

Republic of Iraq
Ministry of Higher Education and Scientific Research
University of Babylon
College of Information Technology
Department of Information Networks



A Developed Sensing Approach in Cooperative Cognitive Radio Networks

A Thesis

Submitted to the Council of the College of Information Technology for
Postgraduate Studies of University of Babylon in Partial Fulfillment of the
Requirements for the Degree of Master in Information Technology-
Information Networks.

By

Doaa Ayed Mohammed

Supervised By

Prof. Dr. Sattar B. Sadkhan

2021 A.D.

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I certify that the thesis entitled (**A Developed Sensing approach in Cooperative Cognitive Radio Networks**) was prepared under my supervision at the department of Information Networks/ College of Information Technology / University of Babylon as partial fulfillment of the requirements of the degree of Master in Information Technology-Information Networks.

Signature:

Supervisor Name: **Prof. Dr. Sattar B. Sadkhan**

Date: / /2022

The Head of the Department Certification

In view of the available recommendations, I forward the thesis entitled “**A Developed Sensing approach in Cooperative Cognitive Radio Networks**” for debate by the examination committee.

Signature:

Prof. Dr. **Saad Talib Hasson Aljebori**

Head of Information Networks Department

Date: / /2022

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Name :**Doaa Ayed Mohammed**

Date: / / **2022**

Acknowledgement

In the name of **Almighty Allah**, Most Gracious, Most Merciful. At first, Praise be to Him and thanks to God and the satisfaction of parents and conciliation only from Almighty Allah greatest praise is to **Allah** for His assistance in facing the difficulty that I have met in my study, and for His help to achieve my aims, also for His great graces and boons all the time.

I would like to express my deepest thanks to my supervisor **Prof. Dr. Sattar B. Sadkhan** for his valuable advice, motivation, guidance, and fruitful discussions throughout the preparation of this thesis.

I would like to extend my respect and deepest gratitude to the College of Information Technology and the presidency of University of Babylon.

Sincere appreciation and love go to my father, my mother, my husband, my children (Zahraa, Manar and Mustafa) and my sisters and brothers for providing me with optimism, pure affection, great hope, encouragement and support in every step in this thesis.

Finally, Sincere thanks and appreciation to all friends, colleagues and loved ones

Abstract

Cognitive radio is a solution to the spectral congestion problem by introducing opportunistic usage of the frequency bands that are not heavily occupied by licensed users. Spectrum sensing is important in cognitive radio to avoid collisions with licensed users and to improve the efficiency of licensed spectrum use, Primary transmitter's signal could not be detected because of the locations of devices (hidden primary user problem).It can be caused by many factors including severe multipath fading or shadowing observed by secondary users. Cooperative cognitive radio network allows different cognitive radio users(SUs) to share sensing information and increase the accuracy of primary user detection, but the complexity increased with increasing the number of CRs thus increasing number of sensing messages caused consume power, which it effected on Cognitive radio lifetime .This thesis addresses the problem of power consumption and enhance the sensing approach by using external node to do spectrum sensing process.

The proposed system simulates healthcare data type of (ECG and Endoscopy) in cognitive radio network Environment. Moreover, the proposed system has been done using OMNET++ simulation tool. The proposed cooperative sensing system of Group Manager (GM) enhanced throughput as 1.066% for 6 nodes, 10.655% for 10 nodes, and 14.191% for 20 nodes compared with the case of without GM. The power consumed decreased for better results as 66.489%, 67.923% and 88.514%. For the case of 6 Cognitive radio nodes (CR), 10 CR, and 20 CR respectively. The CR life time increase for better results as 10.608%, 10.336%, and 10.031. For the case of 6 CR nodes, 10 CR, and 20 CR respectively.

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List of abbreviations

Abbreviation	Definition
AP	Access Point
BSs	Base Stations
CCC	Common Control Channel
CDR	Constant Detection Rate
CE	Cognitive Engine
CFAR	Constant False Alarm Rate
CH	Cluster Head
CNN	Convolutional Neural Network
CR	Cognitive Radio
CRN	Cognitive Radio Network
CR-VANET	Cognitive Radio-Vehicle Adhoc Network
CSS	Cooperative Spectrum Sensing
CWSNs	Cognitive Wireless Sensor Networks
DCS	Deep Cooperative Sensing
DQN	Deep Q-Network
DSA	Dynamic Spectrum Access
EGC	Equal Gains Combining
EPSO	Enhanced Particle Swarm Optimization
FSA	Fixed Spectrum Assignment
FU	Fusion Center
GSMs	Global System for Mobile Communications
HDF	Hard Decision Fusion
IoT	Internet of thing
LQ	linear-quadratic
LSS	Local spectrum sensing
MAC	Medium Access Control
Matlab	Matrix Laboratory
MBABC	Modified Binary artificial bee colony
ML	machine learning
MRC	maximal ratio combining
NIC	Network Interface Card
MSs	Mobile stations
NS-2	Network Simulator 2
Pd	probability of detection
Pf	probability of false alarms
PF	Parallel fusion

List of abbreviations

Pm	Probability of Miss-detection
PSHU	Probability of Spectrum Hole Utilization
PSO	Particle Swarm Optimization
PU	Primary User
QoS	Quality Of Service
RNN	Recurrent Convolutional Neural Network
ROC	Receiver Operating Characteristic
SDF	Soft Decision Fusion
SDR	Software Define Radio
SNR	Signal to Noise Ratio
SS	Spectrum Sensing
SU	Secondary User
SVM	Support Vector Machine
TLBO	Teaching Learning Based Optimization
TPC	Transmission Power Control
UWB	Ultra-Wideband
VTRCA	Video Transmission Rate Control Algorithm
WSN	Wireless Sensor Network

CHAPTER ONE
General Introduction

1.1 Introduction

Cognitive Radio (CR) is a radio frequency scarcity control technique that can smartly senses and adapts with the changing environment by altering its transmitting parameters, such as modulation, frequency, frame format Etc [1]. The radio spectrum is divided into licensed and unlicensed frequency bands. The licensed spectrum used for private users, for example, TV broadcast, Global System for Mobile Communications (GSMs) and so on. The unlicensed spectrum used available for free by anyone, such as, Bluetooth. CR makes use of unused licensed radio frequencies, known as spectrum holes through given time and location via enabling secondary users CR to autonomously access spectrum holes to increase performance. As a matter of fact, secondary users should take into consideration not to harmfully interfere with the primary users' licensed spectrum [2].

The main attributes of CR are cognitive capability and Reconfigurability. Cognitive capability refers to the ability to sense and gather information from the surrounding environment, such as information about transmission frequency, bandwidth, power, modulation, etc. With this capability, secondary users can identify the best available spectrum. Reconfigurability refers to the ability to rapidly adapt the operational parameters according to the sensed information in order to achieve the optimal performance [3].

Dynamic spectrum access techniques allow the CR to operate in the best available channel. More specifically the CR technology will enable the user to determine which portion of the spectrum is available, detect the presence of primary user (spectrum sensing), select the best available channel (spectrum management), coordinates the access to the channel with other users (spectrum sharing) and migrate to some other channel whenever the primary user is detected (spectrum

mobility) [4]. Figure 1.1 shows operations which are closely related to cognitive radio characteristics through the cognitive radio operation cycle [5].

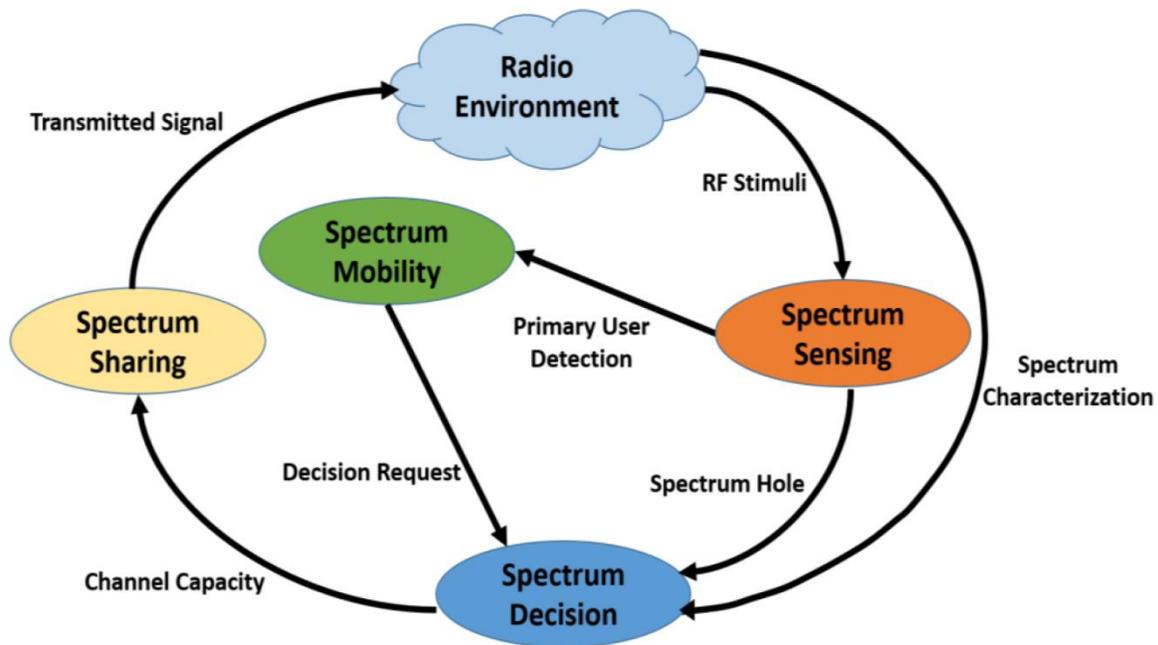


Figure 1.1 Cognitive Radio Operation Cycle

Software Define Radio (SDR) is a radio that includes a transmitter in which the operating parameters including the frequency range, modulation type or maximum radiated or conducted output power can be altered by making a change in software without making any hardware changes, SDR is used to minimize hardware requirements; it gives user a cheaper and reliable solution, but it will not take into account spectrum availability. CR is newer version of SDR in which all the transmitter parameters change like SDR, but it will also change the parameters according to the spectrum availability [1]. Figure 1.2 depicts the relationship between CR networks and SDR.

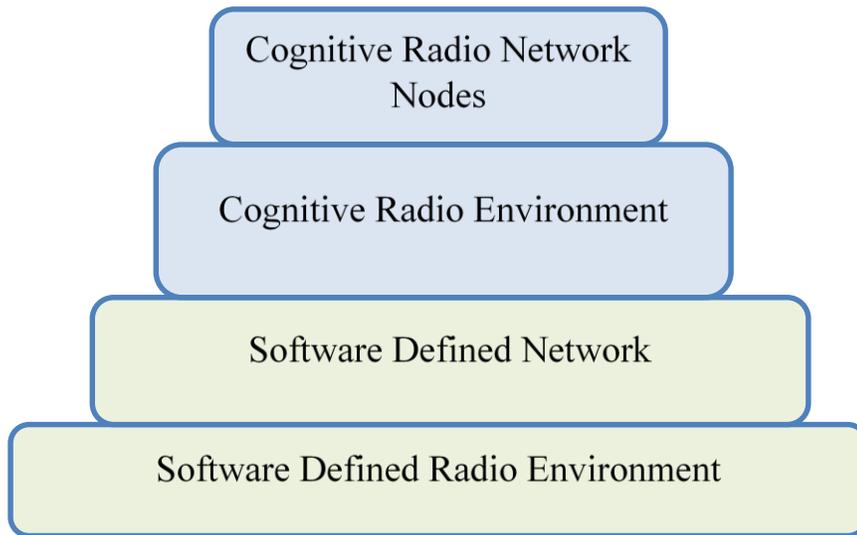


Figure 1.2 the relation between CRN and SDR

CR is based on SDR approach with the addition of Reconfigurability. The purpose of CR is to detect "spectrum holes" in real time and reallocate and obtain frequency bands. Clearly, if the primary user reappears, this spectrum holes should be freed up (s). To achieve these objectives, spectrum sensing techniques have been used [6] :(matched filter detection, energy-detection, cyclostationary detection, eigenvalue detection, autocorrelation detection, wavelet detection, probability-based detection) , each one of the technologies have a hidden node problem, this can be caused by of Multipath fading and shadowing to address this important challenges, Cooperative Spectrum Sensing (CSS) has been suggested [7].

1.2 Literatures Review

There are many proposed enhancement system for cooperative sensing in Cognitive Radio Network applications as within the following literature review from the past up to the latest directions:

Ramzi et al., in [8] proposed three independent heuristic algorithms each of which is capable of solving one of the optimization problems by specifying the FC(Fusion centre), the cooperative sensing nodes, the sensing time and detection threshold for the sensing nodes. The optimization objective in these problems is minimizing sensing and reporting energy, minimizing sensing time or maximizing throughput under the assumption of different SNR value between the PU and CR nodes.

Muhammad et al., (2018) in [9], the cooperative cognitive radio network had been implemented for health care system based on Particle Swarm Optimization (PSO) to reduce the spectrum overloading, higher data rate requirements, achieving low power consumption and decreasing the computational complexity.

Xiangli et al., in [10] presented a new machine learning (Support Vector Machine (SVM))-based Cooperative Spectrum Sensing (CSS) model, which utilizes the methods of user grouping, to reduce cooperation overhead and effectively improve detection performance. Cognitive radio users were properly grouped before the cooperative sensing process using energy data samples and an SVM model. The resulting user group which participates in cooperative sensing procedures is safe, less redundant, or the optimized user group.

Aicha et al., 2018 in [11] presented a comparison between data rate or rate control, that is, video transmission rate control algorithm and transmission power control algorithms for two different cases. First, energy consumption due to high

peak variable data rates in video transmission. Second, energy depletion due to high transmission power consumption and dynamic nature of wireless on-body channel.

In [12], the most recent advances and challenges of cognitive radio technology had been discussed especially in the wideband spectrum sensing research, also classified the sensing techniques into two main categories: narrowband and wideband spectrum sensing. Techniques of each category are then presented, and open directions discussed.

Mohsin et al., (2019) in [13], they presented an analytical framework for the Probability Of Spectrum Hole Utilization (PSHU) of a cognitive radio system with soft cooperative spectrum sensing under a practical consideration of fixed frame structure. In practical systems, the length of a time-frame is generally fixed, where the time-frame consists of sensing, reporting, and transmission durations.

Woongsup et al., in [14] proposed a CSS based on CNN (Convolutional Neural Network) for CR that is the initial ability to apply deep-learning to Cooperative Sensing. CNN is used in DCS (Deep Cooperative Sensing) CNN is used to learn a technique for mixing the Boolean or real-valued independent sensing results of the SUs.

In [15], a cooperative spectrum sensing scheme based on compressive sensing was proposed. In this scheme, secondary users (SUs) are organized in clusters. In each cluster, SUs forward their compressed signals to the cluster head. Then, the cluster heads report the local sensing data to the fusion center to make the final decision.

Preet et al., in [16] presented a basic overview of what CRN's are, a comparative study of CRN's and Spectrum Sensing in recent years as well as its main challenges and applications, help current and new researchers in the field to look for future outlooks and give them a basic run-through of CRN's and Spectrum Sensing and their characteristics.

In [17], the cooperative spectrum sensing is considered in CRN by utilizing the machine learning techniques, specifically Recurrent CNN. Here, we have proposed a Recurrent CNN based algorithm to sense the spectrum holes, cooperatively. In this algorithm, LSTM layer is used to accurately exploit the temporal correlation and convolutional layer to employ the spatial correlation. Hence, the proposed scheme utilizes spectrum spatio-temporal features to alleviate the cooperative sensing and improve the accuracy the sensing.

Yongcun et al., (2020) in [18], a cooperative spectrum sensing strategy has been proposed for CWSNs (Cognitive wireless sensor networks) based on particle swarm optimization. Firstly, the system throughput and energy consumption are quantitatively analyzed, and the mathematical model related to energy efficiency is established. Secondly, the particle swarm optimization (PSO) algorithm is used to obtain the optimal selected nodes set under the limited conditions of false alarm probability and detection probability.

In [19], the authors use Cooperative Spectrum Sensing using energy detection and Hard Decision Rules (OR, AND) for Cognitive Radio. The main advantages of energy detection based spectrum sensing are its simplicity, low computational and implementation costs as well as its ability to work regardless of the actual signal to be detected.

Sundous et al., in [20] considered the main types of machine learning algorithms and categorized the proposed ML-based CSS schemes into three classes, namely unsupervised-based CSS, supervised-based CSS, and reinforcement-based CSS. It also categorized the mathematical algorithms used for feature extraction, dividing them into three types: energy detection-based feature extraction, cyclostationary-based feature extraction, and signal processing-based feature ex-traction.

In [21], the Convolutional Neural Networks (CNN) had been used to extract the features of the observed signal and, as a consequence, improve the sensing performance. More specifically, a novel two-dimensional dataset of the received signal is established and three classical CNN (LeNet, AlexNet and VGG-16)-based CSS schemes are trained and analyzed on the proposed dataset. In addition, sensing performance comparisons are made between the proposed CNN-based CSS schemes and the AND, OR, majority voting-based CSS schemes.

Chakravarthy et al., (2021) in [22], a deep reinforcement learning had been implemented based method called Deep Q-Network (DQN) to find the spectrum holes. The secondary users (SU) uses the DQN to find the vacant channels in the spectrum effectively.

