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Review Article

Unlocking the Full Potential of Spectrum: A Comprehensive Review of Cognitive Radio Technology

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ABSTRACT

Wireless networks are confronted with enormous challenge because of the limited availability of radio spectrum, which has culminated in spectrum congestion and ineffective utilization of the spectrum's resources. This has led to a great deal of innovation in both communication and mobile devices that enable the delivery of high-quality multimedia content from various sources. However, despite these advances, there is still a need to find new ways to utilize existing frequency bands. Recent years have witnessed an awful research on cognitive radio (CR) based networks development. This review paper provides a comprehensive overview of CR technology, its capabilities, and its various applications in wireless communications. It not only provides an understanding of CR technology, its capabilities, and its potential applications; but also serves as a useful resource for researchers, practitioners and students interested in wireless communications and cognitive radio technology.

1. INTRODUCTION

Dynamic Spectrum Access (DSA) is a state-of-the-art technology that facilitates instantaneous access to underutilized spectrum bands, allowing wireless devices to intelligently and dynamically access such bands. This cutting-edge technology has the capability to greatly improve the utilization of spectrum. The primary goal of this technology is to address spectrum scarcity by enabling more effective spectrum utilization, enhancing spectrum access, and reducing interference in the wireless spectrum [1-5]. The progression of cognitive radio technology, its functionalities, as well as the IEEE standard associated with it, are expounded upon below. During the latter part of the 1990s, Joseph Mitola conceptualized the notion of a cognitive radio - a radio capable of observing and adapting to its environment and making informed decisions based on the available spectrum. In 2002, the FCC initiated a rulemaking process that allowed unlicensed devices to operate within the TV broadcast spectrum and demonstrated their proficiency in identifying and avoiding interference with TV signals. This served as an initial step towards facilitating the development and advancement of cognitive radio technology. Once FCC permitted unlicensed devices to use the TV bands, there was a growing interest in cognitive radio technology, according to a study by Liang et al. [6-8]. This technology enables devices to intelligently sense and utilize available spectrum, potentially enhancing spectrum utilization and improving overall wireless network performance. The objective was to design a radio capable of sensing its environment, detecting available spectrum, and dynamically adjusting its broadcast parameters to optimize efficiency. The Institute of Electrical and Electronics Engineers (IEEE) develop a standardized protocol for cognitive radio communications in 2005 [9-12]. The goal was to enable intelligent and efficient utilization of the available spectrum, thereby resolving issues such as spectrum scarcity and interference. The outcome of their efforts was the creation of the IEEE 802.22 standard in 2011, which outlines the framework for CR technology implemented in wireless regional area networks (WRANs).

This paper covers various aspects of the cognitive radio, it starts with an introduction of the concept of CR and its working principles, followed by a discussion of its key features, including spectrum sensing, spectrum management, spectrum sharing, and interference mitigation. This study provides a comprehensive analysis of the IEEE 802.22 standard. The study also examines various updates and releases related to this standard The paper also discusses the different uses of CR technology,

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such as cognitive radio networks for emergency communication systems, cognitive ad hoc networks, cognitive mesh networks, and wireless sensor networks. It also covers various research initiatives that have been undertaken to improve the performance of CR systems, such as advanced spectrum sensing techniques, dynamic spectrum allocation, and cooperative spectrum sensing. Finally, the paper concludes by summarizing the major contributions of CR technology in wireless communications and highlighting the challenges and future research directions for the development of CR systems.

2. CAPABILITIES OF CR TECHNOLOGY

Cognitive radio technology boasts a range of capabilities that enhance spectrum utilization through dynamic spectrum access, empowering wireless devices to efficiently access and utilize the available spectrum. As shown in Figure 1, these capabilities include:

1. Spectrum Sensing: It is a fundamental aspect of CR technology, as it grants the capacity to perceive the existence of primary users and comprehend their surrounding environment, which pertains to authorized spectrum users. These systems employ spectrum sensing methods to discern the signals of primary users across the spectrum, enabling them to evade any interference with their communications.

2. Spectrum Management: Cognitive radios are capable of dynamically managing available spectrum by adjusting their transmission parameters in order to meet the application requirements and available spectrum. This enables cognitive radios to optimize their performance and mitigate interference in highly dynamic and complex wireless environments. Cognitive radios have the potential to enhance spectrum utilization and meet the increasing demand for wireless communication services by adapting to changing conditions, according to [13-15]. This ability to intelligently sense and utilize available spectrum resources can help optimize spectrum utilization, enhance spectrum access, and mitigate interference in the wireless spectrum.

