

SEIZING THE SPECTRUM: COGNITIVE RADIO NETWORKS' PATH TO EFFICIENT COEXISTENCE

Abstract

The escalating demand for wireless communication services has led to a critical shortage of available radio spectrum. Cognitive radio networks emerge as a promising solution to this challenge by enabling dynamic and intelligent spectrum access. This paper presents an in-depth exploration of cognitive radio networks, focusing on spectrum management and coexistence strategies. We delve into the fundamental concepts of cognitive radio networks, highlighting their ability to opportunistically exploit underutilized frequency bands while ensuring minimal interference with licensed primary users. The paper covers essential topics such as spectrum sensing techniques, dynamic spectrum access, spectrum mobility, coexistence protocols, and spectrum sharing models. Case studies illustrate practical implementations in wireless sensor networks, 5G systems, and Internet of Things (IoT) applications. Moreover, we address challenges, including security and privacy concerns, and discuss the integration of cognitive radio networks with emerging technologies like AI, machine learning, and blockchain. This comprehensive overview underscores cognitive radio networks' potential to revolutionize spectrum utilization, offering a path toward efficient and harmonious wireless communication.

Keywords: Cognitive radio networks, spectrum management, coexistence strategies, spectrum sensing, dynamic spectrum access, wireless sensor networks, 5G networks.

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I. INTRODUCTION

- 1. Background and Motivation:** The explosive growth of wireless communication technologies has led to an unprecedented demand for radio spectrum. Traditional spectrum allocation methods, characterized by static and exclusive assignments to licensed users, have resulted in spectrum scarcity and underutilization. This scarcity becomes even more pronounced with the proliferation of wireless devices and the advent of new communication paradigms like the Internet of Things (IoT) and 5G networks. To address this challenge, cognitive radio technology emerges as a revolutionary solution that promises efficient spectrum utilization and improved coexistence between various wireless systems [1].
- 2. Objectives of the Paper:** This paper aims to provide a comprehensive overview of cognitive radio networks, focusing on the critical aspects of spectrum management and coexistence strategies. The primary objectives of this paper are:
 - **Understanding Cognitive Radio Networks:** We will delve into the fundamental concepts of cognitive radio networks, exploring how they enable dynamic and intelligent spectrum access by allowing unlicensed secondary users to opportunistically exploit underutilized frequency bands without causing harmful interference to primary users.
 - **Spectrum Sensing Techniques:** We will examine various spectrum sensing techniques employed by cognitive radios to detect spectrum availability and occupancy. These techniques play a pivotal role in enabling cognitive radios to make informed decisions about accessing specific frequency bands.
 - **Spectrum Management and Allocation:** The paper will explore dynamic spectrum access mechanisms, including database-driven approaches and geolocation databases. We will discuss the challenges associated with real-time spectrum allocation and how cognitive radios adapt to varying network conditions.
- 3. Overview of Cognitive Radio Networks:** Cognitive radio networks are built upon the foundational principle of opportunistic spectrum utilization. In these networks, cognitive radios possess the capability to sense their environment, analyze spectrum availability, and dynamically adjust their transmission parameters to operate on vacant frequency bands. This cognitive capability enables efficient utilization of the available spectrum while coexisting harmoniously with licensed users [2].

Cognitive radios consist of two types of users: primary users (PUs) and secondary users (SUs). Primary users are licensed spectrum holders with exclusive rights to specific frequency bands. Secondary users, on the other hand, are unlicensed and opportunistic users who can access the spectrum when it is not being utilized by primary users. The key challenge lies in enabling secondary users to sense and access the spectrum without causing interference to primary users [3].

In the subsequent sections of this paper, we will delve into the technical aspects of cognitive radio networks, including spectrum sensing techniques, spectrum management strategies, coexistence mechanisms, network protocols, and case studies showcasing practical implementations.

Through a thorough exploration of cognitive radio networks' spectrum management and coexistence strategies, this paper contributes to a deeper understanding of how cognitive radio technology can alleviate the spectrum scarcity challenge and foster the efficient utilization of the radio frequency spectrum.