In [23], a Soft Decision Fusion (SDF) technique Equal Gain Combining (EGC) and Hard Decision Fusion (HDF) technique logical OR is applied to determine the presence of Primary User (PU). Energy detection technique in cooperative manner is used for spectrum sensing and an advanced optimization technique Jaya algorithm is applied to get the minimum Probability of Error.

Abbass et al., (2021) in [24], an in-depth survey on the most recent advances in spectrum sensing for CR has been provided by explaining the Half-Duplex and Full-Duplex paradigms, while focusing on the operating modes in the Full-Duplex. A thorough discussion of Full-Duplex operation modes from collision and throughput points of view is presented. Then, discuss the use of learning techniques in enhancing the spectrum sensing performance considering both local and cooperative sensing scenarios. In addition, recent SS applications for CR-based Internet of Things and Wireless Sensors Networks are presented.

Mohammad et al., (2021) in [25], A novel segment-based CR-VANET (Seg-CR-VANET) architecture is proposed. Roads are divided equally into segments, and they are sub-segmented based on the probability value. Individual vehicles or

secondary users produce local sensing results by choosing an optimal spectrum sensing technique using a hybrid machine learning algorithm that includes fuzzy and naïve Bayes algorithms.

Table 1.1 describes goals of Researchers and The used Simulation Environments

Table 1.1: goals of Researchers and The used Simulation Environments

Ref	Year	goals of the works	Simulation Environment	Performance metrics	result
[8]	2017	minimizing sensing and reporting energy, minimizing sensing time or maximizing throughput under the assumption of different SNR value between the PU and CR nodes	MATLAB	A combination of the detection probability and false alarm probability contribute to the detection accuracy.	Better performance than other existing approaches in terms of total sensing time, total sensing energy and achieved throughput.
[9]	2018	resource Management for Cooperative Cognitive Radio Network in Smart Hospitals based on particle swarm optimization (PSO).	MonteCarlo	N/d	Low complexity of the proposed algorithm.
[10]	2018	Improved cooperative spectrum sensing model based on machine learning for cognitive radio networks	MATLAB	N/d	Significant improvement in sensing accuracy.
[11]	2018	Energy efficiency comparison between data rate control and transmission power control algorithms for wireless body sensor networks	MATLAB	N/d	VTRCA saves more energy about 47.8% than TPC with energy-saving of 40.9% in WBSN.
[12]	2019	A Comprehensive Survey on Spectrum Sensing in Cognitive Radio Networks: Recent Advances, New Challenges, and Future Research Directions	N/d	Probability of detection, probability of miss-detection, probability of false alarm, and sensing time.	1-bit compressive sensing outperforms multi-bit compressive sensing techniques.
[13]	2019	Spectrum Utilization Optimization in Cooperative Spectrum Sensing	MATLAB	Probability of detection, probability of false alarm.	MBABC method outperforms the other methods in terms of an efficient data transmission and QoS.

[14]	2019	Cooperative Spectrum Sensing Based on Convolutional Neural Networks	MATLAB	Probability of detection, probability of false alarm.	The probability of false alarm vs. the probability of detection of K-out-of-N scheme, SVM scheme, DCS with HD, and DCS with SD, are calculated as 0.838, 0.945, 0.95, and 0.952, respectively.
[15]	2019	Cooperative Spectrum Sensing Scheme Based on Compressive Sensing for Cognitive Radio Networks	MATLAB	Probability of detection, compression ratio, probability of error and processing time	Cooperative spectrum sensing achieves a high probability of detection of 97%, a processing time of 2ms, a low compression ratio of 10%, and low error rate of 35 %.
[16]	2020	overview of Cognitive Radio Networks and Spectrum Sensing.	N/d	N/d	The Energy Detection method is the most efficient spectrum sensing methods.
[17]	2020	Deep Cooperative Spectrum Sensing using Recurrent Convolutional Neural Networks.	MATLAB	-the probability of miss detection. -probability of false alarm . -probability of detection in different SNRs .	Lowest sensing error and lowest fluctuations by changing the number of samples and users.
[18]	2020	cooperative spectrum sensing strategy for CWSNs based on particle swarm optimization	N/d	N/d	Improving the throughput of the system while ensuring the sensing performance, and achieve the energy efficiency effectively.
[19]	2020	Cooperative Spectrum Sensing using Hard Decision Rules (OR, AND)for Cognitive Radio Network	MATLAB	N/d	The OR Rules is better than AND Rules
[20]	2020	A Survey explain Cooperative Spectrum Sensing in Cognitive Radio Networks based on Machine Learning Methods.	N/d	N/d	Unsupervised-based CSS is less complex but a bit less accurate than other approaches. CSS offered excellent accuracy, but caused a slight overhead during the training phase. Reinforcement learning offers reasonable accuracy and improves throughput, but may be hard to apply in real time and requires high computational complexity.

[21]	2021	Cooperative Spectrum Sensing Based on Convolutional Neural Networks	N/d	N/d	The sensing accuracy of the proposed schemes is greatly improved.
[22]	2021	Cooperative Spectrum Sensing using DQN in CRN	Python	N/d	The sensing is more accurate in the proposed method of DQN in CRN.
[23]	2021	Optimization of Spectrum Sensing Technique in Cognitive Radio	N/d	N/d	Jaya algorithm achieves 20% reduction in Probability of Error compared to TLBO.
[24]	2021	Spectrum Sensing for Cognitive Radio: Recent Advances and Future Challenge.	N/d	N/d	Survey
[25]	2021	Machine Learning-Based Cooperative Spectrum Sensing in Dynamic Segmentation Enabled Cognitive Radio Vehicular Network	OMNET++	Probability of detection, probability of false alarm.	Probability of detection in the range of 0.95 to 1, which is nearly 50% higher than in the previous works.

- N/D: Not Define

In the above works, Cooperative Spectrum Sensing Based on different techniques such as convolutional neural networks, Machine Learning Methods and particle swarm optimization, also there are three type of cooperative sensing methods(centralized ,distributed , rely assist). The proposed approach, depend on external node as a Group Manager node to perform the sensing and broadcasts the channel occupancy information to cognitive radio users.

1.3 Problem Statement

Spectrum sensing is important in cognitive radio to avoid collisions with licensed users and to improve the efficiency of licensed spectrum use, Primary transmitter's signal could not be detected because of the locations of devices (hidden primary user problem). It can be caused by many factors including severe multipath fading or shadowing observed by secondary users. Cooperative cognitive radio network allows different cognitive radio users(SUs) to share sensing

information and increase the accuracy of primary user detection, but the complexity increased with increasing the number of CRs thus increasing number of sensing messages caused consume power, which it effected on Cognitive radio lifetime. This thesis addresses the problem of power consumption and enhance the sensing approach by using external node to do spectrum sensing process.

1.4 The Aim of the Study

This study is proposed a method to enhance cooperative spectrum sensing in CRN by:

- i. To study the related works and implement the Energy detection sensing technique.
- ii. To design a model of external node as a Group Manager node to perform the sensing and broadcasts the channel occupancy information to cognitive radio users.
- iii. To evaluate the proposed approach using main simulation parameters such as the (Throughput, Power consumption, and CR life Time).

1.5 The Scope of the Study

The proposed approach can be apply in a number of communication domains such as health care ,smart cities, military and intelligent transportation systems that need to enhance the sensing and solve power consumption problem .

1.6 Thesis Outline

Furthermore, this thesis contains four chapters in addition to chapter one:

Chapter Two: This chapter presents the introduction , Characteristics of cognitive radio, Cognitive Radio Network: Benefits, Disadvantages and Challenges, Cognitive Radio Networks Architecture, Cognitive Radio Networks Applications, spectrum sensing and Cooperative sensing in cognitive radio networks , Classification and framework of cooperative sensing, Elements of cooperative spectrum sensing,).

Chapter Three: This chapter presents the proposed approach and illustrates the practical stages of the system and explains the proposed approach.

Chapter Four: This chapter describes the results and evaluates proposed approach.

Chapter Five: This chapter presents the results' conclusion. Also, it describes future works suggestions.

CHAPTER TWO

Theoretical Background

2.1 Introduction

Cognitive Radio Networks (CRN) are one of the most important techniques that have been found to solve radio spectrum problems. In general, fixed spectrum assignment policies for wireless applications significantly waste spectrum resources that are considered to be valuable as a result, and which will be spectrum scarcity. Cognitive radio technology, invented by Mitola, is based on an efficient way to utilize available unused channels through the wireless spectrum range by automatic detection method based on the concept of Dynamic Spectrum Access (DSA) [26]. CRN is classified depending on, how it allow to secondary users using the licensed frequency band into three main patterns [27]:

- The first type known as the Underlay Paradigm. In this type, the SU transmits at the same time with the PU, As long as, the interference generated by SU is below a particular threshold. For instance, the SU's signal can be broadcast over a wide range of frequencies, and transmit below the noise floor of the PU as illustrated in Figure 2.1. The benefit of this patterns is that it doesn't need performing spectrum sensing. In comparison to the interweave paradigm, the SU can benefit in cases where PUs are usually always present in some systems. However, in order to meet the specified threshold, the SU must limit its transmission power. As a result, it's possible that the SU will be forced to transmit over small distances.
- While the second type called the overlay paradigm. In the same way that the SU can exist with the PU in the underlay paradigm, the CR can exist with the PU in the overlay paradigm. However, the SU needs to acknowledge the PU signal completely such as the *message* and *codebook*. In this case, the SU and the PU can coexist, and more importantly, it can transmit at any power (provided that it does not interfere with PUs in any way). Because it is

assumed that the CR has knowledge about the message and the codebook used by the PU, the CR can exploit this information to cancel interference caused by the PU using techniques like dirty paper coding. The main disadvantage of this paradigm is that it assumes complete awareness of the PU signal, which may be unrealistic given the need for extensive coordination between several PU networks and the CRN.

- The third type is an Interweave Paradigm: In this paradigm the SU operates in an Opportunistic Transmission method to gain access to a specific state called Spectrum Holes or white spaces licensed spectrum band which is used to data transmission for example through using TV White Spaces .The proposed system is based on (Interweave Paradigm).

Figure 2.1 shows three major patterns in CR [28].

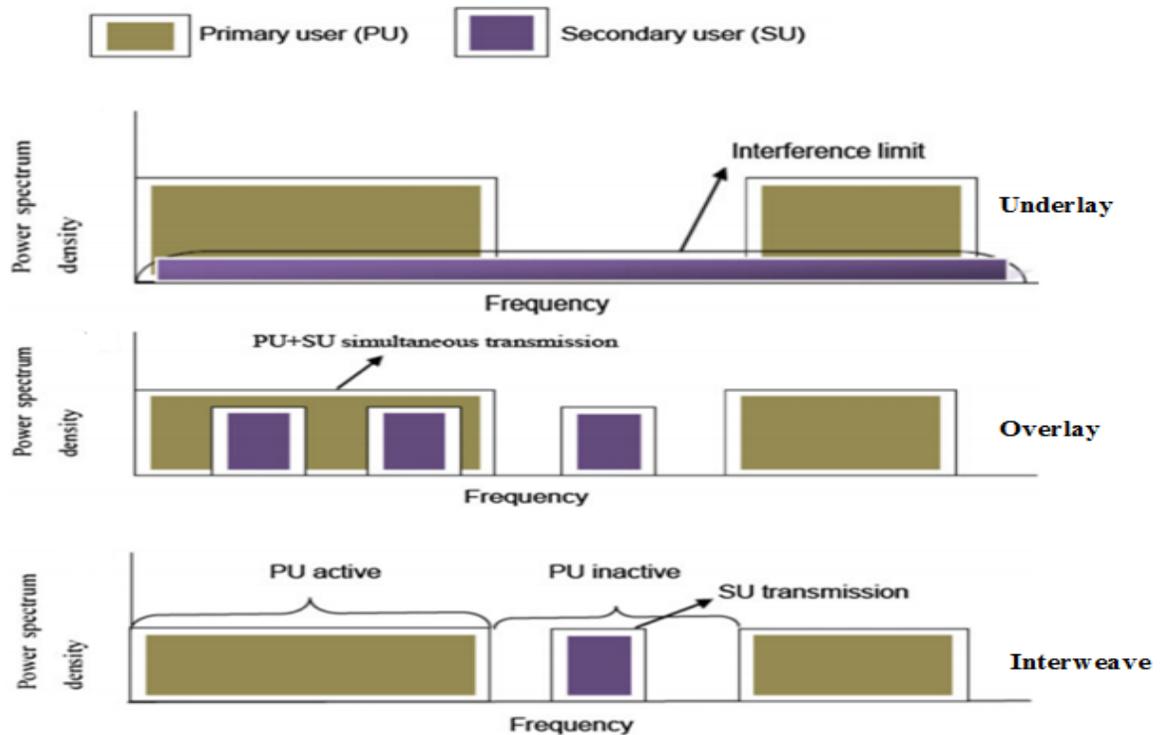


Figure 2.1: Cognitive Radio Paradigms.

2.2 Characteristics of Cognitive Radios

Cognitive radio dynamically selects the frequency of operation and also dynamically adjusts its transmitter parameters. According to [20] the main characteristics of cognitive radios are Cognitive Capabilities and Configurability. Cognitive Capability: Cognitive capability refers to the ability of radio to sniff or sense information from its environment and perform real time interaction with it. The cognitive capability can be explained with the help of three characteristics; Spectrum Sensing, Spectrum Analysis and Spectrum Decision. The spectrum sensing performs the task of monitoring and detection of spectrum holes. The spectrum analysis will estimate the characteristic of detected spectrum hole. In the spectrum decision, the appropriate spectrum is selected by determine the parameters like data rate, transmission mode etc.

Reconfigurable: Configurability refers to the ability of radio that allows the cognitive radio to adjust its parameters like link, operating frequency, modulation and transmission power at run time without any modifications in the hardware components. In other words Reconfigurability of CR is SDR. Doing so it dynamically change all the layers of communication as shown in Figure 2.2. It can use different technologies depending on their spectrum availability with the same hardware [29].

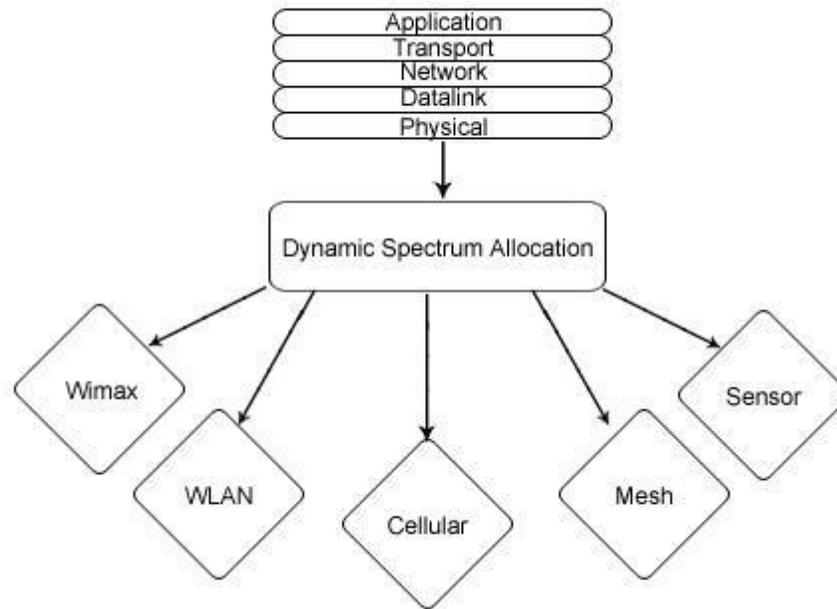


Figure 2.2: All Layers Modify Dynamically [29].

2.3 CRN: Benefits, Disadvantages and Challenges

One of the most important characteristics that made CRN receive this great attention is the ability to increase the availability of spectrum in wireless networks, and get the scarcity of the radio spectrum. It can sense with the parameters for each environment based on the requirements of the application. Besides, it used for its purpose as it is used in applications of different types of data including audio, image, text, and video streaming. It is worth noting that the used system depends on the text for the data type transmission [30]. One of the widely used features of the CRN is the multidisciplinary feature, due to the heterogeneity of its uses, as its benefits evolve in the medical, military, agricultural, and industrial fields, and the vehicle sensor network.

2.3.1 The Benefits of cognitive radio networks

The Benefits of CRNs applications can be summarized with the following points [31]:

1. Dynamic spectrum access.
2. CRNs are self-organizing.
3. Real-time spectrum performance.
4. Increasing spectrum utilization.
5. Enhancing the adaptability of emerging systems.
6. Improving reliability of links, for instance, multipath poor environments to increase channel capacity.
7. Decreasing the cost of the radios spectrum.
8. Mitigate Interference with Cognitive jamming systems.
9. Enhancing SDR techniques by use a set of intelligent algorithms known as a Cognitive Engine (CE) to create a CR that provides a user with a required Quality of Service (QoS), low-cost, multi-band and multimode operation for interoperability with SDR technology.

2.3.2 Disadvantages of Cognitive Radio Networks

CRNs have disadvantages summarized with these topics:

1. Sensing techniques require high-speed changeability by switching the sensing channel, which may cause the channel not to be available for communication, as it affects the decision-making in the future step of the optimal channel proposal [31].

2. Requires prior information of the primary user in operations which are required matched filtering feature, which are considered more difficult to get them especially in tactical environments [32].
3. Interference of channel is highly, because the nature of wireless medium especially for information generated from resources have high sensitivity [33].

