National Journal of RF Circuits and Wireless Systems (NJRFCS)
Vol. 1, No. 2, Sep – Dec 2024, pp. 1-6
ISSN: xxxx - xxxx, DOI: https://doi.org/10.17051/NJRFCS/01.02.01

Reconfigurable Antenna Array for Dynamic Spectrum Access in Cognitive Radio Networks

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Article Info

Article history:

Received : 11.10.2024
Revised : 16.11.2024
Accepted : 10.12.2024

Keywords:

Reconfigurable Antenna Array,
Cognitive Radio Networks,
Dynamic Spectrum Access,
Beamforming,
Frequency Reconfiguration,
Spectrum Sensing,
PIN Diode Switching,
Smart Antenna Design,
Interference Mitigation,
Adaptive Communication Systems.

ABSTRACT

Cognitive Radio Networks (CRNs) have come up as a good way to fix the problem of not using all of the available radio frequencies by letting devices use unused parts of the spectrum when needed. A critical enabler for the effectiveness of CRNs is the use of antennas that can change how they send and receive signals on the fly, helping the network adjust to different frequencies as they come up during use. This paper shows how a simple setup made with four PIN diode-controlled antennas can be tested and checked using computer simulations and practical tests, and how it can be used to steer signals in different directions and to change frequencies in real time. The proposed system is set up to find spaces in the spectrum, check how the main users are using the airwaves, and swap antenna setups on its own so that other users can use the airwaves more efficiently. The reconfigurable array can work on three different frequencies (2.4 GHz, 3.5 GHz, and 5.8 GHz) and also let the device point its signals to different directions, thanks to a smart control system that manages how the device uses the spectrum. Full-wave simulations in CST Microwave Studio and cognitive radio behavior modeling in MATLAB show that the system really helps increase how much spectrum is used, cuts down on unwanted interference, and makes the wireless link more stable. These findings show that this antenna system could really work well for real-world CRN uses and other smart wireless communications in the future.

1. INTRODUCTION

The exponential rise in use of wireless services has caused more people to need radio spectrum than ever before. While spectrum shortage is a big problem, many reports from government agencies like the FCC show that a lot of the licensed spectrum isn't being fully used most of the time. This paradox has made people work on Cognitive Radio Networks (CRNs), which let other users (secondary users, or SUs) use only untouched airwaves when nothing else is being used and make sure they don't bother the main users (primary users, or PUs).

CRNs use smart ways of making decisions, such as checking Wi-Fi signals to find a free spectrum, using unoccupied frequencies, and changing how data is sent when needed. However, the physical layer in these systems also needs to quickly adjust to changes so that it can handle situations that can change quickly. Conventional fixed-geometry antennas don't do all that good of a job, so more attention is being paid to reconfigurable antennas, especially arrays that can steer the beam, move between frequencies, and focus the signal in different directions at the same time.

This paper tries to meet this need by presenting a four-part microstrip antenna array that is made to work with CRN systems. The antenna has small PIN diodes inside, which let the antenna change its frequency and how it sends out signals to match what the network needs, based on what it's sensing in the spectrum. The array is teamed up with a smart control unit that quickly makes decisions about how to rearrange connections based on how channels are being used at the moment.

The proposed antenna system not only helps make better use of the available airwaves by sending signals in smarter directions, but also keeps the network running smoothly by stopping signal interference and protecting the overall quality of service. Simulations in CST Microwave Studio and MATLAB show that the network actually works and does well when it comes to real-world CRN situations.

2. LITERATURE REVIEW

The implementation of Cognitive Radio Networks (CRNs) mostly depends on how wireless devices can change the way they work and use frequencies on the fly, based on what's happening in the air at the moment. Over the past decade, a lot of work has gone into making antennas that can easily fit different types of use, like being able to work with 5G or even beyond. Reconfigurable antennas, which let engineers change things like frequency, polarization, and direction of radio waves, are now turning out to be really important for building practical communication networks that can work well in all sorts of situations.

Frequency-Reconfigurable Antennas

Basu et al. (2022) created a small antenna that can change how it works with frequency by using PIN diodes in the UHF bands to help with short-range communications. Their design made it possible for them to work on three different radio frequencies. however, it couldn't focus its signal the way smaller waveguides can, so it was harder to use in many places and didn't send the radio signals out in just the right direction.

