**A REVIEW OF COGNITIVE WIRELESS NETWORK TECHNOLOGY**

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**Abstract**

Wireless communication systems have limited access to and a valuable resource in the electromagnetic radio spectrum. Nevertheless, the spectrum has run out due to the development of new wireless technologies and rising bandwidth requirements. Remarkably, research has revealed that most of the allotted spectrum is utilized inefficiently, which exacerbates the scarcity problem. The issue stems from both wasteful use and rigid spectrum management. To address the challenge of enhancing bandwidth utilization, this paper explores the concept of cognitive radio networks (CRNs). CRNs introduce a new approach to spectrum access, topology, spectrum sensing techniques, applications, problem formulation, benefits, challenges, and various features that are vital for the development of next-generation cognitive wireless networks (CWN) communication systems. The key idea is to enable secondary users (SU) to access temporarily unused licensed bands, known as white spaces or spectrum holes, without causing significant interference to primary users (PU). This is achieved by adjusting the secondary users' transmitting parameters intelligently. By doing so, CRNs aim to make more efficient use of the available spectrum and alleviate the spectrum scarcity problem.

**Keywords: CR,** CRN, SDR, CR Challenges, Spectrum Sensing, PU, SU

**1.0 Introduction**

It will be challenging to imagine life without wireless communication in this modern era. There are large numbers of users of wireless communication, but the available spectrum is limited. Thus, spectrum scarcity becomes an issue. CR was created and built to be able to sense the wireless environment and communicate effectively and efficiently to lessen this challenge. Many studies have been conducted recently on the usage of these spectrum bands, which are either underutilized or empty. In 1999, Dr. Joseph Mitola made the initial recommendation for CR technology. Software-based CR technology senses the electromagnetic field in which it operates, identifies dormant frequency bands, and then broadcasts in these bands by utilizing radio operating parameters [1].

The objective of CRNs is to efficiently utilize temporarily inactive licensed spectrum resources for communication purposes, either at specific times or in designated locations. In CRNs, users fall into two categories: Primary Users (PUs) and Secondary Users (SUs). PUs, often referred to as licensed users, enjoy priority access to the spectrum and are protected from interference that could potentially disrupt their operations. Secondary Users, or cognitive users, employ advanced radio access techniques and dynamic spectrum allocation procedures to coexist with PUs, ensuring that their own activities do not hinder the performance of the PUs [2]. This approach allows CRNs to effectively address the challenges posed by limited radio frequency availability.

The primary aim of this review is to offer a concise overview of the current state-of-the-art research within the field of cognitive radio systems, as well as anticipated future advancements. The subsequent sections of the review are structured as follows: After covering the foundational concepts of cognitive radio, we delineate the constituents of a cognitive radio network (CRN) and present a concise summary of the primary research challenges. Subsequently, we provide a condensed overview of the latest advancements in spectrum sensing and spectrum-sharing techniques applicable to CR systems. A brief summary of the research related to the economic and security aspects of CRNs is presented. The review then delves into applications, including areas such as smart grid [3,4], machine-to-machine (M2M) communications [5,6], and cloud computing [6], while also addressing the current and forthcoming trends in cognitive radio. Furthermore, we identify and outline the ongoing research topics that remain open for exploration. Lastly, we summarize the standardization efforts pertaining to cognitive radio.

A crucial technology that enables a network to use the spectrum dynamically is CR technology. Governments manage the range of electromagnetic radiation known as a spectrum, which is what allows for wireless communication. A radio that has the ability to alter its transmitter characteristics in response to interactions with its surroundings is known as a cognitive radio [7]. Utilizing unused radio spectrum, CRbecame visible technology recently [8], helping to prevent congestion in wireless communication.

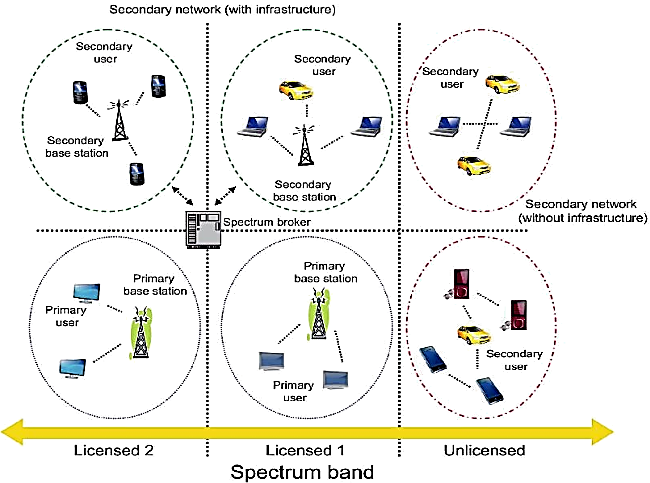
In the realm of transmission and reception parameters, cognitive radio (CR) can be categorized as Full Cognitive Radio and Spectrum-Sensing Cognitive Radio. In the case of Full CR, every individual parameter is meticulously monitored by a wireless node, whereas Spectrum-Sensing Cognitive Radio focuses its attention on monitoring the radiofrequency (RF) spectrum. Concerning spectrum availability, CR is further classified into Licensed-Band Cognitive Radio and Unlicensed-Band Cognitive Radio.

Licensed-Band CR possesses the capability to utilize frequency bands that are officially allocated to licensed users. Notably, the IEEE 802.22 standard was developed to enable wireless regional area networks (WRANs) to operate within TV white spaces, which represent unused television channels. On the other hand, Unlicensed Band Cognitive Radio operates within the unlicensed segments of the radio frequency spectrum [9, 10].

Cognitive radio fundamentally governs how intelligent radio devices and interconnected networks communicate and adapt their operational parameters to align with the requirements of users or networks. This adaptation occurs in real-time and online, involving adjustments to transmission parameters such as transmission power, modulation mode, and frequency band [10]. Communication within Cognitive Radio Networks (CRNs) is established by CR users or nodes, with communication parameters being dynamically modified in response to variations in network topology, radio conditions, user demands, or operational circumstances.

It's essential to emphasize that cognitive radio operates as a secondary user, lacking primary rights to pre-assigned frequency bands. Consequently, it is incumbent upon cognitive radio to effectively detect the presence of primary users within the spectrum [8].

