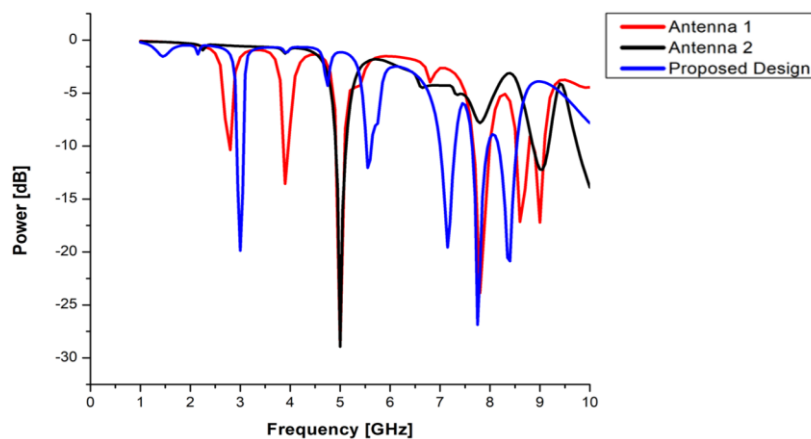


Figure 7. Comparison of simulated S11 for the baseline outer patch design (Antenna 1), the reconfigurable dual-band design (Antenna 2), and the proposed multi-band, pattern-reconfigurable patch antenna

The proposed antenna enhances functionality by adding three slots to the inverted U-shaped structure for multi-band and pattern reconfigurability. Figure 1 shows two vertical slots ($7.5 \text{ mm} \times 18 \text{ mm}$) symmetrically placed and one horizontal slot of the same size at the top. These modifications generate additional current paths, shifting resonant modes and altering field distribution. As illustrated in Figure 2, Mode 1 (PIN diode ON) resonates at 5.00 and 7.75 GHz, while Mode 2 (PIN diode OFF) resonates at 3.10, 5.55, 7.15, and 7.75 GHz. Pattern reconfiguration occurs at 7.15 and 7.75 GHz, demonstrating variation in radiation across modes. Full-wave simulations validate the antenna's compact and reconfigurable design. The structure effectively supports multi-band wireless communication with a single switching element.

Additionally, pattern reconfiguration is observed at 7.15 GHz and 7.75 GHz, indicating variation in radiation characteristics across different modes. These results, obtained through full-wave electromagnetic simulation, confirm the antenna's suitability for multi-band wireless communication systems, offering both compactness and configurability with a single switching component.

The developed reconfigurable patch antenna was evaluated using Ansys HFSS full-wave simulations, enabling precise modelling of electromagnetic behavior, including current distribution, resonant frequencies, and radiation characteristics affected by geometry and switching. The entire antenna geometry including the outer rectangular patch, the inner patch, inverted U-shaped slot, and additional side and top slots were meticulously modelled within HFSS. Fine meshing was applied to critical areas, especially around the slot edges and diode region, to capture high-frequency field variations.

To ensure comprehensive analysis and model validation, Figure 8 shows the fabricated antenna geometry used for both simulation and experimental stages. It provides detailed views of the antenna's top layout (including the slot configuration and feedline) and the bottom copper plane.

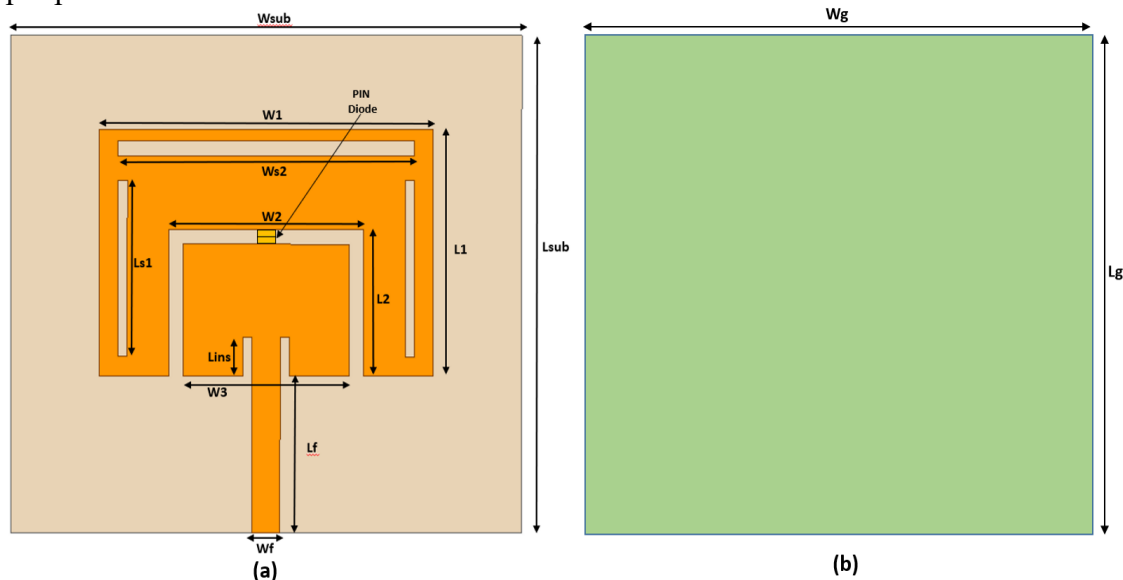


Figure 8. Antenna proposal (a) top view (b) bottom view.

