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Compact Reconfigurable Antenna with Frequency and Polarization Agility for Cognitive Radio Applications

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ABSTRACT

As technology develops, it is CR systems that now offer a way for underused frequency bands to be accessed, suitably filling the available spectrum. In order to take advantage of CR technology, agile antenna systems are required to alter their features in real-time. This paper shows how a compact adaptive antenna was designed and how it was tested for both frequency and polarization agility for use in cognitive radio applications. The suggested antenna uses PIN diodes and varactor tuning elements to help tune its frequency both discreetly and continuously within the range of 1.8 to 3.5 GHz. Its coverage of GSM, LTE and WiMAX means the antenna can be used in many areas without switching to another model. Polarization agility is accomplished with RF switches that directan advantage of the different polarization modes and prevent interference from incorrect polarization effects in different environments. The antenna is built on FR4 and measures only 30 mm by 35 mm. It includes a slot-loaded patch and a partially reconfigurable ground plane to improve the antenna's bandwidth and radiation qualities. Proper simulation of the antenna in CST Microwave Studio and physical measurements with a vector network analyzer and an anechoic chamber proved that it maintains constant radiation, has a maximum gain of 4.5 dBi and its radiation efficiency in all reconfigured states is higher than 85%. Due to its dual-agility, the antenna is able to support various spectrum usage, flexible channels and polarization and as a result, it can be considered for use in new CR transmitters and wireless communication tools.

1. INTRODUCTION

Because wireless communication is expanding so rapidly, the spectrum which supports these services, is becoming scarce. Because most conventional approaches are not flexible, there are periods when a band is empty and other times when there is overcrowding in other bands. Because of dynamic spectrum access (DSA), Cognitive Radio (CR) systems help unlicensed users use channels the primary users do not need. To perform well in fast-changing environments, reconfigurable antennas are essential components on CR devices. Because reconfigurable antennas can modify their frequency, polarization, radiation mode and impedance, they improve the communication system's productivity, signal strength and reliability.

For CR applications, frequency and polarization changing abilities are among the most vital features of reconfigurable antennas. Antennas that can change their frequency easily can use different frequencies to access unoccupied channels and frequencies that can change their polarization boost signal quality and minimize the loss someone might experience due to different path effects in the signal. Currently, designing prototype antennas with more than one type of agility is a difficult challenge and the final design is commonly big and bulky, with only a small number of options. We describe an integrated circuit design for an antenna that can be used on a single planar circuit board and can reconfigures both frequency and polarization at the same time. An antenna suitable for cognitive radio transceivers has a frequency range of 1.8 GHz to 3.5 GHz and can automatically switch between linear and circular modes, making it very useful for cognitive radio transceivers in changing and unsecure spectrum conditions. It satisfies the requirements for flexibility and size in wireless terminals and helps improve real-time adaptability and the use of spectrum in a CR network.

2. LITERATURE REVIEW

2.1 Frequency Reconfigurable Antennas

For cognitive radio to run, antenna devices must be able to swap between frequencies as different ones become available. Frequency reconfiguration has been achieved using PIN diodes, varactor diodes or RF MEMS switches, among other techniques. The reason PIN diodes are often used is that they have a fast switching time and are very affordable.

Pin diodes are commonly used because they switch quickly and cost less. If flexible frequency tuning is what you need, you can achieve it by adjusting the bias of the varactor diodes. The article (Lee et al., 2022) explores a wideband antenna with adjustable resonance, supporting LTE and WiMAX services in the frequency range of 2.2 GHz to 3.4 GHz. Being quite efficient in terms of insertion loss and isolation, RF MEMS face problems with their manufacturing and structure. These designs have been improved, but most of them align poorly or take up too much area which is not practical for portable and small CR terminals.

2.2 Polarization Reconfigurable Antennas

Because of diversity, communication is more robust as it reduces errors that come from multipath signals. Circular reconfigurable antennas that can also be used for linear polarization have become important in CRs, given that signals propagate differently in various places and positions. Researchers Chen et al. (2021) introduced a polarization-reconfigurable patch antenna using RF switches to control how the signal from the feed lines is polarized: vertical, horizontal or circular. Alternative studies have managed to achieve the same function by using patch elements that rotate mechanically or using combined hybrid couplers with phase shifters. Still, this style adds more complexity, takes up more room and performs inadequately in switch networks, so they aren't suitable for small devices or real-time system tasks.