Top of Form

The two groups that comprise the CR network structure in Figure 1 are the primary network and the cognitive network (CN). The primary network (PN) is the legacy network that has the exclusive right to use a specific frequency band. However, CN is not permitted to operate in the designated band. A main network (PN) consists of a primary base station and a collection of primary users. Primary users may use specific licensed spectrum bands in conjunction with primary base station usage. Their transmission should not be impeded by secondary networks (SN). CR services are usually unavailable to principal users and primary base stations. Consequently, in order to prevent interference with the primary transmission in the event that an SN and PN share a legal spectrum band, the secondary network must promptly identify the existence of a primary user and reroute the secondary transmission to a different available band. This is on top of utilizing the optimal spectrum band and identifying the white space in the spectrum. An SN is a network of secondary users (SU) that may or may not have a secondary base station. Secondary users can only access the licensed spectrum while the prime user is not using it. Managing secondary users' opportunistic spectrum access is mostly the responsibility of a secondary base station, a fixed infrastructure component serving as the secondary network's central hub. Both secondary base stations and SU have CR features [11].  
Figure 1: Cognitive radio network topology [11]

**2.0 Review of Related Literature**

Junhui and Tao presented a power control technique tailored for cognitive radio (CR) systems, with a keen consideration of transmitter power constraints and interference temperature limits. Their approach incorporates interference constraints to safeguard the quality of service while incorporating non-cooperative power control models for the primary users (PUs) [12].

Lu Yang delved into the realm of multiuser diversity within uplink multiple-input multiple-output (MIMO) cognitive radio networks. In this context, they introduced a two-stage opportunistic user scheduling scheme [13].

Wenhao Xiong delved into user selection strategies designed for the downlink of MIMO cognitive radio networks. This strategy revolves around the selection of underlay CR secondary users, which share sub-channels with primary users through cognitive base stations (CBS) [14].

Duoying Zhang's investigation revolved around spectrum sharing within a multiple-input multiple-output cognitive interference channel, where numerous primary users (PUs) coexist alongside multiple secondary users (SUs). They introduced an interference alignment (IA) approach that allows SUs to access licensed spectrum without inducing harmful interference to PUs. The numerical results demonstrated that this design not only enhanced the achievable degree of freedom (DoF) for primary links but also delivered significant overall data rates for both secondary and primary transmissions, even under rank limitations [15].

Junhui and Qiping proposed an optimization algorithm that seamlessly combines diverse spectrum sharing bandwidths and power allocation strategies within cognitive radio systems. This innovative approach empowers the cognitive user (CU) to dynamically switch between the Underlay spectrum sharing model and the Overlay spectrum sharing model as needed [16].

Top of Form

Cui & Gao focused on the crucial aspect of supportive spectrum sensing in cognitive radio (CR). Their proposed spectrum sensing algorithm demonstrated significantly improved performance compared to existing algorithms, and it also considered multiple primary users simultaneously [17]. Sidhu and Gao conducted research on resource allocation in relay-assisted orthogonal frequency division multiplexing (OFDM) cognitive radio networks. They employed a combined subcarrier pairing and power allocation approach to maximize the throughput of secondary users while ensuring that interference to primary receivers remained within acceptable limits. They also developed a sub-optimal resource allocation technique to reduce computational complexity, and simulation results showed enhanced performance compared to standard resource allocation methods [18]. Lu and Wang introduced an FD (full-duplex) opportunity spectrum-sharing protocol that takes action when the primary system experiences poor channel conditions. They jointly optimized subcarrier allocation and power distribution to maximize the transmission rate of the secondary system while ensuring that the primary system achieves its target rate. The modelling results suggested that such secondary spectrum access strategies could be beneficial for both primary and secondary systems [19]. In summary, Table 1 in this paper outlines the limitations of existing works and presents the author's contributions to address these gaps in knowledge. The paper provides a comprehensive overview of cognitive radio, covering its topology, spectrum sensing techniques, applications, problem formulation, benefits, challenges, and other essential features crucial to cognitive wireless networks (CWN) communication systems. Ultimately, the paper offers a forward-looking perspective on the necessary steps to expedite the development of this promising generation of wireless communication.

**Table 1.** Limitations of some added related works and contributions.

|  |  |  |  |
| --- | --- | --- | --- |
| **Ref.** | **Focus and Coverage** | **Limitations** | **This Paper’s Contributions** |
| 20  21  22  23  24  25  26  27 | Presented the fundamental concept about CR technology and CR capability functions.  Challenges and security issues of CR networks were discussed.  To explore the application of CR technology in machine-to-machine communication.  The study presents basic theory and Key Technologies in CWN.  Issues from network architecture to multi-dimension sensing technologies and radio resource management.  Introduce the fundamentals of CRN.  Architecture of a CRN and applications.  Provide a study on the recent advances and applications of  CR in various domains, such as military emergency response, communication, and commercial  communication.  The authors provide a brief overview of operation, principles, architecture and  security of CR.  Methods and practices in CRN to improve the performance of the CRN. Various models and schemes in Cross Layer and Design Network environment.  Reviewed CR technology and its numerous  Features.  Roles in the field of next-generation wireless communication networks. | Challenges with enabling technology were not properly stated.  Applications were not clearly outlined.  Related literature not emphasized.  Limited practical applications of CR were presented.  Future focus not presented.  Problem of selecting a suitable frequency band as the working spectrum channel of the testbed.  Future Research Directions not clearly outlined.  Applications are not clearly itemized.  Challenges with supporting  technologies are not clearly defined.  Methods not presented.  Applications not clearly outlined.  Future Research guidelines not outlined.  No clear application was presented.  The challenge with each supporting technology is not well presented.  The importance of the concept is not stated.  No connecting related works outlined.  Challenges with methods and model if any not stated.  No cohesion between the abstract and the conclusion.  Enabling technologies were discussed, but no clearly outlined challenges.  Future focus directions are not presented. | Clear understanding of CR technology.  Its role in national development.  Future focused - Security issues and efficient spectrum management challenges.  Described in full the machine-to-machine communication survey.  Examine the distinctions between wireless communication systems used by CR and conventional methods.  Purpose of the research well presented.  Discussion on Flexible network architecture, cognition of multi-dimension environment, and discretionary resource management were presented as key technologies to make CWN a reality.  Challenge with each supporting  technology presented.  Architecture of a CRN discussed.  Security challenges extensively  discussed.  Enabling technologies clearly outlined.  Clearly outlined key principles of CR.  Applications were presented.  The architecture of a CRN is well discussed.  An overviewof security threats, including physical, link, network and transport layer attacks is presented. The future research focus is clearly outlined.  Performances in Cross Layer networks and solutionsare well outlined.  The needed resources are clearly outlined.  Problems and solutionsare clearly stated.  Future focus stated.  Spectrum sensing techniques in CR were mentioned.  Cyclostationary detection is the best.  spectrum sensing technique, it senses a spectrum even in low SNR. |