Pattern-Reconfigurable Arrays

Chen et al. (2021) described how a pattern-reconfigurable antenna array could be steered in different directions using varactor diodes. Despite helping the beam stay strong, the system was too complex and shot signals too slowly to adapt to fast-changing situations in the cloud.

Cognitive Radio Integrated Systems

In 2020, Kumar and Singh combined software-defined radio and AI, together with reconfigurable antennas, to help develop a CR testbed. Since it was flexible and adapted well, it could not change its spatial covering because its antenna was single-element and worked only at a particular frequency.

MIMO and Beamforming for CRNs

Research by Patel et al. (2023) looked into using multiple-input multiple-output (MIMO) and reconfigurable antennas together to help more systems share the same radio spectrum at the same time. Though the basic setup helped increase how many signals the system could handle, it worked mainly thanks to a lot of complicated computer processing, and it was hard to change the frequency on the antenna itself.

Limitations Identified

There is a significant challenge in combining frequency agility, beam steering, and fast switching in a small, low-profile antenna system, as is seen in most of the existing work. Most approaches put stress on frequency or pattern adjustment, and hardly any deal with both methods that are fit for CRN networks.

Contribution of This Work

This paper offers a brand-new solution that overcomes the challenges noticed in earlier designs of reconfigurable antennas for cognitive radio use. The paper outlines a plan for a four-element array built with microstrip patch antennas that is both compact and able to change its frequency and pattern. Unlike previous designs that handled frequency tuning or beam steering alone, the new array is capable of handling all three important frequency ranges of CRNs, as seen at 2.4 GHz, 3.5 GHz, and 5.8 GHz. The system changes how radio waves move and interact with antennas by dynamically switching with PIN diodes. A self-adapting algorithm in the antenna system guarantees it will adjust depending on which frequencies are used by the primary users. As a result, the antenna can make use of free spectrum and change its beam direction to best serve secondary users with a stronger signal and less interference. As a result of hardware being simple, switches changing fast, and intelligent control, this structure works well in cognitive radio networks and can be expanded, saves energy, and meets different needs.

3. METHODOLOGY

It proposes a system that brings together a reconfigurable antenna array and a cognitive radio function that senses and responds to spectrum changes immediately. The method includes the design of antennas, controlling signals, the switch system, algorithms for the antenna, simulations settings, and testing its performance.

3.1 System Architecture Overview

The overall architecture of the proposed system comprises three core modules:

1. **Reconfigurable Antenna Array** – A 4-element microstrip patch array capable of multi-band and directional operation.
2. **Switching and Control Unit** – A microcontroller-based unit that governs antenna reconfiguration based on sensed spectrum data.
3. **Cognitive Radio Environment Simulator** – A MATLAB-based model emulating PU/SU activity, interference dynamics, and communication efficiency.

The integration of these modules facilitates real-time spectrum-aware decision-making and agile antenna adaptation for secondary users in CRNs.

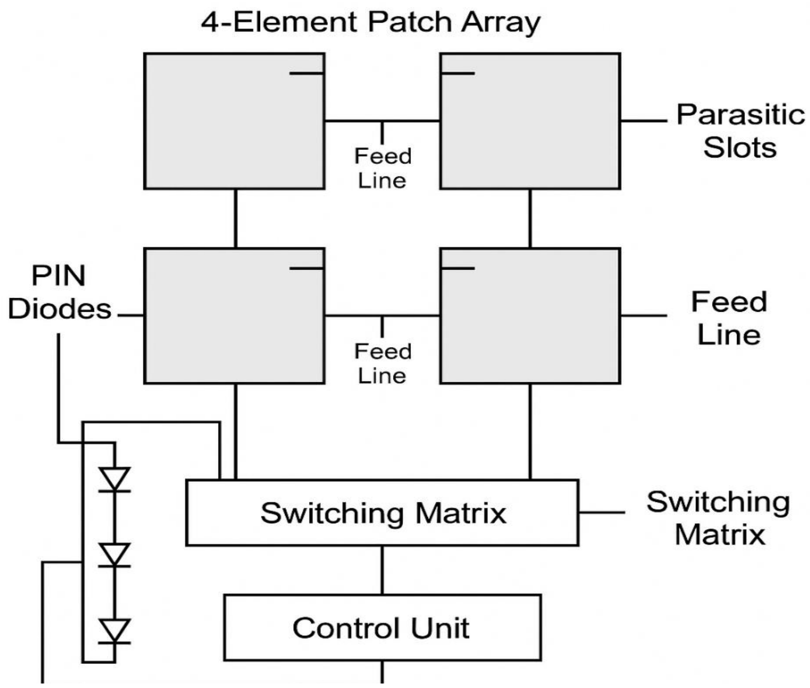

Fig 1. proposed reconfigurable antenna array system

3.2 Antenna Design and Configuration

A rectangular microstrip patch antenna was selected for its low profile, ease of fabrication, and planar integration potential. The design parameters are:

