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Research Article

Spectrum Awareness in 5G Cognitive Radio Networks with Optimized Spectrum Detection Algorithms

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ABSTRACT

This study presents an extensive overview of the key signal processing techniques used in cognitive radio systems, with a particular emphasis on their application in 5G-based contexts. The study commences by addressing the fundamental task of spectrum sensing, which involves the detection of unused or underutilized frequency bands. It thoroughly examines various spectrum sensing methods such as energy detection, matched filtering, and cyclo-stationary feature analysis, providing a comprehensive assessment of their respective advantages and drawbacks within the 5G landscape. Subsequently, the paper explores strategies for spectrum sharing and access. It delves into cooperative spectrum sensing and spectrum handoff algorithms, which play pivotal roles in enabling collaborative spectrum identification and utilization by cognitive radios in 5G networks while ensuring minimal interference with primary users. Additionally, the study investigates the concept of spectrum databases and geo-location databases, which serve as valuable tools for managing spectrum access rights and enhancing overall spectrum utilization.The study's outcomes validate the effectiveness of the proposed algorithms and lend support to the research hypothesis. This research significantly contributes to the field of cognitive radio systems by presenting a reliable and efficient methodology for spectrum sensing. Intelligent spectrum sensing, as demonstrated by the application of machine learning algorithms for preliminary classification and the utilization of specialized signal processing techniques for identifying available channels, holds the potential to enhance spectrum utilization and optimize the performance of cognitive radio networks in the dynamic landscape of 5G technology.

Keywords: *Cognitive Radio, 5G systems, Spectrum awaremness, Spectrum Analysis, Spectrum Detection*

INTRODUCTION

The rapid growth for mobile devices relies on the electromagnetic signal. It emphasizes the significant expansion of mobile device usage, which already surpassed the Earth's population by 2014 and continues to double each year. With the explosion of data creation and consumption globally, reaching 64.2 zettabytes in 2020 and projected to exceed 180 zettabytes by 2025, there is a pressing need to address the increasing demand for processing power and mobile data capacity. Traditionally, spectrum utilization has been handled through a static approach that was developed nearly a century ago. This approach involves dividing the electromagnetic spectrum analysis. The primary objective of this approach is to ensure interference-free communication for the licensed users. However, as some of these licensed bands remain underutilized while others become heavily congested, the issue of spectrum scarcity arises. In other words, there are unused portions of the spectrum that could be made available to accommodate more users efficiently [1-4].

It suggests two main approaches. The first approach is to extend the use of higher frequency bands through technologies like millimetre-wave communication, often assisted by massive multiple-input, multiple-output (MIMO) systems. By leveraging these new technologies, additional frequency bands can be utilized to accommodate more users and increase overall data capacity [5-7]. The second approach involves reforming spectrum utilization policies to incorporate spectrum sharing. Spectrum sharing allows unlicensed secondary users to access licensed bands under specific conditions, without causing harmful interference to the primary licensed users. This approach allows for more flexible and dynamic allocation of the spectrum, making better use of the available resources and enabling improved spectrum efficiency. Overall, growing challenges related to spectrum management and the need for innovative solutions to address the increasing demand for mobile devices and data services. By exploring new technologies and adapting spectrum policies, the goal [8-10] is to optimize spectrum utilization and accommodate the ever-growing number of users and data consumption efficiently. Efficient spectrum allocation brings about various benefits and improvements in wireless communication systems.

