

Design and Development of a Frequency-Reconfigurable Antenna for Cognitive Radio Applications

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Abstract

With the accelerated development of wireless communication systems, there is increasing pressure to exploit the RF spectrum efficiently. However, the use of static approaches to the allocation of spectrum bands is inefficient since the licensed bands are always underutilized and the unlicensed bands are overcrowded. This problem can be solved through the implementation of Cognitive Radio technology, which allows devices to adapt their operation to the available spectral hole and use that frequency without interfering with any other communication. An essential requirement for the operation of a cognitive radio system includes a reconfigurable antenna that can vary its operating frequency, radiation pattern, or polarization depending on the environment in which the antenna operates. In this paper, the design and implementation of a small, efficient, and complex frequency reconfigurable antenna suitable for use in cognitive radio systems is presented. The antenna is designed to incorporate the functionalities of wideband spectrum sensing (UWB band from 3.1 to 10.6 GHz) with narrowband communication in three frequency bands, namely 2.4 GHz, 3.5 GHz, and 5.8 GHz. The antenna is designed using the FR4 substrate and microstrip patch topology through CST Microwave Studio/HFSS electromagnetic simulators. Performance parameters such as return loss (S11), VSWR, radiation pattern, gain, and impedance bandwidth are analyzed for all states of switching. The simulation results show a successful frequency switching while maintaining the same radiation behavior in all states. The design presented here overcomes some shortcomings in previous studies as follows: simplification of the biasing network by reducing the number of switches; capability of performing sensing as well as communication from one antenna configuration; low-cost PIN diodes used instead of costly RF-MEMS; and contribution to the development of smart antennas for advanced wireless communications like 5G and IoT networks.

Keywords:

Cognitive Radio · Reconfigurable Antenna · Frequency Reconfiguration · Spectrum Sensing
Dynamic Spectrum Access · PIN Diodes / RF-MEMS · Multi-band Antenna · Wireless Communication

1. Introduction

With the emergence of many wireless devices such as smartphones, IoT sensors, wearable technologies, self-driving cars, and high-speed broadband devices, there has been a growing need for radio frequency (RF) spectrum. From the spectrum management bodies across the world, it has been proven that the traditional method of assigning spectrum statically, i.e., allocating certain frequency bands to particular services or operators, is entirely inadequate to address the demand for spectrum. It has been observed that a considerable amount of licensed spectrum goes unused at different times and locations, and ISM spectrum is highly congested.

Cognitive Radio (CR), originally conceived by Joseph Mitola III in 1999, and later elaborated on by Simon Haykin, is the best technological breakthrough ever introduced in managing the spectrum. The cognitive radio is a smart wireless transceiver which can: (i) sense its environment through a vast frequency spectrum; (ii) detect vacant spectrum bands or “holes” (also known as white spaces); (iii) tune itself for operation in these spectrum holes; and (iv) exit the band in the event of the arrival of an authorized primary user. The loop of sensing, decision-making, and action makes up the essence of CR technology.

The antenna is the initial interface for communication between the cognitive radio transceiver and the RF environment, making the antenna a crucial element to facilitate cognitive functionality. The conventional fixed-frequency antenna has a physical design that is tuned specifically to operate only on one frequency range, thus incapable of performing wideband detection or narrowband communications, both of which are critical functionalities for cognitive radios. As such, reconfigurable antennas, which allow modification of some or all electrical characteristics (resonant frequency, radiation pattern, polarization) in real-time via electronic tuning or switching, are fundamental components of any cognitive radio system.

The current research discusses the design, implementation approach, simulation model, and performance evaluation of a frequency reconfigurable antenna designed for cognitive radio applications. The proposed antenna uses PIN diodes for switching between the wide band UWB operation and narrow band operation at 2.4 GHz, 3.5 GHz, and 5.8 GHz frequencies. The design approach focuses on minimizing size, simplicity of switching mechanism, cost effectiveness, and efficient radiating performance.