II. FUNDAMENTALS OF COGNITIVE RADIO NETWORKS

- 1. Spectrum Scarcity and Cognitive Radio Solution:** The increasing demand for wireless communication services and the limited availability of spectrum resources have highlighted the need for more efficient spectrum utilization. Traditional static spectrum allocation results in spectrum underutilization, as licensed frequency bands often remain idle in certain geographic locations and time periods. Cognitive radio networks offer an innovative solution to this challenge by introducing dynamic and opportunistic spectrum access.

Cognitive radio technology addresses spectrum scarcity by enabling secondary users to access spectrum bands that are not actively used by primary users. Through real-time spectrum sensing and intelligent decision-making, cognitive radios identify and utilize vacant frequency bands without causing harmful interference to primary users. This adaptive and context-aware approach enhances spectrum efficiency and encourages optimal utilization of the radio frequency spectrum [4].

- 2. Cognitive Radio Architecture:** The architecture of a cognitive radio network is designed to facilitate intelligent spectrum management and coexistence between primary and secondary users. It consists of several key components:
 - **Spectrum Sensing Module:** This module is responsible for monitoring the radio frequency spectrum to detect spectrum holes, which are frequency bands not currently used by primary users. Various spectrum sensing techniques, such as energy detection and matched filter detection, are employed to sense the presence or absence of primary user transmissions.
 - **Cognition Engine:** The cognition engine processes the information gathered from the spectrum sensing module and makes decisions regarding spectrum access. It considers factors such as interference thresholds, quality of available spectrum, and regulatory constraints to determine the appropriate frequency band for secondary user transmission.
 - **Resource Management:** The resource management component allocates available spectrum to secondary users based on the decisions made by the cognition engine. It ensures that secondary users operate within the constraints defined by primary users' spectrum usage.

- **Transceiver:** The transceiver is responsible for the actual transmission and reception of data. It adjusts its transmission parameters, such as frequency, power, and modulation, based on the allocated spectrum and the information provided by the cognition engine [5].
- 3. Primary and Secondary Users:** Cognitive radio networks distinguish between primary users (PUs) and secondary users (SUs). Primary users are the licensed spectrum holders who have exclusive rights to specific frequency bands. These users include established communication systems such as cellular networks, broadcast services, and public safety networks. Primary users have priority access to the spectrum, and cognitive radios must not cause harmful interference to their transmissions.

Secondary users, on the other hand, are unlicensed users who can opportunistically access the spectrum when it is not being utilized by primary users. Secondary users are equipped with cognitive radio capabilities, allowing them to sense the spectrum, identify vacant frequency bands, and adjust their transmissions to avoid interfering with primary users. The goal of secondary users is to access the spectrum opportunistically while ensuring minimal impact on the quality of service experienced by primary users [6].

In the subsequent sections, we will delve deeper into spectrum sensing techniques, spectrum management, coexistence strategies, and protocols that enable the efficient operation of cognitive radio networks.

III. SPECTRUM SENSING TECHNIQUES

Efficient spectrum sensing is a cornerstone of cognitive radio networks, enabling secondary users to identify available frequency bands for transmission without causing harmful interference to primary users. Various spectrum sensing techniques have been developed to detect primary user activity and accurately identify spectrum holes. These techniques cater to different types of signals, noise conditions, and hardware constraints [7].

- 1. Energy Detection:** Energy detection is one of the simplest and most widely used spectrum sensing techniques. It involves measuring the energy levels in a specific frequency band and comparing them to a predefined threshold. If the measured energy exceeds the threshold, a primary user signal is assumed to be present.

Energy detection is suitable for identifying wideband signals but can be sensitive to noise uncertainty and variations in the noise floor. Adaptive thresholding and techniques such as cooperative sensing can mitigate some of these challenges.

- 2. Matched Filter Detection:** Matched filter detection is particularly effective for detecting signals with known waveforms. A matched filter is designed to maximize the signal-to-noise ratio of the received signal, increasing the likelihood of detecting signals even in the presence of noise.

This technique requires knowledge of the primary user's signal characteristics, such as modulation and coding schemes. While effective for signals with distinct waveforms, it might be less suitable for detecting signals with varying or unknown characteristics.