Some of issues in Cognitive radio systems:

- ✓ *Higher Number of Wireless Devices:* By efficiently allocating the spectrum, more wireless devices can be accommodated within the available frequency bands. This allows for increased connectivity and access to wireless services for a larger number of users.
- ✓ *Power Efficiency:* Efficient spectrum allocation enables better power management in wireless devices. By using the spectrum more effectively, devices can optimize their power consumption and extend their battery life, resulting in improved energy efficiency.
- ✓ *Interference Minimization*: Proper spectrum allocation helps minimize interference between different wireless networks and devices operating in close proximity. This reduction in interference enhances overall network performance and reliability.
- ✓ *Throughput Maximization*: Optimizing spectrum allocation leads to increased data throughput and faster data transmission rates. These results in improved network performance and a better user experience, especially in data-intensive applications.
- ✓ *Connectivity Optimization:* Efficient spectrum allocation enhances the connectivity and coverage of wireless networks. It allows for better signal propagation and ensures a more stable and robust connection for users.
- ✓ *Delay Minimization:* By using the spectrum efficiently, communication delays can be minimized, leading to reduced latency in data transmission.
- ✓ *Reliability Maximization*: Effective spectrum allocation contributes to the overall reliability and stability of wireless networks. It reduces the likelihood of signal dropouts and enhances the overall quality of service.

The primary objective of this research endeavour is to utilize spectrum sensing and analysis techniques in order to tackle the issue of spectrum shortages, enhance spectrum consumption, and ultimately optimize the performance and efficiency of wireless communication systems. By utilizing unused spectrum bands effectively, cognitive radio can unlock the potential for better spectrum reuse and alleviate the challenges posed by the growing demand for wireless services and data. It also addresses interference management in cognitive radio systems. It investigates various interference cancellation and suppression techniques, such as interference alignment and cognitive beamforming, which enable cognitive radios to mitigate interference to primary users and coexisting cognitive radios. The remaining part is organised as section 2 describes survey of proposed system, followed by proposed system in section 3. The evaluation is depicted in section 4 which is concluded in section 5.

LITERATURE

Research on signal analysis for cognitive radio has been a topic of great interest and significance in the field of wireless communications. Cognitive radio aims to enhance spectrum utilization by dynamically adapting to the radio environment, which requires robust signal analysis techniques. In this essay, we will explore some key research papers that have contributed to signal analysis in cognitive radio systems.

Haykin, S et.al [11] provides a comprehensive overview of various spectrum sensing techniques for cognitive radio systems. The paper discusses the strengths and limitations of each technique, helping readers understand the suitability of different signal analysis methods in cognitive radio scenarios.

By Cabric, D et.al [12] reviews, the authors explore signal analysis methods and algorithms that enable cognitive radios to identify and utilize available spectrum efficiently. The paper covers various signal processing techniques and their applications in spectrum sensing, channel estimation, and modulation recognition. It highlights the importance of accurate signal analysis for cognitive radio's successful operation and discusses the key challenges and opportunities in this area. Yu, Y et.al [13] proposes a wavelet spectrum sensing technique for cognitive radios. The authors demonstrate how wavelet transform can be used to detect spectrum holes and identify primary user signals in the presence of noise and interference. The paper presents evaluation on validation of effectiveness of proposed Technique and compares it with other spectrum sensing techniques, showcasing its advantages in certain scenarios.

In Wang, H. et.al [14], is survives paper explores the usages of programming based learning techniques in systems. It focuses on signal analysis aspects like modulation classification, channel prediction, and interference identification using machine learning algorithms. The authors discuss the potential of machine learning to improve signal analysis accuracy and adaptability in cognitive radio networks. Chen, M et.al [15]., Park, J. M., & Hossain, E. discusses the integration of spectrum sensing and data transmission in cognitive radio networks. It examines signal analysis techniques that enable cognitive radios to perform both spectrum sensing and communication concurrently, ensuring efficient spectrum utilization.

In supposition, signal analysis is a critical aspect of cognitive radio systems as it enables efficient spectrum sensing, channel estimation, and modulation recognition. The mentioned research papers provide valuable insights into different signal analysis techniques and their applications in cognitive radio networks, contributing significantly to the advancement of this dynamic and adaptive wireless communication paradigm [16-19].