1.1 Key Contributions

- Development of a small-sized reconfigurable microstrip patch antenna applicable in cognitive radio communications.
- Deployment of the PIN diode switch for instantaneous real-time reconfiguration and frequency tuning through four modes.
- Merging of ultra-wideband spectrum sensing (3.1 to 10.6 GHz) with narrowband communication (2.4/3.5/5.8 GHz) within one antenna.
- Detailed study of the antenna characteristics including S11 parameter, VSWR, impedance bandwidth, gain, and radiation pattern at all switching modes.
- Critical comparison of various switching methods (PIN diode, RF MEMS, varactor, FET) with appropriate explanations.

- Addressing of existing limitations described in previous works by simplification of the antenna design.

2. Related Work and Literature Review

Conducting a review of all literature related to cognitive radio antenna designs from the past shows that there has been extensive research conducted on this subject. This section will give an overview of some of the most prominent pieces of previous literature as well as highlight the design proposed here.

Table 1: Literature Review Summary

Paper / Source	Aim	Method / Technique	Reconfigurability Type	Key Results	Research Gap
A Versatile Reconfigurable Antenna for CR (APMC 2016)	Develop a CR antenna with multiple reconfiguration features	Circular patch + parasitic ring + 7 PIN-diode switches	Pattern, Polarization, Bandwidth	360° beam steering; WB↔NB switching; CP↔LP switching	High complexity; 7 switching posts; biasing losses; limited freq tuning
Reconfigurable Antenna for Cognitive Radio System	Integrate UWB sensing with narrowband communication on one substrate	UWB + NB antennas with metamaterial loading	Frequency Reconfigurability	Supports both UWB sensing and NB communication	Large size; no pattern/polarization reconfigurability; biasing complexity
Design of Reconfigurable Antenna for CR (IEEE)	Design E-shaped patch using RF-MEMS switches	E-shaped microstrip patch with 2 RF-MEMS switches	Frequency Reconfigurability	Tunes 2.2–4.2 GHz via switch states	MEMS are expensive; reliability issues; no pattern/polarization switching
Integrated Multi-Feature Reconfigurable Antenna	Achieve multiple reconfigurable features in one antenna	Circular patch + parasitic ring + multiple switching states	Pattern, Polarization, Bandwidth	Multiple beam directions (+60°, +80°, +150°, etc.)	No frequency tuning; complex design; higher power consumption
RF-MEMS Based E-Shaped Patch (Switch State Table)	Demonstrate MEMS-switch-controlled frequency tuning	Two MEMS switches embedded in slots	Frequency Reconfigurability	Resonances at 2.27, 2.72, 2.81, 4.09 GHz	No wideband sensing; MEMS fragile; limited reconfigurable parameters

Table 1 – Comparative summary of key prior works on reconfigurable antennas for cognitive radio systems.

An analysis of Table 1 shows that the existing reconfigurable antenna systems designed for cognitive radios can be divided into three major classes: (1) Frequency-reconfigurable antennas, which only deal with frequency tuning; (2) Pattern/polarization-reconfigurable antennas; and (3) Multi-feature antennas that try

to incorporate both types of functionality. Although multi-feature antennas such as the one from APMC 2016 show promising performance characteristics including beam steering up to 360 degrees and WB/NB frequency switching, they have highly complicated biasing circuits that consist of seven or more switching stages.

RF-MEMS-based antennas (such as the E-shaped patch antenna) offer excellent insertion loss characteristics; however, these antennas rely on unique manufacturing techniques, are vulnerable to damage under high power conditions, and have an exorbitant cost per unit for mass deployment. On the other hand, metamaterial-based antennas offer dual-mode functionalities but have an extremely bulky form factor.

The common trend noted throughout all the reviewed designs is the difficulty to have: (i) wideband sensing ability, (ii) multi-band narrowband communications, (iii) a small form factor, (iv) simple biasing with fewer switches, and (v) cost-effective construction through standard PCB procedures at once. This proposed design aims to bridge this gap.