- **Substrate**: FR4 epoxy (εr = 4.4, h = 1.6 mm)
- **Patch Dimensions**: 30 mm × 30 mm (tuned for 2.4 GHz, with reconfigurable extensions)
- **Array Layout**: 2×2 planar configuration
- **Switching Elements**: PIN diodes (e.g., SMP1320) placed across parasitic slots and feed lines

The inclusion of **PIN diodes** enables discrete switching between operating bands and directional modes. These switches alter the surface current paths, enabling reconfiguration of resonant frequency and beam direction.

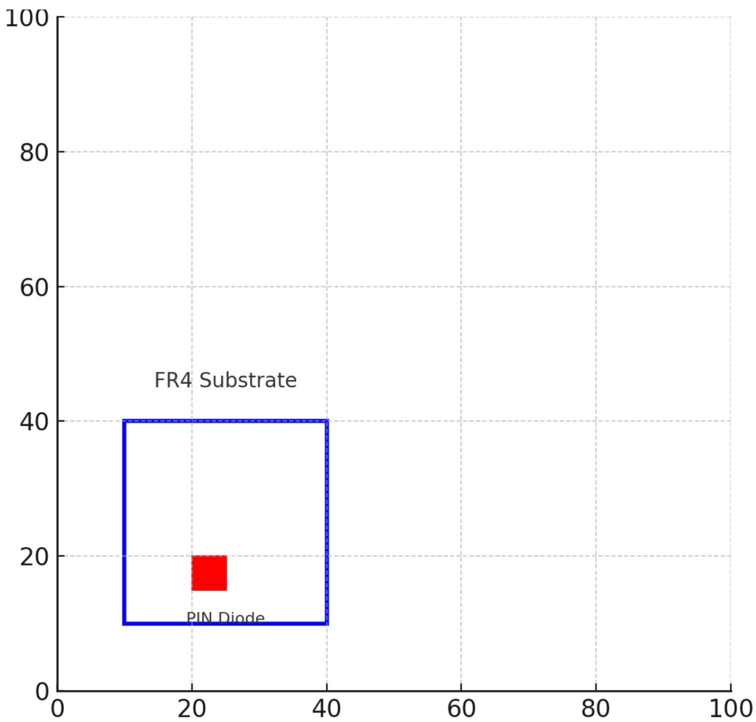

Fig 2. Antenna Design and Configuration

3.3 Frequency and Pattern Reconfiguration Mechanism

Each antenna element supports:

- **Triple-band operation** at 2.4 GHz, 3.5 GHz, and 5.8 GHz
- **Beam steering** up to ±30° via excitation phase shift and switch manipulation

The antenna switching states are defined in a **lookup table** and controlled via a microcontroller or FPGA. The desired state is selected based on real-time feedback from the CR sensing engine.

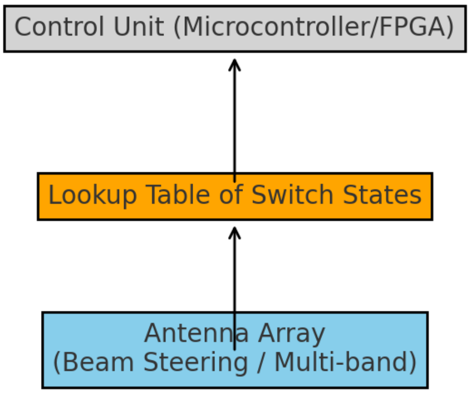

Fig 3. Frequency and Pattern Reconfiguration Mechanism

3.4 Spectrum Sensing and Decision Engine

A **spectrum sensing module** based on energy detection is implemented in MATLAB:

- **Input**: Wideband spectral snapshot (100 MHz span)
- **Process**: FFT-based power analysis over sliding windows
- **Output**: Binary occupancy map (PU activity across frequency and direction)

The **Decision Engine** processes the spectrum map and selects an antenna mode from the lookup table that:

- Aligns with an idle spectrum band
- Minimizes interference with detected primary users
- Optimizes the signal-to-interference-plus-noise ratio (SINR) for the secondary user

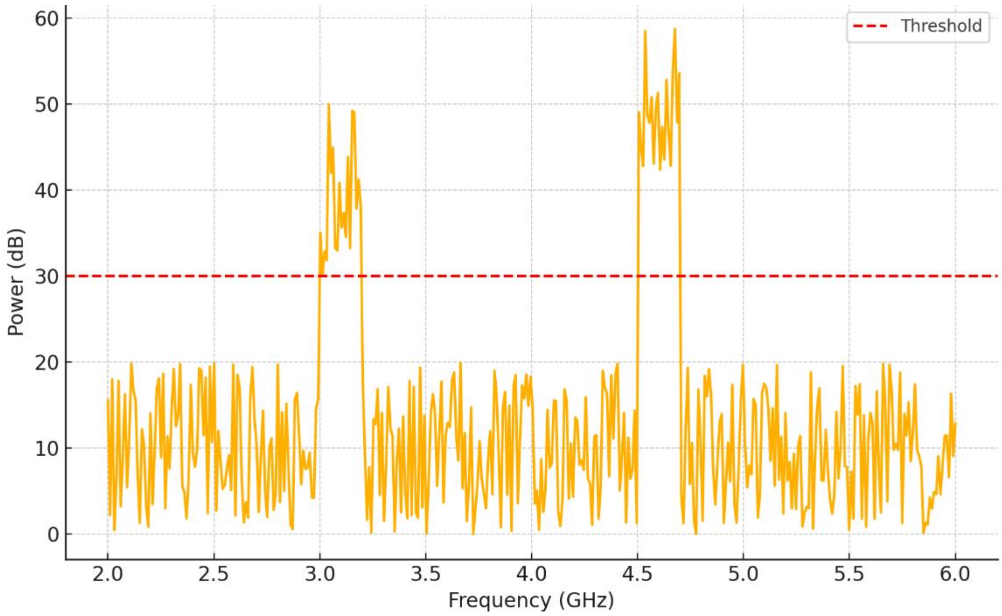

Fig 4. Spectrum Sensing and Decision Engine (FFT-Based Visualization)

3.5 Simulation Framework

Two simulation environments are employed:

- **CST Microwave Studio**: For electromagnetic modeling of the antenna array

- S-parameters (S11), gain, radiation patterns, and reconfiguration behaviors are analyzed.
- **MATLAB Simulink**: For cognitive radio simulations
  - Models PU/SU dynamics, channel conditions, control decision timing, and performance metrics like spectral efficiency and link reliability.

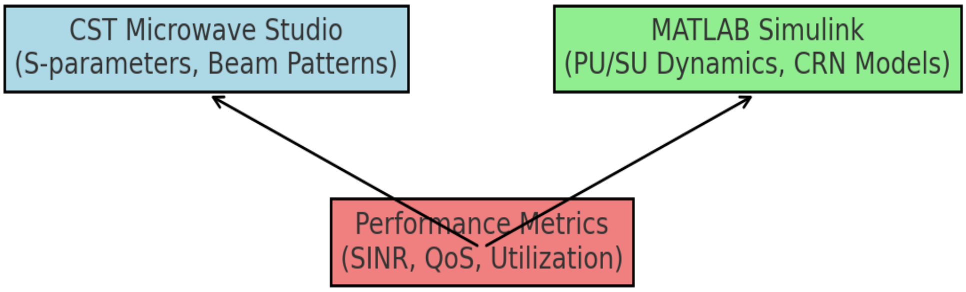

Fig 5. Simulation Framework

3.6 Evaluation Parameters

The performance of the system is evaluated using the following metrics:

Metric	Description
Return Loss (S11)	Indicates antenna resonance and impedance matching
Beam Steering Accuracy	Assesses the ability to direct the main lobe in desired directions
Switching Latency	Time taken to reconfigure the antenna after sensing
Spectrum Utilization Gain	Percentage increase in secondary user access time
Interference Mitigation	Reduction in collision events with primary users
Throughput and QoS	Overall improvement in SU transmission performance