PROPOSE HARDWARE MODEL

In a Spectrum Awareness Network, Cognitive Radio (CR) nodes operate in a non-cooperative manner, meaning they do not have explicit communication or coordination with each other. Instead, they independently sense the spectrum and opportunistically access unused frequency bands for transmission, thus optimizing spectrum utilization. The proposed spectrum sensing algorithms in this context are designed to facilitate efficient spectrum sharing in the CR network. These algorithms can be adapted for both half-duplex and full-duplex communication scenarios. In half-duplex mode, a node can send or receive but not both at the same time. In full-duplex mode, a node can send and receive simultaneously. By supporting both modes, the CR network can dynamically adjust its communication strategy based on network conditions and requirements.

The primary application of this Spectrum Awareness Network centers on the use of Software-Defined Radio (SDR) nodes, specifically referred to as BitSDR as shown in Figure 1. One of the significant advantages of BitSDR in cognitive radio is its ability to rapidly adapt to changing communication environments. By reprogramming the software components, cognitive radios can quickly adjust their processing techniques, enabling them to switch between different communication protocols and frequency bands in a dynamic and seamless manner. This flexibility proves particularly beneficial in cognitive radio scenarios where spectrum availability can vary drastically over time and across geographical locations. BitSDR is designed with specific considerations for power constraints, high-bandwidth data transmission, and low-latency communication. These features make it well-suited for deployment in decentralized peer-to-peer applications where devices need to interact and communicate seamlessly without heavy reliance on centralized infrastructure.

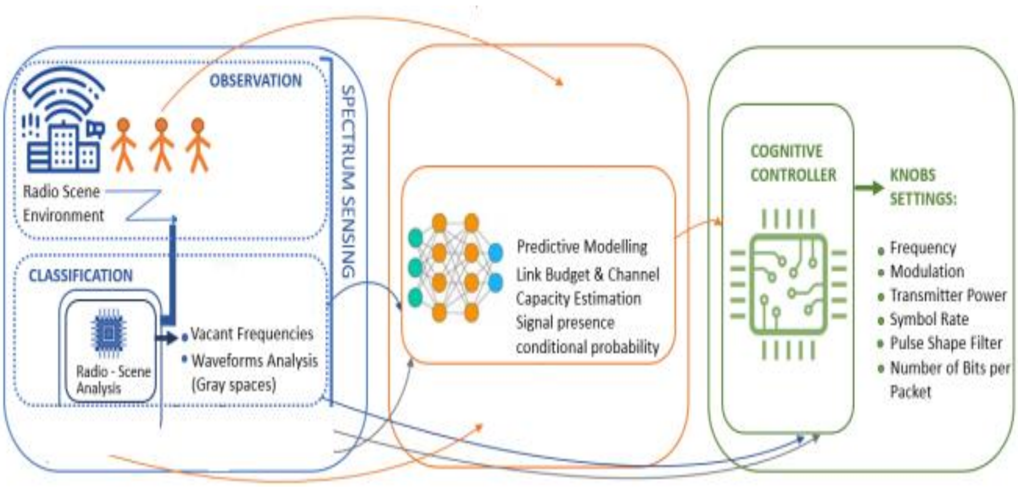

Figure 1. Proposed hardware system.