2.3.3 Challenges of Cognitive Radio Networks

Cognitive radio networks have challenges within different applications, and that can be summarized as follow:

1. Challenges in CRN routing [34].
2. The hidden terminal problem in Cooperative Spectrum Sensing [35].
3. Developing efficient information sharing algorithm and increased the complexity [36].
4. Challenges for machine learning research [37].
5. Detection sensitivity in a wideband spectrum [38].
6. Challenges CR in Wireless Sensor Network (CR-WSN) such as hardware requirements (storage and energy) and topology Changes that effected on the network lifetime in WSNs. In addition, Fault Tolerance, Quality of Service (QoS), Security and Scalability in WSNs [39].

2.4 Cognitive Radio Networks Architecture

The importance of the CRN architecture revolves around the nature of the network components and to achieve the main goal of the CRN architecture by improving the network performance from the user's point of view to provide services anytime and anywhere. Where this architecture consists of the basic components of CRNs categorized into Mobile Station (MS), Base Station-Access

Point (BSs-APs) and Backbone-Core networks. They are the essential parts (MS, BSs-Aps and Backbone-Core) of the three architectures of CRNs: Infrastructure, Ad-hoc and Mesh Architectures [40].

2.5.1 Infrastructure Architecture

This type depends on the basic architecture of the components of the network from infrastructures as backbone base links, interconnect devices such as access points, base stations, communication channels, and CRN nodes, as well as interfaces that connect the components together. Figure 2.3 shows the infrastructure architecture and how network elements connected with each other [41].

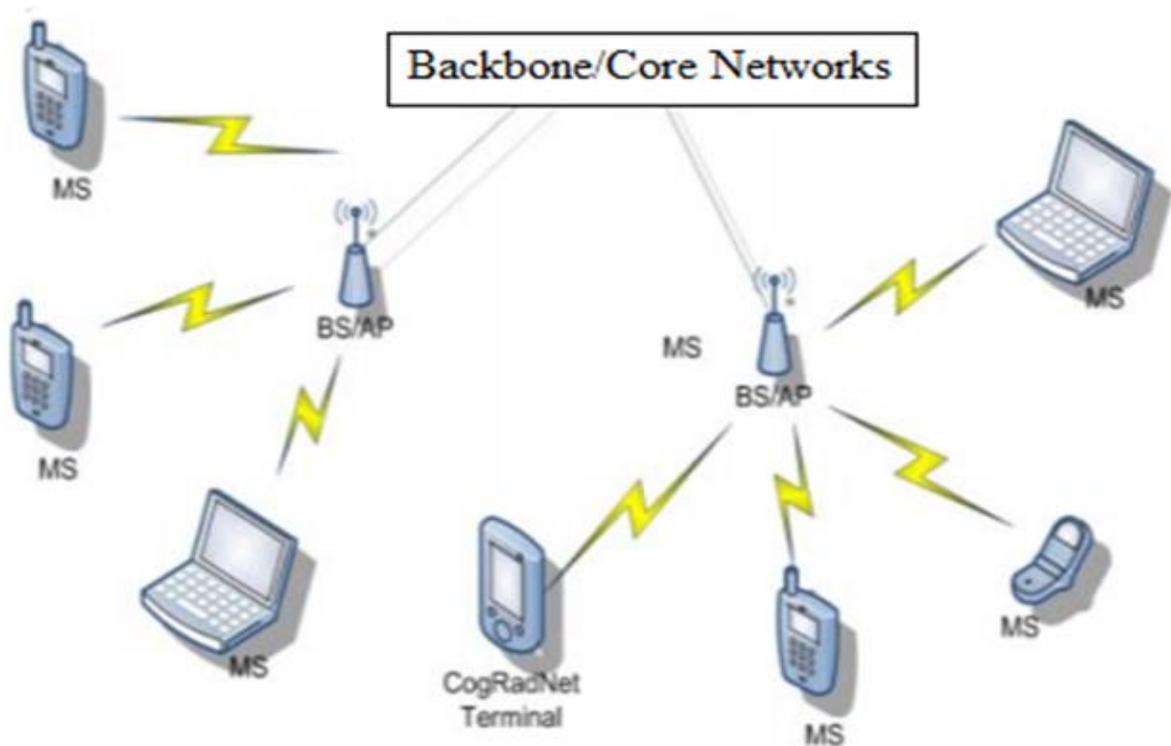


Figure 2.3: CRN Infrastructure Architecture.

2.4.2 Ad-hoc Architecture

This architecture is considered as one of the important architectures as it is directly established on-demand among the nodes that wish to communicate and transmit data using radio frequency through the air without the need to rely on the infrastructure provided by the network. For example, by using Wi-Fi, Bluetooth with spectrum holes in spectrum radio. The Figure 2.4, shows the concept of Ad-hoc networks within the CR environment [42].

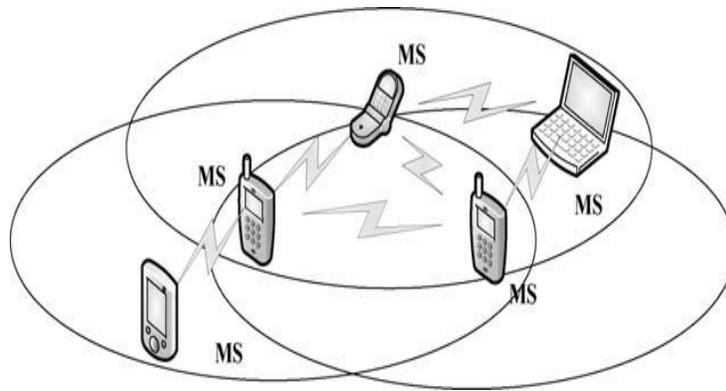


Figure 2.4: The Architecture of CRN Ad-hoc.

2.5.3 Mesh Architecture

This architecture is considered as a combination of the two previous types, as it depends within data communication and transmission on infrastructure architecture as well as on-demand Ad-hoc architecture, where it is possible to see the CR mobile station linked to the access points or gateway through the core backbone side within the infrastructure as well as through the CR node with another CR node directly [43].

This architecture allows improving the performance of the network to the optimal level in the CR environment, as it is based on the benefits provided by the first and second architectural and gets rid of the restrictions and challenges that

face both of the two previous architectures. The Figure 2.5 shows the arcitecture of mesh CRN [44].

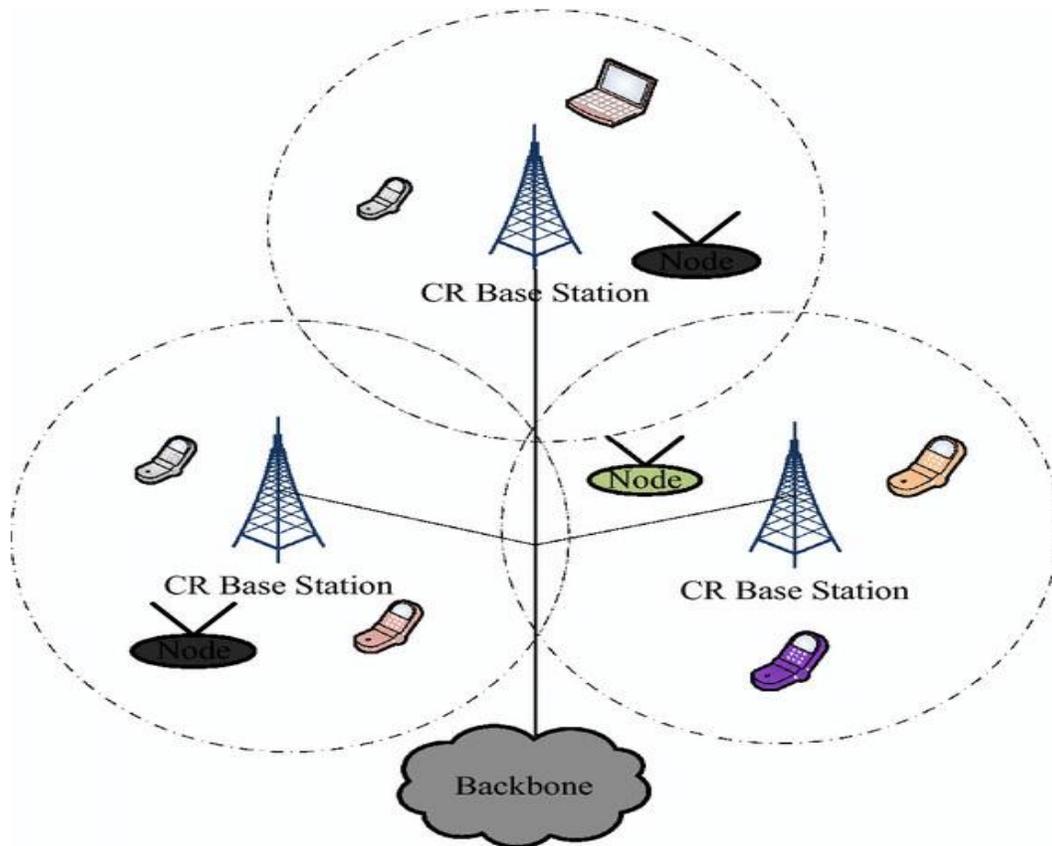


Figure 2.5: Architecture of a CR-mesh network [44].

2.5 Cognitive Radio Networks Applications

CRNs are used in many applications in the various necessary and important fields of human life, for example, health, agricultural, industrial, commercial and military applications, etc. They perform an important role in wireless consulting applications within the human body as well as accuracy agriculture, remote measurement and follow-up of roads, traffic, and the operation of complex systems [45].

2.5.1 Health Care Implementations

The CRN plays an important role in healthcare systems or medical fields where various types of sensors are used inside and outside the human body where patients are dealt with and monitor data acquired at a distance using these sensors. As it is known that the medical data related to human life is very crucial and sensitive, where using traditional WSNs, they are restricted to remote control, especially in congested overloading situations. So, using CRNs in this aspect has achieved Quality of Service (QoS) at a high level as used in the case of a Body Area Network (BAN), which is illustrated in Figure 2.6 [45].

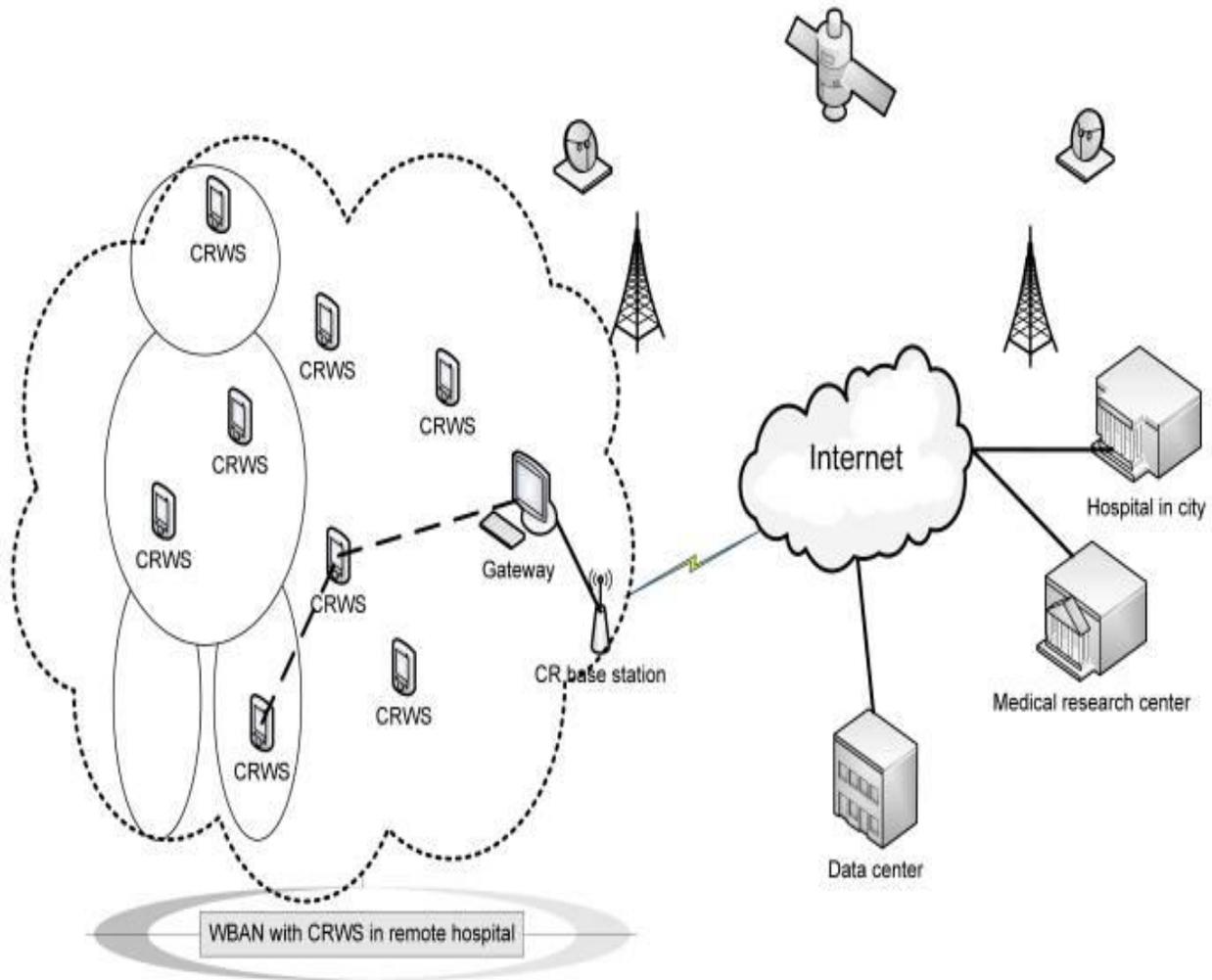


Figure 2.6: Wireless Body Area Network (WBAN) with CR Wireless Sensor.

2.6 Spectrum Sensing and Cooperative Sensing in Cognitive Radio Networks

The ultimate objective of the CR is to obtain the best available spectrum through Cognitive Capability and Reconfigurability. Since there is already a shortage of spectrum, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users as illustrated in Figure 2.7. The CR enables the usage of temporally unused spectrum, which is referred to as spectrum hole or white space [46]. If this band is further used by a licensed user, the CR moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference.

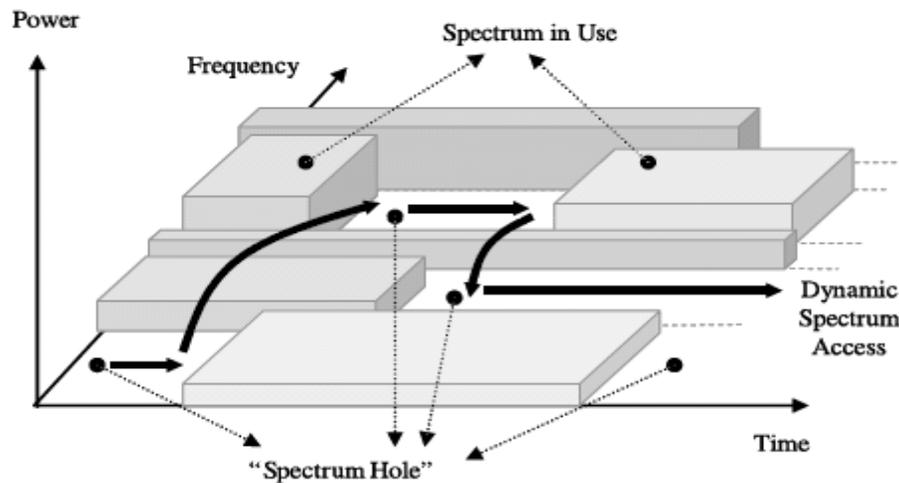


Figure 2.7: Spectrum Hole Concept.

The fundamental task of each CR user in CR networks is to detect the licensed users, also known as primary users (PUs), if they are present and identify the available spectrum if they are absent. This is usually achieved by sensing the RF environment, a process called spectrum sensing. The objectives of spectrum

sensing are firstly, CR users should not cause harmful interference to PUs by either switching to an available band or limiting its interference with PUs at an acceptable level and, secondly, CR users should efficiently identify and exploit the spectrum holes for required throughput and QoS. Thus, the detection performance in spectrum sensing is crucial to the performance of both primary and CRNs.

The detection performance can be primarily determined on the basis of two metrics: probability of false alarm; denotes the probability of a CR user declaring that a PU is present when the spectrum is actually free, and probability of detection; denotes the probability of a CR user declaring that a PU is present when the spectrum is indeed occupied by the PU [47]. Spectrum sensing is extremely important in CR. Many factors in practice such as multipath fading, shadowing, and the receiver uncertainty problem may be significantly compromise the detection performance in spectrum sensing. In Figure 2.8, multipath fading, shadowing and receiver uncertainty are illustrated [48].