To ensure optimal performance and impedance matching across desired bands, key geometrical parameters of the proposed antenna were optimized through parametric analysis using Ansys

HFSS. Table 4 presents the finalized dimensions of the antenna's components, including the patch sizes, slot dimensions, inset feed, and ground plane.

Parameter	Value (mm)	Parameter	Value (mm)
Wsub	55.2	W3	18
Lsub	50.8	Wg	55.2
W1	36	Lg	50.8
L1	25.2	Wf	3
W2	21	Lf	20
L2	15	Lins	4.6
Ls1	18	Ws2	32

Table 4. Comparison of the proposed antenna with other reported work

The frequency and pattern reconfigurability of developed antenna were evaluated using full-wave simulations in Ansys HFSS with an equivalent RC model of the SMP 1345-079LF PIN diode. The diode operates as a short circuit in the ON state, linking the inner and outer patches, and as an open circuit in the OFF state, isolating them. A biasing network ensures proper DC–RF isolation during operation.

The antenna's reflection coefficient (S_{11}) was measured for both switching conditions: Mode 0 (Diode OFF): The antenna resonates at 3.10 GHz and 5.55 GHz and Mode 1 (Diode ON): Resonant frequencies appear at 5.00 GHz, 7.15 GHz, and 7.75 GHz. As depicted in Figure 9, the return loss was evaluated through both simulation and physical testing, exhibiting strong agreement and demonstrating effective impedance matching ($S_{11} < -10$ dB) across the operating bands.

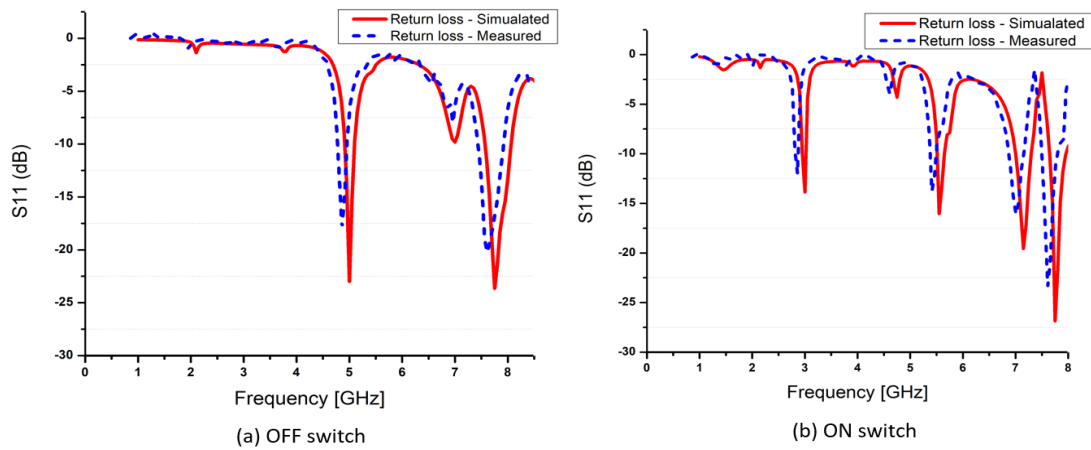


Figure 9. . Return loss measurement for proposed antenna in (a) Mode 0 and (b) Mode 1

Simulated and experimental far-field patterns at 3.10, 5.00, 5.55, 7.15, and 7.75 GHz are compared in Figure 6. The results confirm stable directional radiation with favourable front-to-back ratio and consistent patterns across modes.

