**A Tutorial on Cognitive Radio Principles and Spectrum Sensing**

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**Abstract**

Cognitive Radio Network(CRN) is an all-intelligent radio network that supplants the traditional radio network. The major discrepancy that exists between the traditional radio network and cognitive radio network(CRN) is premised on the fact that; in CRN, all the white spaces (unutilized spectrum) are utilized maximally to the best of the available information at its disposal. The main advantage of the cognitive radio network is that it has the ability to sense and detect available channels from the spectrum frequency and alter the values used for transmission of data. This allows several unused spectrum frequencies to be fully utilized. Research on cognitive radio network(CRN) is still in its elementary stage. Therefore, there is a need for a thorough surveys and descriptions of the cognitive radio sensing mechanisms. The working behavior of the cognitive radio also needs to be revamped. This research work details the sensing and problems with interference in cognitive radio network. It also explains how and why the cognitive radio system is preferred to the conventional radio systems. There exist numerous technologies that are employed in the cognitive radio systems. Among these includes; the Adaptive Radio and Software Defined Radio (SDR). The findings from this research have potential applications in areas such as cognitive-radio-systems design and implementations.

**Keywords**

Cognitive Radio, Radio Spectrum, Radio Transmission, Spectrum Sensing.

## 1. Introduction

Cognitive Radio system has been in existence for over a century. In cognitive radio system is such that all users of a spectrum band may experience interference. The rapid increase in the number of users will significantly constrain the available spectrum. The exponential growth of wireless technology during the past decades has exacerbated the situation. The specifics of the frequency allocations demonstrate that the lack of available frequencies is a significant obstacle to the rising demand of this technology. This is a challenge for every new system that has growth potential. The various sorts of frequency bands include radio, television, satellite, air traffic control, etc. Reallocating frequencies to exiting system is practically impossible as this will impair their very design.  This significant obstacle is the first and most crucial factor that led to the conception of cognitive radio. Improving the quality of radio communication, allocating frequencies to a larger number of users, and achieving a faster data rate without interfering with existing users are needs for the new technology. Utilizing the same frequency bands more efficiently through the use of technical expertise is one method for achieving these goals. For users to be accommodated in the same spectrum, a number of modifications must be made. It has been demonstrated that the modifications made by the government in this regard were ineffective.   Cognitive radio is the application of signal processing techniques to distribute frequencies to new users intelligently and dynamically.

Within the context of a communication system, the life cycle of a cognitive radio encompasses a variety of roles and responsibilities. Sensing, analyzing, reasoning, and adapting are some of these cognitive processes. As depicted in Figure 1, these functions make up the primary stages that are necessary for the cognitive radio to perform its functions. In this article, each of these four (4) stages will be broken down into further detail. The cognitive radio's operating principle was covered in Section 2, the device's life cycle was the primary focus of Section 3, and Section 4 brought the discussion to a close.



Figure 1 Cognitive radio cycle (J. Wang et al., 2011)

## 2. The Working principle of the Cognitive Radio System

A novel technology of this sort (CRN) should meet the following requirements: smart usage of the available spectrum in the frequency domain, compatibility with the channel conditions, there should not be interference with the exiting channels, ability to provide high quality transmission. Before going into the cognitive radio cycle, it is necessary to explain the cognitive radio network paradigm.

## 2.1 Cognitive Radio Network Paradigm

The following are the types of channel information used by the cognitive radio; overlay, underlay, and interweave (Goldsmith et al., 2018). The tendency for interference to occur is always high whenever there is an introduction of new channels and frequencies in cognitive radio systems. When the interference that results from the new users is lower than the mean value of all the frequencies, an underlay is said to exist. In contrast, an overlay exists when the newer frequencies enhance the durability of the already existing frequencies altogether. The new spectrum utilizes the system's unused and leftover spectral gaps in the interweave type. To accommodate the new frequencies in the existing frequency range, cognitive radio often employs these three sorts of network techniques(Goldsmith et al., 2018).