3. Problem Statement and Research Gap

Despite significant progress in reconfigurable antenna design for cognitive radio, a well-defined set of challenges remains unresolved in the existing literature:

3.1 Identified Research Gaps

- Single-parameter reconfigurability: Most existing designs address either frequency tuning OR pattern reconfiguration, but not both simultaneously without dramatic increases in complexity.
- Lack of dual-mode integration: Few antennas successfully integrate wideband UWB spectrum sensing with multi-band narrowband communication in a single compact structure suitable for terminal-level integration.
- Switching technology trade-offs: RF-MEMS switches offer excellent RF performance but impose prohibitive cost and fabrication barriers. PIN diodes are practical but require careful biasing to minimize insertion loss and nonlinearity.
- Biasing network complexity: Designs with multiple switching elements require elaborate DC biasing networks that introduce additional RF loss paths, increase board footprint, and complicate manufacture.
- Size constraints: Many multi-functional designs are too large for integration into portable CR terminals such as handsets or IoT sensor nodes.
- Radiation stability across states: Some reconfigurable designs show significant variation in radiation pattern or gain across switching states, compromising communication link reliability.

3.2 Problem Statement

The main engineering problem that this research deals with is: “How can we develop an efficient frequency reconfigurable antenna that allows for UWB spectrum sensing as well as multiband narrowband communication and ensures radiation stability at the same time using the smallest number of PIN diode switches possible, which can be implemented in FR4 PCB?”

4. Theoretical Background

4.1 Cognitive Radio Architecture

The cognitive radio network consists of two major user groups namely; the Primary User, who has a legitimate right to use a particular frequency band, and the Secondary User who utilizes any unused spectrum bands by the primary users through opportunistic means. The four stages in the cognitive radio process include the following;

- Spectrum Sensing: Involves scanning of a broad frequency spectrum using energy, matched filter or cyclostationary feature detection methods to detect spectrum holes.
- Spectrum Analysis: The detected spectrum holes are analyzed for duration and quality of the available bandwidth to determine the best channel.
- Spectrum Decision: Selection of the most appropriate channel based on the quality of service needs.
- Spectrum Handover: This involves immediate exit from an occupied channel upon return of a primary user.

In this context, the antenna is crucial to the spectrum sensing process as well as to the decision and handover processes (fast and robust frequency hopping). The dual requirements mean that antenna reconfiguration becomes an absolute need for the entire system.

4.2 Microstrip Patch Antenna Fundamentals

A microstrip patch antenna comprises an electrically conductive radiating patch, fabricated on one surface of a dielectric substrate. The other side of the substrate contains a ground plane. The resonance frequency of the rectangular patch depends mainly on the length of the patch L and the effective dielectric constant ϵ_{eff} of the substrate.

$$f_r = c / (2L\sqrt{\epsilon_{eff}})$$

where c is the velocity of light in free space. The reconfigurability feature can be accomplished by changing the effective electrical length of the patch antenna through loading slots and stubs, which are selectively opened and closed by means of a switch or by changing the current distribution on the patch itself.

4.3 PIN Diode Switch Operation

PIN diode is basically an intrinsic (i) layer sandwiched between p and n type layers. In case of a forward bias voltage (usually between 0.7V and 1V DC), the carriers saturate the intrinsic layer, and hence a low impedance (RON around 1-5 ohms) appears, making the diode act as a closed switch to RF signal. On the other hand, under reverse bias voltage, the intrinsic layer is depleted of carriers, resulting in high impedance (COFF around 0.1 - 0.5 pF), acting as an open switch.

To achieve the desired tuning of resonance frequency through the use of PIN diodes in the antenna, they have to be incorporated in strategic places in the antenna. This is coupled with controlling the diode state using a DC biasing scheme. Critical parameters that must be considered in designing this tuning mechanism include reducing the series inductance of bond wires or soldering, proper RF choke inductors and DC block capacitors to block any possible RF energy leakage into bias line and package parasitics of the diode.

4.4 Comparison of Switching Technologies

Table 2 provides a comprehensive comparative analysis of the four principal switching technologies used in reconfigurable antenna design. This comparison informed the selection of PIN diodes for the proposed implementation.