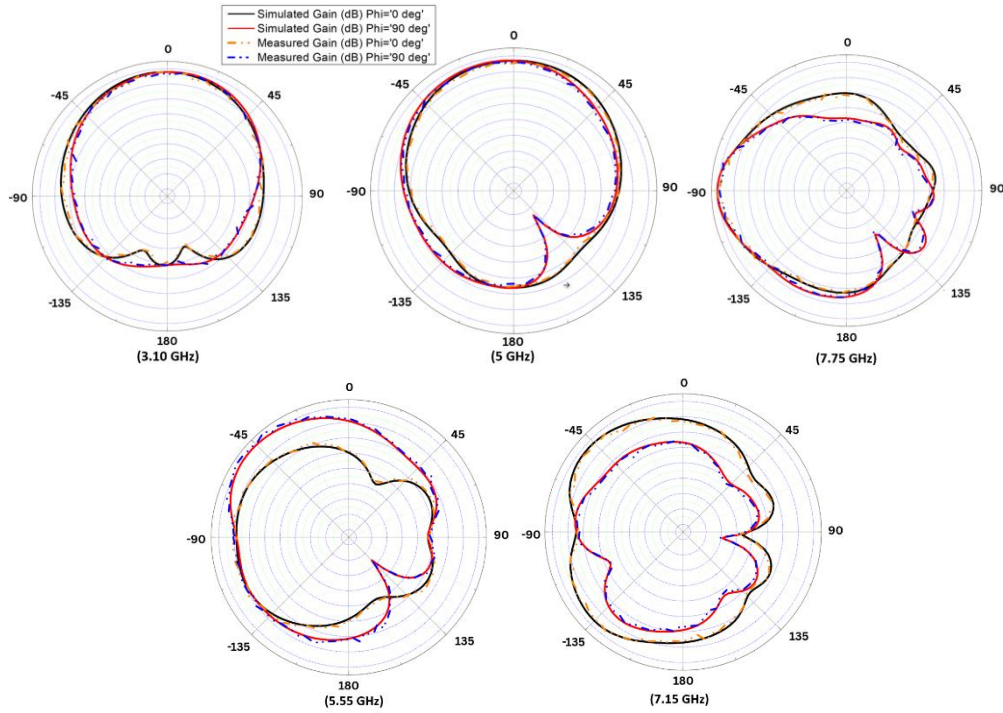


Figure 10. Radiation pattern comparison of proposed antenna between simulated and measured results at different frequencies

The antenna was prototyped on an FR4 substrate ($\epsilon_r = 4.4$, thickness = 1.6 mm) to evaluate and validate the simulated performance. The antenna geometry, including the outer patch, slots, and biasing circuitry, was accurately replicated on the board using standard PCB fabrication techniques. A single PIN diode was mounted at the designated slot location using surface-mount soldering. The final fabricated design is presented in Figure 7, depicting the antenna from both the top and bottom perspectives. The top side features the radiating patch, slot configurations, and diode placement, while the bottom view highlights the feedline, ground plane, and DC biasing elements

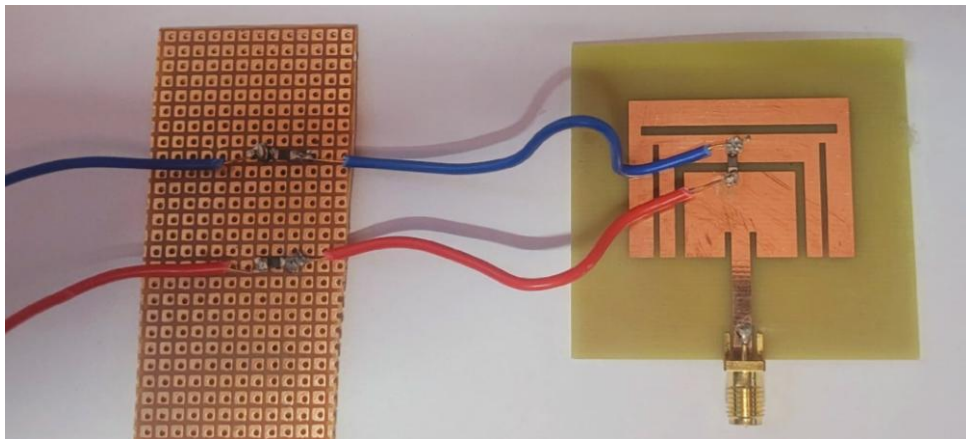


Figure 11. Fabricated prototype of the proposed antenna

Experimental validation of the antenna design was conducted in a shielded anechoic chamber, employing a calibrated VNA for accurate measurements. The antenna was connected via an SMA connector, and operational modes were toggled by applying a controlled DC bias across the integrated PIN diode. To ensure effective separation of RF and DC paths, chip inductors and capacitors were used in the biasing circuit, mirroring the simulation configuration.

Figure 8 illustrates the measurement setup, with Figure 8(a) showing the VNA connection for return loss testing and Figure 8(b) presenting the chamber arrangement for capturing radiation patterns and gain. The measured return loss remained below -10 dB across all resonant frequencies in both operational modes, indicating strong impedance matching. Gain measurements revealed values ranging from 3.69 dBi to 5.59 dBi, with a peak gain of 5.59 dBi observed at approximately 7.75 GHz.

The close alignment between measured and simulated results validates the robustness of the proposed design methodology and the efficacy of using slot-based reconfiguration in combination with a single PIN diode. This design approach not only enables effective frequency and pattern reconfigurability but also minimizes complexity by reducing the need for multiple switching elements and associated circuitry. The compact size, broad operational bandwidth, and reliable radiation characteristics make the antenna well-suited for modern multi-band wireless communication systems.