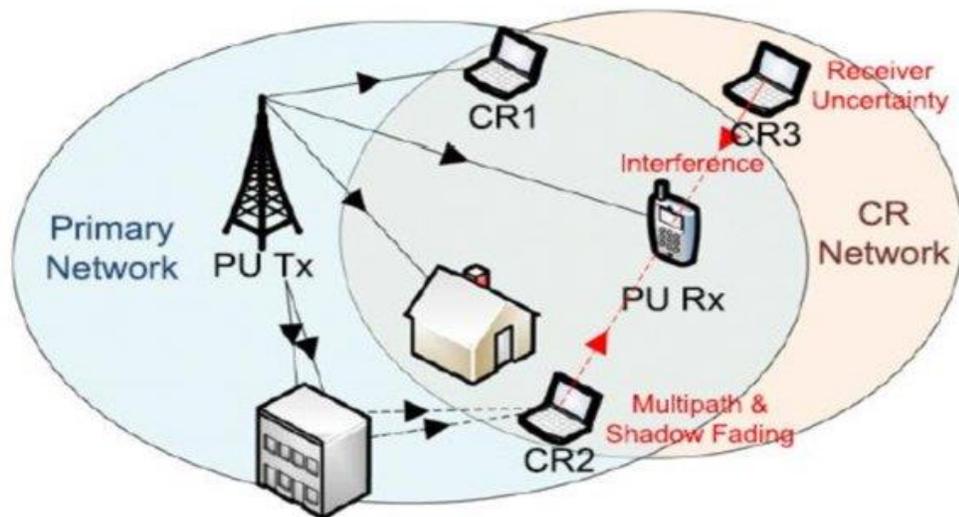


Figure 2.8: Receiver Uncertainty and Multipath/shadow fading [48].

Cooperative sensing is an attractive and effective approach to combat multipath fading and shadowing and mitigate the receiver uncertainty problem.

The main idea of cooperative sensing is to enhance the sensing performance by exploiting the spatial diversity in the observations of spatially located CR users. By cooperation, CR users can share their sensing information for making a combined decision more accurate than the individual decisions [49].

2.7 Classification and Framework of Cooperative Sensing

It presents the primary signal detection in cooperative sensing and introduce the classification and the framework of cooperative sensing.

2.7.1 Primary Signal Detection

The process of cooperative sensing starts with spectrum sensing performed individually at each CR user called local sensing. Typically, local sensing for primary signal detection can be formulated as a binary hypothesis problem that introduced in Equation 2.1 [50]:

$$\mathbf{r}(t) = \begin{cases} \mathbf{n}(t) & H_0 \\ \mathbf{h}s(t) + \mathbf{n}(t) & H_1 \end{cases} \quad (2.1)$$

Where $r(t)$ is the signal received by the CR user, $s(t)$ is the transmitted signal of the PU, $n(t)$ is a zero-mean additive white Gaussian noise (AWGN) and h is the amplitude gain of the channel. H_0 is a null hypothesis, which states that there is no licensed user signal in a certain spectrum band. On the other hand, H_1 is an alternative hypothesis, which indicates that there exists some PU signal. For the evaluation of the detection performance, the probabilities of detection P_d and false alarm P_f Equations are defined in [51].

$$P_d = P\{\mathit{decision} = H_1|H_1\} = \{P\{Y > \lambda | H_1\} \quad (2.2)$$

$$P_f = P\{\mathit{decision} = H_1|H_0\} = P\{Y > \lambda | H_0\} \quad (2.3)$$

Where Y is the decision statistic and λ is the decision threshold. The value of λ is set depending on the requirements of detection performance. Based on these definitions, the probability of a miss or miss detection is:

$$P_m = 1 - P_d = P\{\text{decision} = H_0 | H_1\} \quad (2.4)$$

The plot that demonstrates P_d versus P_f is called the Receiver Operating Characteristic (ROC) curve, which is the metric for the performance evaluation of sensing techniques. In cooperative sensing, the probabilities of detection and false alarms for evaluating the performance of cooperative decisions are denoted by Q_d and Q_f , respectively.

2.7.2 Classifications of Cooperative Sensing

To facilitate the analysis of cooperative sensing, cooperative spectrum sensing classify into three categories based on how cooperating CR users share the sensing data in the network: centralized [52], distributed [53], and relay-assisted [54]. Figure 2.9 depicts these three methods of cooperative sensing [48]

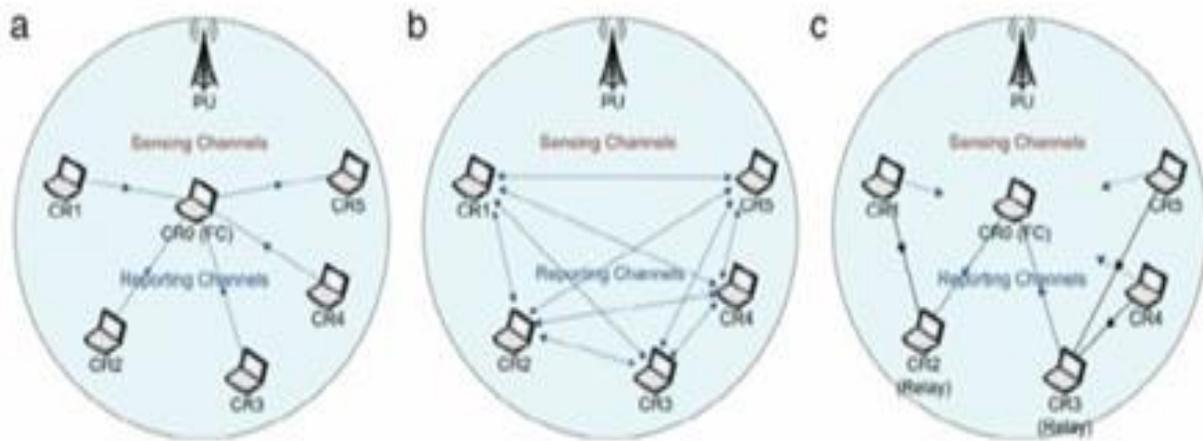


Figure 2.9: Three Types of Cooperative Sensing: (a) Centralized (b) Distributed and (c) Relay-assisted

2.7.2.1 Centralized Cooperative Sensing

There are a central identity called Fusion Center (FC) controls the three-step process of cooperative sensing. First, the FC selects a channel or a frequency band of interest for sensing and instructs all cooperating CR users to individually perform local sensing. Second, all cooperating CR users report their sensing results via the control channel. Third the FC combines the received local sensing information, determines the presence of PUs, and diffuses the decision back to cooperating CR users. As shown in Figure 2.9 (a), CR0 is the FC and CR1–CR5 are cooperating CR users performing local sensing and reporting the results back to CR0. For local sensing, all CR users are tuned to the selected licensed channel or frequency band where a physical point-to-point link between the PU transmitter and each cooperating CR user for observing the primary signal is called a sensing channel. For data reporting, all CR users are tuned to a control channel where a physical point-to-point link between each cooperating CR user and the FC for sending the sensing results is called a reporting channel.

2.7.2.2 Distributed Cooperative Sensing

It does not rely on a FC for making the cooperative decision. In this case, CR users communicate among themselves and converge to a unified decision on the presence or absence of PUs by iterations. Figure 2.9 (b) illustrates the cooperation in the distributed manner. After local sensing, CR1–CR5 share the local sensing results with other users within their transmission range. Based on a distributed algorithm, each CR user sends its own sensing data to other users, combines its data with the received sensing data, and decides whether or not the PU is present by using a local criterion.

2.7.2.3 Relay-assisted Cooperative Sensing

Since both sensing channel and report channel are not perfect, a CR user observing a weak sensing channel and a strong report channel and a CR user with a strong sensing channel and a weak report channel, for example, can complement and cooperate with each other to improve the performance of cooperative sensing. In Figure 2.9 (c), CR1, CR4, and CR5, who observe strong PU signals, may suffer from a weak report channel. CR2 and CR3, who have a strong report channel, can serve as relays to assist in forwarding the sensing results from CR1, CR4, and CR5 to the FC. In this case, the report channels from CR2 and CR3 to the FC can also be called relay channels.

2.7.3 Framework of Cooperative Sensing

The framework of cooperative sensing consists of the PUs, cooperating CR users including a FC, all the elements of cooperative sensing, the RF environment including licensed channels and control channels, and an optional remote database. Figure 2.10 illustrates the framework of centralized cooperative sensing from the perspective of the physical layer [51].

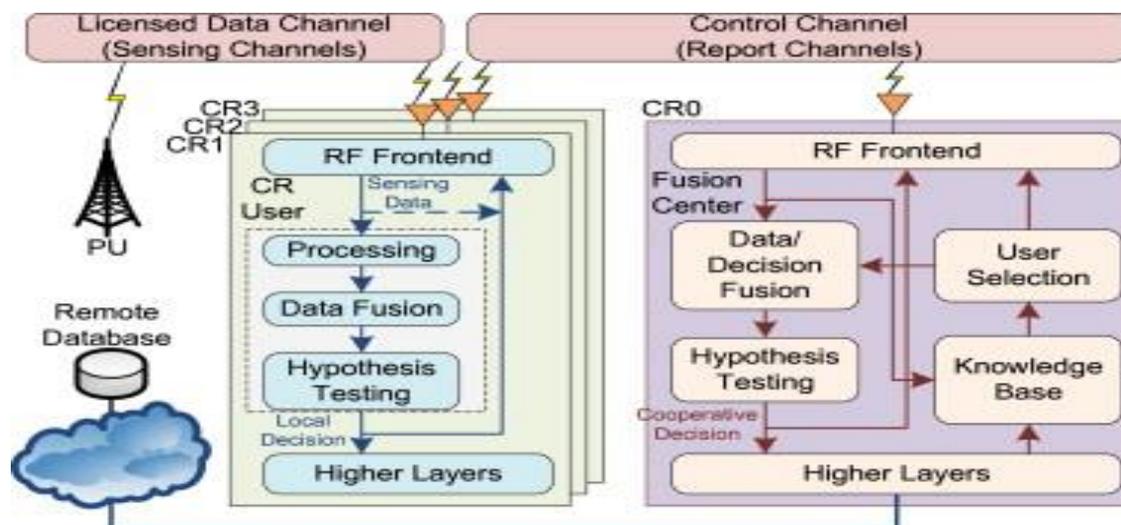


Figure 2.10: Framework of Centralized Cooperative Sensing [51]

In this framework, a group of cooperating CR users performs local sensing with an RF frontend and a local processing unit. The RF frontend can be configured for data transmission or spectrum sensing. In addition, the RF frontend includes the down-conversion of RF signals and the sampling at Nyquist rate by an Analog-to-Digital Converter (ADC). The raw sensing data from the RF frontend can be directly sent to the FC or be locally processed for local decision. To minimize the bandwidth requirement of the control channel, certain local processing is usually required. The processing includes the calculation of test statistics, and a threshold device for local decision. Once the raw sensing data or the local decisions are ready, a Medium Access Control (MAC) scheme is required to access the control channel for reporting the sensing results [51]. The sensing results may also be used by higher network protocol layers. The upper layer of the network also can utilize the results of sensing for spectrum aware routing selection [55].

2.8 Elements of Cooperative Spectrum Sensing

Cooperative sensing is generally considered as a three-step process: local sensing, reporting, and data fusion. In addition to these steps, there are other fundamental components that are crucial to cooperative sensing.

2.8.1 Cooperation Models

The modeling in cooperative sensing is primarily concerned with how CR users cooperate to perform spectrum sensing and achieve the optimal detection performance. The most popular approach is the Parallel Fusion (PF) model in distributed detection and data fusion [56]. And game theory [57]. The PF models aim to achieve the detection performance by using the distributed signal processing techniques to determine how the observations are combined and tested and how the

decisions are made. Unlike the PF models, game theoretical models focus on improving the sensing-parametric utility function by analyzing the interactions and the cooperative or non-cooperative behaviors of CR users. It can be informally stated that the parallel cooperation model emphasizes the “sensing” part while the game model focuses on the “cooperative” part in cooperative sensing.

2.8.1.1 Parallel Fusion Model

In the distributed detection and data fusion [56], a group of spatially distributed sensors observes a physical phenomenon H through the observations y_i and report their observations u_i to a central processor known as a FC. The FC combines the reported data by data fusion and makes the global decision u by using binary hypothesis testing. This PF model in the context of cooperative sensing is illustrated in Figure 2.11 [56].

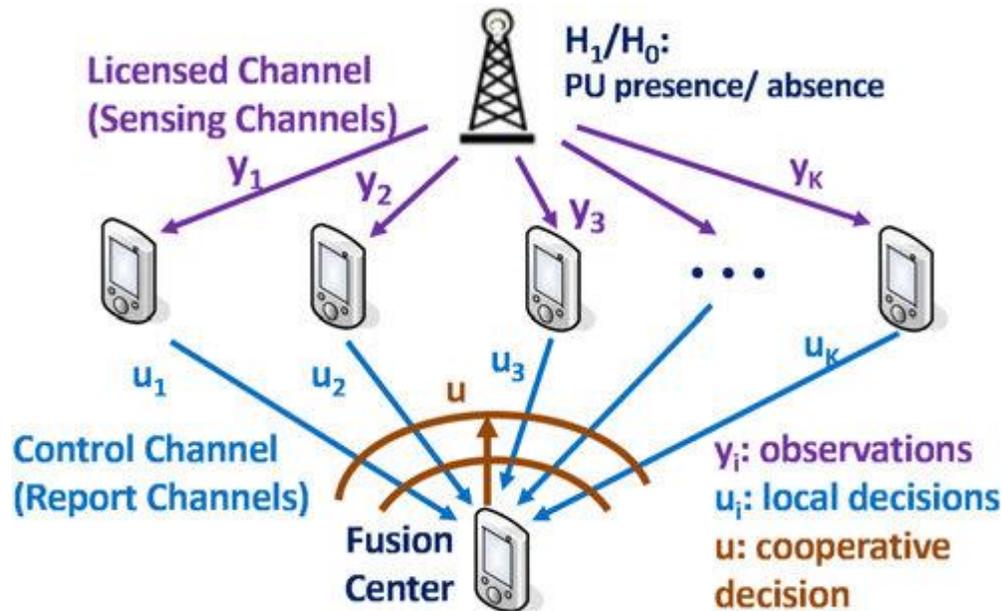


Figure 2.11: Cooperation model: parallel fusion model.

In this approach, cooperative sensing follows the same three-step process: local sensing, data reporting, and data fusion. All CR users are assumed to be synchronized by the FC for sensing the channel or the frequency band of interest

and reporting the sensing results. The FC combines the reported local sensing data and makes a cooperative decision. This decision is broadcast to all cooperating CR users.

2.8.1.2 Game-theoretical Model

In game theoretical models, cooperative sensing is modeled as a game with a set of players, which are the cooperating CR users. Depending on the nature of the game, the behaviors of cooperating CR users are modeled differently. For example, in a coalitional game [58], CR users cooperate in the form of groups, called coalitions while in an evolutionary game [59], CR users are selfish users who may choose to cooperate or not cooperate depending on their own benefits. Figure 12. An illustrative example of coalition formation for collaborative spectrum sensing among SUs.

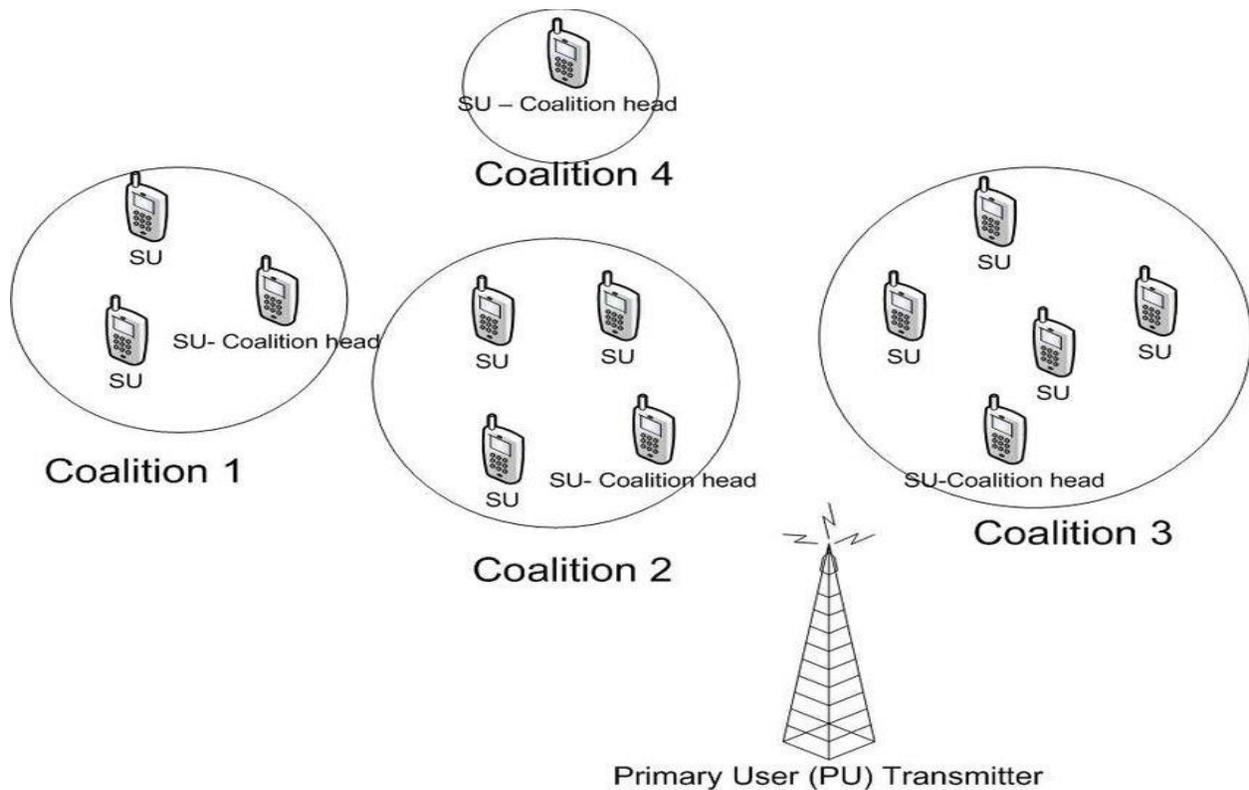


Figure 12. An illustrative example of coalition formation for collaborative spectrum sensing among SUs

2.8.2 Sensing Techniques

Regardless of the cooperation models, the process of cooperative sensing starts with local spectrum sensing at each cooperating CR user. Similar to traditional spectrum sensing without cooperation, the objective of the local spectrum sensing is primary signal detection. Sensing techniques are crucial in cooperative sensing in the sense that how primary signals are sensed, sampled, and processed is strongly related to how CR users cooperate with each other. Thus, sensing techniques are one of the fundamental elements in cooperative sensing. Figure 2.13 show the classification of sensing approaches, the most common spectrum sensing methods in cooperative sensing is energy detection, cyclostationary detection and feature detection [60].