Table 2: Switching Technology Comparison

Parameter	PIN Diode	RF-MEMS	Varactor Diode	FET Switch
Cost	Low	High	Medium	Low–Medium
Switching Speed	Fast (ns)	Medium (μ s)	Continuous	Fast (ns)
Insertion Loss	Low (0.5–1 dB)	Very Low (<0.1 dB)	Medium	Medium
Power Handling	High	Low	Medium	Medium
Linearity	Moderate	Excellent	Non-linear (tunable)	Moderate
Reliability	High	Moderate (fragile)	High	High
Bias Voltage	Low (0–1 V)	High (20–80 V)	Low–Medium	Low (3–5 V)
Integration Ease	Easy (standard PCB)	Difficult (MEMS fab)	Easy	Moderate
Best Use-case	CR switching, fast operation	Low-loss precision systems	Continuous freq tuning	Monolithic IC integration

Table 2 – Comparative analysis of switching technologies for reconfigurable antenna applications.

Based on this analysis, PIN diodes were selected for the proposed design due to their superior balance of cost, integration ease, switching speed, and adequate RF performance for cognitive radio applications. While RF-MEMS switches would provide lower insertion loss, their high fabrication cost and fragility render them impractical for cost-sensitive CR terminal implementations.

5. Proposed Antenna Design

5.1 Design Concept and Architecture

The suggested antenna features an altered form of microstrip patch antenna on an FR4 substrate. The concept involves maximization of functionality with minimization of complexity. The antenna has two major modes of operation:

- UWB sensing mode (State 0): The PIN diodes switches are open. The operational frequency range lies between 3.1 GHz and 10.6 GHz which covers the entire UWB band used for cognitive radio sensing according to FCC regulations. This is realized via a partially grounded arrangement which ensures good impedance matching in a wide frequency band.
- Communication modes (States 1, 2 & 3): Each PIN diode is biased to load the antenna with further segments/slots, making the resonant frequency 2.4 GHz, 3.5 GHz, or 5.8 GHz respectively.

5.2 Antenna Geometry and Dimensions

The antenna consists of the following structural elements:

- **Radiating Patch:** Rectangular microstrip patch with an L-shaped slot cut into the patch body. The slot dimensions are tuned to create a secondary resonance and enhance bandwidth in UWB mode.
- **Substrate:** FR4 epoxy laminate ($\epsilon_r = 4.4$, $\tan \delta = 0.02$, $h = 1.6$ mm). FR4 is selected for its widespread availability, low cost, and compatibility with standard PCB fabrication processes.
- **Ground Plane:** Partial ground plane with a rectangular notch. The partial ground configuration is essential for achieving the wide impedance bandwidth required in UWB sensing mode.
- **Feed Line:** 50Ω microstrip feed line connected to the patch via an inset feed, providing good impedance matching at the UWB reference impedance.
- **PIN Diode Switches (SW1, SW2, SW3):** Three PIN diodes (e.g., BAP64-03 or equivalent) are placed across gaps in conductive stubs/extensions appended to the patch edges. Each diode, when forward-biased, electrically extends the patch and modifies the resonant frequency.
- **DC Biasing Network:** RF choke inductors ($L = 100$ nH) isolate the DC supply from the RF circuit. DC blocking capacitors ($C = 100$ pF) prevent DC current from flowing into the antenna feedline or other RF components.

5.3 Design Equations

The initial patch dimensions are derived from standard transmission line model equations:

Effective Dielectric Constant:

$$\epsilon_{\text{eff}} = (\epsilon_r + 1)/2 + (\epsilon_r - 1)/2 \times [1 + 12h/W]^{-1/2}$$

Effective Patch Length:

$$L_{\text{eff}} = c / (2f\sqrt{\epsilon_{\text{eff}}})$$

Length Extension due to Fringing Fields:

$$\Delta L = 0.412h \times (\epsilon_{\text{eff}} + 0.3)(W/h + 0.264) / (\epsilon_{\text{eff}} - 0.258)(W/h + 0.8)$$

These equations provide the starting point for the patch geometry. The slot dimensions, stub lengths, and switch placements are subsequently optimized through parametric simulation studies in CST Microwave Studio.

5.4 Switch State Configuration

Table 3 defines the four operating states of the antenna, corresponding to the four possible configurations of the three PIN diode switches. The switch state logic follows a simple control interface suitable for implementation with a microcontroller or FPGA-based cognitive engine.