## Underlay: Underlay cognitive radios (UCRs) intelligently leverage multiuser channel quality information (CQI) and codebook sharing to enable a secondary user to have access to a prime user's spectrum. The primary requirement is that, in comparison to their cognitive counterparts, the interference brought about by non-cognitive users should be below the threshold. To enable the transmission of both users, the difference should be lower than the threshold value. There are numerous ways to accomplish this goal. One unique technique is the employment of multiple antennas to direct the signals from both the cognitive and non-cognitive systems away from one another. The second approach is to employ a broad bandwidth, which ensures that the cognitive signals are spread below the noise level and are beamed at the receiver end. To prevent any transmission concerns, these techniques guarantee that the interference stays at a low level and that the signals do not overlap(B. Wang & Liu, 2011). It is also feasible to design the cognitive signal transmitter so that the output power is kept as low as possible in order to maintain the threshold level.  It is safer to explain that the underlay approach can only be used for short-range communications using cognitive signals by employing this method as the fundamental concept.

This method(underlay) is employed by various users for different unlicensed bands(B. Wang & Liu, 2011). The parameter used as the reference for evaluating the underlay radio is the interference temperature(Goldsmith et al., 2018). This measure indicates the power of the RF by the antenna during transmission. This power can be used to evaluate if the interference is higher or lower than the limit of threshold. This can be seen as follows. The average power received (in terms of interference) is roughly similar to the transmitter's secondary power constraint. Signal-to-Noise Ratio (SNR) can be used to evaluate the value and the level of interference. It is crucial to note that if the interference is at its maximum, the signals would not be transmitted because of the limitation of the threshold. The maximum value of the power however would fall below the predetermined level. The quality of service(QoS) provided with respect to the underlay method is such that it is the average of all the powers of the transmitters in the cognitive radio network. The maximum transmission power is determined first followed by the zero-transmission level. Different users of the cognitive band may be given priorities that differ from one another. This possibility makes it feasible for users to have different types of channels transmitting different data using the same type of cognitive bands. A simple case of two transmitters and receivers is explained in figure 2. An n-length codeword is employed whenever the encoder t wants to transmit the messages Mt to the receiver Wt. Rt represents the rate. A similar case is represented in figure 2.



Figure 2: Interference channels [6]

## Overlay: The major distinction between an overlay and an underlay is that an overlay enables for the continuous use of both cognitive and non-cognitive users. It allows the two users to transmit data without interference. Again, it is possible that there are only two users present and that one of the users' data is hidden from the other. Encrypting the data is critical for preventing collisions between the cognitive and non-cognitive users' transmissions. To avoid interference, the cognitive user should be aware of the type of information transmitted by the non-cognitive user. When the channel information of one is unknown to another, there is a risk of interference that could jeopardize the entire communication system. When the two channels are relatively close to each other, this is possible. In the event of any combination of problems, such as a delay or retransmission, the problems become severe enough to cause the communication to fail. To ensure that the transmission is smooth and free of interference, various encoding techniques are utilized to encode cognitive and non-cognitive information.

## Interweave: The aforementioned overlay technique requires the knowledge of raw information sent by the non-cognitive channel to propagate the data without interference. This is the main route when it comes to different applications. As the channels got closer, there is more signal delay and loss of signal quality due to channel difficulties and interference. To separate the message from both channels and to keep the SNR high enough for accurate reception, encryption techniques are required. The parameter at the center of this discussion is interference. The concept of "Interweave approach" is the methodology and strategies used to spread information while avoiding interference and crossing gaps. When the information about non-cognitive propagation is known, it is possible to achieve both cognitive and non-cognitive transmissions. The interweave method's most critical component is the essence and details of the transmissions of non-cognitive systems. As a result of signal fading, the problems with user identification of non-cognitive systems is complex. When unlicensed channels and frequencies contribute their data to the already existing signal spectrum, the system's noise value increases. The non-cognitive data is not a constant value, which presents another problem in its detection. Over time, it changes. The signal value is dynamic. The detection strategy should be such that the data is periodically checked throughout time. Sensing undelivered communications is one effective way to detect the users. During the calculations, incorrect negative numbers are also taken into account.