- 3. Cyclostationary Feature Detection:** Cyclostationary feature detection exploits the cyclostationary nature of many communication signals. It involves analyzing the cyclic properties of a received signal to detect its presence. Cyclostationary techniques can distinguish between primary user signals and noise, making them robust against varying noise conditions.

However, cyclostationary detection can be computationally intensive and might require synchronization with the primary user's signal [8].

- 4. Cooperative Sensing:** Cooperative sensing leverages multiple secondary users to sense the spectrum. Each secondary user's local sensing results are combined to make a joint decision about spectrum availability. Cooperative sensing improves detection reliability, especially in fading environments and in the presence of hidden primary users.

However, cooperative sensing introduces overhead due to communication between secondary users and the need for coordination mechanisms.

- 5. Sensing Challenges and Trade-offs:** While these spectrum sensing techniques offer various advantages, there are inherent challenges and trade-offs:

- **Sensing Time:** Rapid detection requires a shorter sensing time but might result in higher false alarms. Longer sensing times improve detection accuracy but delay spectrum access.
- **Noise Uncertainty:** Noise variations can impact detection accuracy. Adaptive thresholding and collaborative sensing can mitigate this challenge.
- **Hidden Primary Users:** Primary users might be located outside a secondary user's sensing range, leading to missed detection. Cooperative sensing can address this issue.
- **Spectrum Sensing Energy:** Spectrum sensing itself consumes energy, which must be balanced with the benefits of accessing vacant frequency bands.

In the subsequent sections, we will explore dynamic spectrum management, coexistence strategies, and how cognitive radio networks address these challenges to achieve efficient spectrum utilization.

IV. SPECTRUM MANAGEMENT AND ALLOCATION

Efficient spectrum management and allocation are critical components of cognitive radio networks. These mechanisms ensure that secondary users can access available spectrum bands while minimizing interference to primary users. Various strategies and approaches have been developed to achieve dynamic and intelligent spectrum access.

- 1. Dynamic Spectrum Access (DSA):** Dynamic Spectrum Access (DSA) is at the core of cognitive radio networks. It enables secondary users to opportunistically access vacant spectrum bands in real time. DSA requires cognitive radios to sense the spectrum, identify available frequency bands, and select appropriate channels for transmission. The dynamic nature of DSA allows cognitive radios to adapt to changing spectrum availability and varying network conditions.

DSA strategies can include both **opportunistic accesses**, where secondary users use spectrum opportunistically when it's unused, and **interweave access**, where secondary users operate in between primary user transmissions without causing interference.

- 2. Spectrum Mobility and Handoff:** Spectrum mobility refers to the ability of cognitive radio users to switch between different frequency bands based on changing environmental conditions. Spectrum mobility can be initiated by factors such as changes in primary user activity or variations in signal quality. Cognitive radios must seamlessly transition from one frequency band to another to maintain their quality of service.

Spectrum handoff involves the process of releasing the current spectrum band and acquiring a new one. Handoff decisions are influenced by factors such as available spectrum, quality of service requirements, and interference levels [9].

- 3. Spectrum Sharing Models:** Cognitive radio networks operate under different spectrum-sharing models to ensure coexistence with primary users. These models include:

- **Underlay Spectrum Sharing:** Secondary users transmit concurrently with primary users as long as interference to primary users is limited.
- **Overlay Spectrum Sharing:** Secondary users transmit during the idle periods of primary users' transmissions, ensuring minimal interference.
- **Overlay with Interference Temperature:** The total interference caused by secondary users is controlled to maintain a permissible level of interference at primary users' receivers.

- 4. Database-Driven Approaches:** Database-driven approaches involve central databases that provide information about spectrum availability, regulatory constraints, and primary user activities. Cognitive radios query these databases to determine suitable frequency bands for transmission. These databases can significantly improve the accuracy of spectrum availability information and reduce the chances of harmful interference.

Database-driven approaches also facilitate the implementation of geographic and temporal spectrum usage policies.

- 5. Geolocation Databases:** Geolocation databases store information about the geographic locations of primary users and their associated spectrum usage. Cognitive radios can query these databases to identify available frequency bands in their current location.

Geolocation databases enhance spectrum sensing accuracy, especially in cases where secondary users have limited awareness of primary user activity.

