**A REVIEW OF COGNITIVE WIRELESS NETWORK TECHNOLOGY**

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**Abstract**

The electromagnetic radio spectrum is a valuable and limited resource for wireless communication systems. However, with the emergence of new wireless technologies and increasing bandwidth demands, the spectrum has become depleted. Surprisingly, studies have shown that much of the allocated spectrum is used inefficiently most of the time, contributing to the scarcity issue. The problem is not only due to inflexible spectrum management but also inefficient usage. 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. To mitigate this difficulty, CR was developed and designed such that it can communicate effectively and efficiently by sensing the wireless environment. Currently, much research has been done on the use of these spectrum bands which are either empty or not in use at full capacity. CR technology was first recommended by Dr. Joseph Mitola in 1999. CR is a software-based technology that senses the electromagnetic environment in which it functions, detects inactive frequency bands, and uses the radio working parameters to broadcast in these bands [1].

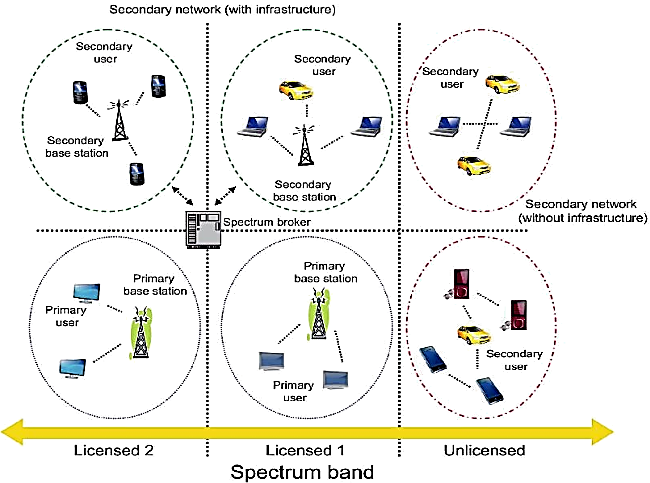
The goal of CRNs is to effectively use the temporarily inactive licensed spectrum for communications at a specific time or in a specific location. Primary users (PUs) and secondary users (SUs) are two categories for users in a CRN. A PU, often referred to as a licensed user, is given priority access to the spectrum and is exempt from interference from other users that could be damaging. To coexist with the PU, an SU or cognitive user uses cutting-edge radio access techniques and dynamic spectrum allocation procedures, provided that the SU's interference does not impair the PU's performance [2]. This strategy enables a CRN to get around the radio frequency shortage.

This review's objective is to provide a succinct summary of current state-of-the-art research in cognitive radio systems as well as anticipated future advances. The review's remaining sections are organized as follows: Following a review of the fundamental CR ideas, we outline the components of a CRN and provide a viewpoint summary of the main research issues. Then, we provide a summary of the most cutting-edge spectrum sensing and spectrum-sharing methods currently available for CR systems. A quick summary of the research on the economics and security of CRNs follows here. The applications (such as smart grid [3,4], machine-to-machine (M2M) communications [5,6], and cloud computing [6]) and the present and next trends in CR are discussed, and the open research issues are listed. The standardization efforts on CR are finally summed up.

CR technology is an important technology that allows a network to utilize the spectrum in a dynamic manner. A spectrum is the range of electromagnetic radiation that enables wireless communication and is controlled by governments. A Cognitive Radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates [7]. Recently, CR became apparent technology which is used to avoid congestion in wireless communication by utilizing unused radio spectrum [8].

In terms of transmission and reception parameters, CR is categorized as Full Cognitive Radio and Spectrum-Sensing Cognitive Radio. In Full CR every single parameter is monitored by a wireless node while in Spectrum-Sensing CR the radiofrequency (RF) spectrum is monitored. In terms of spectrum availability, it is classified as Licensed-Band Cognitive Radio and Unlicensed-Band Cognitive Radio. Licensed-Band CR is able to utilize bands which are allocated to licensed users. A standard was developed for wireless regional area network (WRAN) by IEEE 802.22 to operate on TV white spaces (unused television channels). Utilization of unlicensed parts of the radio frequency spectrum occurs in Unlicensed Band Cognitive Radio [9, 10]. It explained the manner in which intelligent radio devices and connected networks communicate and are able to modify their operating parameters to match the needs of the user/network. It does this by adjusting the transmission parameters (e.g., transmission power, modulation mode, and frequency band) in a real-time and online manner [10]. Communications among CR users/nodes can be established using CRN. Communication parameters are adjusted to respond to changes in the topology, radio environment, user requirements or operating conditions. Cognitive radio does not have primary rights to pre-assigned frequency bands because it operates as a secondary user; this makes it necessary for it to detect the presence of primary users [8].

The primary network and the cognitive network (CN) are two groups that make up the CR network structure in Figure 1. The legacy network with the sole authority to use a particular spectrum band is known as the primary network (PN). CN is not authorized to operate in the intended band, though. A primary base station and a group of primary users make up a primary network (PN). Certain licensed spectrum bands may be used by primary users with the cooperation of primary base stations. Secondary networks (SN) should not obstruct their transmission. Primary users and primary base stations typically do not have CR services available to them. Therefore, if an SN and PN share a licensed spectrum band, the secondary network must immediately detect the presence of a primary user and direct the secondary transmission to another accessible band to avoid interfering with the primary transmission. This is in addition to detecting the spectrum white space and using the best spectrum band. A network of secondary users (SU) with or without a secondary base station is referred to as an SN. Only when a primary user is not using the licensed spectrum may secondary users access it. A secondary base station, a fixed infrastructure element acting as the core of the secondary network, is primarily responsible for organizing the opportunistic spectrum access of secondary users. CR features are available on both SU and secondary base stations [11].

  
 Figure 1: Cognitive radio network topology [11]

**2.0 Review of Related Literature**

Junhui and Tao presented a power control technique for cognitive radio (CR) systems, taking into account constraints on transmitter power and interference temperature. They considered interference limitations to ensure the quality of service and non-cooperative power control models for the primary users (PUs) [12]. Lu Yang explored the multiuser diversity in uplink multiple-input multiple-output (MIMO) cognitive radio networks. They proposed a two-stage opportunistic user scheduling scheme [13]. Wenhao Xiong investigated user selection approaches for the downlink of MIMO cognitive radio networks. The approach involved selecting underlay CR secondary users to share sub-channels with primary users using cognitive base stations (CBS) [14]. Duoying Zhang studied spectrum sharing in a multiple-input multiple-output cognitive interference channel, where multiple PUs coexists with multiple secondary users (SUs). They introduced an interference alignment (IA) approach to allow SUs to access the licensed spectrum without causing harmful interference to PUs. Numerical results showed that this design increased the achievable degree of freedom (DoF) of primary links and provided a significant sum rate for both secondary and primary transmissions under rank limitations [15]. Junhui and Qiping proposed an optimization algorithm that combines diverse spectrum shared bandwidth and power allocation in cognitive radio systems. The approach allows the cognitive user (CU) to switch between the Underlay spectrum sharing model and the Overlay spectrum sharing model [16].

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.  Present detailed survey on machine-to-machine communication.  Analyze the diﬀerence between conventional and CR Machine to Machine wireless communication system.  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 overview of 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 solutions are well outlined.  The needed resources are clearly outlined.  Problems and solutions are 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 implementation of radio-scene analysis includes the estimation of the interference temperature of the area's radio environment, environment prediction modelling, and spectrum hole identification. For coherent message signal recognition and better spectrum utilization, the receiver must have channel identification implemented. Finally, the transmitter's dynamic spectrum management and transmit-power control system uses the data from the radio-scene analysis and channel identification to decide on the transmission parameters.