**3** **Three Major Tasks of the CR**

(i) Radio-scene analysis,

(ii)Channel identification, and

(iii) Dynamic spectrum management and transmit-power control. [28]:

The receiver's execution of radio-scene analysis encompasses several key tasks, including the assessment of the interference temperature within the local radio environment, predictive modeling of the environment, and the identification of spectrum gaps. To facilitate coherent message signal recognition and enhance spectrum utilization, the receiver also incorporates channel identification. Ultimately, the transmitter's dynamic spectrum management and transmit-power control system leverage the insights gained from radio-scene analysis and channel identification to make informed decisions regarding transmission parameters.

**4 Fundamental Cognitive Radio Cycle (CRC)**

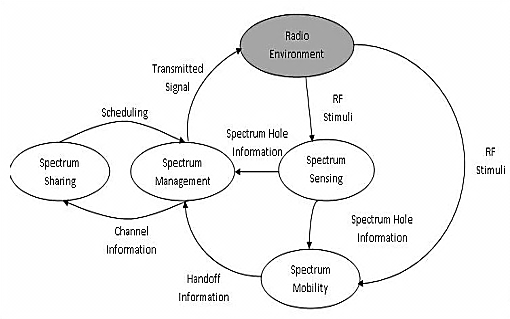
Spectrum sensing, spectrum mobility, spectrum management, and spectrum sharing are the fundamental CR operations. Some fundamental features of CR technology benefit consumers in the following ways:

*(i) Spectrum sensing* - to detect the part of the spectrum that is free and detect the presence of licensed users when a user is active in a licensed band. It is the first and fundamental function of cognitiveradio; unused portions of the spectrum are used opportunistically upon detection.

*(ii) Spectrum management* to choose the optimal channel that is offered. The CR needs to be able to choose the channel that best fits its communication needs when spectrum gaps are found.

*(iii) Spectrum sharing* - -to arrange for other users' access to this channel. An algorithm must be scheduled in a CR network to guarantee that each cognitive radio has an equal opportunity to access the spectrum.

*(iv) Spectrum mobility* - when detecting a licensed user, to release the channel. The CR is assigned a lower priority, so when a licensed user returns, they should be able to easily switch to another free channel and end their conversation [1]. Comprising a Cognitive radio cycle is Figure 2. 23]

  
 Figure 2 Cognitive Radio Cycle

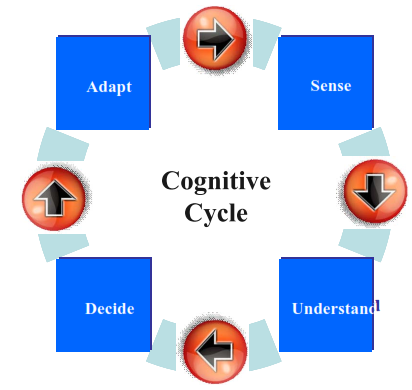
The CR can also be considered a continuous process consisting of the following steps:

(i) Sensing,

(ii) Understanding,

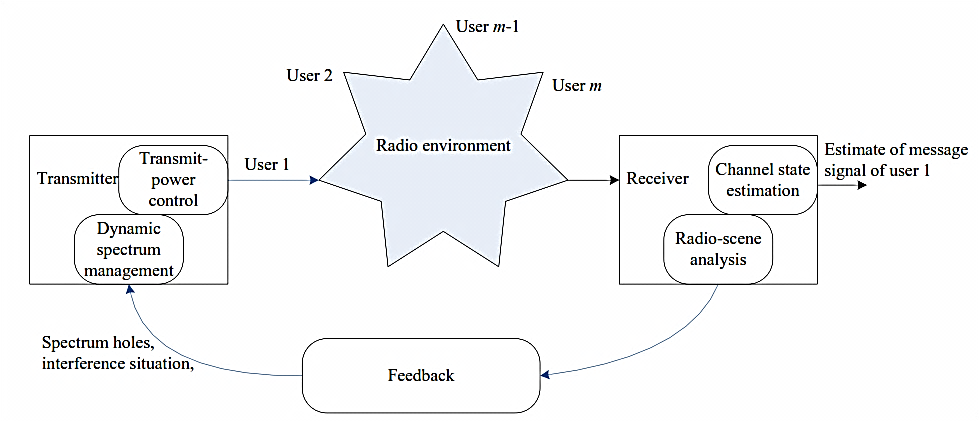
(iii) Deciding

(iv) Adapting

according to Figure 3. CR takes use of this cycle by making the spectrum the primary object to be felt, with all subsequent processes centered around handling the spectrum in light of the observations.Reference [28]  
Figure 3. Generic CRC.

The cognitive tasks encompassing the CC are depicted in Figure 4. The feedback channel, serving as the conduit for intelligence within the CR, plays a pivotal role. It is essential for conveying the following information [29]:

1. The centre frequencies and bandwidths of the spectrum holes,
2. The combined variance of interference plus thermal noise in each spectrum hole,
3. The estimate of SNR for adaptive transmission.

A CC link with the transmitter and receiver located in different CR devices is seen in Figure 4. The CR devices are transceivers and have a radio scene analysis unit on the transmitter side to detect the spectrum in the immediate area of the transmitter. However, this sensing unit is not depicted in Figure 4 because it is part of a different link.  
Figure 4. CC for cognitive radio link. [29]

If several SNs share one common spectrum band, their spectrum usage may be organized by a central network, called spectrum broker [30].