## 3.0 The Cognitive Life Cycle

This section explains a cognitive radio's whole life cycle, from sensing to analysis, reasoning, and adaptability.

## 3.1 The sensing phase

The sensing phase is responsible for detecting the white spaces in the spectrum. White space refers to the frequency range that is unused by the primary users. This space is freely available for other transmissions, and cognitive radio frequencies will make use of this. During the sensing phase, spectrum gaps are scanned for the existence of spectrum users(Goldsmith et al., 2018; Tannious & Nosratinia, 2010). The sensing phase detects the activities that take place in both the available and unavailable spaces. The monitoring stage should make sure that the second users do not show any interference patterns. The monitoring is real time and requires accurate detection of the white spaces (J. Wang et al., 2011). The sensing of the spectrum space is followed by the identification of the white space(s) with a suitable frequency that has a higher quality following the Quality of Service (QoS). There are many other requirements that should be met by the available white space before it can be regarded as suitable for the transmission. If both primary and secondary users are busy in transmission, the secondary users are allowed to modify the frequency band using these requirements. Noise levels, losses, and error rates are usually regarded as the parameters to evaluate the quality of the frequency available. It is important to note that the frequency specifications are available to both primary and secondary users. It is the design of the cognitive radio that suitable frequency can be allocated for secondary users after checking the parameters(J. Wang et al., 2011). The spectral efficiency in a traditional radio network is not utilized effectively. There are many capacity limitations and the techniques which are usually different when a design for a cognitive radio is suggested. The spectrum usage is considered to be the best in cognitive radio. The technical information about the channels, messages, and node shares is paramount in terms of the design and spectrum utilization(J. Wang et al., 2011). In the literature reviewed, various sensing techniques are used. They are: matched filtering, spectrum detection, and interference temperature.

* **Interference Temperature:** This method senses the temperature due to the interference by the primary and the secondary users. By sensing the frequencies, the presence of the primary users is detected. The power of the transmitter is restricted so that no interference occurs, and it can be measured by the noise at the interference (Levorato et al., 2019). This approach has not been successful since its inception. This is as a result of the fact that limiting the frequency and the power of a signal is not practical. This would result in signal losses and low quality of transmission. It is also possible that any other undesirable noise causing interference surfaces. The interference (Khalid & Anpalagan, 2010) temperature is the measure of the power at the receiving antenna. In this kind of sensing, the parameter that is detected is the signal's energy. This method is the most simplest of all, and does not require any information of the primary signals (Levorato et al., 2019). This method has a particular disadvantage because of lack of knowledge of the signals’ data. It is much possible that the sensing has high number of false positives due to the inaccurate calculation of the noise value. If the signal quality is so weak, the unpredictability of the calculation will increase. This method also fails to distinguish between the primary signal and signals from the other sources, which is a possibility in case of several signals (Cheng et al., 2011).
* **Spectrum Sensing**: This technique ensures that many parameters of the transmission are determined and the specifics of the available spectrum are also evaluated (Hayar et al., 2007). Basically, this method looks for the available frequency gap which meets the requirements for efficient transmission of the cognitive radio. It belongs to the feature detection category of spectrum sensing. The density of the spectrum and the features that are used to define a high-quality signal is utilized as a parameter. The characteristics of a primary signal are defined in the design and serves as the input for the feature detection mechanism (Ghasemi & Sousa, 2007; Peha, 2005). This method is complex than the power detection, but offers robustness against the noises. This method is efficient in finding the interference pattern at low signal strength since there are many other characteristics utilized to determine the presence of the signal. It is also possible that this approach can identify different signals and separate the primary signals from other available signals. This strategy requires the knowledge of the characteristics of the primary signals. Although efficient, this method involves sophisticated design procedure especially characterizing the signals based on the characteristics that are unique to the particular system designed (Tajan et al., 2012).
* **Matched filtering**: Another method that leverages the pattern of a signal's waveform to examine and distinguish between primary and secondary signals. This method employs a coherent detection mechanism to differentiate between the waveforms of the primary and secondary signals. The detected signal match is compared to the required signal to determine the presence of the primary signal. This method is simpler in comparison since the signal's features are stored and a comparison is conducted with fewer samples. It is also resistant to noise and low-quality transmissions. The design is complex, however, because this method necessitates a detailed examination of the signal that might be used for comparison.