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

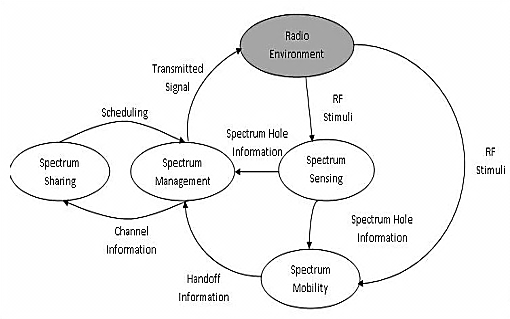
The basic functions of CR are Spectrum Sensing, Spectrum mobility, Spectrum management and Spectrum Sharing. CR technology has some basic functions, and these functions help users in the following ways:

*(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 cognitive radio; unused portions of the spectrum are used opportunistically upon detection.

*(ii) Spectrum management* - to select the best available channel. When spectrum holes are detected, the CR must have the capability to select the channel that matches its communication requirements.

*(iii) Spectrum sharing* - to organize access to this channel with other users. In a CR network, there must an algorithm scheduled to ensure that all the cognitive radios get an impartial chance to use the spectrum.

*(iv) Spectrum mobility* - to free the channel when a licensed user is detected. Since the CR is given a lower importance, they should be able to interrupt their communication when a licensed user comes back and seamlessly move onto another free channel [1]. Figure 2 shows a Cognitive radio cycle. [23]

  
 Figure 2 Cognitive Radio Cycle

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

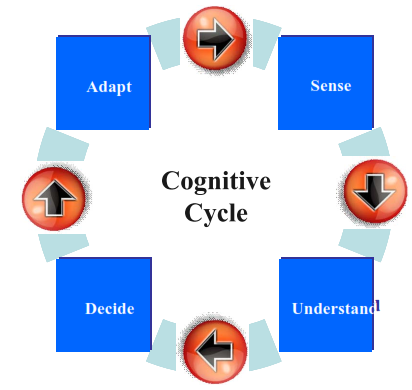
(i) Sensing,

(ii) Understanding,

(iii) Deciding

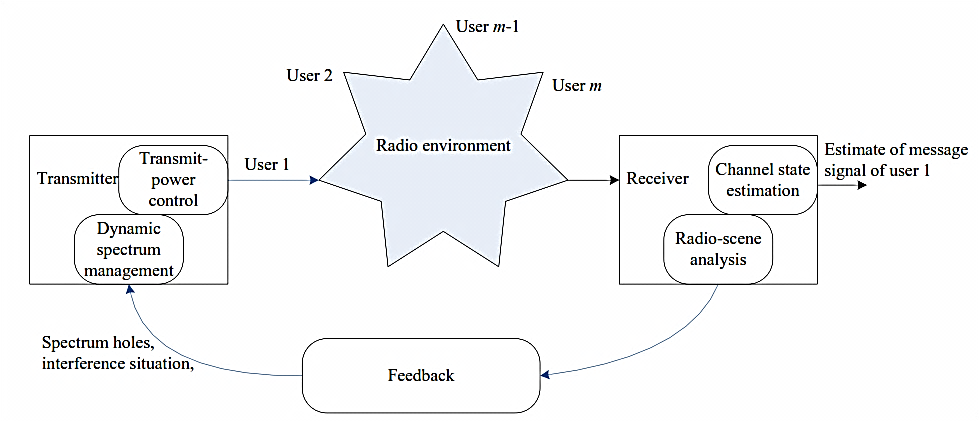
(iv) Adapting

As shown in Figure 3. CR exploits this cycle in a way that the spectrum is the main figure to be sensed, and all the subsequent process focuses also on how to handle the spectrum based on the observations. [28]

  
 Figure 3. Generic CRC.

The CC containing the cognitive tasks is shown in Figure 4. The feedback channel between the receiver and the transmitter is the facilitator for intelligence in the CR. The feedback channel is required to transmit 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 serious issue of CR technology because of the fading, time-varying nature of wireless channels and shadowing. To sense unused or limited frequency bands, several approaches for spectrum sensing have been suggested in the literature review. Examples are 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. An excellent method for examining singularities and edges is the wavelet transform. In the wavelet-based spectrum sensing technique, the interest frequency bands are often decomposed as a train of subsequent frequency sub-bands [54]. Wavelet transform is used to detect anomalies in these bands and determine whether the spectrum is full or empty.

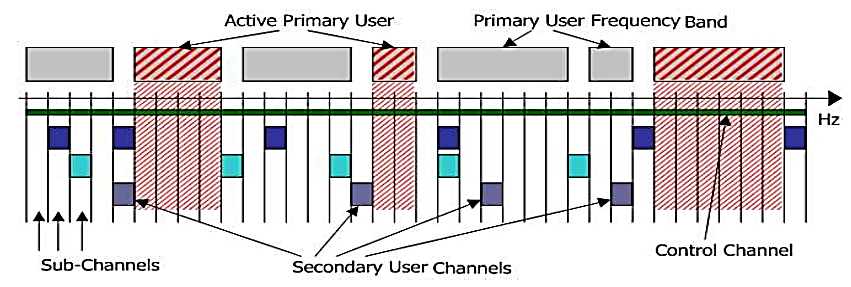
Hybrid models, which combine the use of two or more detection strategies, have recently been developed to increase a CRN's capacity for spectrum sensing. Hybrid models frequently employ machine learning algorithms (MLA) and artificial intelligence (AI) [55].

**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)* - radio technology's capacity to gather data from its radio environment. By identifying the portions of the spectrum that are inactive at a specific time or location, the optimal spectrum and the most appropriate operating parameters can be chosen.
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].

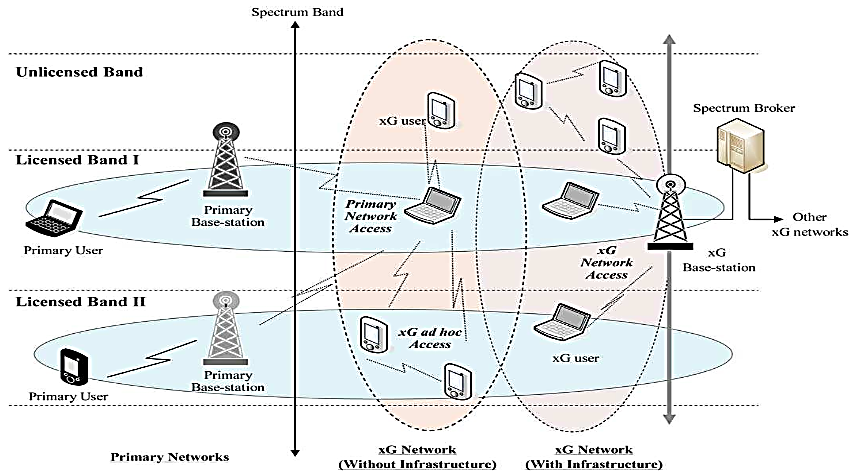


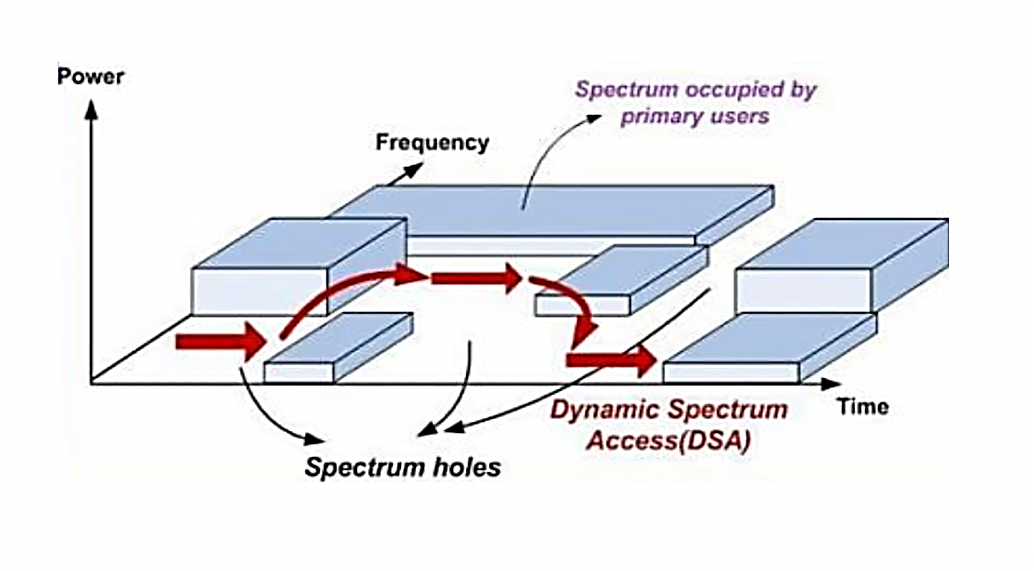
Figure 6: Cognitive radio network system [56].