In the subsequent sections, we will explore coexistence strategies, network protocols, practical implementations, challenges, and the future directions of cognitive radio networks.

V. COEXISTENCE STRATEGIES

Efficient coexistence between secondary users (SUs) and primary users (PUs) is a fundamental goal of cognitive radio networks. Coexistence strategies ensure that cognitive radios can access the spectrum opportunistically while minimizing interference to licensed users. These strategies encompass various techniques and protocols that enable harmonious operation in shared spectrum environments [10].

- 1. Interference Management and Mitigation:** Interference management is a crucial aspect of coexistence. Cognitive radios employ techniques such as **cognitive interference alignment** to coordinate their transmissions and avoid causing harmful interference to primary users. Adaptive transmission parameters, such as power levels and modulation schemes, are adjusted to mitigate interference effects.
- 2. Opportunistic Spectrum Access:** Opportunistic spectrum access involves secondary users detecting and utilizing vacant frequency bands whenever they are not occupied by primary users. By leveraging real-time spectrum sensing and dynamic channel selection, secondary users can avoid interfering with ongoing primary user transmissions.
- 3. Listen-Before-Talk (LBT) Protocols:** Listen-Before-Talk (LBT) protocols ensure that secondary users first listen to the channel to detect primary user activity before initiating their transmissions. LBT reduces the likelihood of interference and respects the priority of primary users.

LBT protocols incorporate mechanisms to manage contention and access priority, ensuring fair spectrum utilization among secondary users.

- 4. Power Control Techniques:** Power control techniques are employed to manage interference levels. Cognitive radios adjust their transmission power based on the quality of available channels and the proximity of primary users. Power control helps maintain acceptable signal quality while minimizing the impact on primary users.
- 5. Beamforming and MIMO in Cognitive Radio:** Beamforming and Multiple-Input Multiple-Output (MIMO) techniques enhance spectrum efficiency by directing signals toward intended receivers while minimizing interference to other users. Cognitive radios can adapt their beamforming strategies based on the locations of primary and secondary users.

MIMO technology enables cognitive radios to transmit multiple data streams simultaneously, improving spectral efficiency without compromising coexistence.

In the subsequent sections, we will delve into cognitive radio network protocols, case studies showcasing practical implementations, challenges related to security and privacy, and the promising directions that cognitive radio networks are taking in the context of emerging technologies.

VI. COGNITIVE RADIO NETWORK PROTOCOLS

The effective operation of cognitive radio networks relies on well-defined protocols that govern how secondary users access the spectrum, communicate with each other, and ensure quality of service while coexisting with primary users. These protocols are designed to optimize spectrum utilization, minimize interference, and uphold the principles of fairness and efficient coexistence [11].

- 1. MAC Layer Protocols for Cognitive Radios:** The Media Access Control (MAC) layer plays a pivotal role in cognitive radio networks, managing access to the shared spectrum resource. MAC protocols for cognitive radios must address challenges such as dynamic spectrum access, spectrum sensing coordination, and priority-based access for primary and secondary users.

Protocols like **Dynamic Spectrum Access MAC (DySPAN)** and **IEEE 802.22** provide guidelines for effective medium access, channel selection, and spectrum handoff in cognitive radio networks.

- 2. Routing in Cognitive Radio Networks:** Routing in cognitive radio networks must consider the dynamic nature of the available spectrum and the need to minimize interference. Traditional routing protocols may need to be adapted or enhanced to incorporate spectrum-aware routing decisions. Cognitive radio networks can benefit from routing protocols that take into account factors like available spectrum bands, signal quality, and interference levels.

Routing approaches like **Opportunistic Routing** and **QoS-aware Routing** aim to efficiently route packets while respecting spectrum availability and maintaining coexistence.

- 3. Quality of Service (QoS) Provisioning:** Maintaining Quality of Service (QoS) is essential in cognitive radio networks to ensure that users experience reliable and satisfactory communication despite varying spectrum conditions. QoS provisioning involves mechanisms for allocating spectrum resources based on application requirements, traffic demands, and interference constraints.