## 3.2 Analysis Phase

Another important phase of the cognitive radio characteristics is the spectrum analysis (Pandit & Singh, 2017). The important action performed in this stage is the detection of the white spaces in the spectrum. Through this, any portion of frequency that is unutilized for transmission by other users of the spectrum is effectively detected for the transmission. The other action of this phase is that the users who were already transmitting or making use of the spectrum will effectively continue their operation via the same channel as before. The analysis stage makes sure that there is no interference between the existing and the new detected unutilized spaces. The secondary users will be allowed to choose the frequencies that suit their requirement. This phase is important as the selection process determines the efficiency of the system (National Telecommunications and Information Administration (NTIA), “FCC frequency allocation chart, 2003). One of the primary techniques for controlling interference in cognitive radio networks is to determine the appropriate mapping between available licensed channels and cognitive radios to ensure optimal performance (CRNs). This is termed dynamic allocation. In this process, primary users are given topmost priority (National Telecommunications and Information Administration (NTIA), “FCC frequency allocation chart, 2003). If the primary users request the band which is allocated to the secondary users, as per the design, the primary users can take the secondary users’ frequency (Tannious & Nosratinia, 2010). The secondary users may then choose the frequency that is free to use after sensing the frequencies. The design also allows the sharing of the frequency allocation between primary and secondary users. This technique allows the most efficient use of the frequency spectrum by all the users. This phase also marks the rapid characterization of the frequency bands allocated for the primary and secondary users.

**3.3 Reasoning Phase**

The next phase is the reasoning phase in which the best response strategy will be determined for the allocation of frequencies. Once the analysis of the frequency band has been successfully completed, the details of the allocation are shared to the secondary users by the design. Different algorithms are employed to sense and work on the determination of the frequencies. At this stage, the comparison, selection, and the reasoning process of frequencies is done (N.Michelusi et al., 2013). The efficiency of the system is evaluated by the design of this algorithm. There are various parameters of a user which can be utilized to determine if the secondary user can be allocated a frequency. The smartness of the design lies in this phase. Advanced machine learning methods can also be employed to analyze the parameters. The most important factor is that the primary and secondary users should not cause any interference in the system. On the other hand, no white space should be free despite the parameters allowing the allocation. This phase also includes the allocation of frequency after all the parameters have been found to be satisfactory.

**3.4 Adaptation Phase**

When the reasoning phase is completed, the frequencies are to be allocated with new parameters to the new transmission (Musavian et al., 2019). This phase is the final phase in the life cycle of the cognitive radio. This Phase also signifies the end of one cycle of the cognitive radio. Both the primary and secondary users are making use of the respective frequencies at this point (Chung & Goldsmith, 2001). The new users need to adapt to the variations, whereas the primary users should not be disturbed, and no interference should result from the process. The transmission and reception action of both primary and secondary users can continue in this phase for as long as needed. Ideally, the interference should not take place, transmissions should be free of noise and a high SNR should be maintained. Once the transmission is complete, the cycle returns back to the sensing phase where the unused frequencies are sensed for next phase. This cycle runs in a loop as long as the secondary users require transmission frequencies.

## 4.0 Conclusion

Cognitive radio is a new technology with applications in many fields of wireless communication systems. The research in this area is restricted and needs to be prioritized at the survey level. This survey study addresses the fundamental operation of cognitive radio, network paradigms, and sensing processes. The most significant aspects of cognitive radio and its functionality have been thoroughly discussed. The next stage is to design a cognitive radio. The phases of sensing, analysis, reasoning, and adaptation are covered, completing the cognitive life cycle. The information offered in this report will be useful to researchers in this domain. The findings also offer different instances and procedures for how cognitive radio can be used efficiently by employing various sensing and transmission mechanisms. The findings are generic in nature and can be applied to any cognitive radio application. Spectrum sensing techniques for Cognitive radio systems with numerous antennas are being studied for the design's future scope.

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