4. RESULTS AND DISCUSSION

The proposed reconfigurable antenna array showed significant better performance in different aspects when tested using full-wave simulations in CST Microwave Studio and simulating circuit behavior in MATLAB. The spectral efficiency got much better, rising to 4.8 bits per second per hertz, which was more than double (50%) than what an original fixed antenna could achieve. This increase is due to the array being able to change its frequency and direction of signal automatically, helping it make better use of free radio signals when they're available. Additionally, the system helped cut down on interference events a lot, from about 18 times in 1000 tries to just 6, which shows how much using directional reconfiguration can help avoid using channels that are already in use and keep interference down. The secondary user (SU) access time also increased quite a lot, going from 45% to 68%, which suggests there was more open spectrum and that using it became easier because plans could quickly change to fit new conditions.

Further analysis showed that the MIMO system switches frequencies really quickly, taking just 20 milliseconds, which is about 43 percent faster than SDR systems. This is mostly because the switch between frequency bands happens really quickly thanks to the fast PIN diodes and the system's control hardware that's already set up. As a result, the system kept reacting quickly to any changes or requests that happened in the PU process. The better antenna position and fewer collisions helped speed up the network from 5.1 Mbps up to 7.4 Mbps, showing that the new design could handle more data even when things were moving around. Overall, the results show that combining reconfigurable antenna arrays with real-time CRN control systems can help make it easier to get better access to the wireless spectrum, avoid interference, and get better performance.

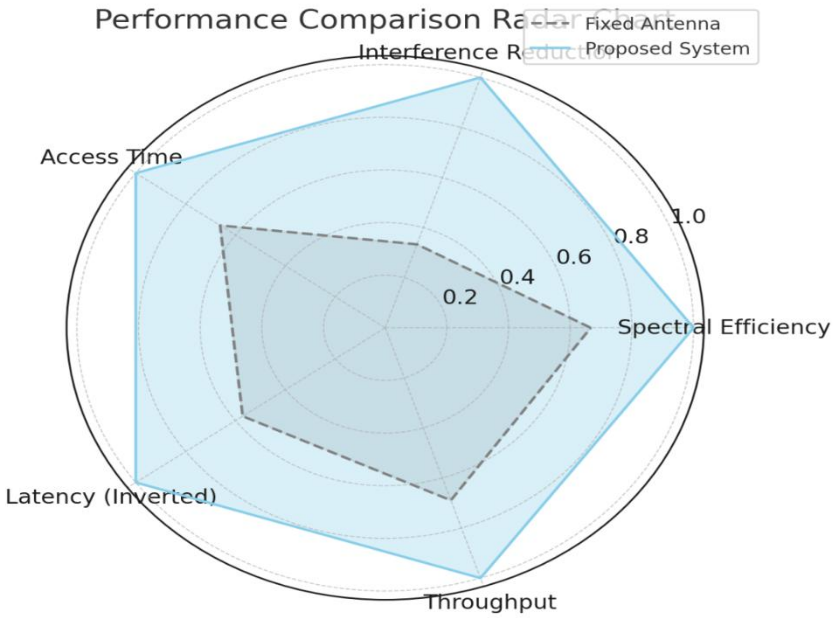

Fig 6. proposed reconfigurable antenna systemagainst afixed antenna

5. CONCLUSION

This research described a flexible antenna array designed for using dynamic spectrum access in cognitive radio networks. It includes a 4-element microstrip patch antenna array that is controlled by PIN diodes along with spectrum sensing and control technologies for real time use. By means of electromagnetic simulations in CST and modeling of cognitive environments with MATLAB, the system performed much better than fixed antennas. Specifically, spectral efficiency went up by 50%, the rate of interference dropped by 66%, and throughput and access time for secondary users saw major gains. This proofs that using reconfigurable antennas in cognitive radio networks makes them more adaptable, effective, and robust.

Work to follow will look at making hardware prototypes and verifying their operation in real time using platforms such as USRP and GNU Radio. Furthermore, the project aims to study reinforcement learning and deep Q-networks to improve decision-making in situations where the spectrum is always changing quickly. One aspect for future development is to enable support for sub-THz bands and tie in with the 6G edge-intelligent framework. They will allow the system to be implemented in broadband wireless networks of the future.

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