**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. After SDR, cognitive radio is seen as the next stage in reconfiguration flexibility since it allows for adaptability and reconfiguration. Saying that a cognitive radio is a software-defined radio, in which the software secures the radio's cognitive functionality, would not be out of place. SDR that lacks cognition is not always 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].

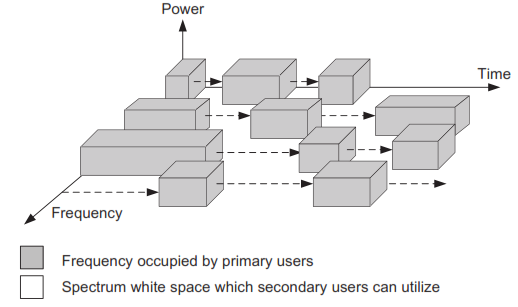


Figure 8: Example of a Spectrum Distribution Graph.

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

1. Temporal spectrum hole: This refers to a frequency band that remains unoccupied by a primary user (PU) for a certain period. By employing advanced spectrum sensing techniques, a secondary user (SU) can detect these spectrum holes and opportunistically access them without negatively impacting the quality of service for the primary user.
2. Frequency spectrum hole: In this case, the activities of the secondary user do not cause any harmful interference to the primary users. This allows the secondary user to utilize the spectrum without disrupting ongoing primary user communications.
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.

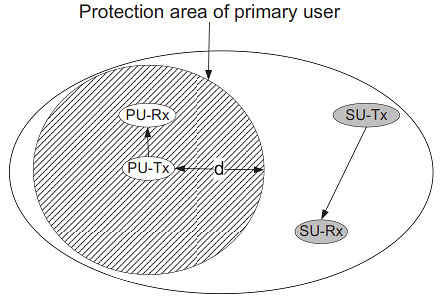


Figure 9: Spatial spectrum hole where the secondary user (SU) is not permitted to operate within the protected area of the primary user (PU).

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 influenced by natural phenomena like multi-path fading, shadowing, and noise, which can impact the strength of the received signal. For instance, if a primary user (PU) is located far from a secondary user (SU), or if the PU's signal is obstructed by a large obstacle, the signal received at the SU may be weak. As a result, accurately detecting the presence of a PU becomes challenging. Figure 10 illustrates a scenario where the PU's transmitter (PU Tx) is hidden behind an obstacle, making it difficult for the secondary transmitter (SU Tx) to sense the PU Tx signal. Consequently, the SU Tx might unknowingly cause harmful interference to the PU's receiver (PU Rx) as it begins using the licensed spectrum to communicate with the secondary receiver (SU Rx).

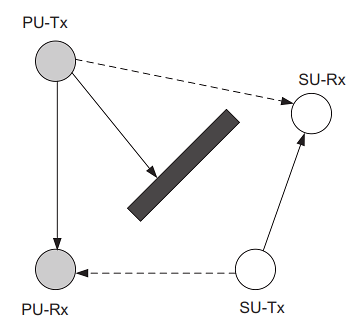


Figure 10: Example of a hidden PU where SU Tx can’t sense the presence of the PU Tx due to obstacles.

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.

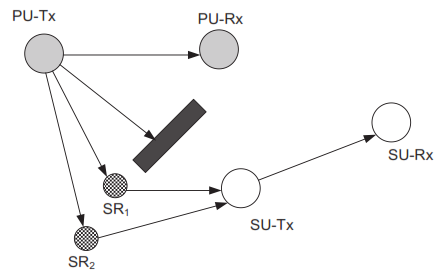


Figure 11: Two SRs support the SU Tx in detecting a hidden PU Tx.

**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 aspects include spectrum sensing [64–77], spectrum measurements, and statistical modelling of spectrum usage [78–84], as well as signal and waveform design [85–95]. Additionally, the review covers multiple access, resource allocation, and power control, spectrum mobility [96–105], cognitive learning, adaptation, and self-configuration [106–117], and multihop transmission and routing [118–123].

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

Acquiring accurate information about spectrum usage by Primary Users (PUs) is essential for Secondary Users (SUs) to opportunistically access the spectrum. To gain such knowledge, research focuses on the following aspects:

(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:**

The waveform and modulation design for signals from Secondary Users (SUs) can be adjusted to reduce interference to Primary Users (PUs). For instance, in a scenario with underlay spectrum access, SUs can use ultra-wideband transmission and modify the pulse width and/or position to avoid interfering with the narrowband transmission of PUs. Similar to this, in an overlay spectrum access scenario, SUs can reduce interference by using multicarrier modulation methods like orthogonal frequency division multiplexing (OFDM).

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

In a spectrum underlay scenario, the complexities of achieving optimal spectrum sharing among Secondary Users (SUs) can be formulated as an optimization problem with an appropriate objective function and a set of constraints. These constraints encompass factors such as user fairness, ensuring Quality of Service (QoS) for SUs, and adhering to interference limitations for Primary Users (PUs). In situations where the optimization problem becomes infeasible due to stringent constraints or high network load, an admission control mechanism is employed to limit the number of admitted SUs. Subsequently, power allocation for the admitted SUs can be performed.

To achieve fairness among SUs in practical scenarios using Code Division Multiple Access (CDMA) technology at the physical layer (PHY), an approach proposed in [99] addresses the joint problem of admission control and power allocation. It is essential to estimate instantaneous channel gains among SUs and interference from Secondary Transmitters (STs) to Primary Receivers (PRs) for power allocation solutions. When only estimates of average channel gains are available, conservative power allocations for STs are necessary to meet the target interference constraint violation probability for PRs [101].

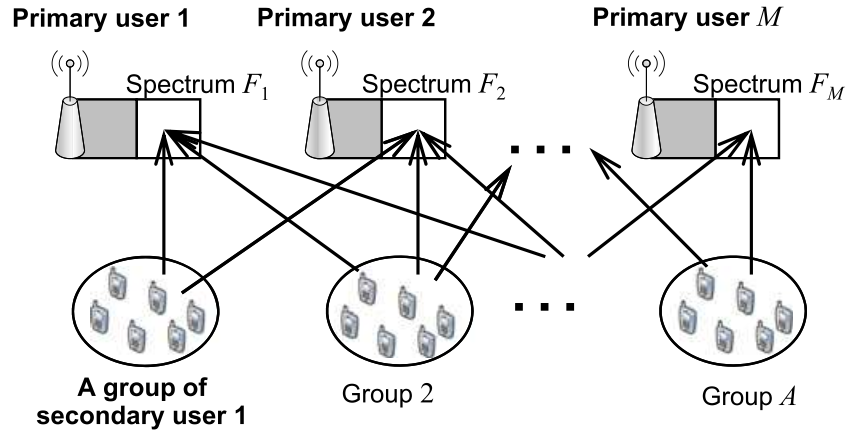
In [102], the challenge of maximizing the sum-rate for STs is investigated in a Cognitive Radio Network (CRN) with multiple STs and PRs (each equipped with one antenna) under joint beamforming and power allocation. Additionally, [103] reviews dynamic resource allocation strategies for CR systems using the interference temperature-based spectrum sharing model.