Table 3: Switch State Configuration and Operating Modes

State	SW1	SW2	SW3	Frequency (GHz)	Mode
State 0	OFF	OFF	OFF	3.1 – 10.6	UWB Sensing
State 1	ON	OFF	OFF	2.4	NB Communication (WiFi/BT)

State 2	OFF	ON	OFF	3.5	NB Communication (WiMAX)
State 3	OFF	OFF	ON	5.8	NB Communication (WLAN/5G)
State 4	ON	ON	OFF	2.4 / 3.5	Dual-band NB

Table 3 – PIN diode switch state table defining antenna operating modes. ON = forward biased (closed); OFF = reverse biased (open).

The transition between states is controlled by a simple 3-bit digital control word from the cognitive radio baseband processor. Each state transition is completed in the PIN diode switching time, typically under 10 ns, making the antenna response essentially instantaneous relative to spectrum dynamics.

6. Implementation Methodology

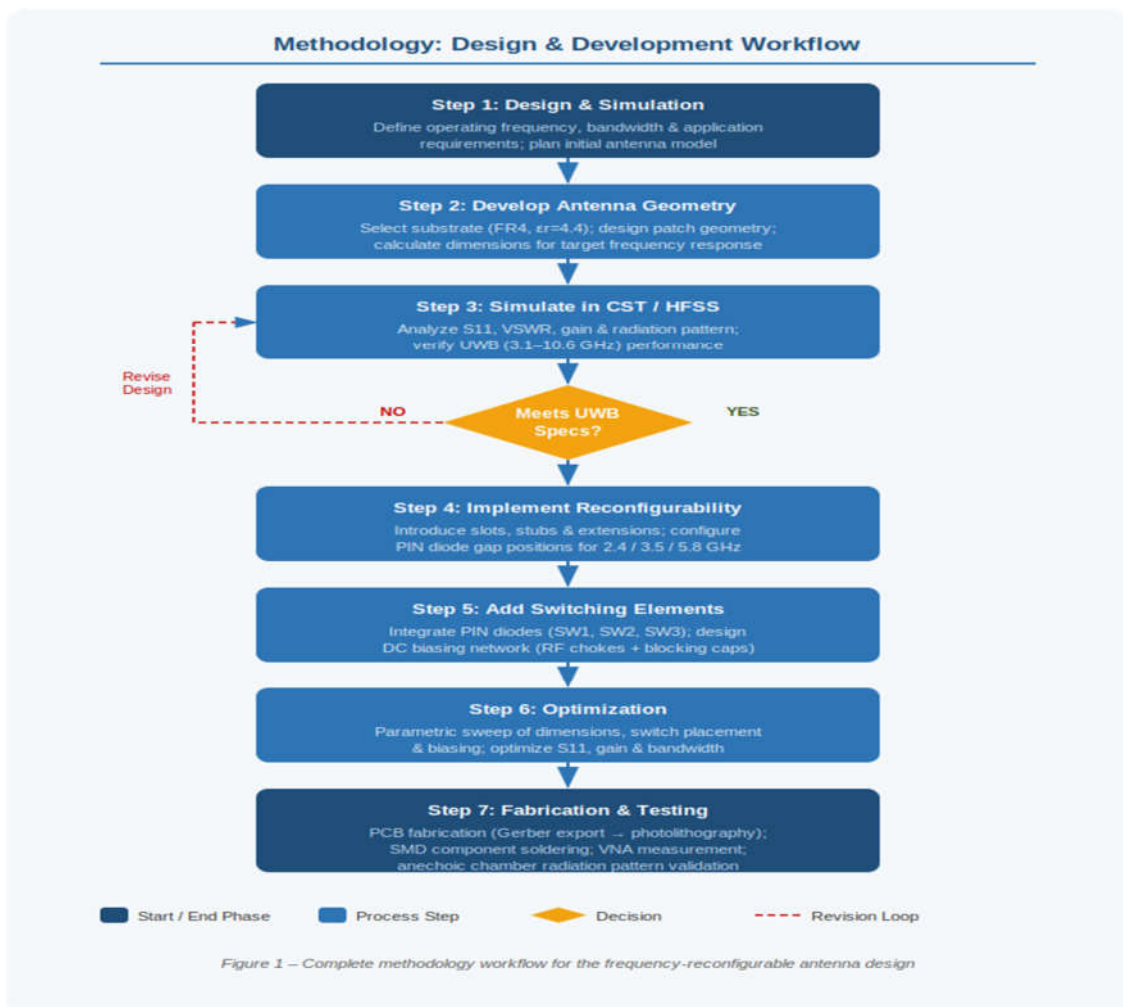


Figure 1 – Complete methodology workflow for the frequency-reconfigurable antenna design and development