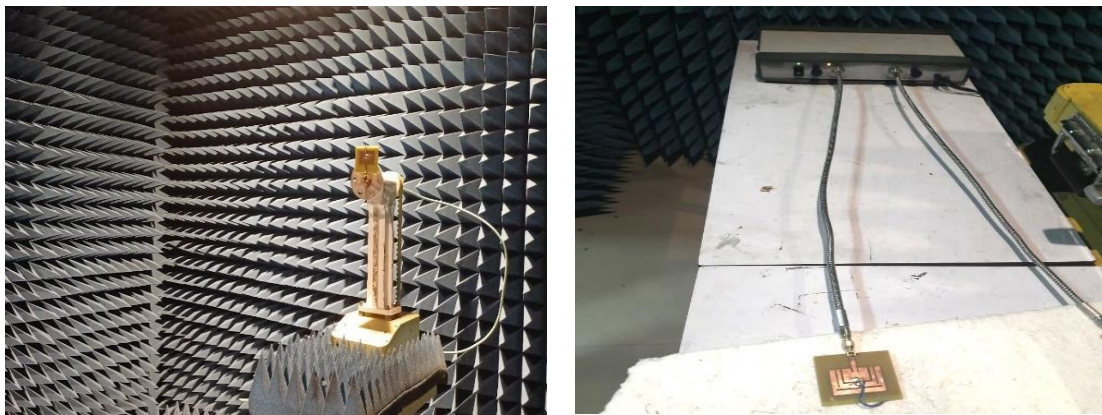


Figure 12. Measurement set of proposed antenna (a) Measurement of the radiation pattern in anechoic chamber (b) Measurement of S_{11}

A comparative analysis with existing reconfigurable patch antennas is presented later in this section to highlight the improvements in key parameters such as gain, bandwidth, frequency agility, and substrate efficiency.

This measurement setup enabled precise characterization of key antenna parameters, including return loss, radiation patterns, and gain in both switching states. By replicating simulation conditions in the prototype, measured data were directly compared with simulations, providing strong validation of the design. The close agreement between results confirms the effectiveness of the slot-based reconfiguration and single PIN diode switching.

Ref	Size(mm3)	No. of switches	Reconfigurable frequency (GHz)	Pattern reconfigurable	Maximum gain (dBi)
[23]	50*50*1.6	4	4.5&4.8/5.2&5.8	Yes	3.8
[24]	61*38*1.5	3	2 to 10(8 bands)	NA	NA
[25]	80*30*1.6	4	2.4 to 6.5(4 bands)	No	4.5
[26]	60*50*1.6	3	5.2,5.8	Yes	3

[27]	30*49*1.61	8	1.98 to 2.76 (Multiband)	No	1.8
[28]	60*40*1.6	12	2.3 to 5.87 (4 bands)	Yes	12.87
[29]	60*66*1.6	4	2.96 and 3.26	Yes	3.29
[30]	50*45*1.52	5	2,3.5 and 5.3	Yes	1.8
[31]	40*50*0.254	2	1.64 to 2.54 (3 bands)	Yes	NA
Prop.	50.8*55.2*1.6	1	3.10,5,5.55,7.15,7.75	Yes	5.59

Table 5. Result validation through Comparison of simulation and testing results for proposed antenna prototype

The fabricated antenna's performance aligns well with simulations, with only minor differences caused by fabrication tolerances, soldering inaccuracies, and parasitic losses near the PIN diode. To highlight novelty and competitiveness, a comparative study with recent reconfigurable antennas was conducted. Table 5 summarizes this comparison, covering frequency range, reconfigurability type, and number of switches, substrate, and design complexity.

The proposed antenna stands out by achieving both frequency and pattern reconfigurability using only a single PIN diode, thereby significantly reducing circuit complexity, minimizing potential RF distortion, and simplifying the DC biasing network. Additionally, the careful placement of biasing components away from the active radiating structure preserves radiation efficiency. These advantages demonstrate that the proposed antenna offers a compact, low-cost, and high-performance solution suitable for modern multi-band wireless communication systems.

7.3 Reconfigurable antenna design using Slotted Circular Patch (CMSA) with 2 PIN Diodes

This work proposes a Circular Microstrip Antenna (CMSA) designed for multi-state frequency reconfigurability. The design utilizes a unique combination of etched slots and active switching components:

- Top Layer Radiator: A circular patch featuring two T-shaped slots integrated with a PIN diode to control surface current distribution.
- Defected Ground Structure (DGS): An inverted U-slot on the bottom layer, also controlled by a PIN diode, to further enhance the tuning range and switching capability.

By strategically toggling the bias states of these two PIN diodes, the antenna achieves four distinct operational modes, transitioning between dual-band and single-band characteristics. This flexibility makes the proposed design highly suitable for modern communication environments where frequency agility and spectrum efficiency are paramount.