**8.1 Economics of Cognitive Radio Networks:**

In CR systems, pricing plays a vital role and encourages primary and secondary users to share vacant spectrum through spectrum trading [127]. Spectrum trading allows entities in the CR system, such as primary and secondary users, spectrum owners, service providers, and subscribers, to exchange radio resources, either through monetary transactions or other resource exchanges (bartering). Two major approaches for spectrum trading are auction-based and open market-based.

**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 following problems were identified in the review. First, the problem of optimization that occurred during the transmission of data, the complexity problem on multiple cognitive base stations (CBS) and PU. Others are the interference channel scenario with multiple CBSs and PUs; primary and secondary cognitive base station and User problem, and the transmission rank problem on many 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 is time-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 vulnerable to intruding challenger nodes that can gain access to the system and pose as authorized nodes. These malicious nodes can influence the overall spectrum sensing decision of the CRN, resulting in a security issue known as Spectrum Sensing Data Falsification (SSDF). In this attack, false information is persistently reported, leading to the perception of a busy channel. Detecting and identifying this attack is quite challenging.

(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’ defence mechanisms.

(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. In November 2004, the IEEE established the 802.22 Working Group (WG) for Wireless Regional Area Networks (WRANs). This WG's objective was to develop an air interface (PHY and MAC) based on CRs for unlicensed operation in TV broadcast bands. The focus of IEEE 802.22 is to provide rural broadband wireless access, covering a substantially larger distance than that of IEEE 802.16 [137]. In summary, a variety of standardization efforts are currently underway in the field.

**12.1. IEEE 802.22:**

A summary of the 802.22 architecture, including entities, connections, and topology, as well as its requirements like service coverage, MAC layer details, and service capacity, along with applications and coexistence challenges (e.g., TV, antenna, and wireless microphone protection and sensing), was provided in [138, 139]. The IEEE 802.22 networks operate in the frequency band of 54–862 MHz in North America, accommodating various international TV channel bandwidths of 6, 7, and 8 MHz. These systems utilize a fixed point-to-multipoint air interface, where the base station controls the consumer premise equipment (CPEs).

**12.2. IEEE 1900–SCC41-DYSPAN:**

The IEEE Standard Coordinating Committee 41 (SCC41), formerly known as the IEEE 1900 task force [140], was established to focus on dynamic spectrum access (DSA) networks for standardizing Cognitive Radio (CR). SCC41 comprises four Working Groups (1900.x), each dedicated to specific aspects of CR standardization. The key standards developed under SCC41-DYSPAN are as follows:

**IEEE P1900.1** (Terminology and Concepts for Next Generation Radio Systems and Spectrum Management): This standard defines a vocabulary of key terms and ideas for Software-Defined Radio (SDR), Adaptive Radio, Policy-Defined Radio, Spectrum Management, and Interconnected Technology. It compares several technologies and outlines their capabilities [141].

**IEEE P1900.2** (Recommended Practice for Interference and Coexistence Analysis): The 1900.2 Working Group proposes a framework for monitoring and evaluating interference and sets standards for interference analysis. This standard provides a methodical way to deal with interference and coexistence problems.

**IEEE P1900.3** (Dependability and Evaluation of Regulatory Compliance for Radio Systems with DSA): The 1900.3 Working Group focuses on test techniques to evaluate SDR devices. Its main objective is to verify the coexistence and compliance of software modules for CR devices before certifying final devices.

**IEEE P1900.4** (Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks): This standard was created for radio systems that utilize various Radio Access Technologies (RATs) [142, 143]. With the use of several RATs and Cognitive Radio capabilities, it supports end-user terminal users and enables flexible operations in various frequency bands. In order to facilitate decision-making at the terminal and network levels, IEEE 1900.4 defines the reconfiguration of management entities.

**12.3. International Telecommunication Union Standardization**

The International Telecommunication Union (ITU) Radio communication sector (ITU-R) Study Group 8, which deals with Radio Determination, Mobile, Related Satellite Services, and Amateur Services, is in charge of standardizing Cognitive Radio Networks (CRNs). Software Defined Radio (SDR) has been the subject of two reports from ITU-R Study Group 8 [144, 145]. In these publications, the use of SDR technology inside IMT-2000 (International Mobile Telecommunications-2000) systems is specifically examined. Third-generation mobile IMT-2000 systems provide access to a range of telecommunication services supported by fixed telecommunications networks (such PSTN/ISDN/IP) as well as those designed specifically for mobile users. Mobile radio access networks' base stations and controllers use SDR technology, which increases the networks' adaptability and flexibility.

**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.

**References**

[1] Mitola, J. (2000). Cognitive Radio: An integrated agent architecture for software-defined radio. PhD dissertation, KTH Royal Institute of Technology, (Sweden, 2000)

[2] Hung, T. (2013). Performance Analysis of Cognitive Radio Networks with Interference Constraints. School of Computing. Publisher: Blekinge Institute of Technology, SE-371 79 Karlskrona, Sweden. Printed by Printfabriken, Karlskrona, Sweden 2013

[3] Deng, R, Chen J, Cao, X, Zhang, Y., Mahajan, S. and Gjessing S. Sensing-performance tradeoff in cognitive radio enabled smart grid. *IEEE Transactions on* *Smart Grid* 2013; **4**(1): 302–310.

[4] Huang J, Wang H, Qian Y, Wang C. Priority-based trafﬁc scheduling and utility optimization for cognitive radio communication infrastructure-based smart grid. *IEEE Transactions on Smart Grid* 2013; **4**(1):78–86.

[5] Zhang Y, Yu R, Nekovee M, Liu Y, Xie S, Gjessing S. Cognitive machine-to-machine communications: visions and potentials for the smart grid. *IEEE* *Network* 2012; **26**(3): 6–13.

[6] Wu SH, Chao HL, Ko CH, Mo SR, Jiang CT, Li TL, Cheng CC, Liang CF. A cloud model and concept prototype for cognitive radio networks. *IEEE* *Wireless Communications* 2012; **19**(4): 49–58.

[7] Abu, B., Soumik, G., Ashok, K., & Magdy, B. (2007). A Cognitive Radio Perspective for Next Generation (XG Communication, IEEE CIRCUITS AND SYSTEMS MAGAZINE, 2007.

[8] LIU, X., & ZHONG, W. (2015). Optimization and Performance Analysis for Bandwidth Spectrum Sensing in Cognitive Radio. *Journal of Southwest Jiaotong* *University,* 50 (1). Available from <http://jsju.org/index.php/journal/article/view/191>

[9] PREET, A., & KAUR, A. (2014). Cognitive Radio Networking and Communications. *International Journal of Computer Science and Information Technologies*, 5 (4), pp. 5508-5511.

[10] Bakare, B.I., & Okolie, E.E. (2022). A Review of Cognitive Radio (CR) Technology Application, Prospect and Challenges. European Journal of Advances in Engineering and Technology, 2022, 9(1):1-5

[11] [50] Popoola, J., & Van, R. (2011). Application of neural network for sensing primary radio signals in a cognitive radio environment, in IEEE Africon ’11, Livingstone, 13–15 September 2011. [https://doi.org/10.1109/AFRCO N.2011.6072009](https://doi.org/10.1109/AFRCO%20N.2011.6072009)

[12] Junhui Z., Tao, Y., & Yi, G. (2013). Power Control Algorithm of Cognitive Radio Based on Non-Cooperative Game Theory [J]. China Communications, vol. 10, no. 11, pp. 143-154, 2013.

[13] Lu, Y. (2014). “Opportunistic User Scheduling In Mimo Cognitive Radio Networks” IEEE International Conference on Acoustic, Speech and Signal Processing (ICASSP)- 2014.

[14] Wenhao, X. (2016). “MIMO Cognitive Radio User Selection with and without Primary Channel State Information” IEEE-2016.