**5 Spectrum Sensing Methods**

CR is a crucial technique that enables opportunistic, efficient use of scarce and underutilized frequency bands. Whether the spectrum sensing function is carried out correctly or not has a significant impact on the communication performance and stability in CR networks.

Spectrum sensing is a significant concern in CR technology due to the wireless channels' fading and time-varying characteristics, along with shadowing effects. Various spectrum sensing approaches have been proposed in the literature to detect unused or underutilized frequency bands. These include techniques such as cyclostationary-based sensing [31, 32], waveform-based sensing [32], matched filtering [34, 35], eigenvalue-based sensing [36, 37], energy detection sensing [38–39], and wavelet-based sensing [40].

1. Cycle-based detection. is a method for detecting PU transmissions that makes use of the received signal's cyclostationary characteristics [41]. To detect the presence of PUs, it makes use of the periodicity in the primary signal that was received. This allows the detector to differentiate between PU signals, SU signals, and interference. However, the effectiveness of this detection method depends on having enough samples, which makes the calculation more difficult. performs well in comparison to other detection systems despite its nonlinearity, spectrum leakage of large amplitude signals, and expensive costs [42].
2. Sensing based on waveforms. utilized in systems that have recognized signal patterns. Preambles, midambles, regularly broadcast pilot patterns, and spreading sequences are examples of these patterns [43]. A midamble is communicated in the middle of a burst or slot, whereas a preamble is an identifiable sequence transmitted before each burst. With a known model, the function of spectrum detection is carried out by comparing the received signal to a duplicate of itself.
3. Detection using matched filtering. If specific signal characteristics, such as bandwidth, modulation type and grade, operating frequency, frame structure of the PU, and pulse shape, are known, matched filtering detection approaches with shorter detection times are employed [44, 45]. This technique's detection performance mostly depends on the channel reaction. To get around this, both the physical and media access control layers must be perfectly timed and synchronized. The sensing performance, however, rapidly deteriorates if the PU information is provided improperly to the matched filter detector. [46, 47]
4. Spectrum sensing is based on eigenvalues. It is not necessary to have a thorough understanding of PU signals and noise power [48] for this. This detection method idea was first presented in 2007 [49]. The decision threshold for making hypothesis testing in the eigenvalue-based spectrum detecting techniques was obtained using random matrix theory. The decision threshold is compared to the test statistic created using the ratio of the greatest or average eigenvalue to the minimum eigenvalue to determine the existence or absence of the PU signal. However, this method's high-functioning complexity is negative [50, 51].
5. Energy detection is a spectrum sensing approach that works by detecting the received signal energy and comparing it to a threshold to determine whether the PU is present or not. The noise power affects how the threshold function is calculated [4652]. Depending on the channel circumstances, the threshold may change or remain constant. However, this method is unreliable [53].
6. The wavelet transform is a great tool for investigating edges and singularities. The interest frequency bands in the wavelet-based spectrum sensing technique are frequently broken down into a series of successive frequency sub-bands [54]. To find out if the spectrum is full or empty, abnormalities in these bands are detected using the wavelet transform.

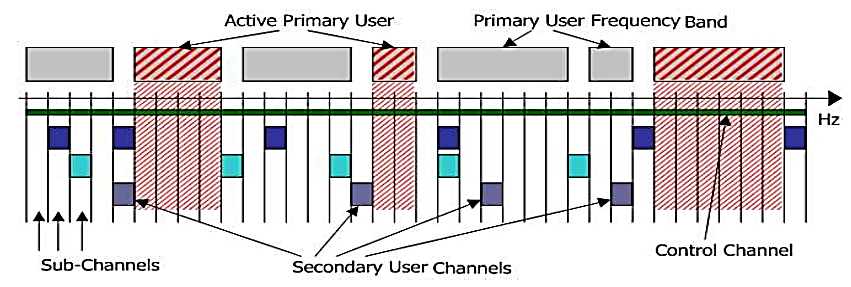
Hybrid models, which combine the use of two or more detection strategies, have recently been developed to increase a CRN's capacity for spectrum sensing. Hybrid models frequently employ machine learning algorithms (MLA) and artificial intelligence (AI) [55].

**5.1 The Best Standard Spectrum Detection Techniques are:**

(i) Cyclostationary feature detection

(ii) Energy detection

(iii) Matched filter detection

  
Figure 5: Spectrum pooling idea [56]

**6.0 Features of the Cognitive Radio:**

1. *Cognitive capability (CC)* - The ability of radio equipment to collect information from its radio surroundings. The best spectrum and the most suitable operational parameters can be selected by determining which parts of the spectrum are inactive at a given time or place.
2. Reconfigurability (RC) - Reconfigurability enables the radio to be dynamically programmed in accordance with the radio environment, whereas spectrum awareness is provided by the CC. More specifically, CRs can be designed to employ a variety of transmission access protocols provided by their hardware and to broadcast and receive data at a wide range of frequencies, as shown in Figure 6 [9].

