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Dynamic Spectrum Access through Cognitive Radio Technology: A Survey

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ABSTRACT

The radio spectrum endures underutilization of the available spectrum. Assigning chunks or segments of the radio spectrum to specific users through the static model of spectrum assignment, by and large known as the command and Control Model (CCM) is the regular model of spectrum allocation. The increasing growth in the use wireless and mobile devices triggers the call for more dynamic and efficient access techniques for both licensed and unlicensed spectrum. Dynamic Spectrum Access (DSA) is a promising technology to increase spectrum efficiency by encouraging spectrum usage, this technology is a new model of spectrum access that allows other users to access the white spaces or spectrum holes, temporarily in a licensed spectrum band. Cognitive Radio (CR) technology is one of these dynamic access tools, this radio can monitor, observe and reacts to Radio Frequency (RF) events in its specified environment. This paper makes an extensive overview of the cognitive radio features, cognitive radio functional blocks, and furthermore examines cognitive radio research challenges.

INTRODUCTION

The cognitive radio refers to a Software Defined Radio (SDR) that can be programmed and configured dynamically, introduced to complement spectrum access which eventually tends to increase spectrum efficiency. The system is capable of sensing the Radio Frequency (RF) environment of other radios in the same vicinity. Based on this information, it then modifies its transmission and reception characteristics (transmit power, the frequency of operation, waveform, protocols) and other parameters to dynamically reuse available radio frequencies in a licensed spectrum locale, to allow more simultaneous wireless communication[1]. The radio dynamically searches for idle channels in the wireless spectrum of the licensed user. Its inherent ability to switch to the best channels in the spectrum makes it able achieve close to a licensed spectrum band performance even when using an unlicensed band, compared to the mandatory tedious frequency planning in some wireless technologies operating on static channels in order to prevent interference from equipment operating on adjacent channels [2]. More so, introducing the concept of the licensed band, unlicensed band and white space also referred to as spectrum hole is vital to the scope of this research.

MATERIALS AND METHODS

Licensed Spectrum Band

A portion of the radio spectrum is allocated to a specific user by spectrum allocation and regulatory agencies through the command and control model of spectrum allocation. Users in this band are protected from any form of electromagnetic interference as no other user is permitted to transmit on the spectrum[3], they are also referred to as the Primary Users (PUs) of the band.

Unlicensed Spectrum Band

Wireless transmitters operate at particular frequencies without rules, regulations and authorization binding the operations. Users are subjected to interference as multiple users operate at the same frequency[3]. As users in this band experience interference, spectrum allocation and regulatory agencies observe spectrum efficiency which is the ultimate goal of radio spectrum management.

White Space

The term 'White Space' also referred to as 'Spectrum hole refers to portions of a licensed band that users do not use all the time at all locations. White spaces can also be an unlicensed band, or frequencies left for guard between licensed adjacent channels to prevent destructive interference. Several spectrum regulatory agencies around the world are moving towards allowing unlicensed access to these vacant frequencies, subject to the condition that the licensed transmission is not affected. Increased spectrum efficiency is expected. Users in this band are referred to as Secondary Users (SUs) of a spectrum[3,4]. **Figure 1** below depicts the white spaces in a licensed spectrum.

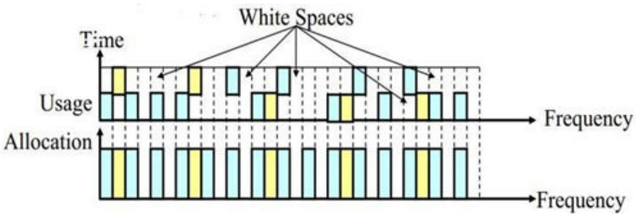

Figure 1. White Space [5].