[15] Duoying, Z. (2016). “Rank-Constrained Beamforming for MIMO Cognitive Interference Channel” Hindawi Publishing Corporation Mobile Information Systems Volume 2016

[16] Junhui, Z., Qiping, L., & Yi, G. (2018). Joint Bandwidth and Power Allocation of Hybrid Spectrum Sharing in Cognitive Radio[C]// IEEE 87th Vehicular Technology Conference (VTC Spring), 2018.

[17] Cui, T., Gao, F., & Nallanathan, A. (2011). Optimization of Cooperative Spectrum Sensing in Cognitive Radio[J]. IEEE Transactions on Vehicular Technology, vol. 60, no. 4, pp. 1578-1589, 2011.

[18] Sidhu, G. A. S., Gao, F., & Wang, W. (2013). Resource Allocation in Relay-Aided OFDM Cognitive Radio Networks[J]. IEEE Transactions on Vehicular Technology, vol. 62, no. 8, pp. 3700-3710, 2013.

[19] Lu, W., & Wang, J. (2014). Opportunistic Spectrum Sharing Based on Full-Duplex Cooperative OFDM Relaying. IEEE communications letters, vol. 18, no. 2, pp. 241-244, 2014.

[20] Oladele, R. O., & Damilola, N. A. (2019). Contemporary Issues in Cognitive Radio Network Anale. Seria Informatica. Vol. XV fasc. 2 – 2017 Annals. Computer Science Series. 15th Tome 2nd Fasc. – 2017

[21] Negasa, B. T., & Habib, M. H. (2018). Review on Cognitive Radio Technology for Machine to Machine Communication. ICST Institute for Computer Sciences, Social Informatics and Telecommunications Engineering 2018 F. Mekuria et al. (Eds.): ICT4DA 2017, LNICST 244, pp. 347–355, 2018. <https://doi.org/10.1007/978-3-319-95153-9_31>

[22] Ying, X., Zhiyong, Feng., & Ping, Z. (2012). Research on Cognitive Wireless Networks : Theory, Key Technologies and Testbed. CROWNCOM 2011, June 01-03, Osaka, Japan Copyright © 2012 ICST <https://doi.org/10.4108/icst.crowncom.2011.245826>

[23] Pooja, A., Nidhi, J., & Mahima, K. (2014). Cognitive Radio: A Review. *International Journal of Engineering Research & Technology (IJERT) NCETECE`14 Conference Proceedings ISSN: 2278-0181*

[24] Ayushi, & Priyanka, J. (2023). Methods for Detecting Energy and Signals in Cognitive Radio: A Review. International Research Journal of Engineering and Technology (IRJET). Volume: 10 Issue: 04 | Apr 2023.

[25] Nikita, T., Archana, I., Karishma, R., & Madhura, T. (2015). Cognitive Radio Network – A New Paradigm in Wireless Communication. *International Journal of Computer Applications (0975 – 8887) National Conference on Role of Engineers in Nation Building (NCRENB-15)*

[26] Rushabh, M. (2016). Cognitive Radio Networks Issues and Solutions. <https://www.researchgate.net/publication/311949773>.

[27] Nandhakumar, P., & Arun, K. (2017). A Review on Cognitive Radio for Next Generation Cellular Network and its Challenges. *American Journal of Engineering and Applied Sciences* 2017, 10 (2): 334.347 <https://doi.org/10.3844/ajeassp.2017.334.347>.

[28] Haykin, S. (2005). “Cognitive radio: Brain-empowered wireless communications,” *IEEE Journal on Selected Areas in Communications*, vol. 25, pp. 201–220, February 2005.

[29] S. M. Haykin, Cognitive radio and radio networks. INFWEST seminar in Helsinki, 27-28 June 2007.

[30] Raman, C., Yates, R. D., & Mandayam, N. B. (2005). “Scheduling variable rate links via a spectrum server,” in Proc. IEEE Symp. New Frontiers in Dynamic Spectrum Access Networks (DySPAN), Baltimore, MD, Nov. 2005, pp. 110–118.

[31] Urriza, P., Rebeiz, E., & Cabric, D. (2013). Multiple antenna cyclostationary spectrum sensing based on the cyclic correlation signiicance test. IEEE J. Sel. Areas Commun. **31**(11), 2185–2195 (2013). <https://doi.org/10.1109/JSAC.2013.131118>.

[32] Li, Y., & Jayaweera, S. (2013). Dynamic spectrum tracking using energy and cyclo stationarity-based multi-variate non-parametric quickest detection for cognitive radios. IEEE Trans. Wirel. Commun. **12**(7), 3522–3532 (2013). <https://doi.org/10.1109/TW.2013.060413.121814>

[33] Iqbal, M., & Ghafoor, A. (2012). Analysis of multiband joint detection framework for waveform-based sensing in cognitive radios, in 2012 IEEE Vehicular Technology Conference (VTC Fall) (3–6 September 2012), pp. 1–5. [https://doi.org/10.1109/VTCFa ll.2012.6399372](https://doi.org/10.1109/VTCFa%20ll.2012.6399372)

[34] Proakis, J., & Salehi, M. (2007). Digital Communications, 5th edn. (McGraw-Hill, Boston, 2007).

[35] Tandra, R., & Sahai, A. (2005). Fundamental limits on detection in low SNR under noise uncertainty, in 2005 International Conference on Wireless Networks, Communications and Mobile Computing (13–16 June 2005), pp. 464–469. [https://doi.org/10.1109/WIRLE S.2005.1549453](https://doi.org/10.1109/WIRLE%20S.2005.1549453)

[36] Zeng, Y., Koh, C., & Liang, Y. C. (2008). Maximum eigenvalue detection: theory and application, in IEEE International Conference on Communications, ICC ’08 (19–23 May 2008), pp.4160–4164. <https://doi.org/10.1109/ICC.2008.781>

[37] Pillay, N., & Xu, N. (2012). Blind eigenvalue-based spectrum sensing for cognitive radio networks. IET Commun. **6**(11), 1388–1396 (2012). <https://doi.org/10.1049/iet-com.2011.0506>

[38] Ruttik, K., Koufos, K., & Jantti, R. (2009). Detection of unknown signals in a fading environment. IEEE Commun. Lett. **13**(7), 498–500 (2009). <https://doi.org/10.1109/LCOMM.2009.090169>

[39] Herath, S., Rajatheva, N., Tellambura, C. (2011). Energy detection of unknown signals in fading and diversity reception. IEEE Trans. Commun. **59**(9), 2443–2453 (2011). <https://doi.org/10.1109/TCOMM.2011.071111.090349>

[40] Lu, L., Zhou, X., Onunkwo, U., & Li, G. (2012). Ten years of research in spectrum sensing and sharing in cognitive radio. EURASIP J. Wirel. Commun. Netw. **1–16**, 28 (2012). <https://doi.org/10.1186/1687-1499-2012-28>

[41] Rao, S.V.R.K., & Singh, G. (2012). Wavelet-based spectrum sensing techniques in cognitive radio. Procedia Eng. (2012). <https://doi.org/10.1016/j.proeng.2012.06.111>

[42] Mohapatra, S., Mohapatra, A.G., & Lenka, S.K. (2013). Performance evaluation of cyclostationary based spectrum sensing in cognitive radio network proceedings of the International Multi-Conference on Automation, Computing, Communication, Control and Compressed Sensing, Mar. 22-23, IEEE Xplore Press, pp: 90-97. <https://doi.org/10.1109/iMac4s.2013.6526389>

[43] Gardner, W.A. (1999). Exploitation of spectral redundancy in cyclostationary signals. IEEE Signal Process. Mag. **8**(2),14–36 (1991). <https://doi.org/10.1109/79.81007>

[44] Yucek, Y., & Arslan, H. (2009). A survey of spectrum sensing algorithms for cognitive radio applications. IEEE Commun. Surv. Tutor. **11**(1), 116–130 (2009)

[45] Ma, L., Li, Y., & Demir, A. (2012). Matched filtering assisted energy detection for sensing weak primary user signals, in IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), 25–30 March 2012, pp. 3149–3152. <https://doi.org/10.1109/ICASSP.2012.6288583>

[46] Zeng, Y., & Liang, Y.-C. (2009). “Spectrum-sensing algorithms for cognitive radio based on statistical covariances,” IEEE Trans. Veh. Technol., vol. 58, no. 4, pp. 1804–1815, May 2009.