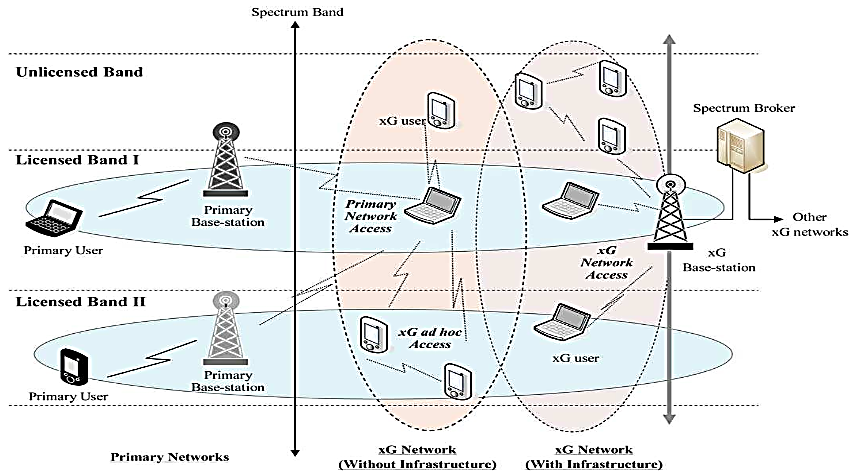


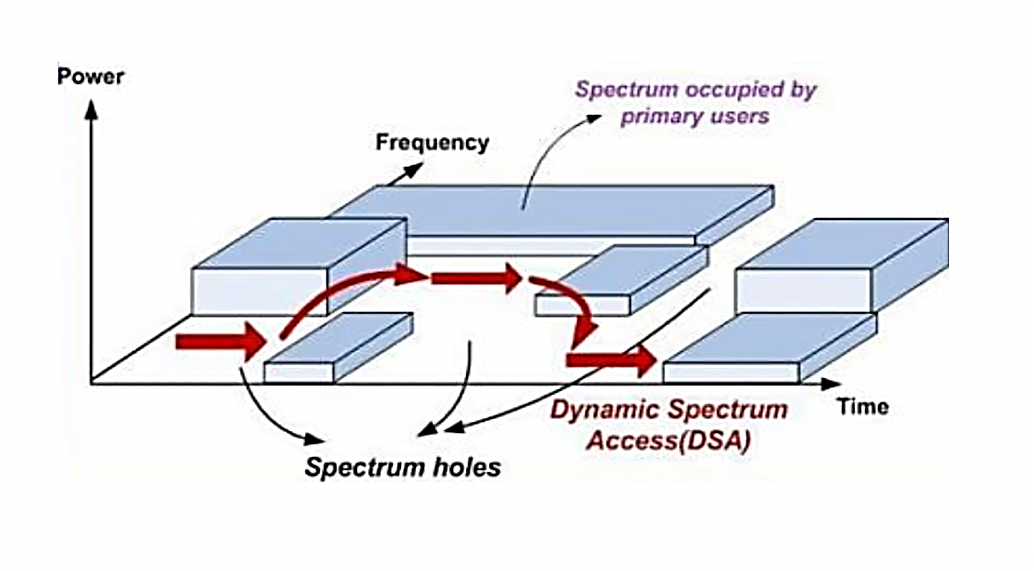
Figure 6: Cognitive radio network system [56].

**6.1 Cognitive Radio (CR) and Software Defined Radio (SDR)**

A type of radio known as SDR has physical layer functionalities that are defined by software. This contrasts with hardware radio, where changes to the communications scheme can be made by altering the hardware, as opposed to software that is factory-programmed and cannot be changed due to radio topological rigidity. Given its capacity for adaptation and reconfiguration, cognitive radio is regarded as the next evolution of reconfiguration flexibility, following SDR. It wouldn't be incorrect to characterize a cognitive radio as a software-defined radio, where the radio's cognitive functionality is secured by the software. Not every SDR with cognitive impairment is a CR [57].

**6.2 Spectrum Hole or White Space**

Spectrum Hole or white space is nothing but the available free spectrum of the primary user. It is shown in bellows Figure 7. The main challenge for cognitive radio systems is to sense the spectrum when it lies within such a spectrum hole [58]. High Utilization of lower frequency band and lower utilization of higher frequency spectrum. This lower spectrum utilization is known as a spectrum hole. CR searches the free frequency and allocates this frequency to spectrum utilization is termed a spectrum hole [16**]**

  
Figure 7: Spectrum hole (white space concept)

In another view, a spectrum hole is deﬁned as a band of frequencies readily allocated to a PU, though; it may not always be used by the PU at a particular time or in a geographic area (see Figure 8), [28].

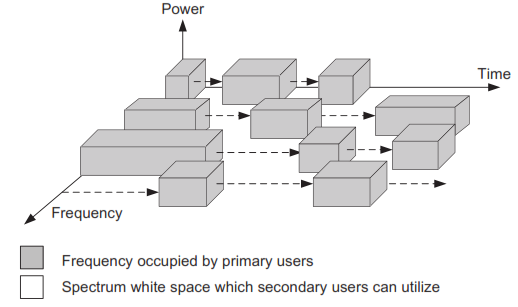


Figure 8: Example of a Spectrum Distribution Graph.

The following frequency, time, or space parameters can be used to determine spectrum holes depending on the communication environment [59, 60]:

1. i. A temporal spectrum hole is a frequency band that is not used by a principal user (PU) for a predetermined amount of time. A secondary user (SU) can identify these spectrum holes and take advantage of them without impairing the primary user's quality of service by using sophisticated spectrum sensing techniques.
2. ii. Frequency spectrum hole: In this instance, the secondary user's actions don't negatively interfere with the primary user’s activity. This keeps primary user communications uninterrupted while enabling the secondary user to use the spectrum.
3. Spatial spectrum hole: This type of spectrum hole pertains to a specific geographical area where the transmission of the primary user is currently occupying the spectrum. However, if the secondary user is located outside of this area (as depicted in Figure 9), they can make use of this spectrum without causing interference to the primary user's transmission.



Figure 9: Spatial spectrum hole where the secondary user (SU) is not permitted to operate within the protected area of the primary user (PU).

Furthermore, spectrum holes can be classified into different spaces as described below [28]:

(i) Black spaces: These are areas where high-power signals interfere with control for a certain period.

(ii) Gray spaces: In these spaces, low-power signals cause moderate interference with control.

(iii) White spaces: No interfering signals are present, but natural noises like broadband thermal noise and impulsive noise can be observed.

**7 CR Characteristics**

A cognitive radio network (CRN) differs from conventional wireless communication networks primarily by its cognitive capabilities. With the help of these skills, a secondary user (SU) can identify numerous characteristics of the radio environment in its vicinity, including distance, temperature, noise power, and other variables. The SU can choose the best frequency, transmit power level, and modulation scheme based on the information gathered to achieve optimum performance. The following traits should be included in CRNs during actual implementation [59]:

1. Efficient spectrum sensing and analysis methods should be employed by the SU to ensure continuous spectrum availability and reliable communication.
2. The SU should share spectrum information with other users and coordinate communication to minimize interference and avoid collisions with primary users using the same frequency bands.
3. The SU's architecture should be unified and designed across different layers to meet diverse Quality of Service (QoS) requirements.
4. Dynamic spectrum access methods should be employed by the SU, allowing it to adapt to the fluctuating nature of the CRN.