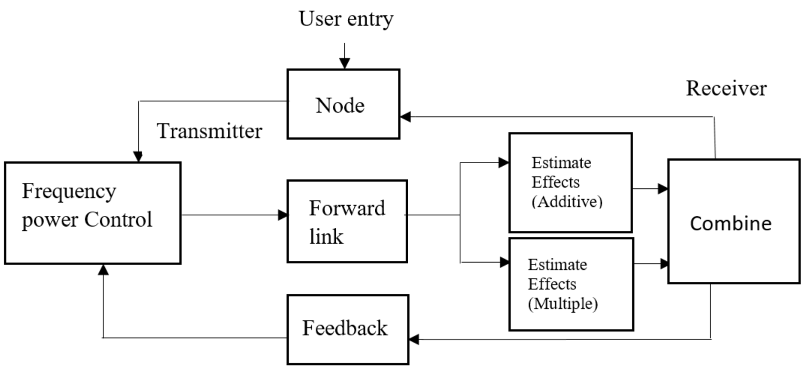

Figure 2. Signal Analysing module

The described communication process outlines the operation of a distributed non-cooperative cognitive radio network (CRN) using peer-to-peer (P2P) type communication as shown in *figure 2*. Cognitive Nodes (CNodes) in the network can efficiently sense and use spectrum. The steps involved in communication between two CR terminals (nodes) are as follows:

Step 1. Spectrum Sensing and Information Transmission:
Each CR terminal performs spectrum sensing locally to detect available frequency bands. Spectrum sensing data is sent to a shared control channel. Nodes communicate spectrum data through the common control channel.

Step 2. Spectrum Information Combination and Broadcasting:
The CNode, which plays a central role in the CRN, receives the spectrum sensing information from all the CR terminals through the common control channel. The CNode combines this information to obtain a comprehensive view of the spectrum utilization across the network. After processing and analysing the combined data, the CNode broadcasts the resulting spectrum information to all CR terminals in the network.

Step 3. Initiation of Communication:
Upon receiving the broadcasted spectrum information from the CNode, CR terminals that have the permission to communicate in specific frequency bands are allowed to establish communication. The process of communication between two terminals begins with initial steps, such as exchanging training sequences for channel estimation. Once the channel is estimated and tracked, actual data transmission takes place between the two CR terminals.

Step 4. Periodical Spectrum Sensing:
During the ongoing data transmission, the CR terminals periodically perform spectrum sensing at predefined intervals (Δt seconds). This periodic sensing allows the network to monitor changes in the spectrum occupancy and adapt dynamically to the evolving radio environment. Data transmission is temporarily interrupted during the sensing process, ensuring that the network operates efficiently while minimizing interference with primary users.

In this communication process in a non-cooperative cognitive radio network enables CR terminals to sense the spectrum locally, share the sensing information through a common control channel, and utilize the combined spectrum information from the CNode to facilitate peer-to-peer communication between willing nodes. The periodic spectrum sensing ensures that the network operates in a dynamic and adaptive manner, optimizing spectrum utilization and ensuring coexistence with other wireless systems.

SPECTRUM AWARENESS FOR COGNITIVE RADIO

A primary user transmits 1/4 phase shift key technique symbols on a 1 MHz channel with 4 MHz. 500 k symbols/s are sent. Complex additive white Gaussian noise (AWGN) during transmission contaminates the receiving signal. Baseband is used to analyse the received signal. Welch period gram is used to confirm user data noise. Welch's period gram estimates energy-based spectrum analysis (PSD) for user data. It identifies signal energy by comparing the incoming signal PSD to a specified detection threshold. The primary user's transmission is detected when the received signal's energy surpasses the detection threshold. M segments are used to compute the Welch period gram from the input signal. Signal PSD is calculated for each segment. Figure 3 shows L as the number of frequency bins to average around zero. This averaging helps to improve the accuracy of the spectral estimation, reducing the effects of noise and providing a more reliable detection mechanism. In the analysis of the system's performance, five different scenarios are considered and compared:

1) Power Spectral Density (PSD) of the signal when only noise is present.
2) PSD of the signal when the primary user is sending QPSK symbols, and noise is present.
3) PSD of the signal when only noise is present (different snapshot).
4) PSD of the signal when the primary user is sending QPSK symbols, and noise is present (different snapshot).
5) PSD of the signal when only noise is present (another different snapshot).

The comparison of these scenarios helps illustrate the effectiveness of the Welch period gram in distinguishing between the presence of the primary user's signal and the background noise. By analysing the PSD of the received signals at different points and snapshots, the performance of the detection method can be evaluated in terms of detection accuracy and robustness against noise. Overall, the Welch period gram is a valuable tool in detecting the primary user's signal amidst the presence of noise in the CRN. It plays a crucial role in enabling cognitive radio devices to efficiently sense the spectrum and identify available frequency bands for opportunistic communication, optimizing spectrum utilization and ensuring coexistence with primary users.