[47] Zeng, Y., & Liang, Y.-C. (2007). “Covariance based signal detections for cognitive radio,” in Proc. IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, Dublin, Ireland, Apr. 2007, pp. 202–207.

[48] Zhang, X., Chai, R., & Gao, F. (2014). Matched filter based spectrum sensing and power level detection for cognitive radio network, in IEEE Global Conference on Signal and Information Processing (Global SIP), Atlanta, 3–5 December 2014, pp. 1267–1270. <https://doi.org/10.1109/GlobalSIP.2014.7032326>

[49] Tsinos, C.G., & Berberidis, K. (2015). Decentralized adaptive eigenvalue-based spectrum sensing for multiantenna cognitive radio systems. IEEE Trans. Wirel. Commun. **14**(3), 1703–1715 (2015). <https://doi.org/10.1109/TWC.2014.2372756>

[50] Zeng, Y., Koh, C. L., & Liang, Y. C. (2008). Maximum eigenvalue detection: Theory and application, in 2008 IEEE International Conference on Communications (ICC ’08), 19–23 May 2008, pp. 4160–4164. <https://doi.org/10.1109/TCOMM.2009.06.070402>

[51] Atapattu, S. (2011). Energy Detection based cooperative spectrum sensing in cognitive radio networks. IEEE Trans. Wirel. Commun. **10**(4), 1232–1241 (2011). [https://doi.org/10.1109/TWC.2011.01241 1.100611](https://doi.org/10.1109/TWC.2011.01241%201.100611)

[52] Digham, F. F., Alouini, M. S. & Simon, M. k. (2007). On the energy detection of unknown signals over fading channels. IEEE Trans. Commun. **55**(1), 21–24 (2007). [https://doi.org/10.1109/TCOMM .2006.887483](https://doi.org/10.1109/TCOMM%20.2006.887483)

[53] Sansoy, M., & Buttar, A. (2015). Spectrum sensing algorithms in cognitive radio: A survey. Proceedings of the IEEE International Conference on Electrical, Computer and Communication Technologies, Mar. 5-7, IEEE Xplore Press, pp: 1-5. <https://doi.org/10.1109/ICECCT.2015.7226181>

[54] Gorcin, A., Qaraqe, K.A., Celebi, H., & Arslan, H. (2010). An adaptive threshold method for spectrum sensing in multi-channel cognitive radio networks, in 17th International Conference on Telecommunications (ICT’10), Doha, 4–7 April 2010, pp. 425–429. [https://doi.org/10.1109/ICTEL .2010.54787 83](https://doi.org/10.1109/ICTEL%20.2010.54787%2083)

[55] Zhi, T., Giannakis, G. (2006). A wavelet approach to wideband spectrum sensing for cognitive radios, in 2006 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications, 8–10 June 2006, pp. 1–5. [https://doi.org/10.1109/CROWN COM.2006.36345 9](https://doi.org/10.1109/CROWN%20COM.2006.36345%209)

[56] Mahamuni, S.M., Vivekanand, M., Wadhai, V.M. (2010). Cognitive Networks: Smart Network. *Journal of Engineering Research and Studies. JERS/Vol.I/ Issue II/Oct.-Dec.,2010/121-134*

[57] Brown, T. X. (2005). “An analysis of unlicensed device operation in licensed broadcast service bands,” in Proc. IEEE DySPAN 2005, pp. 11–29, Nov. 2005.

[58] Wassim, E., Haidar, S., & Mohsen, G. (2011), Survey of Security Issues in Cognitive Radio Networks, Journal of Internet Technology Volume 12 (2011) No.2

[59] Ma, J., Li, G., & Juang, B. H. (2009). “Signal processing in cognitive radio,” Proc. IEEE, vol. 97, no. 5, pp. 805–823, May 2009.

[60] Tandra, R., Sahai, A., & Mishra, S. (2009). “What is a spectrum hole and what does it take to recognize one?” Proc. IEEE, vol. 97, no. 5, pp. 824–848, May 2009.

[61] Letaief, K. B., & Zhang, W. (2009). “Cooperative communications for cognitive radio networks,” Proc. IEEE, vol. 97, no. 5, pp. 878–893, May 2009.

[62] Ghasemi, A., & Sousa, E. (2005). “Collaborative spectrum sensing for opportunistic access in fading environments,” in Proc. IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, Baltimore, U.S.A., Nov. 2005, pp. 131–136.

[63] Ganesan, G., & Li, Y. (2007). “Cooperative spectrum sensing in cognitive radio, part I: Two user networks,” IEEE Trans. Wireless Commun., vol. 6, no. 6, pp. 2204–2212, Nov. 2007

[64] Yucek T, Arslan H. A survey of spectrum sensing algorithms for cognitive radio applications. *IEEE* *Communications Surveys and Tutorials* 2009; **11**(1): 116–130.

[65] Zeng Y, Liang YC, Hoang AT, Zhang R. A review on spectrum sensing for cognitive radio: Challenges and solutions. *EURASIP Journal on Advances in Signal* *Processing* 2010; **2010**. Article ID 381465.

[66] Sutton PD, Nolan KE, Doyle LE. Cyclostationary signatures in practical cognitive radio applications. *IEEE* *Journal on Selected Areas in Communications* 2008; **26**(1): 13–24.

[67] Molisch AF, Shaﬁ M, Greenstein LJ. Propagation issues for cognitive radio. *Proceedings of the IEEE,* Special Issue on Cognitive Radio 2009; **97**: 787–804.

[68] Ghasemi A, Sousa ES. Fundamental limits of spectrum-sharing in fading environments. *IEEE* *Transactions on Wireless Communications* 2007; **6**(2): 649–658.

[69] Zeng Y, Liang YC. Eigenvalue based spectrum sensing algorithms for cognitive radio. *IEEE Transactions* *Communications* 2009; **57**(6): 1784–1793.

[70] Mariani A, Giorgetti A, Chiani M. Effects of noise power estimation on energy detection for cognitive radio applications. *IEEE Transactions on Communications* 2011; **59**(12): 3410–3420.

[71] Tandra R, Sahai A. SNR walls for signal detection. *IEEE Journal of Selected Topics in Signal Processing* 2008; **2**(1): 4–17.

[72] Haykin S, Thomson D, Reed J. Spectrum sensing for cognitive radio. *Proceedings of the IEEE,* Special Issue on Cognitive Radio May 2009; **97**(5): 849–877.

[73] Liang YC, Zeng Y, Peh ECY, Hoang AT. Sensing– throughput tradeoff for cognitive radio networks. *IEEE Transactions on Wireless Communications* 2008; **7**(4): 1326–1337.

[74] Letaief KB, Zhang W. Cooperative communications for cognitive radio networks. *Proceedings of the* *IEEE* 2009; **97**(5): 878–893.

[75] Ganesan G, Li Y. Cooperative spectrum sensing in cognitive radio, part I: two user networks. *IEEE* *Transactions on Wireless Communications* 2007; **6**(6): 2204–2213.

[76] Ganesan G, Li Y. Cooperative spectrum sensing in cognitive radio, part II: multiuser networks. *IEEE* *Transactions on Wireless Communications* 2007; **6**(6): 2214–2222.

[77] Unnikrishnan J, Veeravalli VV. Cooperative sensing for primary detection in cognitive radio. *IEEE Journal* *of Selected Topics in Signal Processing* 2008; **2**(1): 18–27.