2.3 Dual Reconfigurability in Compact Designs

Although both frequency and polarization reconfiguration have been well-investigated, incorporating both features in a small design is still a tough task. Few studies have tried to use jointly the two major agility mechanisms which led to complicated multi-layer constructions or impressive antennas. As an example, Singh et al. (2020) designed a reconfigurable antenna by adding slots and dual-feed networks but still had to depend on a bulky external matrix and large printed circuit board space. Alternatively, the proposed research focuses on making a low-profile single-layer patch antenna that uses both PIN diodes to adjust its frequency and controlled feeding to adjust its polarization. This type of design is smaller and offers the flexible operation needed by CR systems.

2.4 Gaps and Motivations for the Proposed Work

The analysis of previous studies suggests that reconfigurable antenna designs today suffer from narrow tuning bands, larger sizes and complex control systems. Furthermore, the majority of current designs can only change frequency or polarization separately, stopping them from being utilized in real-time CR scenes. As a result of these shortcomings, this work proposes using a dual-agile antenna that offers both small size, easy manufacturing, adjustable frequencies and instant switching. The architecture laid out should aid both spectrum adaptability and polarization-based communication, boosting the next-generation wireless network's intelligence.

Table 1. Comparative Review of Reconfigurable Antenna Designs

Reference / Study	Technique Used	Proposed Work Advantage
Ali et al. (2023)	PIN diode-based triple-band switching	Proposed antenna offers both frequency and polarization agility in a single compact design
Lee et al. (2022)	Varactor diode for continuous frequency tuning	Achieves discrete tuning across 1.8–3.5 GHz with simplified biasing and better stability
Chen et al. (2021)	Orthogonal feeds for polarization switching	Integrated dual-feed system with compact switching for seamless polarization reconfigurability
Singh et al. (2020)	Dual-feed and slot loading (bulky with external control circuits)	Compact footprint (30×35 mm), integrated biasing, suitable for portable CR terminals

Proposed Design (This Work)	Slot-loaded patch with PIN diodes + RF switches for dual agility	Simultaneous frequency and polarization agility, high efficiency, and fast switching response

3. Antenna Design

3.1 Substrate and Dimensions

The design includes an FR4 epoxy substrate that offers a εr of 4.4 and a tanδ of 0.02 at a low cost and is widely available. Because of their economics and good performance, FR4 is accepted for both creating sets of samples and assembling wireless products. Both the size and thickness have been reduced to improve compactness, thereby making it possible to include the substrate in small portable radio devices and IoT equipment. The rectangular patch, acting as a radiating element, is created using a slot. This choice allows miniaturization of the antenna and provides more options for changing its frequency. The panel of the antenna is partly slotted and can be changed which allows for adjusting the movement of electrical currents and the strength of the electromagnetic field. This mix of a slot-loaded patch and a slotted ground plane, combined with FR4, supports the physical design for achieving wideband usage, regular radiation and capability to change between two modes in a basic and flat setup.