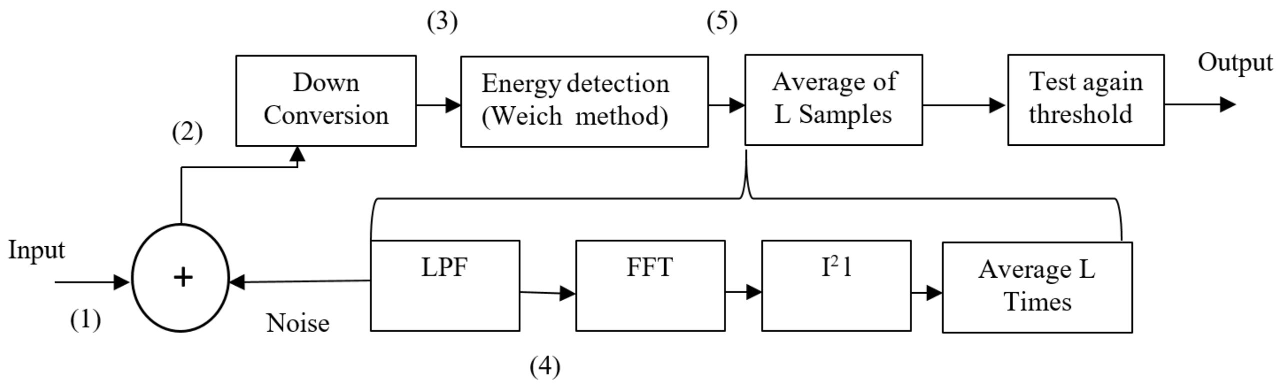

Figure 3 Model used for Simulation

Note that the specific shape of the probability of detection vs. SNR curve can vary based on the detection method used, system parameters, and environmental conditions. The curve is a crucial tool for system designers to optimize the cognitive radio's performance and ensure efficient spectrum sharing while minimizing interference to primary users.

1. At very low SNR levels: The probability of detection is low since the cognitive radio may have difficulty distinguishing the weak primary user signal from the background noise.
2. As SNR increases: The probability of detection also increases since the primary user signal becomes more distinguishable from the noise.
3. At high SNR levels: The probability of detection may saturate and approach 100% as the primary user signal is significantly stronger than the noise, and reliable detection becomes easier.

RESULTS AND DISCUSSION

BitSDR is specifically engineered with considerations for power constraints, high-bandwidth data transmission, and low-latency communication. These features make it exceptionally well-suited for decentralized peer-to-peer applications where devices must interact and communicate seamlessly without heavy reliance on centralized infrastructure. In such applications, the ability to sense and adapt to the available spectrum efficiently is vital for ensuring reliable and efficient communication.

In conclusion, spectrum awareness is the cornerstone of cognitive radio networks, where CR nodes independently sense and utilize the available spectrum, optimizing its use without coordination. The integration of BitSDR, with its rapid adaptability and flexibility, plays a pivotal role in achieving efficient spectrum sharing and supporting a wide range of applications, especially those that demand decentralized, low-latency, and high-bandwidth communication. This spectrum awareness enables CRNs to thrive in dynamic and challenging communication environments, making them a promising solution for addressing the ever-growing demands on wireless networks.