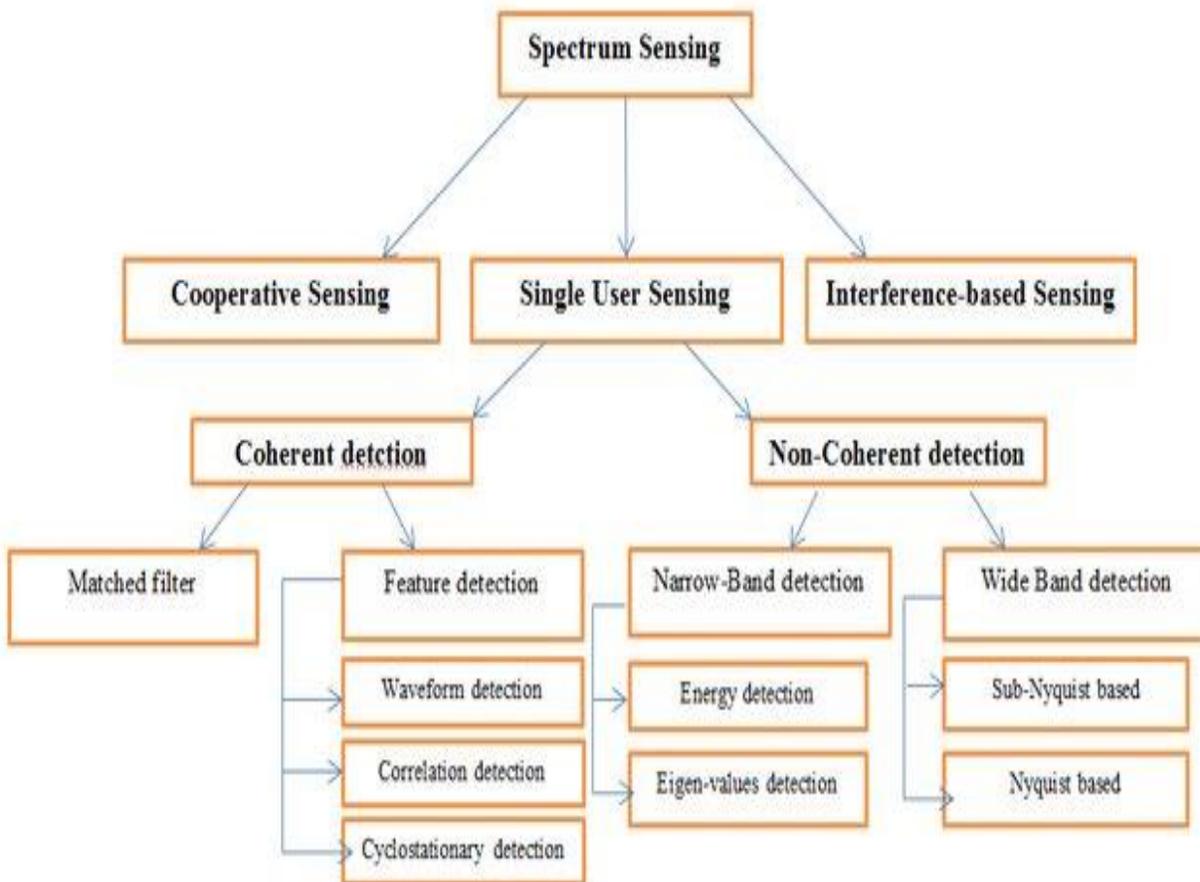


Figure 2.13: Classification of Sensing Techniques [60]

In this section, energy detection technique will be explain. The basic concept for the energy detection technique is computation of energy of samples of licensed user and its subsequent comparison to a predefined threshold. In case of energy detection, the energy higher than the assigned threshold will result in the consideration of the existence of primary user. Similarly, if the energy detected is lower than the assigned threshold, it results in the non-availability of primary user. This is done to obtain the sensing decision. Since it is a non-coherent scheme, therefore advance information of PU signal is not needed. Due to less computational complexity and a small delay compared to other available methods, it is considered as an elementary and simple detection technique.

One of the basic disadvantages for this technique is that its performance drastically decreases with noise uncertainty. Similar behavior is experienced under low SNR. For energy detection, if there is uncertainty in case of noise, the SNR Wall prevails. SNR Wall is that value of SNR under which there is no detection authenticity, even if the sensing operation is performed for long stages in time. However it requires accurate noise power information, therefore, this technique is rendered ineffective in case of noise uncertainty. The selection of center frequency and required bandwidth is done by eliminating the unwanted noise. This is accomplished by the use of a band-pass filter. This filter can be employed by quantifying the received energy using a squaring device before the application of an integrator. In order to decide the availability of primary signal, the integrator output $T(Y)$ is compared with the threshold. This can be shows Equation 2.5 [61]:

$$T(Y) = \frac{1}{N} \sum_{n=1}^N Y[n]^2 \quad (2.5)$$

Where N denotes the total number of received samples, and $Y[n]$ identifies the received sample.

2.8.3 Hypothesis Testing

Hypothesis testing is a statistical test to determine the presence or absence of a PU. This test can be performed individually by each cooperating user for local decisions or performed by the FC for cooperative decision [62].

2.8.4 Control Channel and Reporting

In cooperative sensing, a Common Control Channel (CCC) [63] is commonly used by CR users to report local sensing data to the FC or share the sensing results with neighboring nodes. As a result, a control channel is the element of cooperative sensing. The control channel can be implemented as a dedicated channel in licensed or unlicensed bands, or an underlay Ultra-Wideband (UWB) channel. A MAC scheme for multiple access is generally used by all cooperating CR users to access the control channel. From the perspective of the physical layer, a physical point-to-point link from a cooperating CR user to the FC is called a reporting channel. For reporting sensing data, three major control channel requirements must be satisfied in cooperative sensing: bandwidth, reliability, and security. Thus, bandwidth and reliability requirements in this subsection explained as follow:

2.8.4.1 Bandwidth Requirement

The bandwidth of the control channel is identified in [64] as one the factors of determining the level of cooperation. This is because the amount of local sensing data that can be transmitted to the FC or shared with the neighbors is limited by the control channel bandwidth. In [65], the problem of cooperative sensing under control channel bandwidth constraints is addressed by censoring and quantizing local sensing data.

2.8.4.2 Reliability Requirement

In addition to the bandwidth requirement, the reliability of the control channel has the great impact on cooperative sensing performance. Like data channels, the control channel is susceptible to multipath fading and shadowing. Hence, the channel impairments must be considered in the reliability issue of the control channel. While early studies [66] assume a perfect error free control channel in cooperative sensing, recent studies investigate the effect of Gaussian noise [67], multipath fading [68], and correlated shadowing [69] on the control channel and the sensing performance.

2.8.5 Data Fusion

Combining local sensing data for hypothesis testing, which is also an element of cooperative sensing. Depending on the control channel bandwidth requirement, reported sensing results may be of different forms, types, and sizes. In general, the sensing results reported to the FC or shared with neighboring users can be combined in three different ways in descending order of demanding control channel bandwidth: *(i)* Soft Combining: CR users can transmit the entire local sensing samples or the complete local test statistics for soft decision. *(ii)* Quantized Soft Combining: CR users can quantize the local sensing results and send only the quantized data for soft combining to alleviate control channel communication overhead. *(iii)* Hard Combining: CR users make a local decision and transmit the one bit decision for hard combining. Obviously, using soft combining at the FC can achieve the best detection performance among all three at the cost of control channel overhead while the quantized soft combining and hard combining require much less control channel bandwidth with possibly degraded performance due to the loss of information from quantization [70].

2.8.6 User Selection

The selection of CR users for cooperative sensing plays a key role in determining the performance of cooperative sensing because it can be utilized to improve cooperative gain and address the overhead issues. For example, when cooperating CR users experience correlated shadowing, it is shown in [71] that selecting independent CR users for cooperation can improve the robustness of sensing results. Moreover, removing malicious users from cooperation ensures the security and the reliability of the network.

2.8.6.1 Centralized selection

The centralized user selection schemes is usually performed at the FC to take advantage of the available information collected from all cooperating CR users. For example, the FC is able to select independent users for cooperation to counter the effect of correlated shadowing based on the location estimates of CR users.

In [72], three user selection algorithms with different degrees of the knowledge of CR user positions are proposed for cooperative sensing to address the shadow correlation problem in a cellular system. The first algorithm aims to select a set of cooperating users with the minimum correlation measure among them by a greedy approach. Specifically, users with the largest summed correlation with respect to the remaining users are successively removed one at a time from the set until the desired number of CR users for cooperation is reached. Based on the knowledge of CR user locations, the correlation can be evaluated from the distance between two CR users. Starting with the BS only in the set of cooperating users. The second algorithm selects users by successively adding uncorrelated users to the set if the selected users are located at a distance greater than the decorrelation distance d_0 from all existing members of the set. The third algorithm

finds K cooperating users within the radius r of the BS that satisfy the desired probability of uncorrelated K users with only the radius information from the BS to users.

2.8.6.2 Cluster-based Selection

Centralized user selection may incur high overhead such as control channel bandwidth, energy efficiency, and reporting delay when a large number of CR users need to cooperate in sensing and report the results to the FC. To alleviate this problem, grouping the cooperating users into clusters [73, 74] or coalitions [75] for cooperative sensing is an effective approach to reduce the cooperation range and the incurred overhead.

2.8.7 Knowledge Base

The performance of cooperative sensing schemes largely depends on the knowledge of PU characteristics such as traffic patterns, location, and transmit power. The PU information, if available in a database, can facilitate the PU detection. The database that stores all the knowledge of the RF environments is called a knowledge base. Knowledge base is an indispensable element of cooperative sensing because it can be utilized to assist, complement, or even replace cooperative sensing for detecting PU signals and identifying the available spectrum. Knowledge base serves as two roles in cooperative sensing: (i) to enhance the detection performance by utilizing the accumulated knowledge and the learned experience such as statistical models in the database and (ii) to alleviate the burden of cooperative sensing by retrieving the spectrum information such as a list of PU occupied channels from the database [76].

2.9 Evaluation Metrics

- **Throughput(Kbps)** : often characterize the amount of data that the network can transfer per unit of time. This can be show in Equation 2.6 [77].

$$\text{Throughput} = \frac{\text{Total Data signal(Kb)}}{\text{Time(300)}} \quad (2.6)$$

- **CR lifetime(ms)**: the time of power supply provided by batteries before they drained, directly impacting the sensor node's liberty. This can be show in Equation 2.7 [11].

$$\text{CR lifetime} = \text{the time of power supply} - \text{power consumption} \quad (2.7)$$

- **Power consumption (mW)**: it is the energy consumption of each sensor node per unit of time. This can be show in Equation 2.8 [78]. We suppose 0.355 Kbps of power consume for every 1 signal in ECG and Capsule endoscopy reports [11].

$$\text{Power consumption} = \text{total size} \times 0.355 \quad (2.8)$$

2.10 Simulation Tools Used to Enhance CSS in CRN

In addition to the real implementations of the CRN, there are many simulations, programming languages, and frameworks that allow the possibility of applying this network and various research directions, especially in the field of cooperative sensing in cognitive radio networks as in the simulations tools mentioned below:

2.10.1 MATLAB

It is the most accessible and most productive software to simulate a different type of cooperation sensing approach for example, in [79] the author discuss the

Performance evaluation of energy detection based cooperative spectrum sensing in cognitive radio network, while in [80] the author use cooperative spectrum sensing based on hard decision rule to solve the hidden node problem.

2.10.2 Network Simulator 2

It is considered one of the most important simulation tools that are used in the field of networks in general and cognitive radio networks in special, where it is applied in the field of cooperative spectrum sensing [81], for example, it studies the optimization problem of energy detection based Cooperative Spectrum Sensing (CSS), with the main focuses on the optimality of K out of N fusion strategy and cooperative user number.

2.10.3 Network Simulator 3

It is one of the developed open-source versions of the NS2 simulator. It contains numerical simulation frameworks appropriate for different types of networks and their applications as it is widely used in the cognitive radio network field to detect the primary user [82]. It used within [83] for spectrum sensing techniques for handoff/hand over and PUs detections within smart environments.

2.10.4 OPNET

It provides many benefits to the cognitive radio network, as it depends on an easy-to-use graphical user interface and depends on it to implement Spectrum Sensing and Management in Cooperative Cognitive Radio [84].

2.10.5 Monte Carlo

It deals with series of dependent variables with probability distribution approach. In cognitive radio network used in different module such as Cooperative Spectrum Sensing in CRNs [85]. As well as another work proposed optimized

sensing and enhances the performance of detection probability for given Signal to Noise Ratio (SNR) in CRN [86].

2.10.6 OMNeT++

It is considered one of the open-source simulators, which is characterized by the ease of installation and learning, as it is one of the simulations that it has many used the field of information technology as one of the most important academic tools because of its easy-to-use GUI interfaces and application as well by adding extension tools attached to the implementation of the cognitive radio network such as Castalia and Simulink [87]. In [88] focuses on cooperative spectrum sensing under two sensing operating modes: the Constant False Alarm Rate (CFAR) and the Constant Detection Rate (CDR) mode.

In this thesis, all the simulations are implemented in OMNET++ simulation tool. Choosing OMNET ++ because, it's easy to use with (Tkenv) Graphical User Interface (GUI) for the windows operating system. This GUI provides different features of tracing, debugging and execution:

1. It's recommended in the main development simulation stage since it allows to get a detailed picture of the simulation state at any point of execution timeline.
2. It is a modular with different (Frameworks, Libraries, Models, etc.) which save time and effort for researchers to carry out research simulations like the real environments.
3. Following what happens inside the network.
4. The flexibility of learning where it depends on C ++ programming language.

5. OMNET++ graphical user interface based on NED topology description language which its trace what happens inside the network.
6. The lack of requirements for the installation state in windows operating system. According to the general network architecture of Cognitive Radio Network, all the communication takes place on the primary-secondary user model where primary users act as a base station and secondary users as healthcare application units.

Many processes are done to build and execute C++ code within Omnet++ simulator, where it based on different simulation parameters that come from a different files header and source and initial files and supporting file for core messages and network description files.

Besides, there are many simulation tools used to simulate different approaches within cognitive radio networks, for example, J-Sim, NetSim, Qualnet, COOJA and so on. There are different simulation tools because it has many research directions on various parts of the network and even at the level of application of the network, for example, there are research directions regarding the first layers (Physical layer, data link layer) of communication and others regarding the routing features as the network layer, etc. Also, the diversity of the cognitive network applications made this diversity in the application tools of CRNs simulators and programming languages. Table 2.1, shows general simulation tools and the core programming language used that can apply to achieve cognitive radio network.

Table 2.1: Cognitive Radio Network Simulation tools and Official Websites.

Simulation-Tool	Core programming language	Official-Website
MATLAB	C, C++, C#, Java, Fortran and Python	https://www.mathworks.com/
NS_2	OTcl, C++	https://www.isi.edu/nsnam/ns/
NS_3	Python, C++	https://www.nsnam.org/
OMNeT++	C++, Java, C#, NED	https://omnetpp.org/
OPNET	C, C++	www.opnet.com
Qualnet	Parsec, C++	http://www.qualnet.ca/
MONTE CARLO	JavaMonte	http://www.goldsim.com/Home/
COOJA	Java/C	http://www.contiki-os.org/
J-Sim	Java	https://www.physiome.org/jsim/
NetSim	Java/C	https://www.tetcos.com/

2.11 The Cognitive Radio Network Layers in OMNET++

The architecture of the Cognitive Radio Network is similar to most types of wireless networks architecture based on the five popular communication layers for sending and receiving data as well as various data types like text, sound, and video since the proposed systems based on (**Text**) data type. The practical side of each of these modules as C++ core for OMNET++ simulation code will be represented for each system module. The used system description in each layers (Application

Layer, Transport Layer, Network Layer, Data Link Layer, and Physical Layer) is as following [89]:

2.11.1 CR Application Layer

It does not send real data. Instead, it uses only a request signals through the layers lower to the MAC layer. The MAC Layer creates a random amount of data packets (specified in **.ini file**): it allows giving values of parameters during initial time which effects later on overall simulation execution ,on the other hand, experimenting with the model by running it several times with different parameters.

It is important to clarify the parameters that are expected to change (or make sense to be changed) during experimentation should be put into ini files.), and attempts to send it to a destination. As well as, it creates a random amounts of transmission data depending on the settings in the configuration file. Furthermore, it collects the successful and failure communication statistics based on the signaling feature. Figure 2.14 shows the main steps of the used application layer. The used application layer is based on the two stages or phases showed as the initial stage responsible about initializing or definition simulation parameters values which they pass from lower layers and the handler stage responsible about data signaling process and how to deal with them.