The physical realization of the design is illustrated in Figure 13, which displays the fabricated prototype of the reconfigurable Circular Microstrip Antenna (CMSA). The prototype serves as a validation of the simulation results, demonstrating the practical integration of active components within the printed circuit board (PCB) environment.

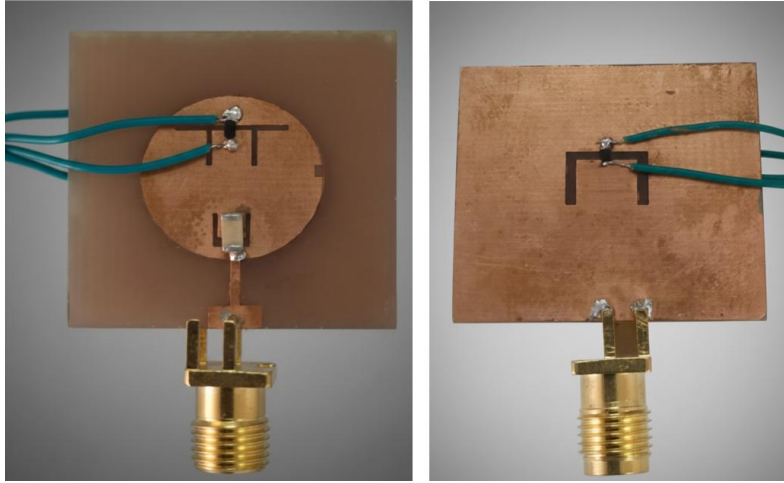


Figure 13. *Fabricated CMSA antenna (a) Top layer (b) bottom layer*

The fabricated prototype is illustrated in Figure 20, showing both the circular patch on the top layer and the ground plane on the bottom. The setup includes an RF Anechoic Chamber for measuring radiation patterns and gain in an interference-free environment.

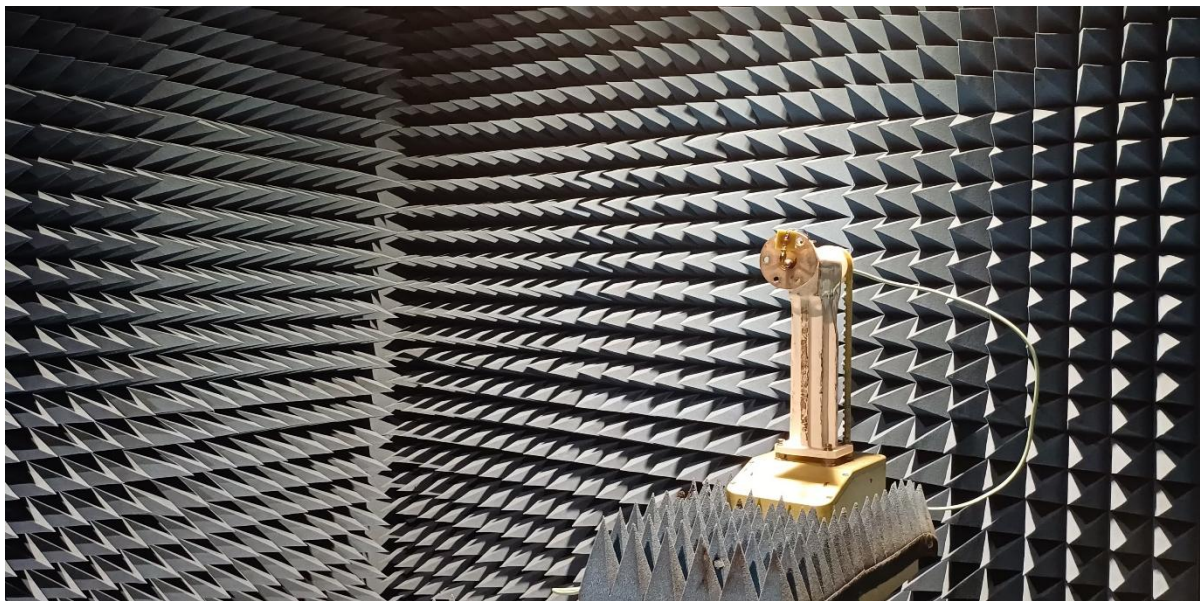


Figure 14. *Radiation measurement inside RF Anechoic Chamber*

As illustrated in Figure 15, Anritsu MS46122B Compact USB VNA was utilized to precisely measure the S-parameters and bandwidth for all four reconfigurable states.