Cognitive radio networks often employ QoS mechanisms such as admission control, bandwidth reservation, and dynamic spectrum allocation to prioritize users and applications based on their QoS requirements.

In the subsequent sections, we will explore practical implementations of cognitive radio networks through case studies, delve into challenges related to security and privacy, and discuss the potential role of cognitive radio networks in the context of emerging technologies [12].

VII. COGNITIVE RADIO STANDARDS AND REGULATIONS

The deployment and operation of cognitive radio networks are influenced by various standards and regulations that govern spectrum usage, coexistence, and interference management. These standards and regulations provide a framework for ensuring responsible and efficient utilization of the radio frequency spectrum.

- 1. IEEE 802.22 Standard:** The **IEEE 802.22** standard, also known as "Wireless Regional Area Networks (WRAN)," is a prime example of a cognitive radio standard. It specifies the operation of cognitive radio networks in the TV white space spectrum. The standard defines protocols for dynamic spectrum access, coexistence with TV broadcast services, and efficient utilization of unused TV channels.

IEEE 802.22 incorporates techniques such as geolocation databases and cognitive sensing to ensure that secondary users operate within regulatory constraints and do not interfere with incumbent users.

- 2. FCC Regulations and Spectrum Sharing Rules:** In the United States, the **Federal Communications Commission (FCC)** plays a pivotal role in regulating spectrum usage and enabling cognitive radio technology. The FCC's regulatory framework promotes dynamic spectrum access and efficient coexistence while ensuring the protection of incumbent users.

The FCC's **TV White Space (TVWS)** regulations allow unlicensed devices to operate in unused TV channels. These regulations mandate geolocation and database-driven approaches to prevent interference with TV broadcasters.

- 3. International Regulatory Framework:** Cognitive radio networks operate in a global context, and international regulatory bodies establish frameworks to harmonize spectrum usage across countries. The **International Telecommunication Union (ITU)** allocates frequency bands and sets regulations to ensure global spectrum compatibility.

The ITU's **Radio Regulations** define how spectrum should be allocated for various communication services. Cognitive radio networks must adhere to these regulations to ensure cross-border coexistence and prevent harmful interference.

In the subsequent sections, we will delve into case studies showcasing practical implementations of cognitive radio networks, explore challenges related to security and privacy, and discuss the potential synergy between cognitive radio networks and emerging technologies[13].

VIII. CASE STUDIES AND PRACTICAL IMPLEMENTATIONS

Real-world case studies and practical implementations highlight the tangible benefits and challenges of integrating cognitive radio technology into diverse communication scenarios. These examples demonstrate how cognitive radio networks can enhance spectrum utilization, coexistence, and communication efficiency.

- 1. Cognitive Radio in Wireless Sensor Networks: Wireless Sensor Networks (WSNs)** often operate in challenging environments with limited available spectrum. Cognitive radio technology can be employed to enable intelligent spectrum access for sensor nodes, enhancing their communication reliability and minimizing interference.

For instance, in environmental monitoring applications, cognitive radios can help WSNs adapt to changing spectrum conditions due to environmental factors and coexist with other wireless systems.

- 2. Cognitive Radio in 5G and Beyond:** The integration of cognitive radio into **5G** and future communication systems presents opportunities for dynamic spectrum access and improved quality of service. In **5G networks**, cognitive radios can enhance resource allocation, support ultra-dense networks, and enable efficient utilization of millimeter-wave spectrum.

Cognitive radio can help address the spectrum scarcity challenges in these high-capacity networks while ensuring coexistence with other services.

- 3. Cognitive Radio Applications in IoT:** The **Internet of Things (IoT)** landscape involves a multitude of devices with varying communication needs. Cognitive radio technology can play a crucial role in optimizing spectrum access for IoT devices while respecting their diverse QoS requirements.

In industrial IoT applications, for example, cognitive radios can dynamically allocate spectrum to devices with different bandwidth and latency needs, ensuring efficient coexistence and minimal interference.

In the subsequent sections, we will explore the challenges and considerations related to security and privacy in cognitive radio networks, discuss potential advancements in machine learning and AI techniques for spectrum management, and conclude by summarizing the key findings and implications of cognitive radio networks in the modern wireless landscape[14].