5.1 Signal to Noise Ratio:

The probability of detection (Pd) measures how well cognitive radio systems can dependably discover primary users (PU) in the spectrum. The system's detection performance is commonly shown against the Signal-to-Noise Ratio (SNR). The probability of detection refers to the likelihood that a cognitive radio accurately identifies the existence of a primary user signal when it is present. It is expressed as in (1) :

$$P_d = \frac{Number\ of\ correctly\ detected\ primary\ user\ signals}{Total\ number\ of\ primary\ user\ signals\ present.} (1)$$

The SNR, on the other hand, represents the ratio of the signal power to the noise power and is commonly measured in decibels (dB). It is a crucial parameter that characterizes the quality of the received signal in the presence of noise. In cognitive radio systems, the probability of detection vs. SNR curve is obtained by performing simulations or theoretical analysis. During these analyses, different SNR levels are considered, and for each SNR level, the probability of detection is calculated. Figure 4 illustrates the SNR detection of proposed system.

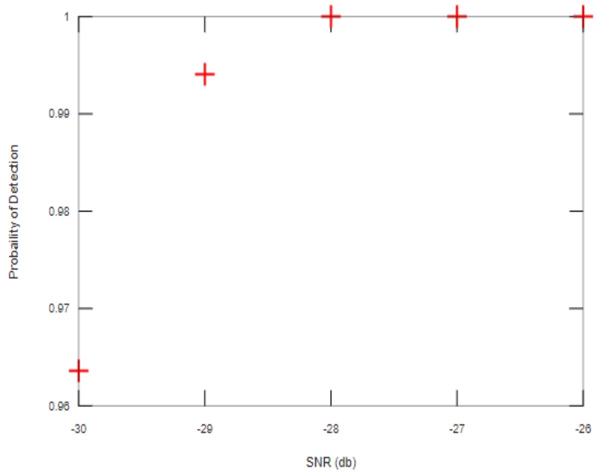

Figure 4 SNR detection of proposed system

5.2 Power Spectral Density

The Power Spectral Density (PSD) is a key concept in cognitive radio systems, serving as a critical tool for comprehending and controlling the usage of the electromagnetic spectrum. The Power Spectral Density (PSD) of a cognitive radio is a measure of how power or energy is distributed across different frequency components within a specific bandwidth. The tool is highly valuable for conducting analysis and characterizing the spectral properties of signals found in the radio environment. The PSD provides valuable information about the power levels of signals at different frequencies, enabling cognitive radio devices to distinguish between occupied and vacant frequency bands.

The Power Spectral Density is a fundamental concept in cognitive radio systems that enables efficient spectrum sensing and sharing. By analyzing the PSD of received signals, cognitive radios can intelligently detect primary user signals, identify vacant frequency bands, and adaptively select suitable channels for secondary user communication, ultimately optimizing spectrum utilization and enhancing the coexistence with other wireless systems in the radio environment. The power spectral density is shown in figure 5.

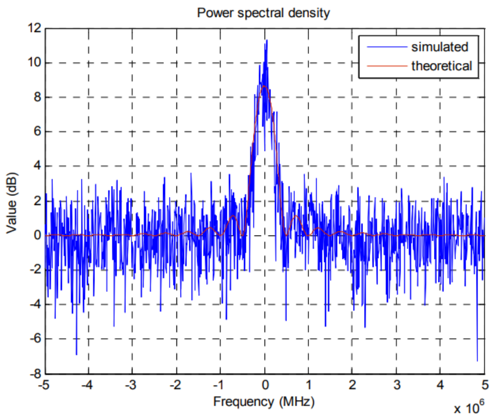

Figure 5 Power Spectral Density (PSD)

5.3 Potential node vs. Sensing Nodes

The study considers scenarios with two and three cooperating cognitive radios (nCR = 2 and nCR = 3), and a comparison is made with the case of a single cognitive radio. The network layout comprises fifteen nodes randomly placed within a one square kilometre area. Each node has a transmission range of 300 meters, marked by circles around them. Among these nodes, one is randomly selected for sensing (marked in red in the figure 6). The selection of the sensing node is based on the condition that it must have a minimum of nCR-1 (either one or two) nodes within its transmission range. This criterion identifies the potential candidates for cooperation. The figure 6 highlights the potential cooperating nodes by marking them in green.