**7.1 Cooperative Spectrum Sensing (CSS)**

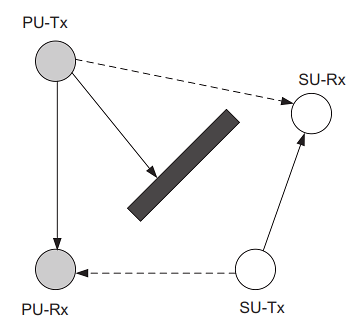
Wireless communications are susceptible to natural phenomena like multi-path fading, shadowing, and noise, all of which can affect the received signal's strength. For example, if there is a considerable distance between a primary user (PU) and a secondary user (SU), or if the PU's signal is obstructed by a significant obstacle, the signal received by the SU may be attenuated. Consequently, accurately detecting the presence of a PU can become quite challenging. Figure 10 depicts a scenario in which the PU's transmitter (PU Tx) is obscured by an obstacle, making it problematic for the secondary transmitter (SU Tx) to perceive the PU Tx signal. This situation may lead the SU Tx to inadvertently introduce detrimental interference to the PU's receiver (PU Rx) while it starts utilizing the licensed spectrum for communication with the secondary receiver (SU Rx).

Figure 10: Example of a hidden PU where SU Tx can’t sense the presence of the PU Tx due toobstacles.

CSS has been recommended to prevent these hiccups [61, 62]. Multiple users' separate fading channels and spatial diversity have been shown to be advantageous for improving detection probability and cutting down on sensing time in cooperative networks [63]. Figure 11 depicts a case where CSS might be used. With the aid of SR1 and SR2, two secondary relays (SRs), the SU Tx may detect the PU Tx.

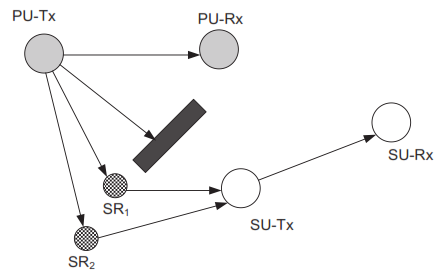


Figure 11: Two SRs support the SU Tx in detecting a hidden PU Tx.

**7.2 Current State-of-the-Art Review on Spectrum Sharing in CRNs**

This review encompasses the development of cognitive radio (CR) research, encompassing diverse aspects of spectrum sharing. These elements consist of signal and waveform design [85–95], statistical modeling of spectrum consumption [78–84], spectrum measurements, and spectrum sensing [64–77]. Furthermore included in the paper are spectrum mobility [96–105], multiple access, resource allocation and power regulation, cognitive learning, adaptability, and self-configuration [106–117], as well as multihop transmission and routing [118–123].

**7.2.1 Spectrum sensing, interference modelling,measurements, and statistical modellingof spectrum usage:**

In order to allow Secondary Users (SUs) to take advantage of opportunities to access the spectrum, it is imperative that PUs provide accurate information about how they are using the spectrum. In order to acquire this information, the following areas are the focus of research:

(i) Spectrum sensing: This fundamental process enables SUs to assess whether PUs is currently utilizing the spectrum. Without this information, SUs may face challenges in accessing idle spectrum effectively, leading to reduced spectrum utilization, or they might unknowingly interfere with PUs occupying the spectrum.

(ii) Interference modeling: SUs may encounter interference on the spectrum due to two main reasons. First, SUs must ensure that their own transmissions do not disrupt ongoing PUs' communications. Second, when interference is present, SUs needs to access the spectrum in a manner that satisfies their transmission requirements. Interference modeling helps SUs achieve these objectives.

(iii) Measurements and statistical modeling of spectrum usage: While spectrum sensing provides instantaneous information about the spectrum status, spectrum measurement is conducted over a more extended period, often spanning several months, to gather statistical data about PUs' usage patterns. This valuable knowledge assists SUs in devising their spectrum access strategies, such as selecting specific times of the day to minimize interference to PUs.

**7.2.2 Waveform and Modulation Design for Cognitive Radios:**

It is possible to modify the waveform and modulation design of signals coming from Secondary Users (SUs) in order to lessen the interference that PUs receive. In an underlay spectrum access scenario, for example, SUs can employ ultra-wideband transmission and adjust the pulse width and/or position to prevent interfering with PUs' narrowband transmission. In a similar vein, SUs can minimize interference in an overlay spectrum access scenario by employing multicarrier modulation techniques such as orthogonal frequency division multiplexing (OFDM).

**7.2.3 Multiple Access, Resource Allocation, Power Control, and Spectrum Mobility:**

The difficulties of attaining the best possible spectrum sharing among Secondary Users (SUs) in a spectrum underlay scenario can be expressed as an optimization problem with a suitable objective function and a set of constraints. These limitations include things like user equity, maintaining Quality of Service (QoS) for SUs, and complying with interference thresholds for Primary Users (PUs). An admission control method is used to restrict the number of admitted SUs in cases when highly loaded networks or strict limitations make the optimization problem unfeasible. Power allocation for the admitted SUs can then be carried out.

Using Code Division Multiple Access (CDMA) technology at the physical layer (PHY), a strategy suggested in [99] addresses the dual challenge of admission control and power allocation to achieve fairness across SUs in real-world scenarios. For power allocation solutions, it is crucial to predict the instantaneous channel gains among SUs and the interference from Secondary Transmitters (STs) to Primary Receivers (PRs). To satisfy the target interference constraint violation probability for PRs, cautious power allocations for STs are required when only estimates of average channel gains are known [101].