3. Spectrum Sharing: Cognitive radios possess the capacity to collaborate with other cognitive radios, facilitating the sharing of the available spectrum resources. Collaboration between different wireless devices improves spectrum utilization while avoiding interference [16-19]. This collaborative use of spectrum resources can help improve overall wireless network performance and alleviate issues such as spectrum scarcity. Through the use of advanced communication protocols and algorithms, cognitive radios can dynamically and seamlessly negotiate spectrum sharing arrangements with other cognitive radios in the vicinity.

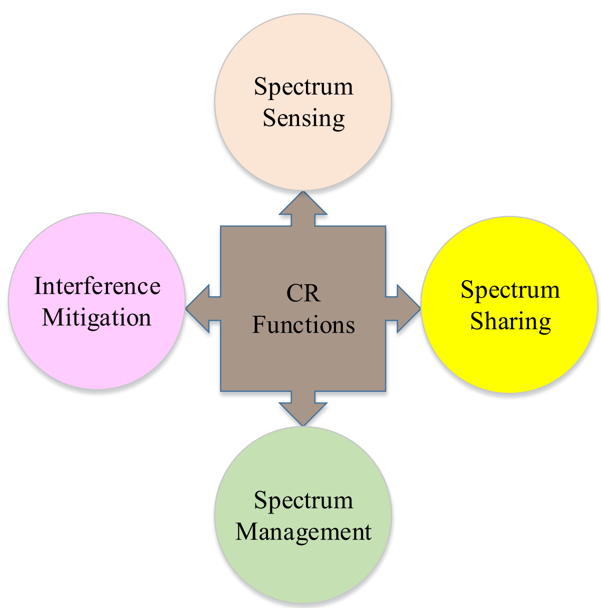

Fig.1. Cognitive Radio Functions

4. Interference Mitigation: Cognitive radios are capable of effectively mitigating interference by adaptively altering their transmission parameters. This ensures that there is no disruption to primary users and other cognitive radios. By monitoring the spectrum in real-time, cognitive radios can dynamically adjust their transmission parameters. This adaptive approach enables cognitive radios to optimize their performance in highly dynamic and congested wireless environments, while minimizing interference and maximizing spectrum utilization.

3. IEEE 802.22 STANDARD FOR COGNITIVE RADIO TECHNOLOGY

IEEE 802.22 standard was the first protocol developed for cognitive radio technology [20-22]. This standard outlines the specification of a CR system WRANs that can operate within the TV broadcast spectrum (54-862 MHz). The standard describes several key attributes that are essential for effective CR operations.

1. *Dynamic Spectrum Access*: Spectrum sensing is a critical function of CR systems that enables them to sense RF environment, detect primary users, and reconfigure themselves to optimize performance [23-24]. By analyzing the spectrum characteristics, CRs can identify primary users and other cognitive radios operating in the same channel. This information is then used to adjust transmission parameters to avoid interference with primary users and other cognitive radios to maximize spectrum utilization.
2. *Geolocation Capability:* Accurate determination of geographic location is a critical function for a cognitive radio system, as it is used to determine the available spectrum. By knowing its location, a cognitive radio can identify the applicable regulations and policies governing spectrum usage in that region. This information can be used to determine the available spectrum for a particular application, as well as to avoid interfering with primary users and other cognitive radios operating in the same area. To accurately determine its location, a cognitive radio system typically uses a combination of satellite-based positioning systems, such as GPS, and terrestrial-based positioning technologies, such as triangulation and signal strength analysis. These methods allow cognitive radios to accurately determine their location and to adjust their transmission parameters accordingly. The ability to accurately determine location is essential for effective cognitive radio operation, particularly in dynamic wireless environments where the available spectrum can change rapidly. By knowing its location and the associated spectrum regulations, a cognitive radio can dynamically adjust its transmission parameters to avoid interference and optimize performance. As such, accurate location determination is a key element of any successful cognitive radio system.
3. *Spectrum Sensing*: Spectrum sensing and primary user detection are key functions of a cognitive radio system. Spectrum sensing involves monitoring the available spectrum in real-time, while primary user detection involves identifying licensed users operating in that spectrum.
4. *Spectrum Management:* The cognitive radio system must be able to manage the available spectrum by analyzing the spectrum utilization and identifying available channels for communication. It must also be able to determine the optimal channel for a given application and reconfigure parameters accordingly. This enables the CR system to maximize its performance and efficiency, while minimizing interference with other users in the same frequency band. Dynamic adjustment of transmission parameters is essential for cognitive radios to operate effectively in dynamic and complex wireless environments.
5. *Spectrum Sharing:* Sharing of the available spectrum is a crucial capability of cognitive radio systems, which enables more efficient utilization of the spectrum. Collaboration between cognitive radio systems can facilitate the sharing of available spectrum resources while minimizing interference with primary users and other cognitive radios [25].
6. Coexistence: The cognitive radio system must be able to coexist with primary users and other cognitive radios without causing interference.
7. *Security:* The cognitive radio system must be secure and protect against unauthorized access and interference.