[78] Stuber GL, Almalfouh SM, Sale D. Interference analysis of TV-band white space. *Proceedings of the IEEE* 2009; **97**(4): 741–754.

[79] Rabbachin A, Quek TQS, Shin H, Win MZ. Cognitive network interference. *IEEE Journal on* *Selected Areas in Communications* 2011; **29**(2): 480–493.

[80] Roberson DA, Hood CS, LoCicero JL, MacDonald JT. Spectral occupancy and interference studies in support of cognitive radio technology deployment, In *Proc. of First IEEE Workshop on Networking* *Technologies for Software Deﬁned Radio Networks*, September 2006; 26–35.

[81] Datla D, Wyglinski AM, Minden GJ. A spectrum surveying framework for dynamic spectrum access networks. *IEEE Transactions on Vehicular Technology* 2009; **58**(8): 4158–4158.

[82] Ghosh C, Pagadarai S, Agrawal D, Wyglinski AM. A framework for statistical wireless spectrum occupancy modeling. *IEEE Transactions on Wireless* *Communications* 2010; **9**(1): 38–44.

[83] Wellens M, Mähönen P. Lessons learned from an extensive spectrum occupancy measurement campaign and a stochastic duty cycle model. *Mobile* *Networks and Applications June 2010* 2010; **15**(3): 461–474.

[84] Canberk B, Akyildiz IF, Oktug S. Primary user activity modeling using ﬁrst-difference ﬁlter clustering and correlation in cognitive radio networks. *IEEE/ACM Transactions on Networking* 2011; **19**(1): 170–183.

[85] Wei F, Xia P, Yang Z, Tian F. Decentralized waveform design for MIMO cognitive radio under interference temperature constraint, In *Proc. of 2011* *Second International Conference on Networking and* *Distributed Computing (ICNDC)*, September 2011; 159–162.

[86] Zhou LL, Zhu HB, Zhang NT. Iterative solution to the notched waveform design in cognitive ultra-wideband radio system. *Progress In Electromagnetic Research* 2007; **75**: 271–284.

[87] Tian Z, Leus G, Lottici V. Joint dynamic resource allocation and waveform adaptation in cognitive radio networks, In *Proc. of IEEE International Conference* *on Acoustics, Speech and Signal Processing (ICASSP* *2008)*, April 4 2008-March 31 2008; 5368–5371.

[88] Chakravarthy V, Li X, Wu Z, Temple M, Garber F, Kannan R, Vasilakos A. Novel overlay/underlay cognitive radio waveforms using SD-SMSE framework to enhance spectrum efﬁciency—part i: theoretical framework and analysis in AWGN channel. *IEEE Transactions on Communications* 2009; **57**(12): 3794–3804.

[89] Pagadarai S, Kliks A, Bogucka H, Wyglinski AM. On non-contiguous multicarrier waveforms for spectrally opportunistic cognitive radio systems, In *Proc.* *of 2010 International Waveform Diversity and Design* *Conference (WDD)*, 8–13 August 2010; 177–181.

[90] Hu Z, Guo N, Qiu R. Wideband waveform design for relay cognitive network, In *Proc. of IEEE Military* *Communications Conference (Milcom 2010)*, November 3-October 31 2010; 749–754.

[91] Hu Z, Guo N, Qiu R. Wideband waveform optimization for multiple input single output cognitive radio with practical considerations, In *Proc. of IEEE Military* *Communications Conference (Milcom 2010)*, November 3-October 31 2010; 1227–1232.

[92] Kollar Z, Horvath P. Physical layer considerations for cognitive radio: Modulation techniques, In *Proc.* *of 2011 IEEE 73rd Vehicular Technology Conference* *(VTC Spring)*, 15–18 August 2011; 1–5.

[93] Chen Y, Alouini MS, Tang L. Performance analysis of adaptive modulation for cognitive radios with opportunistic access, In *Proc. of 2011 IEEE International Conference on Communications* *(ICC), 5–9 June 2011; 1–5.*

[94] Zamanian M, Tadaion AA, Sadeghi MT. Modulation classiﬁcation of linearly modulated signals in a cognitive radio network using constellation shape, In *Proc. of 2011 7th International Workshop on Systems,* *Signal Processing and their Applications (WOSSPA)*, 9–11 May 2011; 13–16.

[95] Khanzadi MR, Haghighi K, Panahi A, Eriksson T. A novel cognitive modulation method considering the performance of primary user, In *Proc. of 2010* *6th Conference on Wireless Advanced (WiAD)*, 27–29 June 2010; 1–6.

[96] Khoshkholgh MG, Navaie K, Yanikomeroglu H. Access strategies for spectrum sharing in fading environment: overlay, underlay and mixed. *IEEE Transactions on Mobile Computing* 2010; **9**(12): 1780–1793.

[97] Tannious RA, Nosratinia A. Cognitive radio protocols based on exploiting hybrid ARQ retransmissions. *IEEE Transactions on Wireless* *Communications* 2010; **9**(9): 2833–2841.

[98] Xing Y, Chandramouli R, Mangold S, Sankar N, S. Dynamic spectrum access in open spectrum wireless networks. *IEEE Journal on Selected Areas in* *Communications* 2006; **24**(3): 626–637.

[99] Le LB, Hossain E. Resource allocation for spectrum underlay in cognitive wireless networks. *IEEE Transactions* *on Wireless Communications* 2008; **7**(12): 5306–5315.

[100] Liang YC, Zeng Y, Peh ECY, Hoang AT. Sensing– throughput tradeoff for cognitive radio networks. *IEEE Transactions on Wireless Communications* 2008; **7**(4): 1326–1337.

[101] Kim DI, Le LB, Hossain E. Joint rate and power allocation for cognitive radios in dynamic spectrum access environment. *IEEE Transactions on Wireless* *Communications* 2008; **7**(12- part 2): 5517–5527.

[102] Zhang R, Liang Y-C. Exploiting multi-antennas for opportunistic spectrum sharing in cognitive radio networks. *IEEE Journal of Selected Topics in Signal* *Processing* 2008; **2**(1): 88–102.

[103] Zhang L, Liang Y-C, Xin Y. Joint beamforming and power allocation for multiple access channels in cognitive radio networks. *IEEE Journal* *on Selected Areas in Communications* 2008; **26**(1): 38–51.

[104] Zhang R, Liang Y-C, Cui S. Dynamic resource allocation in cognitive radio networks. *IEEE Signal Processing* *Magazine* 2010; **27**(3): 102–114.

[105] Hossain E, Le L, Devroye N, Vu M. Cognitive radio: from theory to practical network engineering. In *invited chapter in Advances in Wireless Communications*, Tarokh V (ed.). Springer, 2009.

[106] Nie N, Comaniciu C. Adaptive channel allocation spectrum etiquette for cognitive radio networks, In *Proc. of First IEEE International Symposium on* *Dynamic Spectrum Access Networks (DySPAN05)* November 2005; 269–278.

[107] Pang J-S, Scutari G. Joint sensing and power allocation in nonconvex cognitive radio games: quasi-Nash equilibria. *IEEE Transactions on Signal Processing* 2013; **61**(9): 2366–2382.

[108] He A, Bae KK, Newman T, Gaeddert J, Kim KMenon R, Morales-Tirado L, Neel J, Zhao Y, Reed J, Tranter W. A survey of artiﬁcial intelligence for cognitive radios. *IEEE Transactions on Vehicular* *Technology* 2010; **59**(4): 1578–1592.

[109] Xing Y, Chandramouli R. Human behaviour inspired cognitive radio network design. *IEEE Communications* *Magazine* 2008; **46**(12): 122–127.

[110] Clancy C, Hecker J, Stuntebeck E, OShea T. Applications of machine learning to cognitive radio networks. *Wireless Communications* August 2004; **14**(4): 47–52.