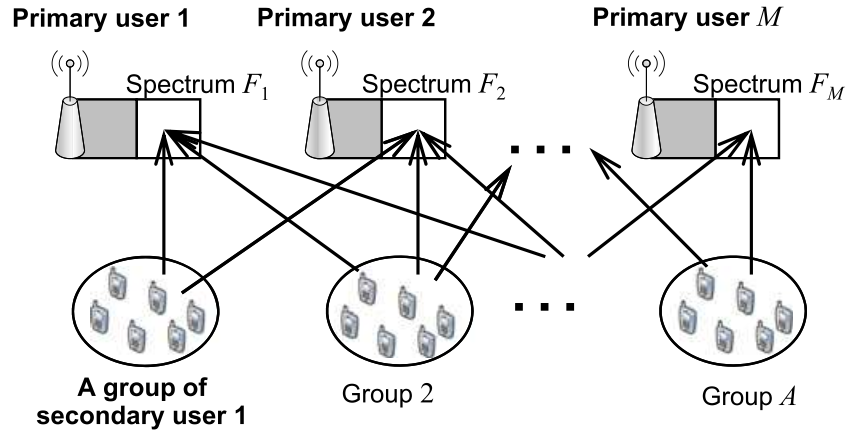
In reference [102], the objective of optimizing the total data transmission rate for secondary transmitters (STs) is explored within a Cognitive Radio Network (CRN) featuring numerous STs and primary receivers (PRs), with each PR being equipped with a single antenna. This optimization encompasses joint beamforming and power allocation strategies. Furthermore, [103] provides an overview of dynamic resource allocation approaches designed for CR systems that operate based on the interference temperature-based spectrum sharing model.

**8.1 Economics of Cognitive Radio Networks:**

Pricing is important in CR systems because it incentivizes primary and secondary users to share available spectrum by engaging in spectrum trading [127]. Through monetary transactions or other resource exchanges (bartering), spectrum trading enables organizations in the CR system, including main and secondary users, spectrum owners, service providers, and customers, to trade radio resources. Auction-based and open market-based strategies are the two main methods used in spectrum trading.

**8.2 Price Competition in the Open Market:**

In the unregulated open market paradigm, main and secondary users are able to freely sell and buy radio resources. The price method used by primary users is significant since it defines their income and affects secondary users' decisions about whether to purchase radio resources. Multiple major networks have been proposed with competitive pricing strategies based on non-cooperative games [128]. A spectrum trading framework for such circumstances was devised in [129]. In more general scenarios, spectrum trading in CR systems may involve many spectrum suppliers and purchasers.

  
**Figure 12.** Spectrum trading in CR with multiple spectrum sellers and buyers [129].

**9.1 Problem Formulation**

The review identified several challenges. Firstly, there is the optimization challenge during data transmission, which encompasses issues related to the complexity associated with multiple cognitive base stations (CBS) and primary users (PU). Additionally, there are challenges involving interference scenarios in channels with multiple CBSs and PUs, as well as issues related to primary and secondary cognitive base stations and user interactions. Lastly, there is the challenge of determining transmission ranks when dealing with multiple users [130].

**9.2 Implementation Challenges**

Implementing a cognitive radio (CR) is a complex and thought-provoking task. The CR system must be designed to ensure that its transmission and reception do not interfere with the operations of Primary Users (PUs). Various techniques can be employed to avoid such interference and enable efficient frequency tuning [131], including:

(i) Adaptive frequency hopping

(ii) Dynamic frequency selection

(iii) RF band switching

Furthermore, there are several other challenges in deploying a Cognitive Radio Network (CRN), particularly in terms of monitoring the surrounding environment and logically acquiring resources based on established practices. These important challenges in implementing a cognitive radio are [132]:

(i) RF front-end-transceiver challenges

(ii) ADC and DAC challenges

(iii) Baseband challenges

Successfully addressing these challenging issues is crucial for cognitive radio to achieve sustainable and reliable communication.

**9.3The Technical Challenges Are:**

As mentioned in [133], cognitive radio (CR) encounters highly demanding obstacles to establishing efficient communication. These challenges involve the design of the RF front-end, ensuring the performance and flexibility of ADC/DAC, and enabling support for flexible wideband multiband communication. Additionally, CR must address issues related to spectrum sensing, channel estimation, modulation and coding, spectrum shaping, transmit power control, interference avoidance, and the capability to sense, discover, negotiate, and transfer.

**9.4 Security Challenges in CRNs**

Security and privacy have been crucial concerns since the beginning of the information era. To address these concerns, a well-defined security system has been established, comprising security mechanisms, security attacks, and security requirements/services. This system allows for a systematic approach to defining, studying, and evaluating security challenges.

In the context of wireless communication, security is of utmost importance. Traditional wireless networks often face significant security attacks, posing major issues. In Cognitive Radio Networks (CRNs), two main types of security issues have been identified [134]:

(i) Traditional security threats

(ii) CRN-specific threats

The categorization of security attacks in CRNs includes two categories: infrastructure-based and infrastructure-less CRN-specific attacks.

**9.3.1 Infrastructure-Based CRN Attack***.*It istime-consuming and costly. The CRNs will practically be adjusted towards frequency bands with second-importance spectrum stability. There are several attackers in the infrastructure-based CRN, they are:

(i) IE (Incumbent Emulation)

(ii) Control channel jamming

(iii) SSDF (Spectrum Sensing Data Falsification)

**9.3.2 Infrastructure–Less CRN Specific Attacks.**

There are three major types of attackers in this context:

(i) Intruding Attackers:

Ad-hoc Cognitive Radio Networks (CRNs) are susceptible to challenger nodes that attempt to enter the system under false pretenses and impersonate authorized nodes. The CRN's total spectrum sensing decision may be influenced by these malicious nodes, which could lead to a security vulnerability called Spectrum Sensing Data Falsification (SSDF). This exploit creates the impression of a busy channel by repeatedly reporting bogus information. This attack is difficult to detect and identify.

(ii) Exogenous Attacker:

An exogenous attacker is not a part of the CRN and, therefore, is not included in the CRN's spectrum sensing process. However, this attacker can still disrupt the functioning of the ad-hoc CRN.

(iii) Jamming:

Jamming is a commonly used attack on wireless transmissions. It involves transmitting noise over the receiving channel, reducing the Signal-to-Noise Ratio (SNR) below the desired threshold [135].

**9.3.3 Other security challenges**

(i) Confidentiality: The prevention of unauthorized disclosure of transmitted information, which could occur due to passive attacks like eavesdropping, is ensured. This is achieved by implementing encryption and cyphers to encode the data before transmission, using a secret key that is shared exclusively with the intended recipients.

(ii) Integrity: The protection against any unlawful modification of transmitted information is guaranteed. This includes preventing unauthorized changes, creations, deletions, replaying of messages, or delays in transmission.