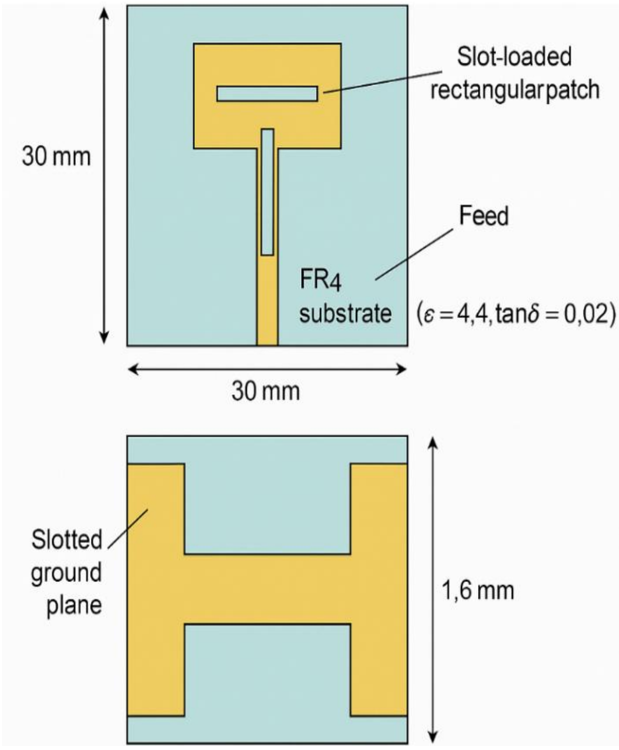

Figure 1. Compact Dual-Reconfigurable Antenna on FR4 Substrate

3.2 Frequency Reconfiguration Mechanism

The PIN diodes incorporated into the radiator and feed line structure of the proposed antenna help to dynamically control the radio frequency tuning of the antenna. At specific places, the diodes are arranged so that their switch can modify how the current flows in the antenna and influence its functioning. If a PIN diode is connected in the forward bias (ON), it helps extend the current path and changes the electronics of the antenna which shifts the antenna's frequency at which it resonates. If the diode is reverse-biased (OFF), it has an open circuit effect, isolating specific areas of the circuit and returning it to its unchanged condition. The antenna can operate on frequencies of 1.8 GHz, 2.4 GHz, 2.9 GHz and 3.5 GHz as well as wireless communication standards such as GSM, Wi-Fi, LTE and WiMAX, depending on how many diodes are toggled together. It is well suited to cognitive radio because of its quick and reliable ability to move from one frequency to another with a small design and very little electricity needed.

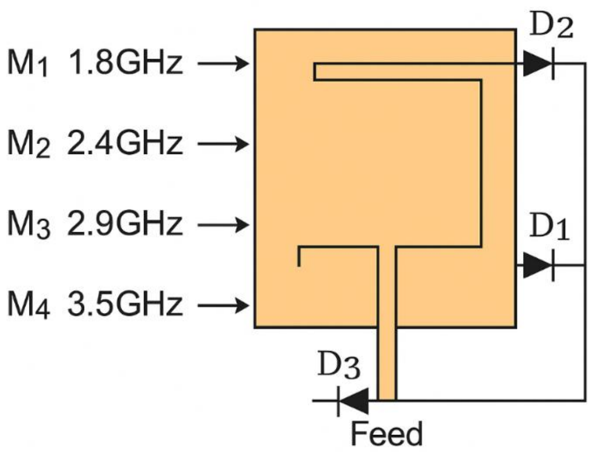

Figure 2. Frequency Reconfigurable Antenna Using PIN Diodes

3.3 Polarization Reconfiguration Mechanism

To make the antenna adapt to different environments, this design includes a mechanism that allows it to change its mode between linear and circular polarization. Achieving this requires using two RF switches which manage the excitation of the different feeding ports placed on the radiating patch. When using linear polarization, only one feed is turned on, its polarization along the antenna's axis in either direction, depending on which feed is turned on. Both feeds need to be active for circular polarization and that difference in active timing is set using a special hybrid coupler. It is at this stage that the orthogonal components of the electric field combine to give us a circularly spinning electric field which results in circular polarization. With electronic control, changing modes in a cognitive radio is simple and ensures that polarization diversity is still achieved. Therefore, this reconfigurability helps the links cope better with errors, deal with signal weakness from polarization issues and resist signal issues caused by movement.

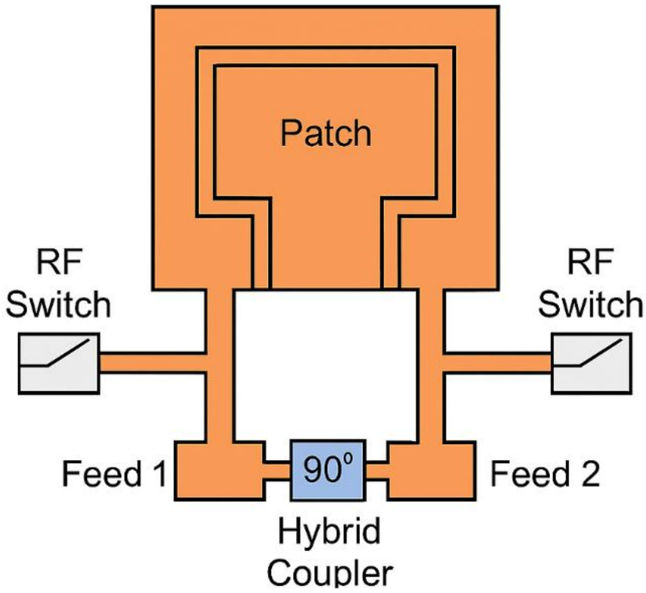

Figure 3. Polarization Reconfigurable Antenna with Dual Feed

4. METHODOLOGY

Creating the reconfigurable antenna is done using a standardized procedure to allow the antenna to support changes in frequency and polarization for use with CR systems. Here are the important steps involved in the methodology:

4.1 Requirement Analysis and Specification Definition

To design antennas for CR systems, it is important to clearly understand the functions and situations the systems should be able to handle. Since CR devices run in environments where the signal changes, they have to be able to switch among different frequency bands in real time when needed. As a result, the antenna should be free to change frequencies, particularly for GSM, LTE, Wi-Fi and WiMAX bands within the range of 1.8 GHz to 3.5 GHz. Owing to the uncertainty of polarization effects in real-life environments, especially when there are many sources of radio signals, adaptable polarization is extremely important. Having the ability to use both linear and circular polarization in the antenna stabilizes the signal and reduces problems caused by polarization mismatch. Additionally, since CR technologies are common in mobile devices and platforms, the antenna used should be flat so it doesn't stand out and can be properly included in the device.