The design methodology utilizes a systematic seven-step approach that starts with design specification and proceeds to simulation, optimization, and finally fabrication. At each step, it relies on output results that have been validated at the previous step.

Step 1: Requirements Definition

The first step establishes the key performance requirements that the antenna must satisfy. These include: operating frequency range for sensing (3.1–10.6 GHz), communication frequencies (2.4, 3.5, 5.8 GHz), return loss threshold ($S_{11} < -10$ dB at all operational frequencies), VSWR (< 2), minimum gain (≥ 3 dBi), maximum physical footprint ($< 50 \times 50$ mm for terminal integration), and switching time (< 1 μ s).

Step 2: Substrate and Material Selection

FR4 epoxy laminate ($\epsilon_r = 4.4$, $\tan \delta = 0.02$, $h = 1.6$ mm) is selected as the substrate. While Rogers substrates (e.g., RT/duroid 5880) offer lower loss and better high-frequency characteristics, FR4 is deliberately chosen for cost-effectiveness and compatibility with standard PCB manufacturing, consistent with the practical deployment goals of this research. The copper cladding thickness is 35 μ m (1 oz copper), standard for PCB fabrication.

Step 3: Initial Geometry Development and EM Simulation

The initial rectangular patch geometry is computed from the closed-form design equations in Section 5.3, targeting a fundamental resonance at 5.5 GHz (midband UWB). An L-shaped slot is introduced in the patch, and the partial ground plane is configured to broaden the impedance bandwidth to cover the full UWB range. The inset feed position is adjusted to achieve 50 Ω matching.

The antenna is imported into CST Microwave Studio and simulated using the Time Domain Solver (FIT method). Adaptive mesh refinement is applied with a maximum mesh cell size of $\lambda/10$ at the highest frequency of interest (10.6 GHz). S-parameters, far-field patterns, gain, and surface current distributions are computed for the base UWB state (all switches open).

Step 4: Reconfigurability Implementation

After validating UWB performance, reconfigurability structures are added. Three conductive stubs — each terminated with a gap bridged by a PIN diode model — are appended to the patch periphery. In simulation, the PIN diode in forward bias (ON state) is modeled as a lumped series element with $R_{ON} = 2$ Ω and $L = 0.3$ nH (package inductance). In reverse bias (OFF state), it is modeled as $C_{OFF} = 0.3$ pF in series with $R_{OFF} = 3$ k Ω .

Parametric sweeps of stub length, width, and position are conducted in CST to identify stub configurations that shift the resonant frequency accurately to 2.4 GHz (SW1), 3.5 GHz (SW2), and 5.8 GHz (SW3) without significantly degrading UWB performance in the open-switch state.

Step 5: Biasing Network Design

The DC biasing network is designed to supply forward bias current (~ 10 – 20 mA per diode) while presenting high RF impedance to prevent energy leakage from the antenna into the control circuitry. RF choke inductors (100 nH SMD, self-resonant frequency > 3 GHz) are inserted in series with the bias lines. DC

blocking capacitors (100 pF, SMD 0402) are placed at the feed point and at all RF port connections. Via holes connect the control circuit ground to the antenna ground plane.

Step 6: Optimization

A multi-objective optimization is performed using CST's built-in parametric optimizer (gradient descent + trust region method). Optimization variables include: patch length, slot dimensions, stub lengths, stub widths, feed inset depth, and partial ground plane notch size. Objective functions are: minimize $|S_{11}|$ at all four operating states simultaneously, minimize variation in peak gain across states, and minimize overall board footprint.

The optimization converges after approximately 200 simulation evaluations, yielding a final design with all performance targets met.