(iii) Authentication: Authentication safeguards protected systems from unauthorized access by verifying both the identity and authority of users. It is a necessary process to ensure that only approved users can gain access.

(iv) Non-repudiation: non-repudiation ensures that neither the sender nor the receiver of a message can deny the transmission. In the context of Cognitive Radio Networks (CRNs), non-repudiation techniques can be utilized to prove the misbehaviour of malicious CRUs that violate the protocol, resulting in the banning of such malicious users from the network.

(v) Availability: Devices and applications should continue to be able to access the network services via communication channels. The ability of Primary Users (PUs) and Cognitive Radio Users (CRUs) to access the spectrum is referred to as availability in the context of CRNs. For PUs, availability refers to their capacity to transmit in the authorized spectrum without suffering detrimental CRU interference [135].

**10.1 Benefits of Cognitive Radio**

The following are some of the benefits of CWN.

(i) Implementation cost is low

(ii) It increases link reliability

(iii) Less complexity.

(iv) Overcome radio spectrum scarcity

(v) It has easy network topology.

(vi) It offers better spectrum utilization and efficiency.

(vii) Uses modern network topology.

(viii) Configuration and upgrade are easy.

**11.1 Areas for Future Consideration**

CR technology has many areas for future investigations which can be considered to better understand the behaviour of user detection. Under listed are some of these areas:

(i) Cooperative approach for detecting and isolating intruders.

(ii) Assessment of denial-of-service (DoS) attack scenarios and methods for defence.

(iii) Implementation of hybrid sensing approach.

(iv) Consideration of multiple attackers’ defencemechanisms.

(v) Investigations to introduce capable preventive techniques to mitigate threats and attacks that CR networks face.

(vi) Using Cyclostationary detectors which employ second-order signal structure.

**12 CR STANDARDIZATION**

At present, the primary standards governing Cognitive Radio (CR) are IEEE 802.22 and SCC 41, which have gained significant attention in the field of Cognitive Radio [136]. Nonetheless, several other standards are currently in the developmental stage. The IEEE formed the 802.22 Working Group (WG) for Wireless Regional Area Networks (WRANs) in November 2004. The goal of this working group was to provide an air interface (PHY and MAC) for unlicensed operation in TV broadcast bands based on CRs. The primary objective of IEEE 802.22 is to offer broadband wireless connectivity in rural areas, with a significantly greater coverage area than that of IEEE 802.16 [137]. In conclusion, there are numerous standardization initiatives presently in progress in the industry.

**12.1. IEEE 802.22:**

Those who have studied 802.22 architecture [138, 139] have provided an overview of its entities, connections, and topology; requirements such as service coverage, MAC layer details, and service capacity; and applications and coexistence challenges (e.g., TV, antenna, and wireless microphone protection and sensing). The IEEE 802.22 networks support several international TV channels with bandwidths of 6, 7, and 8 MHz and operate in the 54–862 MHz frequency spectrum in North America. With these systems, the consumer premise equipment (CPEs) is controlled by the base station via a fixed point-to-multipoint air interface.

**12.2. IEEE 1900–SCC41-DYSPAN:**

To standardize Cognitive Radio (CR), the IEEE 1900 task force [140] was replaced by the IEEE Standard Coordinating Committee 41 (SCC41), which was created with an emphasis on dynamic spectrum access (DSA) networks. Four Working Groups (1900.x) make up SCC41, and they are all focused on different facets of CR standardization. The following are the main standards created under SCC41-DYSPAN:

**IEEE P1900.1** (Terminology and Ideas for Spectrum Management and Next-Generation Radio Systems): Key terms and concepts for Software-Defined Radio (SDR), Adaptive Radio, Policy-Defined Radio, Spectrum Management, and Interconnected Technology are defined in this standard. It lists the capabilities of several technologies and compares them [141].

**IEEE P1900.2** (Recommended Practice for Interference and Coexistence Analysis): The 1900.2 Working Group establishes guidelines for interference analysis and provides a framework for tracking and assessing interference. An organized approach to handling interference and coexistence issues is provided by this standard.

**IEEE P1900.3** (Dependability and Evaluation of Regulatory Compliance for Radio Systems with DSA): The 1900.3 Working Group is devoted to developing test methods for SDR device evaluation. Before final devices are certified, its primary goal is to confirm that software modules for CR devices are compliant and coexist.

**IEEE P1900.4** (Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks): For radio systems that make use of different Radio Access Technologies (RATs), this standard was developed [142, 143]. It facilitates flexible operations in several frequency bands and supports end-user terminal users through the use of multiple RATs and Cognitive Radio capabilities. IEEE 1900.4 describes the reconfiguration of management entities to aid in decision-making at the terminal and network levels.

**12.3. International Telecommunication Union Standardization**

The standardization of Cognitive Radio Networks (CRNs) falls under the purview of the International Telecommunication Union (ITU) Radio communication sector (ITU-R) Study Group 8. This study group is responsible for Radio Determination, Mobile, Related Satellite Services, and Amateur Services. There have been two reports issued by ITU-R Study Group 8 [144, 145] that focus on Software Defined Radio (SDR) technology. These reports specifically explore the integration of SDR technology within IMT-2000 (International Mobile Telecommunications-2000) systems. IMT-2000 systems of the third generation provide access to a wide array of telecommunication services, both those supported by fixed telecommunications networks (such as PSTN/ISDN/IP) and those tailored for mobile users. SDR technology is utilized in the base stations and controllers of mobile radio access networks, enhancing the adaptability and flexibility of these networks.

**Conclusion**

Cognitive Radio (CR) represents a novel approach to developing intelligent wireless networks that address the issue of spectrum scarcity and significantly enhance spectrum efficiency. We have conducted a comprehensive review of research activities in the field of Cognitive radio communication networks. The review encompassed major challenges in CR design, including spectrum sensing, dynamic spectrum access (DSA), applications, and standardization. Additionally, we provided a historical perspective on CR as a driving force for dynamic and efficient next-generation wireless systems. Various methods of spectrum sharing in CR were examined, and security and economic considerations were also discussed. Moreover, we explored future research focuses and highlighted open research areas. Finally, some standardization activities related to CR were summarized.

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