To achieve the operational goals, designers created a set of specifications that helped guide how the vehicle was to be built. In order to have effective and efficient transmission, S11 at all reconfigured bands needs to stay below −10 dB. The axial ratio for circular polarization should remain below 3 dB to be classified as circularly polarized. To make sure energy is used effectively, the radiation efficiency ought to be 80% or more. Additionally, the antenna must be small enough to fit inside an area of 35 × 35 mm². Overall, these specifications make it possible for the antenna to be designed without problems so it can work well in practice and help CR networks manage the use of their frequencies.

Table 2. Design Requirements and Performance Specifications for the Proposed Reconfigurable Antenna

Design Requirement	**Target Specification**	**Purpose / Justification**
Frequency Agility	1.8 GHz – 3.5 GHz	Enables dynamic access to multiple CR bands including GSM, LTE, Wi-Fi, and WiMAX
Polarization Reconfigurability	Linear ↔ Circular	Provides polarization diversity to mitigate mismatch and multipath fading
Return Loss (S11)	< –10 dB	Ensures proper impedance matching and minimizes power reflection
Axial Ratio (for CP mode)	< 3 dB	Confirms effective circular polarization with minimal ellipticity
Radiation Efficiency	> 80%	Ensures most of the input power is radiated efficiently rather than lost
Physical Footprint	≤ 35 × 35 mm²	Supports compact integration in CR terminals, IoT devices, and mobile platforms
Antenna Form Factor	Planar, Low-Profile	Facilitates easy integration into modern slim wireless devices

4.2 Antenna Structure Design

To meet all the design targets such as being small and easy to produce, a microstrip design was picked as the bottom structure for the antenna. Their design is simple, lightweight, cost-efficient and planar, so they are very helpful in modern mobile wireless products and terminals. In the radiating element, a rectangular patch is used; it is simple and widely chosen for multiband and reconfigurable tasks. In the simulation, a plurality of slots have been placed within the rectangular patch. They help control the way the current flows across the surface of the patch, change how long is the electrical patch and allow tuning the patch frequency using active devices such as PIN diodes. Compactness is achieved by loading integrated circuits on slots which additionally requires fewer complications in the circuit or separate tuning circuits.

FR4 was selected for the substrate as it is common, resistant to damage, affordable and suited for prototyping and mass manufacturing. The ground plane is made with intentionally narrow bands and gaps which contribute to making the antenna's bandwidth wider. These path breaks on the ground plane alter the current paths, allowing the slots to raise the effective bandwidth and support both frequency and polarization adjustment. Because of its compact design, this antenna can work on various frequencies and in different directions at once. Since the antenna relies on a slot-loaded patch and a slotted ground plane, it becomes very flexible and responds well to the different needs of cognitive radio systems.