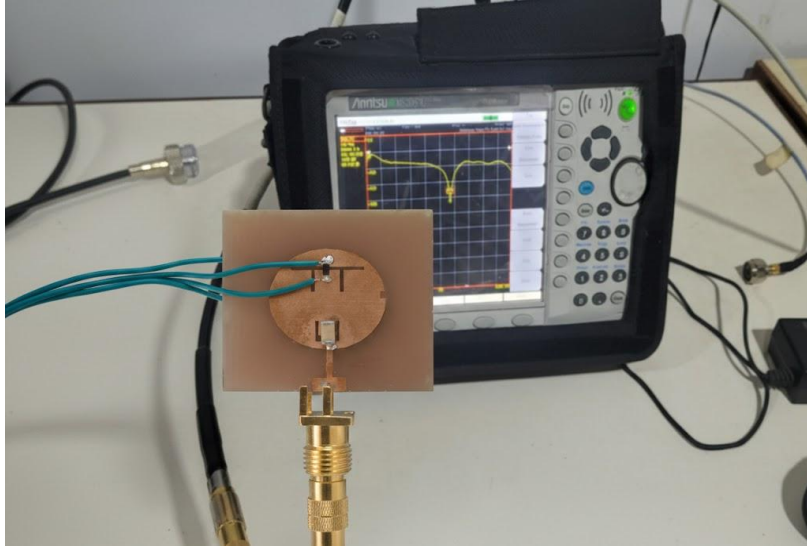


Figure 15. Return loss measurement setup with Anritsu MS46122B Compact USB VNA

Figure 16 presents the simulated and measured S_{11} characteristics, illustrating the clear frequency shifts across the four reconfigurable states. These plots confirm the transition between dual-band and single-band modes as the PIN diodes toggle the electrical paths of the slots.

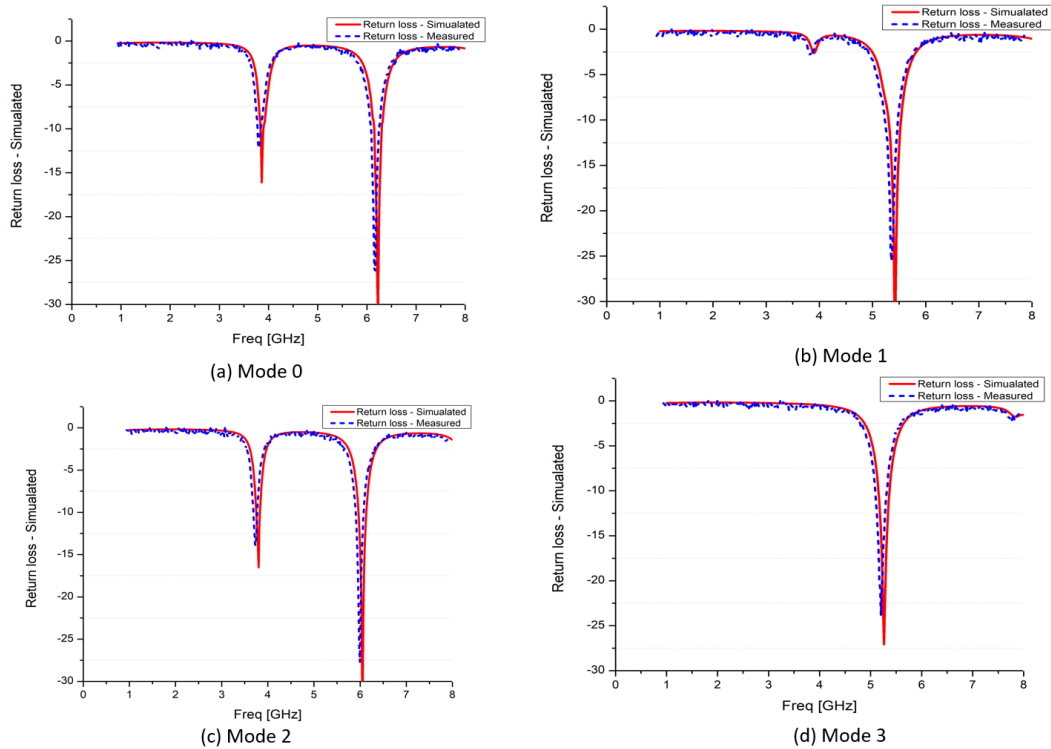


Figure 16. Return loss – simulated and measured of different modes (a) Mode 0 (b) Mode 1 (c) Mode 2 and (d) Mode 3

The simulated and measured radiation patterns for the E-plane and H-plane are illustrated in the Figure 17 across the various frequency bands offered in each operational mode. A strong correlation is observed between the HFSS electromagnetic models and the

experimental data obtained from the anechoic chamber, validating the antenna's design reliability. These patterns demonstrate stable radiation characteristics and consistent main-lobe orientation, ensuring robust signal coverage despite the dynamic frequency shifts enabled by the switching matrix.