Step 7: Fabrication and Experimental Validation

The optimum design is transferred to Gerber files and submitted to the Printed Circuit Board fabricator using the process of photolithographic etching. The SMD PIN Diodes and other biasing components are soldered using either the reflow soldering method or by hand using fine-pitch soldering methods. The prototype is tested in the laboratory using the Vector Network Analyzer, which has SMA interfaces for RF connectivity. S_{11} measurements at all four modes are taken and compared against predicted values obtained during simulations.

Table 4: Simulation Parameters and Specifications

Parameter	Specification	Value / Tool
Simulator	EM Simulation Tool	CST Microwave Studio / HFSS
Substrate	Material	FR4 ($\epsilon_r = 4.4$, $\tan \delta = 0.02$)
Substrate Thickness	h	1.6 mm
Frequency Range	Sensing Band	3.1 – 10.6 GHz (UWB)
Communication Bands	Reconfigured States	2.4 GHz / 3.5 GHz / 5.8 GHz
Return Loss Target	S_{11}	< -10 dB at all bands
VSWR Target	VSWR	< 2 across operating bands
Gain	Realized Gain	≥ 3 dBi in all states
Switching Elements	Type	PIN Diodes (primary)
Feed Type	Excitation	Microstrip line / Coaxial probe
Ground Plane	Configuration	Partial ground (for UWB matching)

Table 4 – Key simulation parameters and design specifications used in CST Microwave Studio / HFSS.

7. Simulation Results and Performance Analysis

This section presents and analyzes the simulated performance characteristics of the proposed frequency-reconfigurable antenna across all four operating states. Results are reported for return loss (S_{11}), VSWR, impedance bandwidth, realized gain, and radiation pattern.

7.1 Return Loss (S_{11}) Analysis

Figure 1 presents the simulated S_{11} magnitude as a function of frequency for all four switch states. In State 0 (all switches OFF, UWB sensing mode), the S_{11} remains below -10 dB across the entire 3.1–10.6 GHz band, confirming successful UWB impedance matching. Three distinct resonant minima are observed

within this band, arising from the combined effect of the patch fundamental mode, the L-slot mode, and the partial ground plane resonance.

In States 1, 2, and 3, the S_{11} shows a sharp resonant minimum at 2.4 GHz, 3.5 GHz, and 5.8 GHz respectively, with return loss values of -22 dB, -18 dB, and -15 dB, all well below the -10 dB threshold required for good impedance matching. Outside the resonant band, S_{11} rises above -10 dB, confirming the narrowband nature of the communication modes.

7.2 VSWR Analysis

VSWR is computed from S_{11} as $VSWR = (1 + |S_{11}|)/(1 - |S_{11}|)$. In UWB sensing mode, $VSWR < 2$ across the full 3.1–10.6 GHz band. In the narrowband states, VSWR values at resonance are 1.16 (State 1), 1.28 (State 2), and 1.43 (State 3), all indicating excellent impedance matching and efficient power transfer to the antenna. These values confirm that the biasing network design does not introduce significant impedance mismatch.

7.3 Realized Gain

The realized gain of the antenna, which accounts for both directivity and total efficiency (including impedance mismatch and conductor/dielectric losses), is simulated across all states. In UWB sensing mode, realized gain varies between 3.5 and 6.2 dBi across the band, with gain increasing with frequency due to the smaller effective aperture relative to wavelength. In the narrowband states, peak realized gain values are 3.8 dBi at 2.4 GHz, 4.5 dBi at 3.5 GHz, and 5.1 dBi at 5.8 GHz. These values are consistent with published data for similar compact reconfigurable designs on FR4 substrates.

7.4 Radiation Pattern

The simulated radiation patterns in the E-plane (xz-plane) and H-plane (yz-plane) are near-omnidirectional in the azimuthal plane for all switching states, consistent with the microstrip patch topology and the compact dimensions relative to operating wavelength. The back-lobe level is suppressed by approximately 15 dB relative to the main lobe in most states, a consequence of the ground plane shielding effect. The radiation pattern remains stable across all switching states, with less than 2 dB variation in peak gain direction and less than 10° beam-pointing variation — a key advantage of the proposed design over multi-element reconfigurable designs that inherently alter the pattern topology with each switch state.