COGNITIVE RADIO

The recent approval of the use of an unlicensed device in the licensed band by the Federal Communications Commission (FCC) to improve the issue of spectrum scarcity and spectrum inefficiency [6], has created a lot of attention in this area of research. Cognitive radio is one of the key enabling technologies to achieve this goal, it is a Software-Defined Radio (SDR), reconfigurable and reprogrammable. Software-defined refers to the use of software processing within the radio system to implement its operations [7]. Cognitive radio is an intelligent wireless communication system that adapts its operation parameters based on the interaction with the radio environment in which operates [6] in real time, with three primary objectives:

- Highly reliable communications
- Efficient spectrum utilization
- Minimal interference at the primary transceiver

Designing a radio with the ability to offer multiband operations, multi-standard support, multi-service support, and multichannel support is required for the high degree of reconfiguration for different system functionalities[8].

Features of a Cognitive Radio

Cognitive radio exhibit two main features which are defined as follows:

Cognitive capability: This is the ability of a radio to sense RF information in its environment. Monitoring only the transmit power level in some spectrum band of interest is not sophisticated enough to realize this feature. To avoid interference at the primary transceiver, more refined techniques such as autonomous learning and action decisions are required to identify and capture the idle and spatial variations in the radio environment [7].

Reconfigurability: The cognitive radio is programmed to operate at various frequencies and also to use different transmission access techniques supported by its hardware design. Its ability to reconfigure refers to, adapting both the software and hardware configuration to suit the RF information it identifies from its specified environment [7].

Figure 2 illustrates how cognitive radio concept can be realized through the radio characteristics. The cognitive radio knows about its radio environment through learning and observation and then makes appropriate decisions accordingly. Based on these decisions, the radio alters its reconfigurable parameters. Reconfigurable parameters integrated into the cognitive radio include:

- Frequency of operation
- Power level
- Modulation techniques
- Communication protocols etc.

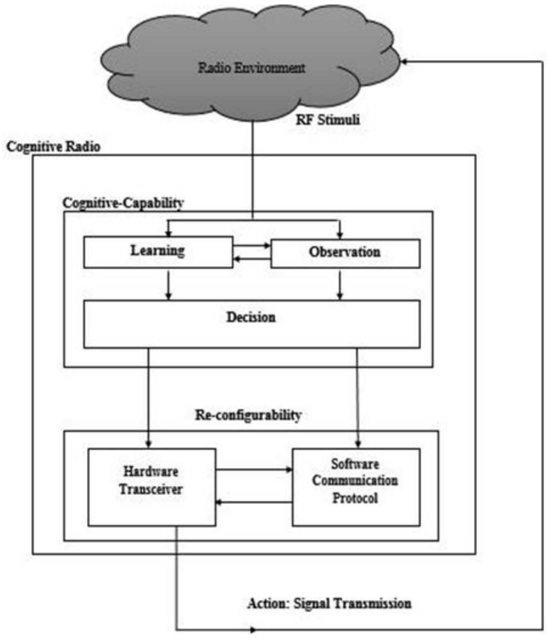

Figure 2. Cognitive radio features [7].

Through these features, the cognitive radio enables the spatial reuse of idle frequencies in a licensed band. The secondary user then continues to monitor the spectrum band and yields to primary users whenever the PUs start using the band, to avoid disturbance to the authorized users of the spectrum [7].

Cognitive radio functional blocks: The radio performs its cognitive capability and reconfigurability in a predefined cycle [9] the four-stage cycle is briefed as follows and also illustrated in Figure 3 below:

- Spectrum sensing
- Spectrum decision or management
- Spectrum sharing
- Spectrum mobility

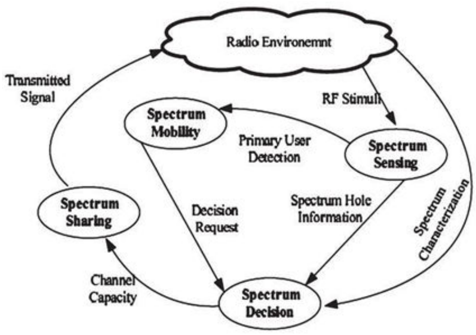

Figure 3. Cognitive radio cycle [9].