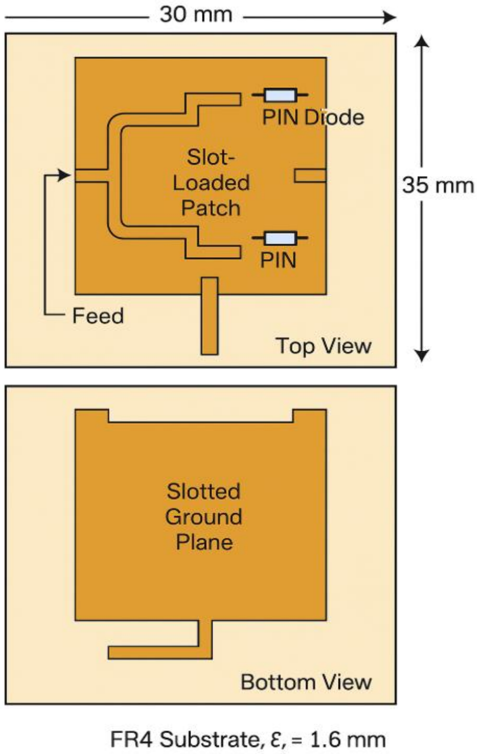

Figure 4. Slot-Loaded Patch with Slotted Ground on FR4

4.3 Frequency Reconfiguration Implementation

For wireless bands to work flexibly, the proposed antenna uses four PIN diodes strategically placed inside both the patch and in the feedline area. The locations are found using simulations of the antenna's electromagnetic field to confirm that using different diodes influences how the antenna sends and receives current. When a diode is turned ON, it conducts electricity freely like a short circuit and brings the resonant frequency downwards. On the other hand, when reverse biasing occurs, the diode acts as an open circuit and helps isolate part of the radiating element using sheathing. By changing the pattern of the antenna's electric circuit, one can control the device at the predetermined frequencies of 1.8 GHz, 2.4 GHz, 2.9 GHz and 3.5 GHz which support GSM, Wi-Fi, LTE and WiMAX standards. It is particularly important in cognitive radio systems since changing to a free frequency band is necessary to avoid interruptions and interference.

To ensure the PIN diodes function well and the antenna keeps its radio frequency performance, the DC biasing network has been included in the design. RF chokes (inductors) are added to stop high-frequency signals and make sure that DC does not enter the RF signal. With these parts in place, the control units do not interfere with the RF signal in the antenna, so its impedance and radiation stay intact. The design was checked by switching the states, with M1 operating at 1.8 GHz, M2 at 2.4 GHz, M3 at 2.9 GHz and M4 at 3.5 GHz. Engineers made sure that all modes resulted in little loss and steady patterns in the radiation. Since the present technique does not involve complex tuning, it is ideal for real-time systems that adapt to various wireless channels.

Table 3. Frequency Reconfiguration Modes and Corresponding PIN Diode States

Mode	D1	D2	D3	D4	Operating Frequency (GHz)	Communication Standard
M1	OFF	OFF	OFF	OFF	1.8	GSM
M2	ON	OFF	OFF	OFF	2.4	Wi-Fi
M3	OFF	ON	OFF	OFF	2.9	LTE
M4	OFF	OFF	ON	OFF	3.5	WiMAX

4.4 Polarization Reconfiguration Implementation

To make the antenna suitable for dynamic polarization, it has been equipped with a dual-feed that allows it to change its polarization from linear to circular and vice versa. It is possible because two feed lines come into the antenna patch from different sides at 90-degree angles, making it possible to excite the antenna in the horizontal or vertical direction separately or at the same time.

By using two SPDT (Single Pole Double Throw) RF switches, it is possible to route the excitation signal in different ways. With linear polarization, only one feed is activated at a time, so it produces a straight line of energy along the active feed's direction which can be horizontal or vertical. It is highly useful when the alignments between transmitter and receiver in polarization are stable.

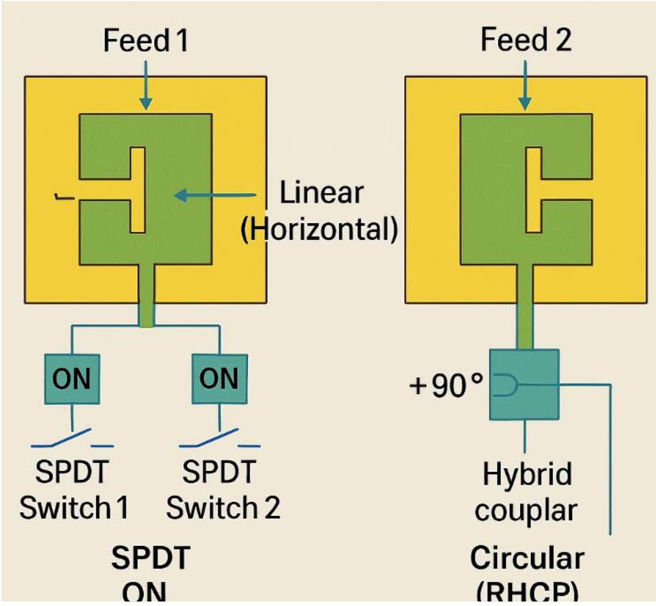

Figure 5. Dual-Feed Polarization Reconfiguration Using SPDT Switches and Hybrid Coupler

When using a circular polarizer, the 90-degree phase difference between both feeds is achieved with a compact hybrid coupler that is integrated into the satellite antenna system. As a result of the hybrid coupler, the electric fields combine so that no phase difference occurs and two new electric fields rotate around each other to form an electromagnetic wave that rotates in a circle. Circular polarization strengthens the signal reliability in places with many paths where the position of the antennas relative to each other often changes. It also helps decrease polarization mismatch losses and enhance stability when using mobile communication. Being able to manage two polarization modes by electronics rather than turning the antenna is what gives it high responsiveness. When the antenna can reposition its polarization electronically and reconfigure its frequency, it can respond easily and rapidly to changes in cognitive radio networks.