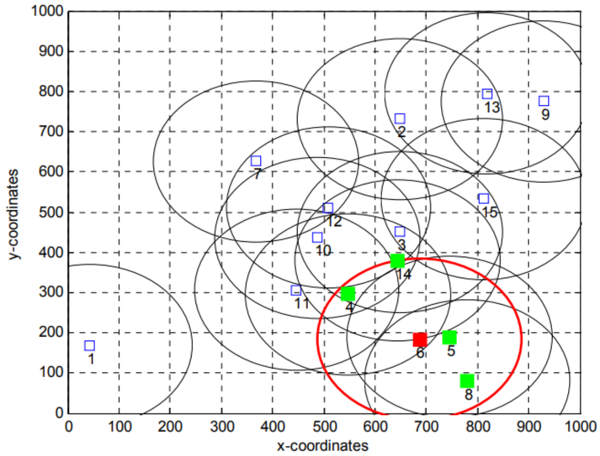

Figure 6. Potential node vs. Sensing Nodes

5.4 Co-operation between nodes.

Cooperation between nodes in cognitive radio is a fundamental concept that enables intelligent and efficient spectrum utilization in wireless communication networks. One of the key advantages of node cooperation in cognitive radio is the ability to collectively gather and exchange spectrum information. Cognitive nodes share their locally sensed spectrum data with each other, creating a comprehensive view of the radio environment. By combining the spectrum information from multiple nodes, the CRN gains a more accurate and reliable understanding of the spectrum occupancy, enabling effective spectrum sensing and decision-making.

In addition to spectrum sensing, cooperative nodes in cognitive radio networks can also share other valuable information, such as channel conditions, interference levels, and transmission capabilities is shown in Figure 7. This cooperative exchange of information allows nodes to adapt their communication strategies and optimize their operations based on real-time network conditions. Furthermore, cooperation facilitates spectrum sharing among cognitive radio devices. Nodes can negotiate and coordinate their transmission schedules to avoid interference with each other and licensed primary users. By dynamically adjusting their transmission parameters, cognitive nodes maximize spectrum utilization, efficiently utilizing available resources, and minimizing the potential for harmful interference.

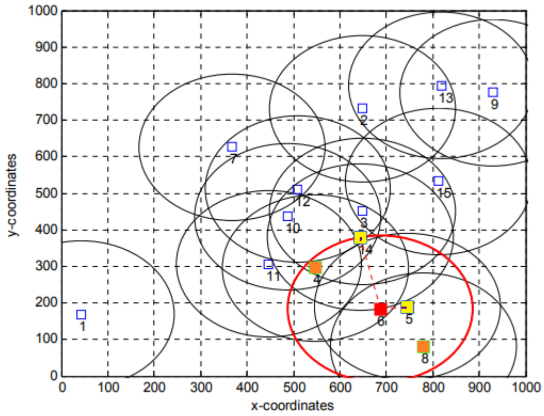

Figure 7. Cooperation of Nodes

5.5 Analysing False Alarm and Detection Probabilities in Cognitive Radio Networks.

Here the spectrum sensing is inherently affected by noise and uncertainties, leading to two potential errors: false alarm and detection.

1. False Alarm: This means that the spectrum sensing algorithm incorrectly identifies noise or interference as a primary user signal, leading to unnecessary spectrum vacating or interference to primary users.
2. Detection: Detection refers to the situation where the cognitive radio system is unable to identify the existence of a primary user signal in the spectrum, even though it is actually present. The failure of the spectrum sensing algorithm to detect primary user transmissions leads to cognitive radio devices being unable to access available frequency bands, resulting in missed opportunities.
3. The selection of an appropriate segment length is crucial in order to find a balance between false alarm rates and finding probabilities, as illustrated in Figure 8. Designing spectrum sensing algorithms that optimize the segment length based on the specific application and environment is crucial to ensure reliable and efficient spectrum utilization in cognitive radio systems.