SPECTRUM SENSING

Spectrum sensing refers to idle spectrum identification. It becomes a key stage in realizing a cognitive radio network, it determines which portion of the licensed spectrum band is available and detects the presence of Pus[10]. There are various ways to classify spectrum sensing and estimation methods, the classification implored in this paper is based on spectrum sensing for spectrum opportunities. Figure 4 below shows the detailed classification of spectrum sensing techniques. They are classified into two main categories, cooperative sensing, and non-cooperative sensing. Non-cooperative sensing also referred to as transmitter detection is further classified into energy-based detection, matched filter based detection and cyclostationary feature based detection

Cooperative sensing is also further classified into three types, centralized, decentralized and hybrid spectrum sensing.

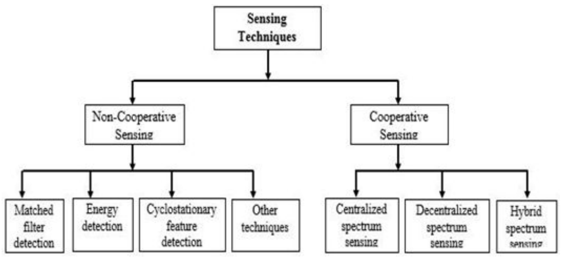

Figure 4. Spectrum sensing techniques [11].

Non-Cooperative Sensing

This form of sensing technique refers to when a cognitive radio acts on its own. The radio detects a weak signal generated from a primary transmitter. Thus, the location of the primary receivers is unknown to the secondary users because of the absence of signaling between the primary and cognitive radio users [12].

- Matched-filter technique: Which requires a comprehensive knowledge of the PU signaling features to achieve a certain probability of false alarm in a short time compared to other methods [10]
- Energy detection based sensing: In this sensing scheme, a signal is detected by making a comparison of the output energy detector with a threshold which depends on the noise floor, no knowledge is required on PUs' signal. It is also of low implementation and computational complexities [13]
- Cyclostationary-based sensing: Primary user signal is detected by exploiting the cyclostationary features. Cyclostationary features are a function of the periodicity in the signal or in its factual data like autocorrelation and mean or can be induced purposely to aid spectrum sensing [13]
- Other non-cooperative sensing techniques include the Waveform-based sensing which requires knowing the PU signal pattern. Used in sensing by performing autocorrelation on the received PU signal [14]

Cooperative Sensing

Cooperative sensing enables a CR to receive sensed RF information from multiple cognitive radios in its range, the number of cognitive radio users lead to more processing overhead and thus, takes time for the final decision but the accurate and better decision is envisaged [10]. Cooperative spectrum sensing is classified into three, based on how the sensed RF information is shared between cooperating CRs in a network: centralized, decentralized or distributed and hybrid. Table 1 below describes the types of cooperative sensing techniques.

Table 1. Cooperative sensing techniques.

Cooperative sensing techniques	Description
Centralized sensing	A central identity called fusion center controls the process of sensing, by selecting a the radio frequency band of interest for CRs to individually perform local sensing. All cooperating CR sends their report to the FC via the control channel, FC then determines the presence of the PU from these process, it makes a decision and diffuses the decision back to all cooperating CRs [15].
Distributed or decentralized sensing	To make a comprehensive decision, CR users do some amount of signaling among each other, then come to a unified decision on the PUs by iteration [16].
Hybrid sensing	Also referred to as relay-assisted cooperative sensing. It involves a CR user with a strong sensing channel and a weak report channel cooperating with a CR user observing a weak sensing channel and a strong report channel to complement and improve sensing performance [17].

SPECTRUM DECISION OR MANAGEMENT

Spectrum decision is required for spectrum access after an efficient and credible spectrum sensing. Spectrum decision is the capability to select the best spectrum hole from the identified available bands to meet the QoS requirements of the application. Spectrum decision is a function of the channel characteristics and primary user operations, the decision is also influenced by the operations of other CR users in the network. Spectrum decision comprises two phases [18]. Each of the spectrum band identified as idle is first characterized, in light of the CR local perception and the factual data of primary users. The most appropriate hole is then selected based on channel characteristics. In the following, channel characteristics in cognitive radio and spectrum decision procedure are examined [18].