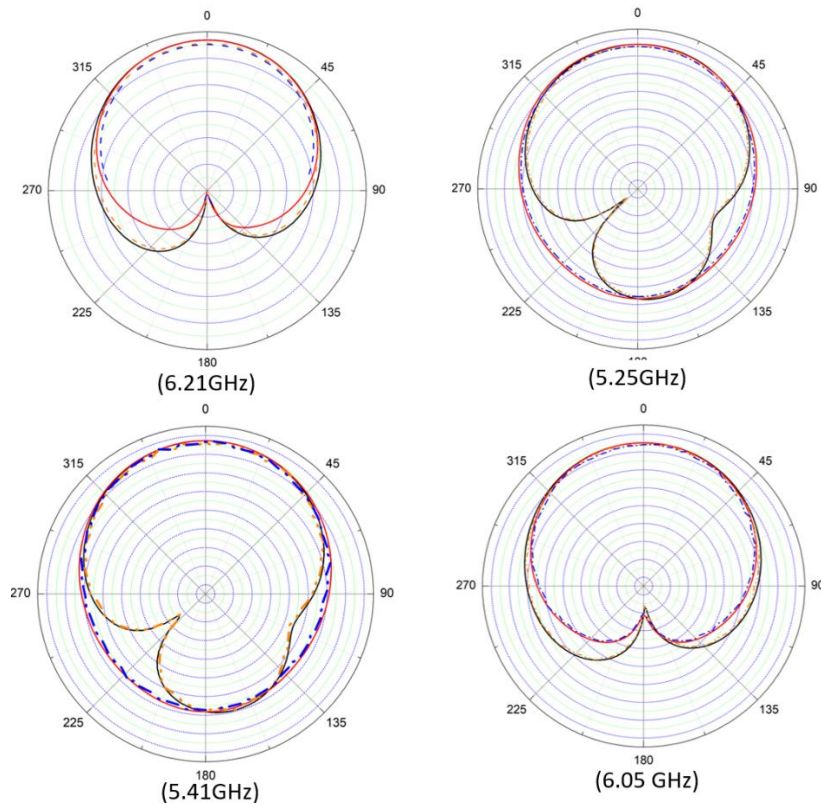


Figure 17. Radiation pattern comparison of proposed antenna between simulated and measured results at different frequencies

The measured performance characteristics of the reconfigurable antenna across four distinct switching states is (Cases 00, 01, 10, and 11) presented in Table 6 which demonstrates high-order spectral agility within the Sub-6 GHz domain. In Mode 0, the antenna operates in a dual-band mode covering the 3.73–3.82 GHz and 6.10–6.28 GHz ranges, achieving a significant return loss of -33 dB and a peak gain of 3.44 dBi at the higher resonance. Mode 2 similarly exhibits dual-band behavior with resonances at 3.77–3.84 GHz and 5.99–6.16 GHz, maintaining consistent gain levels across the tuned states.

Mode	No. of frequency bands	Bandwidth (GHz)	Return loss (dB)	Peak Gain (dB)
0	2	3.73-3.82, 6.10-6.28	-16.53, -33	1.82, 3.44
1	1	5.36-5.58	-26	3.65
2	2	3.77-3.84, 5.99-6.16	-12.75 -32.28	1.82 2.69
3	1	5.15-5.37	-27.72	3.59

Table 6. Switching modes of the proposed antenna prototype

In contrast, Mode 1 and 3 transition the radiator into single-band operational modes. Mode 1 targets the 5.36–5.58 GHz band with a peak gain of 3.65 dBi, while Mode 3 shifts the resonance to the 5.15–5.37 GHz range with a gain of 3.59 dBi. Throughout all states, the antenna maintains a return loss well below the standard -10 dB threshold, confirming efficient impedance matching. These results validate the effectiveness of the switching matrix in dynamically altering the antenna’s electrical length to service multiple wireless standards within a unified physical footprint.

Ref. No	Size (mm ²)	Freq. bands (GHz)	No. of diodes	Peak gain (dB)
[32]	25X25	4.478, 4.986	1	4
[33]	18.3X50	3.49, 3.36, 3.25, 3.10, 2.49, 2.37, 2.26, 2.18, 2.12–3.49	5	0.2–4.8
[34]	50X50	2.43, 2.85, 3.33, 4.4	3	2.5, 2.7, 3.6, 5.3
[35]	25X27	2.3, 5.8, 2.3, 4.5, 5.8	3	0.3, 2.5, 0.7/2.3, 1.8/2.8
This work	25X25	3.78, 3.87, 5.18, 5.41, 6.05, 6.21	2	1.82– 3.42

Table 7. Result validation through Comparison of simulation and testing results for proposed antenna prototype

The experimental validation of the proposed compact frequency-reconfigurable antenna demonstrates superior spectral agility through the implementation of four distinct operational modes. As shown in the result summary, the switching matrix—utilizing only two PIN diodes—enables the radiator to transition between dual-band and single-band states, covering critical allocations such as the 3.78 GHz, 5.18 GHz, and 6.21 GHz bands. The antenna maintains excellent impedance matching across all configurations, with return loss values reaching as low as -33 dB and peak gains topping at 3.65 dBi. This high-order agility confirms that the design successfully optimizes the electrical length of the patch to service multiple Sub-6 GHz standards within a unified physical footprint.