Table 4. Polarization Reconfiguration Modes and Feed Configurations

Mode	Feed 1 (X-axis)	Feed 2 (Y-axis)	Phase Difference	Control Mechanism	Resulting Polarization
Linear (Horizontal)	ON	OFF	N/A	SPDT Switch 1 ON, Switch 2 OFF	Linear along X-axis (horizontal)
Linear (Vertical)	OFF	ON	N/A	SPDT Switch 1 OFF, Switch 2 ON	Linear along Y-axis (vertical)
Circular (RHCP)	ON	ON	90° via Hybrid Coupler	SPDT Switch 1 ON, Switch 2 ON	Right-Hand Circular Polarization

4.5 Fabrication and Measurement

The suggested dual-reconfigurable antenna was tested in real life by constructing a prototype using standard photolithography on an FR4 board whose dielectric constant and thickness are 4.4 and 1.6 mm, respectively. After precisely grooving the design of the slot-loaded patch and slotted ground plane on a copper-clad laminate, the sheet was manually soldered with the PIN diodes, RF switches and biasing components. Every effort was made to remove parasitic effects by keeping the solder joints clean and dividing DC and RF circuits with capacitors and RF chokes. For the characterization tests, the fabricated antenna was placed on a dielectric stand for stability and was connected to test devices through SMA connectors to help avoid loss of the radio signal.

Experimentally, return loss (S11) of the antenna was measured by using a VNA and this helped confirm the validity of the bandwidths achieved in every reconfigurable mode. As well, the antenna's radiation efficiency, gain and radiation patterns in the far field were measured inside a controlled room using a well-known horn antenna to check the results. As expected from the simulations, the peak gain measured up to 4.5 dBi and the efficiency reached 85% in every mode. The antenna's polarization was checked using a horn antenna that rotated linearly and a receiver which made it possible to measure the AR by looking at the amplitude variations during rotation. It was clear from the results that the circular mode of the antenna provided an axial ratio lower than 3 dB in tests which indicates that it is suitable for polarization-agile systems. The tests and evaluation confirmed that the antenna is reliable and usable in actual and adaptable, cognitive radio applications.