The key specifications of the IEEE 802.22 standard are summarized in Table I.

TABLE I. IEEE 802.22 standard parameters

Key Specifications	**Details**
Operating Frequency	54-862 MHz
Absolute Bandwidth	Up to 8 MHz
Channelization	Dynamic channel allocation
Modulation	QPSK, 16-QAM, 64-QAM
Transmit Power	Maximum effective isotropic radiated power (EIRP) of 4 watts
Sensing	Energy detection, cyclostationary feature detection, and matched filtering
Coexistence	Dynamic frequency selection, Adaptive transmit power allocation, and interference avoidance
Security	Authentication, confidentiality, and data integrity

The IEEE periodically updates and amends its standards to keep up with advances in technology and address any issues that may arise. Table 2 summarizes the various year-wise releases and amendments of the IEEE 802.22 standard.

TABLE II. VARIOUS RELEASES AND AMENDMENTS OF THE IEEE 802.22 STANDARD

Year	Release/Amendment	Description
2011	IEEE 802.22	This standard outlines the specification of a CR system for intelligent and efficient use of the available spectrum resources while avoiding interference with primary users and other cognitive radios in the same frequency band. It was first released in 2011 and is commonly referred to as the "Wireless Regional Area Network with Cognitive Radio" standard.
2014	IEEE 802.22.1	The IEEE 802.22 standard was amended in 2016 to include a cognitive coexistence management system for wireless networks. This amendment, known as IEEE 802.22.3, builds on the original standard by providing additional mechanisms for cognitive radio systems to coexist with other wireless networks in the same frequency band.
2016	IEEE 802.22.2	The amendment introduced several new features to the IEEE 802.22 standard, including a radar detection mechanism that enables WRAN devices to detect and avoid radar transmissions in the same frequency bands. The amendment also introduced a power control mechanism that limits the transmission power of WRAN devices to avoid interference with radar systems.
2017	IEEE 802.22.3	This amendment introduced several enhancements to the physical layer to increase the data rate and improve error correction capabilities. These modifications enable the WRAN system to achieve higher data rates while maintaining a robust link in challenging environments.
2018	IEEE 802.22.4	The amendment also introduced new protocols for spectrum sensing and dynamic spectrum access, enabling the WRAN system to operate in a spectrum-efficient manner. These protocols allow the WRAN system to detect and utilize available spectrum without interfering with other licensed services.
2020	IEEE 802.22.5	The 6 GHz band, which includes the frequencies between 5.925 GHz and 7.125 GHz, is a relatively underutilized band that offers significant potential for broadband wireless communication. The amendment added provisions for the use of cognitive radio technology, which enables WRAN devices to sense the available spectrum and utilize unused frequencies for data transmission

4. APPLICATIONS OF CR TECHNOLOGY

CR technology has shown potential for various applications in wireless communication systems. One of the significant applications of CR technology is wireless sensor networks (WSNs). In WSNs, CR technology enables the efficient use spectrum and enhances network performance by reducing interference and improving network capacity [26]. Another application of CR technology is cognitive ad hoc networks (CANs), where CR technology allows the nodes to intelligently and dynamically access the available spectrum, thereby improving network performance and reliability [27]. Cognitive mesh networks (CMNs) are another application of CR technology that offers several benefits, including the efficient use of available spectrum resources, increased network capacity, and reduced interference. CR technology enables nodes in the CMN to sense their environment, adapt to changes in the spectrum, and intelligently access the available spectrum to ensure efficient spectrum utilization [28].