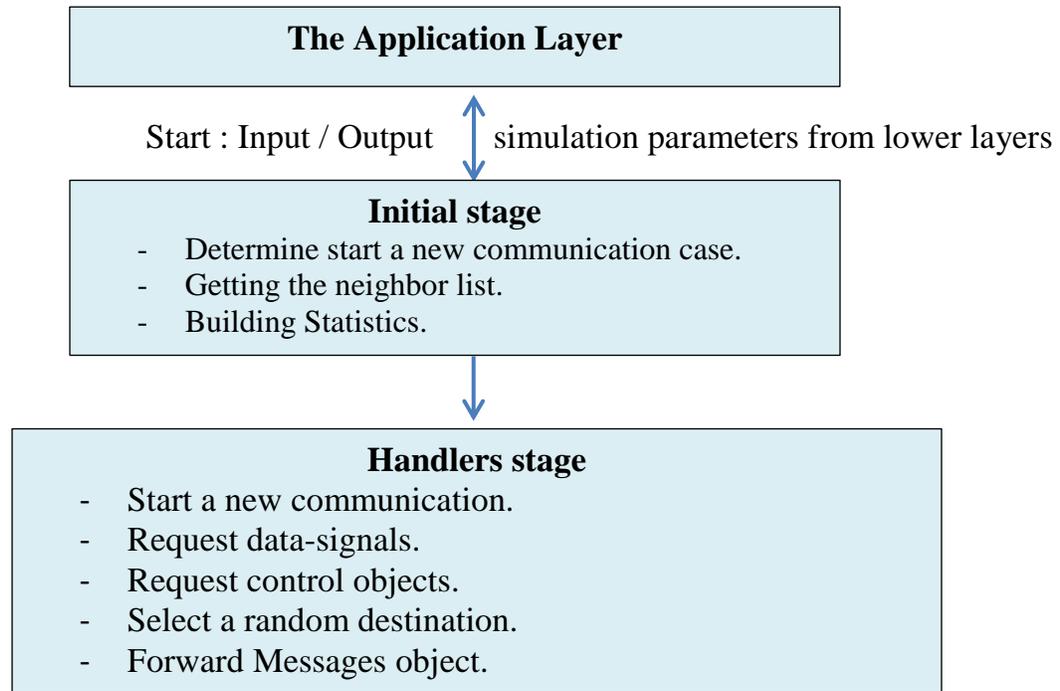


Figure 2.14: main steps of the application layer

3.2.1 CR Transport Layer

The implementation of transport layer as a "pipes" for information is represented by data messages and control messages. It is responsible for establishing session for host to host transmission.

3.2.2 CR Network Layer

The main job of this layer is routing like other traditional network layers so it controls on data coming from upper and lower layer through interfaces to determine destination of packets. So, it selects a random destination node among its one-hop peer nodes in the network. The addresses (source address (own address) and destination (neighbors)) of the one-hop neighbors need to be provided in the topology (.NED) is a file of the network under (address, neighbors) parameters. The folder CrNetworks contains root network description file (.NED). Which is responsible executing project and collect all classes and methods from

other directory as supporting packages invoked them through namespaces section. In addition, general parameters like sub-modules (address, neighbors, etc.) and full-duplex connections among nodes. Overall steps are represented by Figure 2.15 as procedures of behavior of the used network layer.

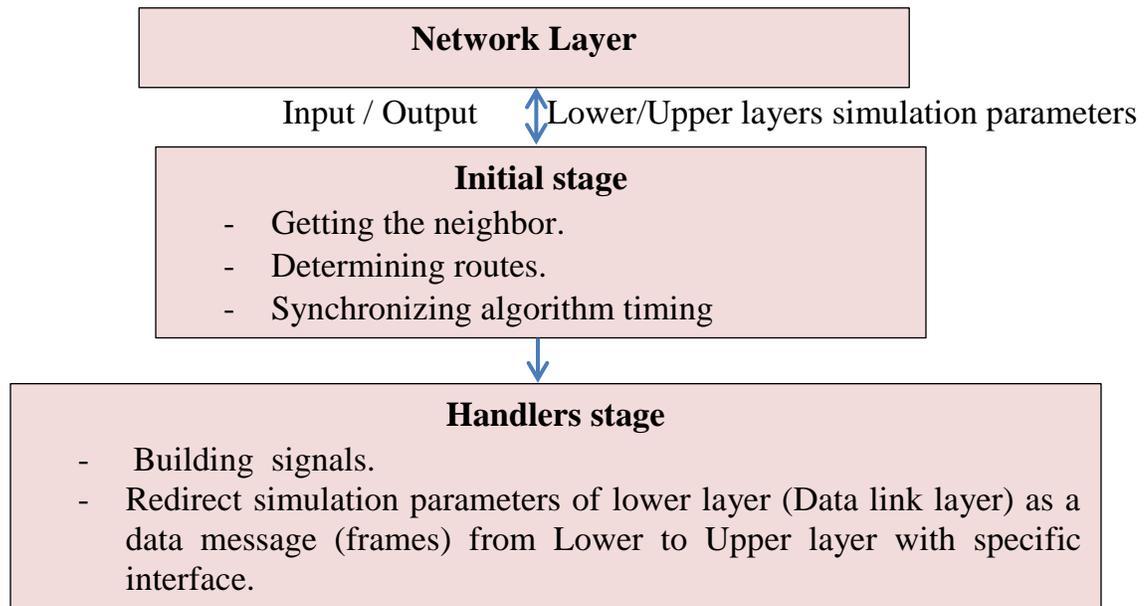


Figure 2.15: The Network Layer steps.

2.11.3 CR MAC Layer

Medium access control is responsible to accomplish tasks related to the smart behavior for selecting the spectrum bands and encapsulation frames for security purpose as well as the mobility feature. In addition, it provides additional specific feature not found in traditional wireless networks.

Through, dynamic channel accessibility, and channel handoff /handover mechanisms with a spectrum sensing provides information about the events of available channels, through selecting the best channel for communication according to a set of parameters that decide efficiency CR-MAC protocol. In addition, the proposed system implements CSMA (RTS, CTS) based MAC protocol with channel dynamically access.

This configurable protocol has many parameters that can be changed through the configuration file. It deals with simulation parameters of data type incoming from physical layer and pass to network layer with specific function of the used system known as [send()] method which calls message based on the different procedures.

The initial state of the data link layer algorithm describes starting point to get parameters values, while processing state or algorithm body is based on the handler function as the main function of data link layer to building simulation objects and passing frames or data signals to build the results within MAC layer. Figure 2.16 shows the main steps of using MAC layer with the different setting for input/output objects between lower/upper layers. The proposed setting starts with the incoming signaling from physical layer and then deals with the building data link layer frames encapsulation configuration and then passes the data signals to the upper layers.

Physical Layer
Interconnection layer signals to pass information as signals between Physical layer and Data Link layer
Data Link Layer
Data signal exchanges as Input/Output signals explained as :
lower layer(CTRL, DATA), upper layer (CTRL, DATA) which is divided into 3 steps :
Step 1: Initialize case with the main functions :
<ul style="list-style-type: none"> - Initialize case the number of total Frames, current Source, current Destination, current Data Channel, used Channel, Link access. - Preparing to frame transmission. - Time management. - Assigning static parameters.

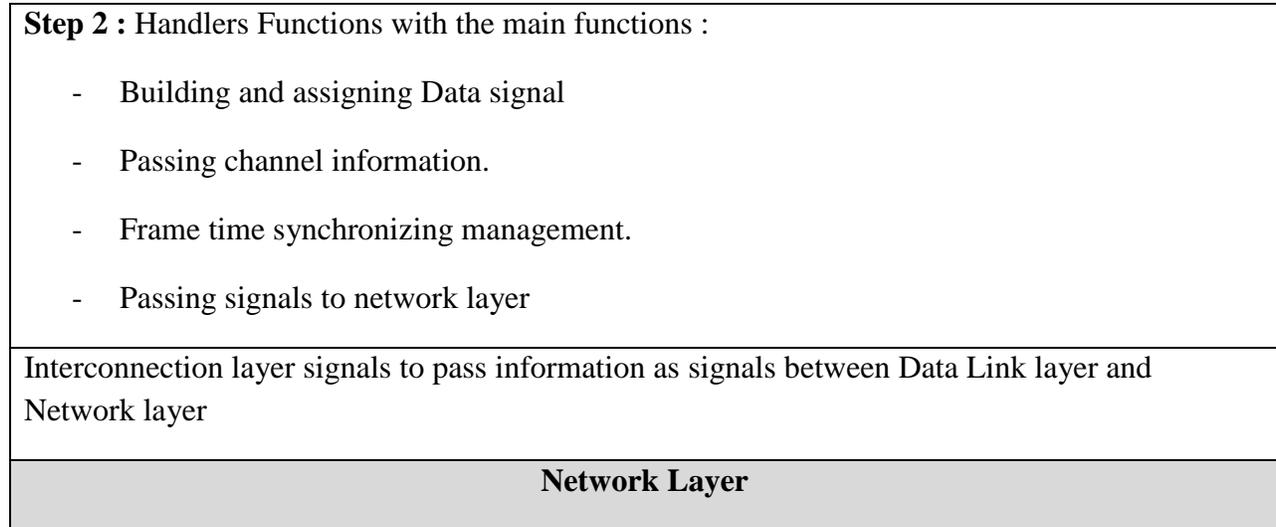


Figure 2.16: The CR MAC Layer steps.

2.11.4 CR Physical Layer

The main job of this layer is concerned with the physical component features and channel proprieties. It receives messages from all connections/channels through any physical layer parameters need to be appended to the outgoing messages. This feature provides dynamically alteration for implementation parameters without need to change the transmission to a new NIC module. So within the used approach of cognitive radio, network can calculate the data signals (Frames) that arrived without error to the receiver on each reception node, and evaluating the quality of the proposed system by using message statistic test which determines how many messages scheduled through overall simulation time for all cognitive radio network nodes. Also, it can determine the number of channels available for users and idle one suggested from the adapting method of cooperative spectrum sensing. The physical layer steps showed within the cognitive radio network in Figure 2.17.

Physical Layer
<p>Input/output : Address, Control Upper, Data Upper, Sensing Spectrum Interface -(Upper Layer Parameters)</p>
<p>step 1 : Initializing transmission parameters</p> <ul style="list-style-type: none"> - Building simulation interfaces to connect network elements. - Assigning physical address for node identification.
<p>step 2 : start handleMessage function</p> <p>Case 1: if Control message (RTS/CTS) from Data link layer</p> <ul style="list-style-type: none"> - Arrived on control redirect Upper to interfaces <p>Case 2: if Data message from Data link layer</p> <ul style="list-style-type: none"> - Sending it to destination node through data rate spectrum module as: <ul style="list-style-type: none"> - Message object arrived on data Upper - Checking data Messages - broadcast(Messages); <p>Case 3: Sensing information arrived through Spectrum sensing interface message deliver to data rate Spectrum module with :</p> <ul style="list-style-type: none"> - msg->arrivedOn("ssInterface\$i) <p>Then (received Message, "dataUpper\$o");</p> <p>Else if Control Message and determine that with Control class then send it for sensing process :</p> <p>send(copy, "ssInterface\$o");</p>
<p>step 3 : broadcast</p> <ul style="list-style-type: none"> - Send data messages arrived for all interfaces (ports) with output array as: <ul style="list-style-type: none"> - Looping to send data messages to all output interfaces - Creating Data Message object - Send created message with (copy, "radio\$o", x) to interfaces. <p>*\ gateSize: Returns the size of the gate vector with a specific name among brackets. (1) for non-vector gates, (0) for doesn't exist gate or the vector has size 0. gate names also accepted with "\$i" or "\$o" suffix.</p>

Figure 2.17: The CR physical layer steps.

2.12 The Cognitive Radio Network Modules in OMNET++

2.12.1 The Supporting Statistics Module

This module is used to collect and extract statistical results related to various variables within layers of cognitive radio nodes architecture. Its objects (cStatistic subclasses such as cStdDev) generate several lines: mean, standard deviation, and so on, by using the vector, scalar and histogram statistics to explain the results.

2.12.2 Cognitive Engine and Resource Map Modules

This module contains source and header files responsible for interconnection layers and supporting signaling and communication module through core and CrNodes [90]. These modules are used for knowledge aggregation and decisions produced from signaling and communication(interconnection among layers) that's later employ to build statistic results, as they shown in Figure 2.18 .

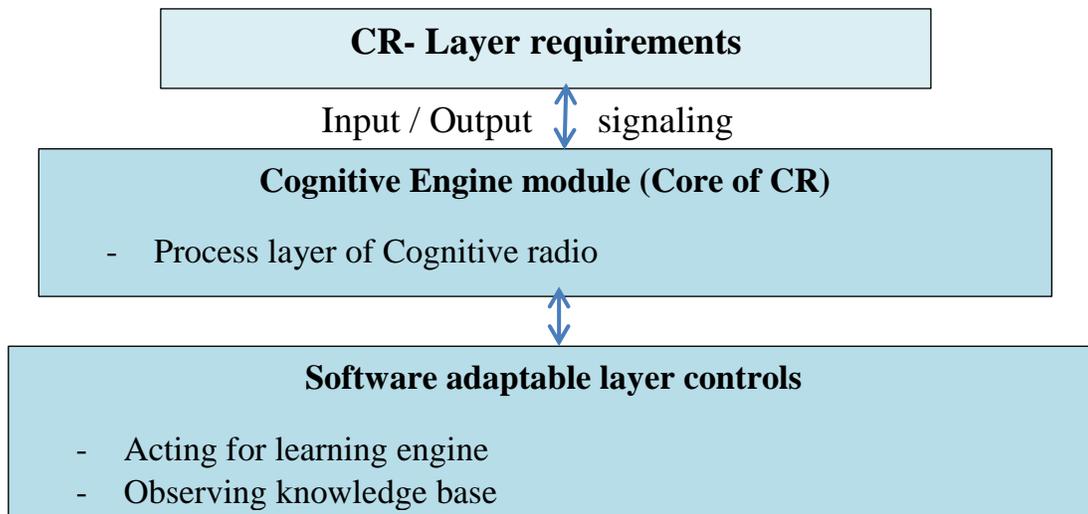


Figure 2.18: The Core Cognitive Engine Module.

-
- **CrNodes Module:** It contains the layer structure and their interconnections like signaling and communication links, statistic and cognitive engine. Moreover it contains the initial default parameters and their data types, gates, definition for sub-modules and some of displays feature related with graphical user interface.
 - **PuNodes Module:** It intended to produce PU activity patterns that match the real observed activities for Global System for Mobile Communications (GSM). The general steps for PU activities summarized as simulating PU behavior and these steps of building Primary user units in cognitive radio network inside (puGSM.cc and puGSM.h) files within OMNET++ simulator.
 - **PuGSM Module:** It describes behaviors for each primary user using parameters and timers for attendance and absence for primary user that affected on handoff and handover state for secondary user without harmful primary user.
 - **Core Folder:** It includes message-files (Control messages, Initial, Setting, Text message objects) which are responsible for messages exchange among hierarchical of the proposed healthcare network. In addition, it contains core classes and namespaces as global parameters for functions and modules used in all simulation environment.
 - **Images Folder:** It contains the images that are used within the layers, background and nodes, as well as changing images during execution time.
 - **Out Folder:** This folder (separate directory) contains files resulted from debugging and compiler process to build executable files in OMNET ++.
 - **Results Folder:** This folder contains a set of files for statistical results as vector and scalar type which can be used for analysis file (anf).

- **Omnetpp.ini:** It contains different types of parameters that can change values during running simulation and given initial value for instance total channel, total frames and sensing duration, on the other word, to change default parameters value entered in source code file, which will effect on the all simulation states. These parameters aren't all parameters within the used system but they are the most common used parameters.

CHAPTER THREE
PROPOSED APPROACH

3.1 Introduction

Cognitive Radio (CR) is a spectrum dynamic manner technology which considered a modern method for enhancing the spectrum utilization within the wireless environment. It's produced based on the concept of a software-defined radio as well as, represented as a smart wireless communication method that is aware of the surrounding environment. The CR uses the methodology of understanding and learns/discovering from the environment to particular parameters, furthermore, it changes in the input parameters stimuli that are affected by the decision-making process for selecting the best idle available channel. CR implements in various types of applications, for instance, CR-leased networks, CR-emergency network, intelligent roadside, safety, vehicles network, cellular networks, multimedia application, healthcare application and the most important application is the military application where cognitive radio plays as an excellent service within this application [90]. The proposed approach implemented of the healthcare application. This study is proposed a method to enhance cooperative spectrum sensing in CRN by implementing:

- i. Energy detection as a sensing technique to sense the presence of PU.
- ii. An external node (Group Manager) to perform the spectrum sensing process and propagation the channel availability information to secondary users (SUs).
- iii. Enhancing cooperative Cognitive Radio (CCR) with the main simulation parameters used such as the (Throughput, Power consumption, and CR life Time).

3.2 The Developed Sensing Approach for cooperative Cognitive Radio Networks

3.2.1 Group Manager Node

In the first stage of simulation run time, group manager node (a node has special specifications) perform the spectrum sensing process using energy detection process and determine if (PU) is presence or not and then propagation the channel information to the connected SUs. Simulation steps are represented inside CRN with (2, 4, 8) channel and making recognition feature for message exchanges among nodes through data rate links and Signaling & Communication Link (SCL). Figure 3.1 explain the architecture of Group Manager Node.