Channel Characteristics

Spectrum holes characteristics vary over time, it is important to characterize these holes considering the time-varying radio environment. Hence, defining parameters that could represent a particular white space is essential to this stage of the cycle. These parameters are briefed as follows:

Interference: The transmit power of the SU utilized as a part of channel capacity evaluation can be estimated from the measure of interference caused at the primary receiver.

- Path loss: The higher the frequency, the higher the path loss, the lower the transmission range. Subsequently, the path loss is an element of both the frequency and separation. Compensating for this bottleneck by increasing the transmit power of the CR might increase interference at other transmitters
- Wireless link errors: The channel error rate varies, in view of the modulation method and the disturbance level of the spectrum
- Link layer delay: Different types of layer 2 protocols at each channel are required, to establish a balance between the previously discussed characteristics and channel integrity. This subsequently results in link layer delays

Decision Procedure

After characterizing the spectrum band identified as idle, the most suitable band is then selected considering QoS requirement and spectrum characteristics. The CR adapts its transmission mode as needs are. The primary user activity is a new metric implored to describe the shared nature of CR network [19], which is the characterized as the probability of an authorized operator appearing on the spectrum during a secondary transmission. Putting how often this authorized user appears on the spectrum band into consideration is vital.

However, due to the activities of the authorized user and the chance of not identifying any spectrum band to meet the QoS requirements, simultaneous utilization of spectrum bands exhibiting no proximity for transmission in CR networks is required. Signals generated from this method are capable of high data throughput and also insusceptible to disturbance and authorized user activity. More so, whatever is left of the spectrum band keeps up continuous transmission regardless of whether one of the dynamic spectrums encounters handoff [18].

SPECTRUM SHARING

This stage of the cognitive radio cycle involves distributing spectrum among CR users, attempting to access the spectrum. Coordinating access to these spaces in the spectrum keeps numerous users crashing in overlapped segments of the spectrum [18]. **Figure 5** below shows three main categories of spectrum sharing techniques: architecture assumption, spectrum allocation behavior and spectrum access technique.

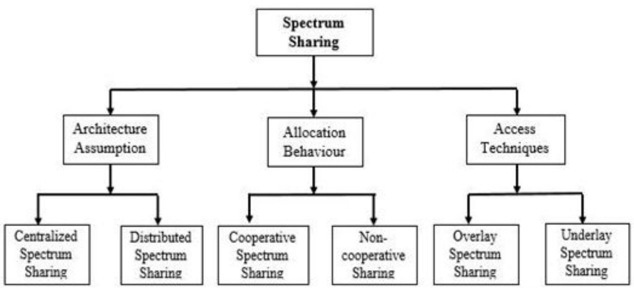

Figure 5. Spectrum sharing techniques.

Each of these categories is further classified into different types. The first sharing technique which is based on architecture assumption is of two types, which are centralized and distributed spectrum sharing technique.

Centralized Spectrum Sharing

This is a sharing process, a central node controls spectrum assignment and access. A spectrum allocation chart is constructed by the central entity utilizing radio resource measurements reports received from other nodes in the CR network [18].

Distributed Spectrum Sharing

In this case, the centralized node is absent. There is a responsibility on each and every node in the CR network to manage spectrum designation and access procedures locally [20]. Distributed spectrum sharing is used when the construction of infrastructure is not a necessity. The second classification for sharing techniques in CR networks depends on spectrum allocation behavior, it can be cooperative or non-cooperative.

Cooperative Spectrum Sharing (Collaborative)

This spectrum sharing scheme renders each node contemplating how its transmission affects other transmitters. Nodes in the CR network shares the interference measurement of each other locally, this technique gives a compelling harmony between a distributed sharing technique and a fully collaborative one.

Non-Cooperative Spectrum Sharing (Non-Collaborative)

It is also referred to as a selfish solution considers only the local node. Measurement reports are not shared among cognitive radio users, this method does not guarantee spectrum utilization.

Analyzing the difference between cooperative and non-cooperative spectrum sharing, factoring in their throughput, decency and spectrum utilization proves that the former performs better than the latter sharing procedure [21].

The third spectrum sharing scheme is based on cognitive radio access techniques and could be subdivided into two types: Overlay spectrum sharing and underlay spectrum sharing [18].