Another application of CR technology in 5G is dynamic spectrum access (DSA), which enables wireless devices to access and utilize the available spectrum dynamically and intelligently. CR technology can also enable seamless handover between different wireless networks in 5G, such as cellular, WiFi, and satellite networks. This can be achieved by using the cognitive radio as a gateway between the networks and dynamically selecting the optimal network based on the user's location and quality of service requirements.

The CR technology can improve the security and privacy of the 5G networks by using spectrum encryption and authentication techniques. By dynamically changing the transmission parameters and frequency hopping, CR technology can make it difficult for attackers to intercept or jam the communication. Moreover, CR technology can also be used in cognitive radio networks for emergency communication systems. In emergency communication systems, CR technology can help to ensure reliable communication even in situations where the existing communication infrastructure is damaged or destroyed [29]. To enhance the functionality of CR systems in diverse applications, numerous research projects have been launched. For example, Zhang et al. suggested a novel spectrum sensing method for WSNs based on empirical mode decomposition (EMD), which increases sensing precision and lowers the rate of false alarms [30]. In another study, Zhao et al. proposed a dynamic spectrum allocation scheme for CANs that efficiently allocates spectrum resources based on the network conditions and user requirements [31].

5. WORLDWIDE RESEARCH INITIATIVES ON CR TECHNOLOGY

There have been various research activities and projects undertaken worldwide to explore and develop the potential of CR technology. In 2004, the Defense Advanced Research Projects Agency (DARPA) launched the XG (Extensible Radio) project to develop a cognitive radio that can adapt to changes in the environment and operate across multiple frequency bands. The XG project aimed to address the challenges associated with spectrum scarcity and enable more efficient and reliable wireless communications in dynamic environments [32]. In 2010, the European Union initiated the COGNITIVE project aimed at developing a cognitive radio platform for ISM applications. Furthermore, numerous universities and

research institutions have also been conducting extensive research on cognitive radio technology [9]. The Cognitive Radio and Networks Research Group at Virginia Tech has been working on various aspects of CR technology. The Wireless@VT research team at Virginia Tech is currently developing a cognitive radio platform specifically designed for implementation in smart grid applications. Similarly, the Cognitive Radio Research Center at the University of Oulu in Finland is engaged in research related to spectrum sensing, interference reduction, and spectrum sharing within CR systems. The University of Oulu's Center for Wireless Communications has been actively engaged in developing cognitive radio technology for various applications, including cognitive radio sensor networks and cognitive radio vehicular networks. The research conducted by the center has contributed significantly to the development of CR technology and its practical usage [10].
Several research initiatives have been undertaken to improve the performance of CR systems, including the development of various spectrum sensing techniques. Such as:

1. *Spectrum sensing:* It is a critical feature of CR technology, and accurate and efficient spectrum sensing is essential for optimal performance. One notable technique is the cyclostationary feature detection (CFD) technique, which can detect weak primary user signals in the presence of noise and interference.
2. *Dynamic Spectrum Management:* CR technology can dynamically manage the available spectrum to optimize performance. Various approaches have been proposed for dynamic spectrum management, such as the cooperative spectrum sensing approach, which uses multiple cognitive radios to sense the spectrum and make decisions collaboratively.
3. *Interference Mitigation Techniques:* Interference mitigation is another important aspect of CR technology. Interference mitigation is a critical aspect of cognitive radio (CR) technology to ensure reliable and efficient communication. Various interference mitigation techniques have been developed, including the adaptive modulation and coding (AMC) technique to mitigate interference and improve performance. The AMC technique is particularly effective in environments with varying channel conditions and interference levels [12].
4. *Resource Allocation Techniques:* The utilization of the spectrum depends upon the the allocation of resources. Several techniques have been suggested for resource allocation, including the joint power and subcarrier allocation (JPSA) technique. This method distributes power and subcarriers among users based on their QoS demands and channel conditions [13].
5. *Security and Privacy:* Security and privacy are major concerns in CR systems. Various techniques have been proposed to enhance security and privacy in CR systems, such as the secure spectrum sensing technique, which can detect and mitigate malicious attacks on the spectrum sensing process.
6. *Machine Learning Techniques:* The application of machine learning techniques has also been utilized to enhance the capabilities of cognitive radio (CR) systems. One such technique is reinforcement learning (RL), which can optimize the transmission parameters of the cognitive radio based on real-time available spectrum and application requirements [14].
7. *Standardization:* Standardization is essential for the widespread acceptance and implementation of cognitive radio (CR) technology. Several standardization initiatives have been launched, including the IEEE 802.22 standard, which outlines the cognitive radio technology for wireless regional area networks (WRANs).