IX. CHALLENGES AND FUTURE DIRECTIONS

The evolution of cognitive radio networks brings both exciting opportunities and inherent challenges. Addressing these challenges and exploring future directions are crucial for realizing the full potential of cognitive radio technology.

- 1. Security and Privacy Concerns:** **Security** and **privacy** are paramount in cognitive radio networks. The dynamic nature of spectrum access and the reliance on databases introduce vulnerabilities. Unauthorized users could exploit cognitive radios for malicious purposes, and personal data stored in geolocation databases might be at risk.

Ensuring secure spectrum sensing, secure database access, and robust authentication mechanisms are imperative. Privacy-preserving techniques must be employed to safeguard user identities and sensitive information stored in databases.

2. **Cooperative Coexistence Techniques:** Cooperative techniques among secondary users can enhance coexistence and spectrum access reliability. **Collaborative sensing** involves secondary users sharing their sensing results to improve spectrum availability detection, particularly in fading environments.
3. **Cooperative beamforming:** Enables multiple cognitive radios to work together to form focused beams, minimizing interference to primary users while maximizing spectral efficiency.
4. **Machine Learning and AI in Cognitive Radio:** **Machine learning** and **artificial intelligence (AI)** techniques hold immense potential for cognitive radio networks. Machine learning algorithms can enhance spectrum sensing accuracy by intelligently adapting to changing noise conditions. AI-based decision-making engines can optimize spectrum access decisions based on historical data, network conditions, and user requirements.

These technologies enable cognitive radios to learn from experience, leading to more efficient spectrum utilization and better coexistence.

5. **Integration with Emerging Technologies:** Cognitive radio networks can complement and integrate with emerging technologies such as **blockchain**, **edge computing**, and **autonomous systems**. Blockchain can enhance spectrum sharing transparency and traceability, edge computing can enable local spectrum management, and autonomous systems can use cognitive radios to make real-time decisions in dynamic environments.

The synergy between cognitive radio networks and emerging technologies opens avenues for innovative applications and solutions.

In conclusion, the journey of cognitive radio networks encompasses addressing technical, regulatory, and security challenges while embracing the potential of emerging technologies. The dynamic landscape of wireless communication requires continual exploration and adaptation, making cognitive radio a catalyst for more efficient, adaptable, and spectrum-aware networks [15].

X. CONCLUSION

Cognitive radio networks stand as a transformative solution to the pressing challenges of spectrum scarcity and inefficient utilization in modern wireless communication. This paper has provided a comprehensive exploration of cognitive radio networks, delving into their fundamentals, spectrum sensing techniques, management and allocation strategies, coexistence mechanisms, network protocols, case studies, challenges, and future directions.

The foundation of cognitive radio networks lies in their ability to dynamically sense the spectrum, intelligently make decisions, and adapt to changing network conditions. By allowing secondary users to access spectrum opportunistically and minimizing interference to primary users, cognitive radio networks pave the way for enhanced spectrum efficiency and coexistence.

From energy detection to cooperative sensing, a spectrum of sensing techniques equips cognitive radios to identify vacant frequency bands accurately. Through protocols like IEEE 802.22 and FCC regulations, cognitive radio networks adhere to standards that ensure responsible and efficient spectrum sharing. Practical implementations, such as integration with wireless sensor networks, 5G networks, and IoT applications, illustrate the versatility and impact of cognitive radio technology across various domains.

Challenges are not without their share of solutions. Security and privacy concerns are met with robust authentication, secure database access, and privacy-preserving techniques. The cooperative coexistence approach harnesses the collective power of secondary users, while machine learning and AI empower cognitive radios to learn, adapt, and optimize spectrum access.

As cognitive radio networks embrace the integration with emerging technologies like blockchain, edge computing, and autonomous systems, the landscape of wireless communication takes a step forward into a more intelligent, adaptable, and spectrum-efficient future.

In conclusion, cognitive radio networks stand as a testament to the power of innovation in addressing complex challenges. Through continued research, collaboration, and vigilance in addressing potential pitfalls, cognitive radio networks have the potential to reshape the wireless communication ecosystem and pave the way for a more connected and harmonious technological world.

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