Overlay Spectrum Sharing

This sharing scheme includes CR users (nodes) to get to the network utilizing white spaces in the primary user spectrum band[18]. This, of course, limits interference at authorized transceivers.

Underlay Spectrum Sharing

In this process, a CR node spectrum operation is considered as noise by PUs, through exploiting the secondary users' spread spectrum techniques[18]. A slight increase in its complexity can further utilize the available bandwidth. Hybrid sharing techniques for CR networks spectrum access could be considered due to this trade-off [18].

Finally, the two main general focus of spectrum sharing techniques classification are internetwork spectrum sharing and intranet work spectrum sharing[18]. Table 2 below describes the differences between these two solutions.

Table 2. Inter and intranetwork spectrum sharing comparison.

Intranetwork spectrum sharing	Internetwork spectrum sharing
This scheme considers spectrum the allocation between nodes of a Cognitive radio network.	Focuses on spectrum allocation between nodes of interconnected CR networks.
The secondary users, in this case, get to the identified accessible spectrum without actually meddling with the PU transmission	A concrete view of the spectrum sharing perception is provided by including certain outlined PU policies.
This sharing scheme is applicable only in a standalone spectrum locale.	Enables an array of systems deployment in Overlapped locations and spectrum

SPECTRUM MOBILITY

This is the last stage in the cognitive radio cycle, this concept involves a CR user vacating a spectrum band when the PU starts transmitting on the initial idle band. This process is the handoff mechanism in cognitive radio network which is different from a handover mechanism in other wireless networks

Two types of users are studied in spectrum mobility based on the priority level, the PU which is the high priority user and SU which is the low priority user. The high priority has the right to override the low priority user transmission and instructs them to vacate the spectrum even when the secondary user has decent received signal strength. The main functionalities of spectrum mobility are as follows.

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Spectrum Handoff

The unexpected appearance of a licensed user on a spectrum occupied by a cognitive radio user triggers the SU to vacate this band as soon as possible. The cognitive radio user would then try to regain the spectrum through the following methods [22].

- SU stays on the spectrum but stops transmission until PU finishes operating on the band
- This is a scheduled method of spectrum handoff, the CR immediately selects a band from the list of previously sensed channels identified as idle bands
- This method of spectrum handoff is sensing-based, the CR switches to a different channel after instantaneous sensing. The SU is constrained to terminate its session if regaining process fails

Connection Management

The compelled decision on CR user to vacate a spectrum whenever a PU arrives on the band has raised issues on what happens to the applications running on the node. Connection management protocols require the spectrum handoff duration and then estimate the latency of the information. Based on these measurements, the effect of time-based unavailability on each protocol is predicted by the CR and then preserves the current transmission with minimum filthy performance through error control techniques and protocol layer reconfiguration [23].

RESEARCH CHALLENGES

This section provides a brief discussion on the research challenges of cognitive radio. Table 3 below simplifies this concept by outlining and describing the core issues associated with cognitive radio [24].

Table 3. Challenges of cognitive radio.

S/N	Challenges	Meaning
1	Spectrum sensing	Although this is the most explored the function of a cognitive, the problem of developing a sophisticated sensing technique sufficiently fast and low Implementation cost arises.
2	Advanced spectrum management	This is essential to improving spectrum utilization by enabling dynamic access to an idle spectrum, the key challenge is realizing an efficient MAC mechanism to control the power level and spectrum allocation among CRs.
3	Spectrum sharing schemes	The key issue with this concept of cognitive radio arises when multiple CR users are sharing which of course there might be a collision.
4	Trusted access and security	Although, the distributed Intelligent the system offers appreciable benefits in the event of attacks. Application the specific secure wireless system is required for intelligent and sensitive application,

RESULT AND DISCUSSION

Cognitive radios as a dynamic spectrum access tool are being developed to proffer a solution to the bottleneck of the limited spectrum availability and inefficiency. This radio is equipped to provide efficient spectrum-aware wireless communication of which it features and functional blocks are presented in this article. Researches are currently ongoing along the lines of cognitive radio limitations introduced in this survey to ensure advancement in efficient spectrum-aware communication.

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