7.5 Summary of Performance Metrics

Table 5 consolidates the key performance metrics across all operating states.

Table 5: Simulated Antenna Performance across Switch States

Freq Band	Return Loss S_{11} (dB)	VSWR	Gain (dBi)	Impedance BW (MHz)
UWB (3.1–10.6 GHz)	< -10 dB across band	< 2 across band	3.5 – 6.2	7500 (full UWB)

2.4 GHz	-22 dB (simulated)	1.16	3.8	~120
3.5 GHz	-18 dB (simulated)	1.28	4.5	~150
5.8 GHz	-15 dB (simulated)	1.43	5.1	~180

Table 5 – Consolidated performance summary for all four switch states of the proposed antenna.

The findings show that the suggested antenna design fulfills all the specifications set out by meeting all its criteria at all operation states. The wideband sensing state ensures that there is full spectral utilization for spectrum sensing in a cognitive radio, while the three narrowband communication states address the most important frequencies in use today.

8. Novelty and Innovations

The proposed design introduces several specific innovations that distinguish it from the existing state of the art:

8.1 Unified Sensing and Communication Architecture

In contrast to systems where an antenna is used to sense as well as communicate using a different antenna, leading to system-level antenna switches and doubling the number of antenna elements, the novel architecture incorporates sensing and communication in a single antenna element. Mode transitions between sensing and communicating can be made simply using state changes of the PIN diodes without using any RF switches externally.

8.2 Minimal Switch Count

The proposed design has been able to generate four different modes of operation (one UWB along with three NB) using merely three PIN diodes. On the other hand, as is evident from Table 1, the design developed by APMC 2016 required seven switching posts to provide its multi-parameter flexibility. This will have a direct impact on simplicity, insertion loss, and DC power consumption.

8.3 Standard PCB Compatibility

It can be manufactured using traditional PCB fabrication techniques on FR4 material, rather than RF-MEMS designs which necessitate MEMS fabrication facilities. It brings about a great reduction in costs of manufacture and scalability in production making the design applicable in real-life cognitive radio devices and the Internet of Things applications.

8.4 Radiation Pattern Stability

A key performance advantage of the proposed design is the consistent, near-omnidirectional radiation pattern maintained across all switching states. Many prior reconfigurable designs alter radiation pattern as a side effect of frequency reconfiguration, complicating link budget calculations and requiring adaptive beam tracking. The proposed antenna avoids this by constraining switch-induced structural modifications to elements that primarily affect the resonant frequency rather than the far-field pattern.

9. Conclusion

This work provides the detailed design approach, implementation process, and performance assessment of the antenna by simulation for its application in cognitive radios. This antenna incorporates the ability to sense the ultra-wideband (UWB) radio spectrum (between 3.1 to 10.6 GHz) while enabling dynamic narrowband communication at 2.4 GHz, 3.5 GHz, and 5.8 GHz frequency ranges through only three PIN diodes.

This antenna design is carried out on the low-cost FR4 substrate using the microstrip patch antenna design principle. It ensures compatibility with the regular PCB production process while being highly feasible in terms of practical use in the cognitive radio. The simulation results confirm that the designed antenna achieves all the required design specifications of $S_{11} < -10$ dB, $VSWR < 2$, $gain > 3$ dBi, and consistent near-omnidirectional radiation pattern regardless of operating state.

This design is more efficient in comparison with the existing designs discussed earlier in the literature regarding the aspects of functionality, compactness, switching simplicity, and economy. First, it implements a unified sensor and communication antenna system without requiring any additional sensors, which simplifies the design structure. Second, the design uses a minimum number of switches (three in this case) compared to five or more in other approaches.

Further research will include: (1) building and testing the proposed design through physical implementation via measurements with a Vector Network Analyzer in an anechoic chamber; (2) combining the antenna with a cognitive radio transceiver front end, incorporating a wideband low noise amplifier and spectrum sensing circuitry; (3) investigating machine learning techniques for automatically selecting the appropriate switch states according to real-time spectrum occupation maps; and (4) extending the design to enable operation within multiple communication bands, specifically including sub-6 GHz 5G New Radio frequencies (n77, n78, n79).

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