All these research initiatives have contributed significantly in enhancing the performance and capabilities of cognitive radio (CR) systems, paving the way for the widespread acceptance and implementation of CR technology in wireless communication.

6. ROLE OF AI AND ML IN COGNITIVE RADIO TECHNOLOGY

The advancement of cognitive radio (CR) technology has significantly been influenced by artificial intelligence (AI) and machine learning (ML). One of the primary challenges in CR systems is its capability to sense and adapt to the dynamic RF environment. AI and ML algorithms can be applied to analyze radio signals and predict the availability of spectrum in a given location and time. This can help cognitive radios make more informed decisions about which frequencies to use and how to optimize their transmission parameters. Additionally, AI and ML techniques can be used to improve spectrum sensing and interference mitigation, as well as to enhance the security and privacy of cognitive radio networks. Deep learning algorithms have been utilized to enhance the accuracy of spectrum sensing by analyzing vast amounts of data from multiple sources, while reinforcement learning algorithms have been applied to optimize spectrum allocation and resource management in cognitive radio networks [15]. Several research initiatives have been undertaken to explore the potential of AI and ML in cognitive radio technology, including the use of neural networks, support vector machines, and decision trees. Overall, AI and ML hold great promise for enhancing the performance and capabilities of CR technology in the future .
There are several challenges for the development of CR systems. Here are some of the key Challenges:

1. *Spectrum Sensing:* Accurate sensing is main challenges in CR technology. Spectrum sensing techniques must be designed to detect primary users in the spectrum accurately and avoid interference with them. However, accurate spectrum sensing can be challenging due to factors such as noise, multipath fading, and shadowing. Several techniques have been proposed to improve spectrum sensing accuracy, including cooperative spectrum sensing, energy detection, and cyclostationary feature detection.
2. *Spectrum Management:* Another key challenge in CR technology is spectrum management. Spectrum management involves dynamically adjusting the transmission parameters of the CR as per spectrum availability and the application requirements. However, effective spectrum management can be challenging due to factors such as spectrum fragmentation, uncertainty in the available spectrum, and the need to balance conflicting requirements such as coverage, capacity, and interference.
3. *Security:* Security is also a major challenge in CR technology. Cognitive radios must be able to operate securely in dynamic and unpredictable environments. However, securing CR systems can be challenging due to factors such as the need for real-time operation, the need to protect against both accidental and intentional interference, and the need to protect against attacks on the spectrum sensing process.
4. *Complexity:* The complexity of CR systems is another challenge. CRs must sense surrounding environment, manage the available spectrum, and make intelligent decisions based on the available information. This requires complex algorithms and software, which can be challenging to develop, optimize, and maintain.
5. *Standards and Regulations:* Standards and regulations are also a major challenge in CR technology. There is a need for standardized protocols and interfaces to enable interoperability between different cognitive radios and to ensure compatibility with existing wireless systems. However, developing and enforcing standards and regulations can be challenging due to factors such as the need to balance the interests of different stakeholders and the need to adapt to rapidly changing technologies and environments.

7. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

As cognitive radio (CR) technology continues to evolve, there are various research areas that require attention to enhance the performance and capabilities of CR systems. One area of future research is to develop advanced spectrum sensing schemes to improve licensed user detection accurately and to reduce false alarms. Another area of interest is to develop efficient spectrum allocation schemes that allow dynamic spectrum access and ensure interference-free communication among various wireless networks. Additionally, there is a dire need for the development of the spectrum management scheme to optimize the usage of available spectrum and to improve network performance. Moreover, integration of artificial intelligence (AI) and machine learning (ML) techniques with CR technology is another area of future research. This integration can lead to the creation of intelligent and self-regulating CR systems that can adapt to changing radio environments, thus improving network performance and efficiency.

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Conflict of interest

The authors declare no conflicts of interest

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