When compared to existing literature (Table 7), this work offers a significant improvement in hardware efficiency and performance density. While conventional designs often require high component counts to achieve multi-band operation—such as the five diodes used in [33] the proposed CMSA with slot and DGS achieves comparable frequency coverage using only two switches. Furthermore, with a compact size of 25X25mm, the antenna matches the miniaturization of V-slot patches while offering more extensive band coverage and stable gain characteristics up to 3.42 dBi. These findings validate that the integration of strategic slotting and defective ground structures provides a robust, low-complexity solution that outperforms current state-of-the-art reconfigurable antennas in both spectral flexibility and structural miniaturization.

8. Achievements with respect to Objectives

The research has successfully met its all-predefined objectives through the development, modeling, and simulation of interference-aware Radio Resource Management (RRM) frameworks. The key outcomes, contributions and its impact upon the real-time 5G and beyond 5G wireless technologies are summarized below:

Research Objective	Technical Achievement	Outcome Achieved
High-Order Spectral Agility	Designed antenna configuration achieving 9 distinct bands across 4 operational modes.	Transcended the 3–6 band limitation prevalent in current hardware-validated literature.
Minimalist Reconfiguration	Utilized a low component count (only 2 PIN diodes for Design 1 and 1 diode for Design 2).	Demonstrated high-order tuning with reduced biasing complexity and lower insertion loss.
Performance Optimization	Maintained a 1.6 mm FR4 profile while achieving peak gains of 5.59 dBi (Design 2) and 3.42 dBi (Design 3).	Mitigated gain and bandwidth degradation typically associated with tunable, low-cost substrates.
Strategic Multi-Standard Support	Developed reconfigurable antennas targeting specific LTE, WLAN, and 5G NR allocations.	Provided a systematic, manufacturable framework for high-traffic Sub-6 GHz applications.

Table-8 Outcomes achieved w.r.t Research Objectives

9. Conclusion

The research presented in this thesis successfully addresses the critical challenges of aperture congestion and hardware rigidity in next-generation wireless terminals by developing a high-order, electronically reconfigurable antenna framework. By integrating advanced physical-layer optimization techniques—specifically minimalist switching matrices, Defective Ground Structures (DGS), and strategic slot-loading—the work demonstrates that spectral agility can be significantly enhanced within a compact footprint without the typical complexity of high-count biasing circuits. The findings confirm that a reconfigurable approach allows a single radiating element to replace multiple fixed apertures, ensuring seamless support for diverse protocols including LTE/4G, 5G Sub-6GHz, WiMAX, and INSAT C-band/X-band applications.

Through extensive electromagnetic modeling in Ansys HFSS and subsequent hardware validation using a 10 GHz Vector Network Analyzer, the research met all its core objectives, proving that strategic reconfiguration outperforms traditional wideband and multi-band antenna strategies. Key achievements include the realization of an unprecedented nine distinct frequency bands using only two PIN diodes and a dual-reconfigurable design (frequency and pattern) that utilizes a single switch to maintain a peak gain of 5.59 dBi on low-cost 1.6 mm FR4 substrates. Ultimately, these contributions—validated by two granted design patents and one pending utility patent—provide a robust, cost-effective, and scalable foundation for the deployment of high-capacity 5G and beyond wireless devices, ensuring hardware-level agility in increasingly dense spectral environments.

10. Publication Details

10.1 Journal Publications

1. Sameer Mansuri, and Shahid Modasiya "A Multi-Mode Frequency Reconfigurable Antenna for 5G and WLAN Applications" in *Indian Journal of Natural Sciences*, Vol.14, Issue 82, pp. 69167-69173, February 2024. **(WoS Indexed)**
2. Mansuri Sameer, and Shahid S. Modasiya. "Reliable Single Diode Patch Antenna With Dual Mode Frequency And Pattern Reconfigurability With Compliance Analysis." *Reliability: Theory & Applications* 20.4 (89) (2025): 1006-1016. **(Scopus Indexed)**

10.2 Patent Publications

1. **Octagonal Frequency Reconfigurable Slotted Patch Antenna:** Successfully secured a granted design patent for a novel octagonal geometry utilizing integrated slots to achieve precise frequency agility, ensuring legal protection for a ten-year duration. (Design no. 440489-001, Date of issue : 19/06/2025)
2. **Slotted Triangular Frequency Reconfigurable Patch Antenna with Stubs:** Obtained a second granted design patent for a triangular patch configuration featuring optimized stubs, providing a proprietary and hardware-validated solution for multi-band wireless communication. (Design no. 440491-001, Date of issue : 11/12/2025)

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