[111] Serrano AG, Giupponi L. Distributed Q-learning for aggregated interference control in cognitive radio networks. *IEEE Transactions on Vehicular Technology* 2010; **59**(4): 1823–1834.

[112] Han Z, Zheng R, Poor H. Repeated auctions with Bayesian nonparametric learning for spectrum access in cognitive radio networks. *IEEE Transactions on* *Wireless Communications* 2011; **10**(3): 890–900.

[113] Clancy T, Khawar A, Newman T. Robust signal classiﬁcation using unsupervised learning. *IEEE Transactions* *on Wireless Communications* 2011; **10**(4): 1289–1299.

[114] Maskery M, Krishnamurthy V, Zhao Q. Decentralized dynamic spectrum access for cognitive radios: cooperative design of a non-cooperative game. *IEEE Transactions on Communications* 2009; **57**(2): 459–469.

[115] Van der Schaar M, Fu F. Spectrum access games and strategic learning in cognitive radio networks for delay-critical applications. *Proceedings of the IEEE* 2009; **97**(4): 720–740.

[116] Baldo N, Tamma B, Manojt B, Rao R, Zorzi MA neural network based cognitive controller for dynamic channel selection, In *Proc. of IEEE International* *Conference on Communications (ICC09)*, June 2009; 1–5.

[117] Tumuluru V, Wang P, Niyato D. A neural network based spectrum prediction scheme for cognitive radio, In *Proc. of IEEE International Conference on* *Communications (ICC’10)*, May 2010; 1–5.

[118] Akyildiz IF, Lee WY, Chowdhury KR. CRAHNs: cognitive radio ad hoc networks. *Ad Hoc Networks* *(Elsevier)* 2009; **7**(5): 810–836.

[119] Yang Z, Cheng G, Liu W, Yuan W, Cheng W. Local coordination based routing and spectrum assignment in multi-hop cognitive radio networks. *ACM MONET* 2008; **13**: 67–81.

[120] Hou YT, Shi Y, Sherali HD. Spectrum sharing for multi-hop networking with cognitive radios. *IEEE* *Journal on Selected Areas in Communications* 2008; **26**(1): 146–155.

[121] Urgaonkar R, Neely MJ. Opportunistic scheduling with reliability guarantees in cognitive radio networks. *IEEE Transactions on Mobile Computing* 2009; **8**(6): 766–777.

[122] Xue D, Ekici E. Cross-layer scheduling for cooperative multi-hop cognitive radio networks. *IEEE* *Journal on Selected Areas in Communications* 2013; **31**(3): 534–543.

[123] Song SH, Hasna MO, Letaief KB. Prior zero-forcing for cognitive relaying. *IEEE Transactions on Wireless* *Communications* 2013; **12**(2): 938–947.

[124] Wei F, Xia P, Yang Z, Tian F. Decentralized waveform design for MIMO cognitive radio under interference temperature constraint, In *Proc. of 2011* *Second International Conference on Networking and* *Distributed Computing (ICNDC)*, September 2011; 159–162.

[125] Zhou LL, Zhu HB, Zhang NT. An iterative solution to the notched waveform design in cognitive ultra-wideband radio system. *Progress In Electromagnetic Research* 2007; **75**: 271–284.

[126] Tian Z, Leus G, Lottici V. Joint dynamic resource allocation and waveform adaptation in cognitive radio networks, In *Proc. of IEEE International Conference* *on Acoustics, Speech and Signal Processing (ICASSP* *2008)*, April 4 2008-March 31 2008; 5368–5371.

[127] Niyato D, Hossain E. Spectrum trading in cognitive radio networks: a market-equilibrium-based approach. *IEEE Wireless Communications Magazine* 2008; **15**(6): 71–80.

[128] Niyato D, Hossain E, Han Z. Dynamics of multiple sellers and multiple-buyer spectrum trading in cognitive radio networks: a game theoretic modelling approach. *IEEE Transactions on Mobile Computing* 2009; **8**(8): 1009–1022.

[129] Niyato D, Hossain E. Competitive pricing for spectrum sharing in cognitive radio networks: Dynamic game, inefﬁciency of Nash equilibrium, and collusion. *IEEE Journal on Selected Areas in Communications* 2008; **26**(1): 192–202.

[130] Hyunsung, K. (2013). Privacy-Preserving Security Framework For Cognitive Radio Networks, IETE Technical Review,Vol 30, Issue 2, Mar-Apr 2013

[131] Samar, K. T. (2020). Cognitive Radio, Journal of Southwest Jiaotong University. Vol. 55 No. 1 Feb. 2020

[132] Nguyen, V., Villain, F., & Guillou, Y. L. (2011). Cognitive radio systems: Overview and challenges. Proceedings of the 3rd International Conference on Awareness Science and Technology, Sept. 27-30, IEEE Xplore Press, pp: 497-502. <https://doi.org/10.1109/ICAwST.2011.6163179>

[133] Brodersen, R.W., Wolisz, D., Cabric, S.M., & Mishra, D. (2004). “Corvus: a cognitive radio approach for usage of virtual unlicensed spectrum,” Berkeley Wireless Research Center (BWRC) White paper, 2004.

[134] Attar, A., Tang, H., Vasilakos, A.V., Yu, F.R., & Leung, V*.* (2012). A survey of security challenges in cognitive radio networks: Solutions and future research directions. Proc. IEEE, 100: 3172-3186. <https://doi.org/10.1109/JPROC.2012.2208211>

[135] Yang, Y. (2015). “Underlay MIMO Cognitive Radio Downlink Scheduling with Multiple Primary Users and no CSI” .semanticscholar.org-2015.

[136] Granelli F, Pawelczak P, Venkatesha Prasad R, Subbalakshmi KP, Chandramouli R, Hoffmeyer JA, Berger S. Standardization and research in cognitive and dynamic spectrum access networks: IEEE SCC 41 efforts and open issues. *IEEE Communications* *Magazine* 2010; **48**(1): 71–79.

[137] Overview of the IEEE 802.22 Standard on Wireless Regional Area Networks (WRAN) and Core Technologies. IEEE 802.22 Working Group Website, (Available from: http://ieee802.org/22/). [accessed on June 2023].

[138] Cordeiro C, Challapali K, Birru D, Shankar NS. IEEE 802.22: the ﬁrst worldwide wireless standard based on cognitive radios, In *Proc. of First IEEE International* *Symposium on Dynamic Spectrum Access* *Networks (DySPAN05)*, 8–11 November 2005; 328–337.

[139] Stevenson C, Chouinard G, Lei Z, Hu W, Shellhammer S, Caldwell W. IEEE 802.22: the ﬁrst cognitive radio wireless regional area network standard. *IEEE* *Communications Magazine* 2009; **47**(1): 130–138.

[140] Murroni M, *et al.* IEEE 1900.6 Spectrum sensing interfaces and data structures for dynamic spectrum access and other advanced radio communication systems standard: technical aspects and future outlook. *IEEE Communications Magazine* 2011; **49**(12): 118–127.

[141] IEEE, Standard Deﬁnitions and concepts for Spectrum Management and Advanced Radio Technologies, June 2007. P1900.1 drafts std, v.031.

[142] Holland O, *et al.* Development of a radio enabler for reconﬁguration management within the IEEE P1900.4 Working Group, In *Proc. of IEEE DySPAN* *2007*, Dublin, Ireland, April 2007.

[143] Buljore S, Merat V, Harada H, Filin S, Houze P. IEEE P1900.4 system overview on architecture and enablers for optimised radio and spectrum resource usage, In *Proc. of IEEE symposium on* *New Frontiers in Dynamic Spectrum Access Networks* *(DySPAN’08)*, October 2008.

[144] ITU-R Report 2063. The impact of software deﬁned radio on IMT-2000, the future development of IMT2000 and systems beyond IMT-2000.

[145] ITU-R Report M.2064. Software-deﬁned radio in the land mobile service.