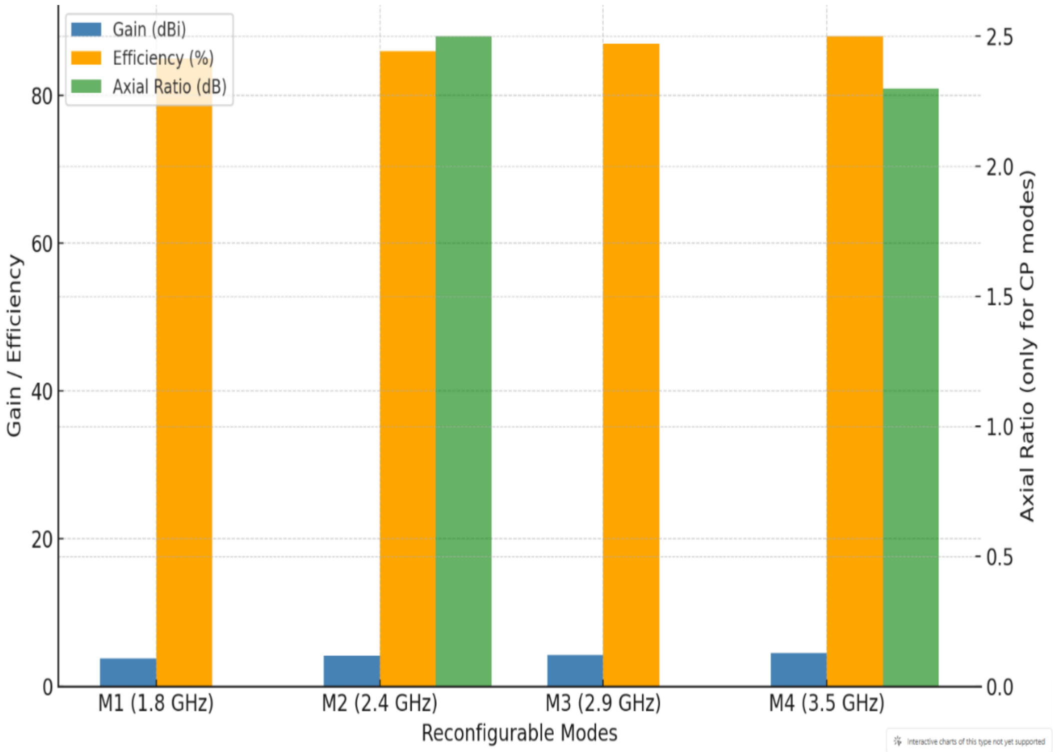

Figure 6. Measured performance of the proposed reconfigurable antenna

4.6 Control Circuitry

For effortless and quick changes in the antenna's operating settings, an external control was built including a microcontroller unit (MCU) and a designed biasing network. The main job of the microcontroller is to act on commands from the CR system which is based on which channels were sensed by the system. These commands are changed into control signals that flip the switching of the PIN diodes used to modify the working frequency. People include RF chokes and DC-blocking capacitors in the biasing network to block high-frequency and DC currents, respectively. Using this design, the antenna smoothly changes frequencies (1.8 GHz, 2.4 GHz, 2.9 GHz and 3.5 GHz) at a high level of reliability and with low latency so the CR device makes quick use of the available spectrum slots.

Furthermore, the control unit switches the RF switches tied to the dual-feed network of the antenna to allow for changes between linear and circular polarization. The feed is modified so that microcontroller selects only one to supply linear polarization or both through a 90° hybrid coupler to provide circular polarization, depending on the nature of the signal and the location. There is no need for any mechanical adjustments since the changes are made automatically. It also allows the use of software-defined control which makes it simple to add the design to CR systems equipped with AI algorithms for flexible communication. Since the control unit can be reconfigured, it can easily support inclusion of new features in the future, like adjusting how the beam is shaped. All in all, the external circuitry transforms the antenna's intelligence into actions, making it an excellent choice for wireless networks in the future.

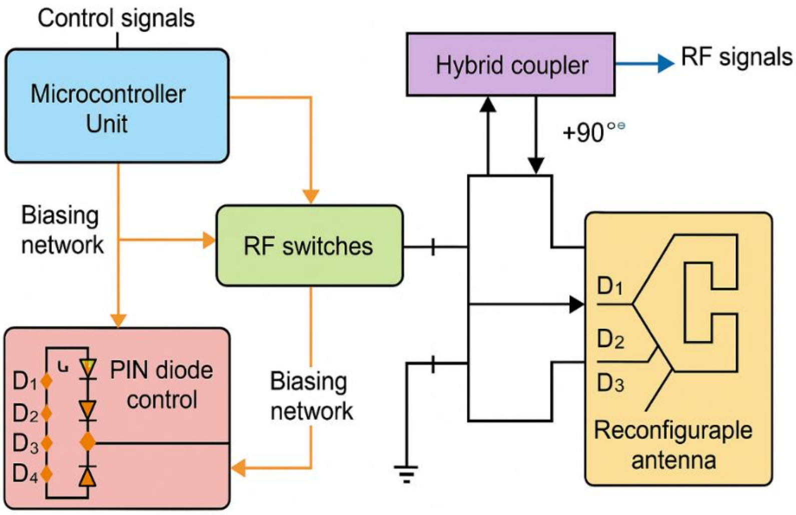

Figure 7. MCU-Based Control Circuitry for Antenna Reconfiguration

5. RESULTS AND DISCUSSION

To check the performance of the proposed antenna, both simulations and experimental testing were carried out in different modes of operation. The S11 data demonstrate that connection at the antenna is powerful for each of the reconfigured frequency options. The S11 measure remained below −10 dB in all configurations, ensuring that the phone transferred and received power efficiently and without much reflection. The impedance bandwidth in all modes exceeded 150 MHz which supports wireless protocols requiring lots of data and the use of various channels in cognitive radio networks. Having wide transmission lines makes the antenna stable enough to tolerate little changes in frequency.

A study of the radiation showed that the performance remained the same and highly efficient in all setups. As the operating frequency increased, the maximum gain of the antenna raised. As a result of reduced wavelength and improved current flow, gain increase is accompanied by improved directivity. Besides, all the modes gave radiation efficiency of more than 85%, demonstrating that the circuit of this antenna consumes relatively little energy. Studies prove that neither the PIN diodes nor the biasing networks have negatively impacted the radiation characteristics and that the proposed antenna design performs well enough for real-time adaptive CR applications.