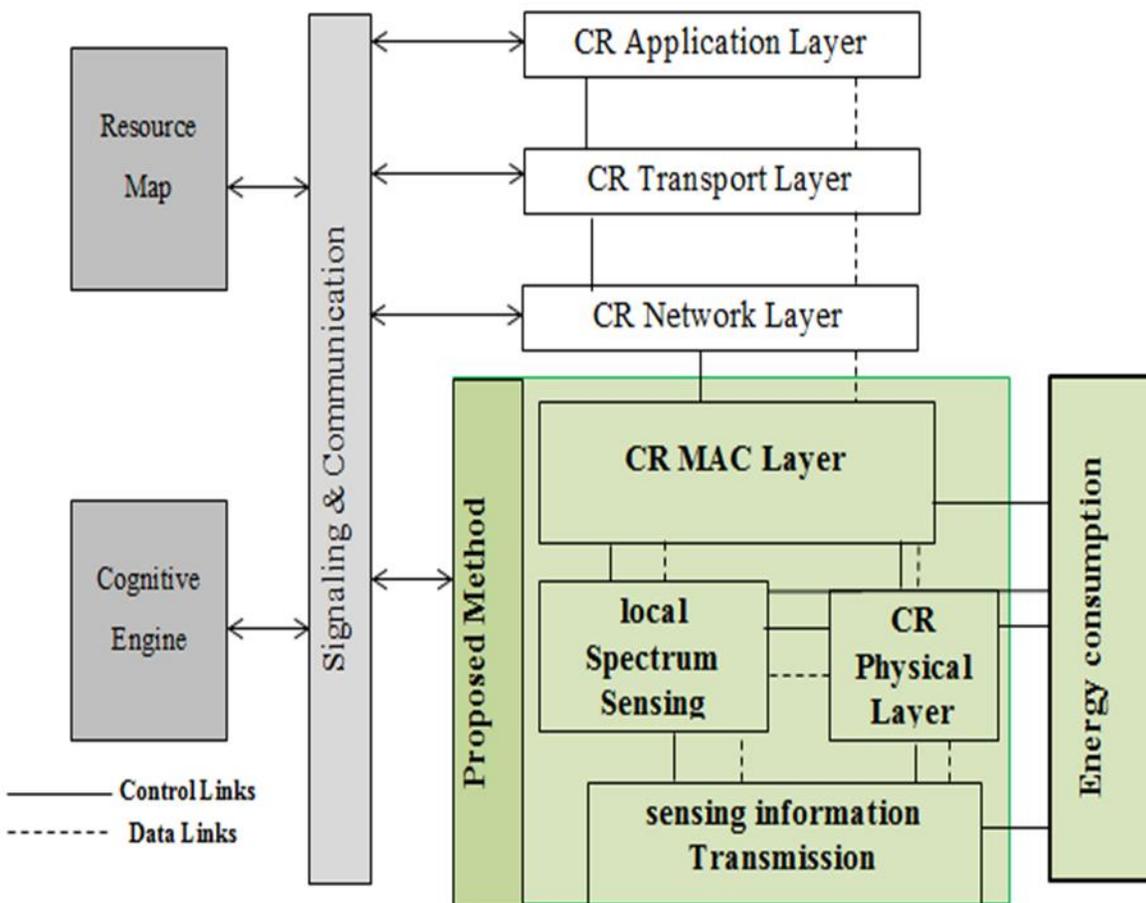


Figure 3.1: The used Group Manager Architecture

This architecture consist of the cognitive radio layers and modules explain in Chapter Two, spectrum sensing process and power consumption process. The proposed approach is implemented based on C++ because it is the core of building libraries and OMNET ++ based on it. The main benefits of interconnection link functions are shown in Figure 3.2.

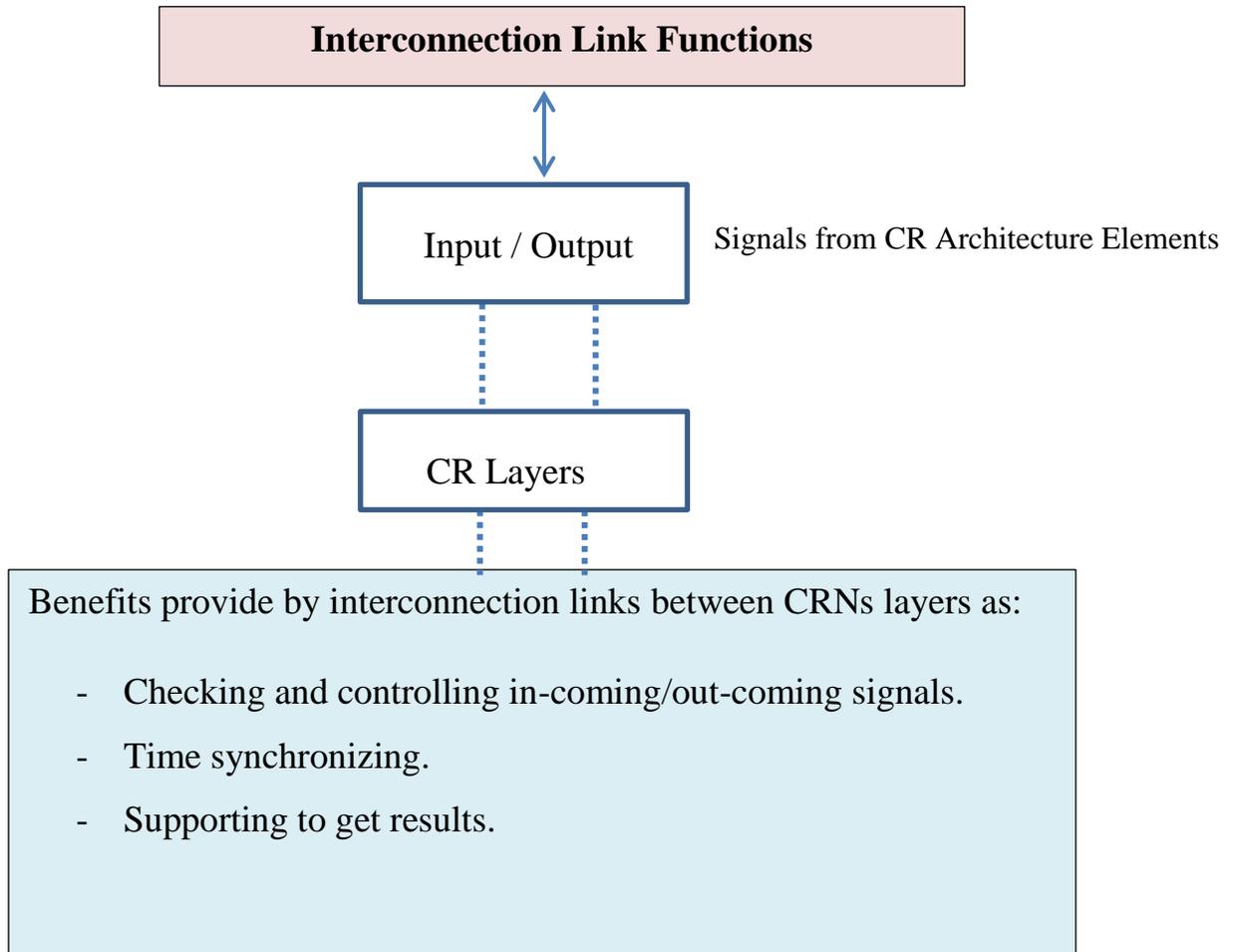


Figure 3.2 : The Interconnection Link Functions

While Algorithm 3.1 explain the proposed primary user algorithm.

Algorithm 3.1: Proposed Primary Users Behaviors

Input:

Primary user signals

gsm1: idle Duration : 0.0300 s

busy Duration :0.0500 s

Power = 0.5;

Threshold = 1;

gsm2: idle Duration: 0.0500 s

busy Duration : 0.4000 s

Power = 5;

Threshold = 1;

gsm3: idle Duration : 0.0600 s

busy Duration :0.0700 s

Power = 0.5;

Threshold = 1;

gsm4: idle Duration : 0.0700 s

busy Duration :0.0600 s

Power = 5;

Threshold = 1;

gsm5: idle Duration : 0.0800 s

busy Duration :0.0900 s

Power = 8;

Threshold = 1;

gsm6: idle Duration : 0.0900 s

busy Duration :0.0800 s

Power = 0.5;

Threshold = 1;

Gsm7: idle Duration : 5.0000 s

busy Duration :4.6000 s

Power = 0.5;

Threshold = 1;

gsm8: idle Duration: 4.6000 s

busy Duration : 5.0000 s

Power = 8;

Threshold = 1;

<p><i>Begin:</i></p> <p>Step 1 : Initialize case represented by:</p> <ol style="list-style-type: none"> 1- Log file recording process 2- Initializing state for application layer timer with channels(gsm1, gsm2,.. gsm20) 3- Assumption of idle/busy Duration for each PU (gsm_n):
<p>Step 2 : Start Handlers functions</p> <ol style="list-style-type: none"> 4- Broadcasting into each connected device through data rate. 5- Indicating transmission state. 6- End of transmission PU END finish PU transmission with specific known signal. 7- Indicating finish transmission <p>End_Algorithm</p>

Algorithm 3.2 explain the proposed RFSpectrum Module for Data rates links, this module is represented by procedures of data rate links and identify setting should data rate takes to working in the proposed system .

<p><u>Algorithm 3.2: Proposed RFSpectrum Module for Data Rates Links</u></p>
<p><i>Begin:</i></p> <p>Step 1 : determines whether the channel is a transmission channel</p> <ol style="list-style-type: none"> 1- Setting duration field of packets. 2- Setting simulation time of the sender will finish (or has finished) transmitting to find out when the channel becomes available. 3- Sum of all previous propagation delays
<p>Step 2 : Process Messages</p> <ol style="list-style-type: none"> 4- Setting propagation delay 5- Setting transmission duration. 6- Check cases of the channel has lost the message. 7- Determination of data rate value <p>End_Algorithm</p>

Algorithm 3.3 explain the local spectrum sensing process, that is responsible for keeping track of the channel state and provide this information to any CR

users requesting it. This implementation works with "crMacLayer" and provides it with request sensing results.

Algorithm 3.3: Local Spectrum sensing algorithm

Input: initialize state with parameters that effect describe channel state

[channelsArray, sensingDuration, myAddress(src), freeSenseTimer(timers for sensing free or data channels), sensedChannel, proposedChannel, currentDataChannel, sensingSignal]

Begin:

step 1 : senseChannel(int type) with three cases :

Case 1 : SenseFreeCHANNEL : **sense any free channel**

1. The currently sensed channels is either busy of occupied by PU
2. The sense channel is free. Notify MAC Layer and give the channel ID

Case 2 : SenseDataCHANNEL : **sense the state of SU channel**

3. data channel is still free.
4. Lost data channel to PU.

Case 3 : SenseProposedCHANNEL : sense the idle channel

Step 3 : scheduleSensing

Case 1 : SenseFreeCHANNEL: **sense any free channel. sense timer 1**

- 5- call scheduleAt(simTime(Returns the current simulation time)+sensingDuration, freeSenseTimer);

Case 2 : SenseDataCHANNEL: **sense the operating channel. sense timer 2**

- 6- call scheduleAt(simTime()+sensingDuration, dataSenseTimer);

Case 3 : SenseProposedCHANNEL:

- 7- Call scheduleAt(simTime()+sensingDuration, proposedSenseTimer);

default: **nothing to schedule**

break;

End_ Algorithm

The general steps for spectrum sensing using energy detection can be shown in Figure 3.3. While, the general steps for simulation processes of cooperative cognitive radio shown in Figure 3.4. from the starting point when the spectrum sensing process begin into data transmission by SUs as they are represented in the following :

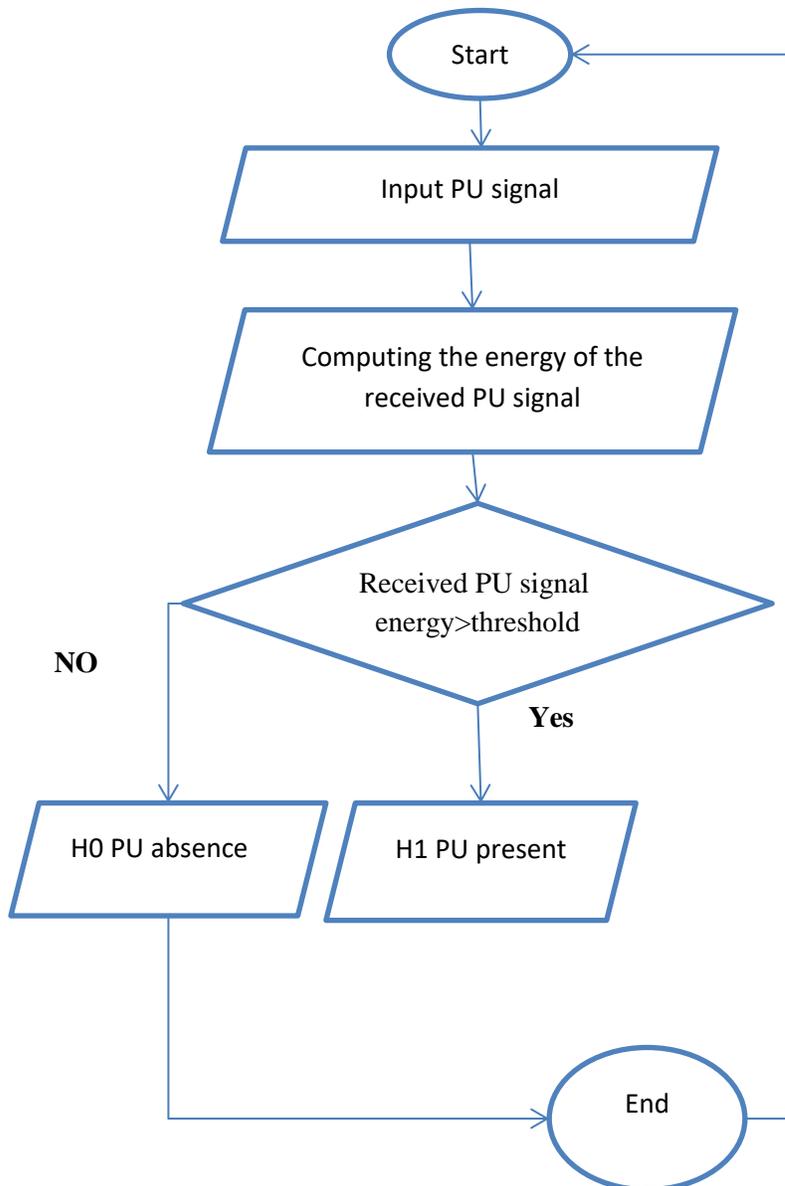


Figure 3.3: general steps for spectrum sensing using energy detection

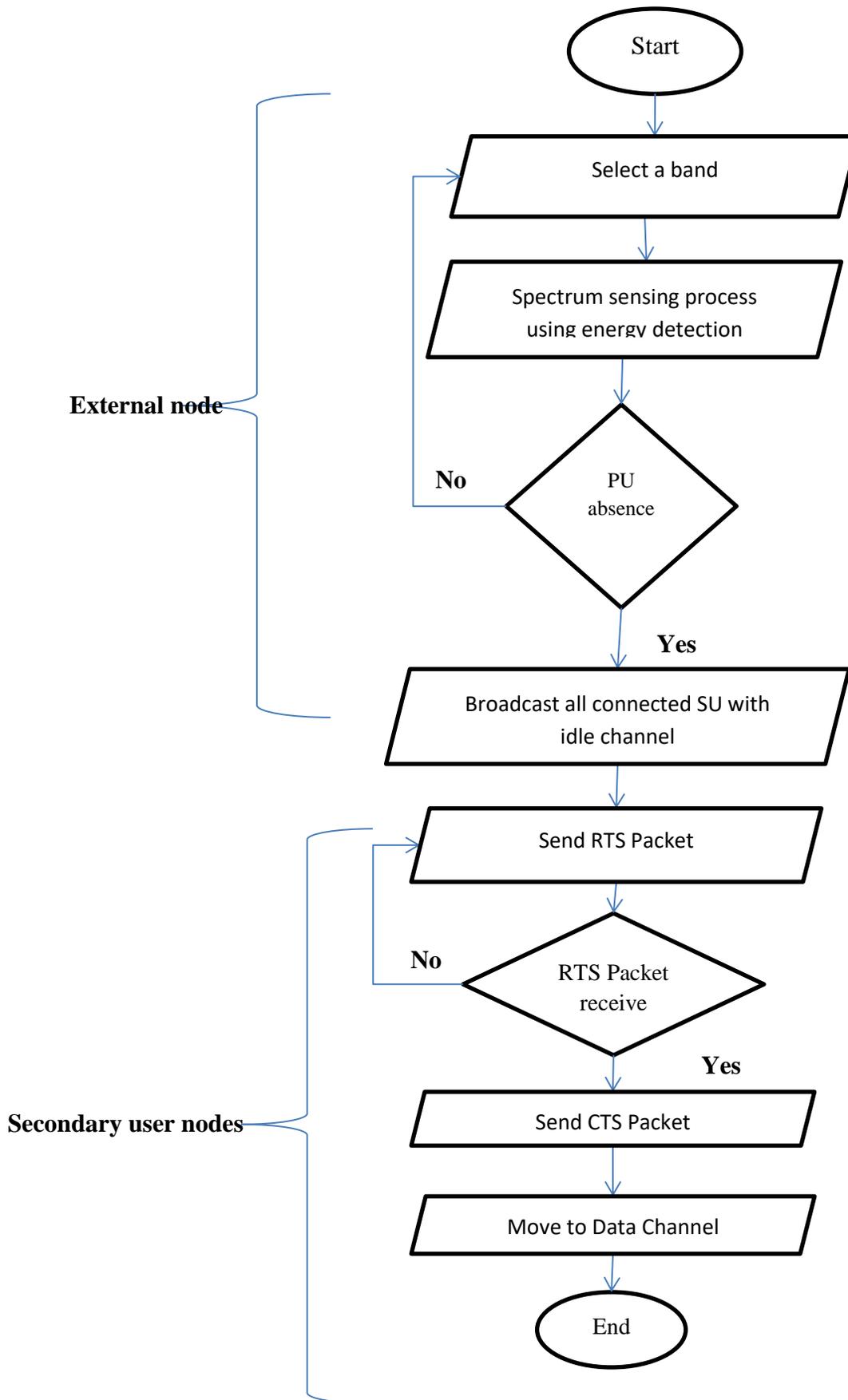


Figure 3.4: General Steps for Cooperative Cognitive Radio

Algorithm 3.4 :explain the **Power consumption algorithm**

<u>Algorithm 3.4: Proposed Power consumption algorithm</u>
<p><u>Input:</u> receives DrawMsg's from one or more devices, updates residual</p> <p><u>Output:</u> notification on battery depletion, and provides time series and summary information to Battery Stats module.</p>
<p><u>Begin:</u></p> <p><i>Step 1:</i> Initialized Sensing Time.</p> <ol style="list-style-type: none"> 1- if (stage == 0) 2- voltage ← par("voltage"); 3- nominalCapmAh ← par("nominal"); 4- if (nominalCapmAh <= 0) 5- error("invalid nominal capacity value"); 6- capmAh ← par("capacity"); 7- End if 8- End if <p><i>Step 2:</i> Publish capacity to BatteryStats every publishTime (if > 0) and whenever capacity has changed by publishDelta (if < 100%).</p> <ol style="list-style-type: none"> 9- publishTime = 0; 10- publishDelta = 1; 11- publishDelta ← par("publishDelta"); 12- resolution ← par("resolution"); 13- EV << "capacity = " << 14- EV << "publishDelta = " << 100 << "%, publishTime = " << publishTime << "s, resolution = " << resolution << "sec" << endl; 15- if (par("ConsumedVector")) 16- mCurrEnergy ← necOutVector("Consumed") 17- residualVec.disable() 18- End if <p><i>Step 3:</i> timeout = new cMessage("auto-update", AUTO_UPDATE);</p>