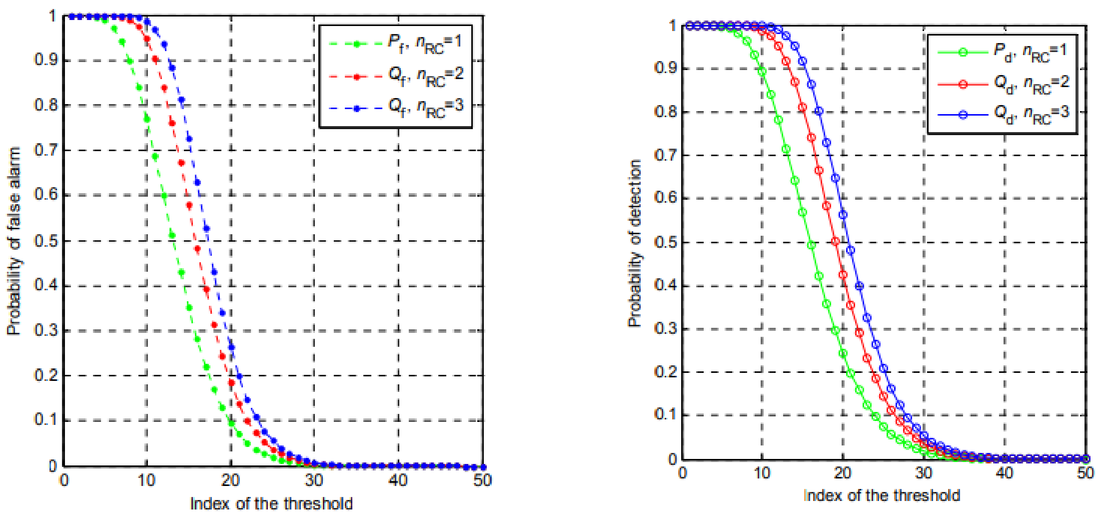

Figure 8. a) False Alarm and b) Detection Probabilities

CONCLUSION

Signal processing plays a pivotal role in empowering cognitive radio systems to effectively sense, analyze, and adapt to the dynamic RF environment. In the context of 5G technology, cognitive radio systems leverage sophisticated signal processing techniques to efficiently harness spectrum resources, mitigate interference, and significantly elevate the reliability and performance of wireless communication.The introduced algorithms in this research constitute substantial contributions to the realm of cognitive radio systems by tackling critical challenges, such as identifying available frequency channels and characterizing waveform attributes. Researchers initially focused on extracting information to make informed decisions regarding spectrum utilization. Dynamic spectrum allocation, a pivotal process, involves cognitive radio devices scrutinizing and selecting the most optimal frequency bands or channels for data transmission while diligently avoiding interference with primary users. Adaptive modulation and coding techniques further enhance data transmission by optimizing it based on channel quality and available resources, deploying a range of machine learning algorithms.

This study underscores the efficacy of employing machine learning for preliminary classification and applying signal processing techniques for vacant channel detection. This underscores the transformative potential of intelligent spectrum sensing in augmenting spectrum utilization and optimizing the performance of cognitive radio networks within the context of 5G technology.The practical implications of this research extend beyond cognitive radio systems and encompass various wireless communication networks poised to exploit opportunistic spectrum access. By optimizing the utilization of available frequency bands, these networks are well-equipped to efficiently cater to the escalating demand for wireless services and data transmission, thereby enhancing overall network efficiency and performance. In conclusion, this research endeavors to advance the realm of cognitive radio technology by underscoring the paramount importance of intelligent spectrum sensing within the 5G landscape. It accentuates how this technology can proficiently harness spectrum resources and augment the capabilities of wireless communication networks. The findings presented in this research offer valuable insights and guidelines for the development of more intelligent and adaptive wireless systems, particularly in the context of 5G technology.

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