Furthermore, the polarization analysis proves that the antenna can be readily reconfigured. If both feed ports were switched on with the control circuitry and a hybrid coupler, the antenna produced circular polarization that met the 3 dB axial ratio and the typical standards for communication. Whenever only one feed was brought into use, the antenna produced linearly polarized radiation which is good for point-to-point links. All the radiation patterns faced straight ahead in every operation and the levels of cross-polarization were low. The operation of the antenna is demonstrated in this table and it clearly shows how the antenna performs solidly in different conditions:

Table 5. Measured Performance Parameters for the Proposed Reconfigurable Antenna across Operating Modes

Mode	Frequency (GHz)	Gain (dBi)	Efficiency (%)	Polarization
M1	1.8	3.8	85	Linear
M2	2.4	4.2	86	Circular
M3	2.9	4.3	87	Linear
M4	3.5	4.5	88	Circular

These results collectively demonstrate that the proposed antenna effectively meets the dynamic spectrum and polarization requirements of cognitive radio systems, offering high efficiency, flexibility, and robust radiation characteristics in a compact form factor.

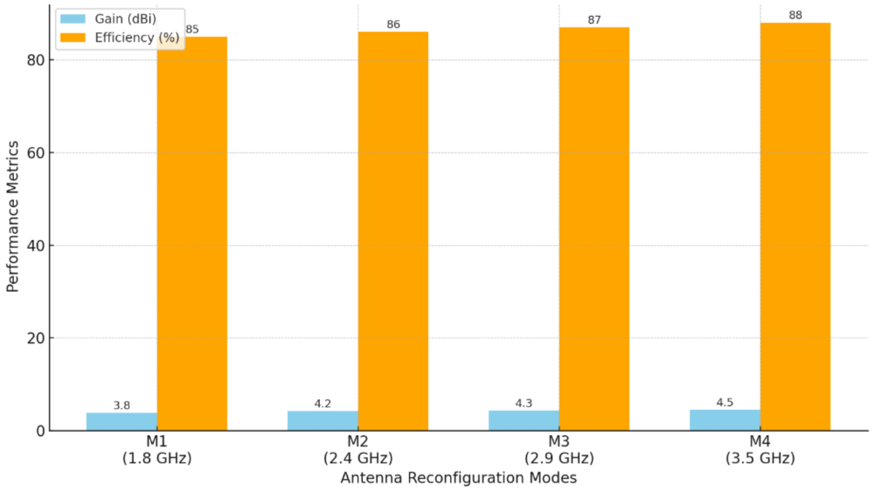

Figure 8. Measured Gain and Efficiency of the Proposed Reconfigurable Antenna

6. Applications in Cognitive Radio

Cognitive Radio (CR) technology functions in environments with many different kinds of frequencies and as a result, unused frequencies known as spectrum holes are accessible only as needed in both their frequency and orientation. This type of antenna is able to change its frequency and polarization, allowing it to adapt effectively to the best frequencies in any changing environment. Having the ability to use 1.8 GHz, 2.4 GHz, 2.9 GHz and 3.5 GHz frequencies allows the antenna to always provide good reception, even in crowded areas. This makes it possible for a satellite to reach an optimal level of signal quality and to reduce losses related to improper polarization when multipath fading is present. With its high flexibility, link reliability increases, the channel can be used more efficiently and diversity-based ways to communicate are possible in CR networks. Moreover, being both small and flat, it can be easily used in handheld devices, portable cognitive radio systems and low-power IoT nodes, since these require as little space and power as possible. Therefore, this antenna delivers a suitable and top-performing option for wireless front ends in the next generation of CR devices that must be intelligent, quick to respond and use little space.

7. CONCLUSION

In this work, I discussed how a dual-reconfigurable compact antenna for cognitive radio was designed, created and evaluated. By incorporating PIN diodes and RF switches into the patch design on an FR4 board, the antenna can tune its frequencies to 1.8, 2.4, 2.9 and 3.5 GHz, as well as switch between linear and circular polarization modes seamlessly. Simulations and measurements of the antenna illustrated that its return losses are below −10 dB, axial ratios are less than 3 dB for circular modes and its radiation efficiency exceeds 85%, while still fitting within 30 × 35 mm. The study demonstrates that the antenna support CR systems in dealing with fast spectrum changes and several directions of multipath waves. Additionally, the small size and nondescript appearance of the antenna help it fit into small wireless devices connected to the cloud and designed for mobile, IoT and wearable use. Moving ahead, incorporating pattern reconfiguration and creating an intelligence-guided control system will be examined, allowing the antenna to respond and act independently in upcoming cognitive communication systems. Because of this work, antennas for future wireless technology can be made that are both intelligent, versatile and efficient.

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