End_algorithm

The message object used with the simulation environment contains the simulation parameters in the Table 3.1.

Table 3.1: Data message Object Simulation Parameters.

Message Object	Simulation Parameters of Data messages(Frames)
Data Message	Source Destination Packet-Length Proposed-Channel RTS-MAC CTS-MAC

While, the main used objects of GSM base station and target cognitive radio node simulation parameters as a standard features build with C++ programming language are in Table 3.2.

Table 3.2: The used of CR-Nodes Object Simulation Features

Used CR-Nodes	Simulation features
CR-Nodes Object	Address: Node Address Neighbors: Neighbor Node Device ID : Identifier Device Type: Cognitive Radio Node Network : CR-GSM

While the used features of GSM base station site as a Primary user station are shown in the Table 3.3.

Table 3.3: The used of primary base station simulation features

The used GSM-Primary user station	Simulation features
GSM-Stations	ID Tx/Rx Channel : Transmit, Receive. Arrival Rate : 0.5 ms Address : Primary GSM Address Capacity : depending on the case study

3.2.2 The Used Cognitive Radio System

The proposed approach will be evaluating based on two main case studies ,the first case study is executed with the implementation of distributed CSS without Group Manager node with different number of SUs (6,10,20) , PU(2gsm,4gsm,8gsm) and channels (2,4,8). Each SUs perform spectrum sensing process to determine idle proposed channel to transmission data messages and take consideration not harmful Primary user known as GSM then decide which channel free or busy, then send the idle channel information to its neighbors.

The second case study is executed with the implementation of cooperative sensing with Group Manager with different number of SUs(6,10,20) ,PU(2gsm,4gsm,8gsm) and channels (2,4,8). Group manager perform spectrum sensing process to determine idle proposed channel and broadcast the idle channels to SUs.

3.2.3 The Proposed Data Frame Format

The header segment bits define the basic feature of the frame, and payload segment (0 - 254 bytes) contains the main data (Messages). It consists from the used components below. Figure 3.14 describes them:

- **Used channel:** it represents which free channel used as idle channel to transmission messages.
- **Frame ID:** it is designed as a slot position. The frame ID indicates the slot in which the frame should be transmitted. A frame ID is used no more than one time on each channel during one communication cycle. Each frame has a unique assigned frame ID corresponding with a unique slot. The frame ID ranges from 1 to 2047 (00000000001 to 11111111111), and the frame ID 0 is an invalid frame ID.
- **Data Length:** it is used to indicate the size of the encapsulation field. The encapsulation field size is encoded in this field by setting it to the number of encapsulation data bytes divided by two (data length x 2 = number of encapsulation data bytes).
- **Source (Src):** it describes source MAC address.
- **Destination (Des):** destination MAC address
- **Data (Text Message):** it specifies input messages (ECG or Capsule Endoscopy) entered during initial simulation state. In Figure 3.5, the used system described frame data transmission field in cognitive radio message format.

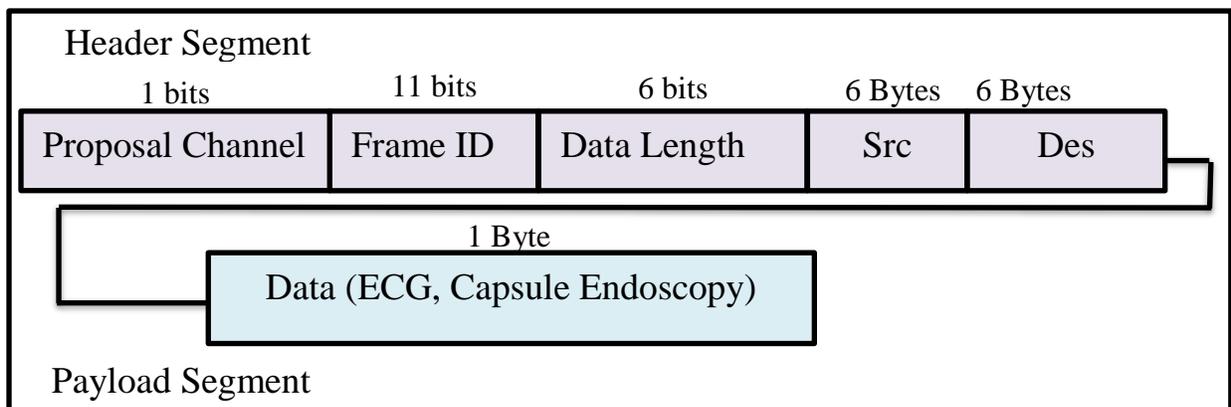


Figure 3.5: The proposal Frame Format.

The sensing result field represents information about the channel from the list (each node has the same channel list). Each field contains information about:

- ✓ Channel occupancy—1 bit (0 for free channel, 1 for detected signal),
- ✓ Sensing channel—1 bit—informed if this channel was used by the node for data transmitting or sensing (0—sensing, 1—data)—if this bit is set to 1.
- ✓ Percentage occupancy of the channel (7 bits).

CHAPTER FOUR

Results and Discussion

4.1 Introduction

This chapter introduces the simulation and discussion of results for the proposed sensing approach in cooperative cognitive radio presented in chapter three. It has simulated by using OMNET++ to implement the cooperative spectrum sensing processes in the developed system. The used system describes a sensing approach in Cooperative Cognitive Radio in OMNET++. All of the used CRNs components in the proposed regions contain (6, 10, 20) secondary users nodes and (2, 4, 8) Global System for Mobile communication (GSM) base station as Primary users as shown in Table 4.1.

Table 4.1: The used installation requirement

Tools	Installation Requirements	Goal of Using the Tool
Omnet++ 4.6	1. Windows 10 (32-bit or 64-bit) 2. 1 GB (32-bit) or 2 GB (64-bit) RAM	Simulating the proposed CRNs in Healthcare environment.

While the used CRNs elements showed in Table 4.2.

Table 4.2: The used CRNs Elements.

	<i>SUs Transmitter Nodes</i>	<i>SUs receiver Nodes</i>	<i>PU(GSMs)</i>	<i>Total CRNs node</i>
<i>Case1</i>	3	3	2	6
<i>Case2</i>	5	5	4	10
<i>Case3</i>	10	10	8	20

Besides, the main simulation parameters are showed as Table 4.3.

Table 4.3: The main simulation parameters for the all case studies.

Parameters	Value
Simulation Time	5 m = 300 second
Total Frames	2028
Sensing interval	0.05 ms
Number of Channels	2,4,8
Application Type	Healthcare Application
PU Arrival Rate	Variable 0.5-1s
PU Tx Duration	0.5s
Number of nodes	6,10,20 SU , 2,4,8 PU,1 Group Manager
Time of power supply	100 ms
Threshold	1mw
MAC Layer	802.11b standard
Data Type	Text Message Packet
Sensing signal size	124 Bytes
Data signal size	ECG = 133 Bytes Endoscopy = 169 Bytes
Ack signal size	23 Bytes

4.2 Cooperative Spectrum Sensing without Group Manager

Case1: 6 Cognitive Radio Nodes

The first state of the 6 CR nodes simulated with 2 PU and the evaluation parameters based on the different variables. The sensing signals details showed in Table 4.4.

Table 4.4: the Sensing signals details of the 6 CR nodes

CR nodes	No. of Sensing signal	Size of each signal	Total size in Bytes
CR1(ECG)	71	124 Bytes	8804
CR2(ECG)	4		496
CR3(ECG)	25		3100
CR4 (Capsule endoscopy)	6		744
CR5 (Capsule endoscopy)	21		2604
CR6 (Capsule endoscopy)	6		744

While the data signals details showed in Table 4.5.

Table 4.5: the data signals with total size in Bytes.

CR nodes	No. of Data signal	Size of each signal	Total size in Bytes
CR1(ECG)	39	133 Bytes	5187
CR2(ECG)	10		1330
CR3(ECG)	13		1729
CR4 (Capsule endoscopy)	20	169 bytes	3380
CR5 (Capsule endoscopy)	8		1352
CR6 (Capsule endoscopy)	17		2873

Besides, the Acknowledgement signals showed in Table 4.6.

Table 4.6: The Ack signals of the 6 CR nodes.

CR nodes	No. of Ack. signal	Size of each signal	Total size in Bytes
CR1(ECG)	21	23 Bytes	483
CR2(ECG)	6		138
CR3(ECG)	9		207
CR4 (Capsule endoscopy)	11		253
CR5 (Capsule endoscopy)	5		115
CR6 (Capsule endoscopy)	13		299

Table 4. 7 showed the total sensing, data, and ACK signals with the summation and total size in Kbps, as showed the sample of statistics from OMNET++ in Appendix D.

Table 4.7: Summation and total size for 6 CR signals

Active CR Nodes	Total Sensing signal with size	Total Data signal with size	Total Ack. signal with size	Summation In Byte	Total size in Kb
CR1(ECG)	8804	5187	483	14474	115.792
CR2(ECG)	496	1330	138	1964	15.712
CR3(ECG)	3100	1729	207	5036	40.288
CR4(Capsule endoscopy)	744	3380	253	4377	35.016
CR5(Capsule endoscopy)	2604	1352	115	4071	32.568

CR6(Capsule endoscopy)	744	2873	299	3916	31.328
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While table 4.8 showed the data signals convert from Byte to Kilobits (1 Byte = 0.008 Kb) and calculate the throughput. So, Throughput = $\frac{\text{Total Data signal(Kb)}}{\text{Time(300)}}$

Table 4.8: Throughput for the data signals of 6 CR nodes.

Active CR Nodes	Total Data signal with size	Total size in Kb	Throughput in Kbps
CR1 (ECG)	5187	41.496	0.13832
CR2 (ECG)	1330	10.64	0.035467
CR3 (ECG)	1729	13.832	0.046107
CR4 (Capsule endoscopy)	3380	27.04	0.090133
CR5 (Capsule endoscopy)	1352	10.816	0.036053
CR6 (Capsule endoscopy)	2873	22.984	0.076613
Total Throughput in Kbps	0.422693		

Besides, Table 4.9, and Figure 4.1 showed Power Consumption and CR Life Time based on the total signals (Sensing, Data, Ack.). We suppose 0.355 Kbps of power consume for every 1 signal in ECG and Capsule endoscopy reports [11]. Hence, CR Life Time = Time of power supply – power consumption.

Table 4.9: Power Consumption and CR Life Time of 6 CR case.

Active CR Nodes	Total size in Kb	Power Consumption(mw)	CR Life Time (ms)
CR1(ECG)	115.792	41.106	58.894
CR2(ECG)	15.712	5.577	94.423
CR3(ECG)	40.288	14.302	85.698
CR4 (Capsule endoscopy)	35.016	12.430	87.569
CR5 (Capsule endoscopy)	32.568	11.561	88.439
CR6 (Capsule endoscopy)	31.328	11.121	88.879

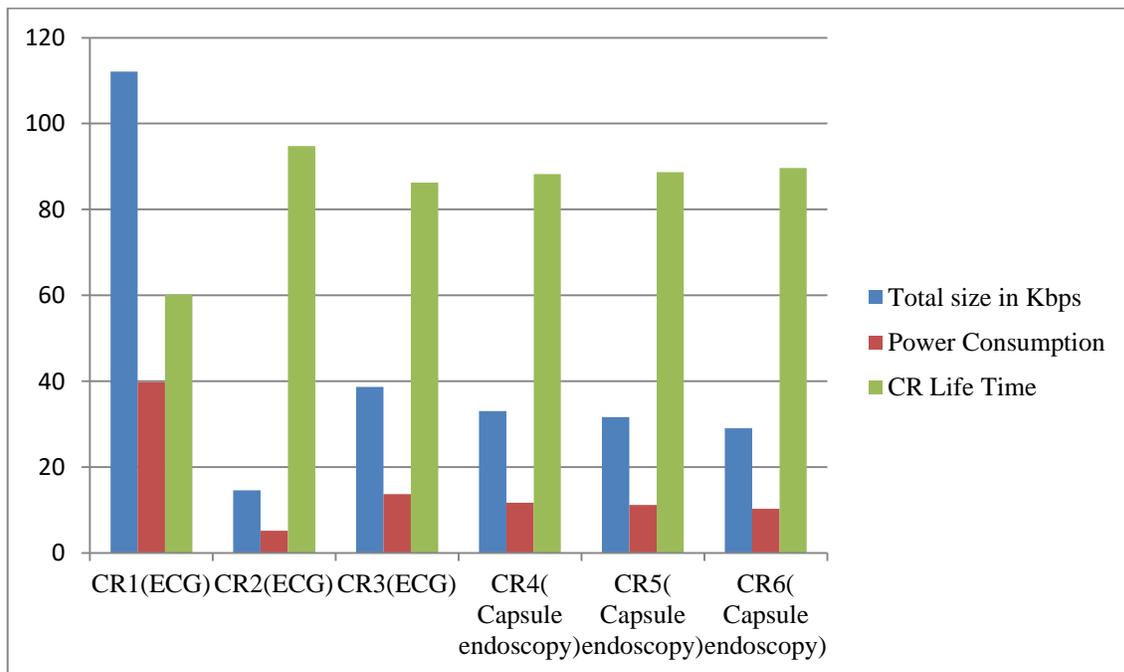


Figure 4.1: Power Consumption and CR Life Time of 6 CR nodes.

Case2: 10 Cognitive Radio Nodes

The second state of the 10 CR nodes simulated with 4 PU and the evaluation parameters based on the different variables. The sensing signals details showed in Table 4.10.

Table 4.10: the Sensing signals details of the 10 CR nodes

CR Nodes	No. of Sensing signal	Size of each signal	Total size in Bytes
CR1(ECG)	53	124 Bytes	6572
CR2(ECG)	3		372
CR3(ECG)	19		2356
CR4(ECG)	4		496
CR5(ECG)	16		1984
CR6 (Capsule endoscopy)	5		620
CR7 (Capsule endoscopy)	6		744
CR8 (Capsule endoscopy)	8		992
CR9 (Capsule endoscopy)	11		1364
CR10 (Capsule endoscopy)	4		496

While the data signals details showed in Table 4.11.

Table 4.11: the data signals with total size in Bytes.

Active CR Nodes	No. of Data signal	Size of each signal	Total size in Bytes
CR1(ECG)	28	133 Bytes	3724
CR2(ECG)	8		1064
CR3(ECG)	9		1197
CR4(ECG)	14		1862
CR5(ECG)	5		665
CR6 (Capsule endoscopy)	11	169 bytes	1859
CR7 (Capsule endoscopy)	4		676
CR8 (Capsule endoscopy)	6		1014
CR9 (Capsule endoscopy)	9		1521
CR10 (Capsule endoscopy)	13		2197

Besides, the Acknowledgement signals showed in Table 4.12.

Table 4.12: The Ack. signals of the 10 CR nodes.

Active CR Nodes	No. of Ack. signal	Size of each signal	Total size in Bytes
CR1(ECG)	13	23 Bytes	299
CR2(ECG)	4		92
CR3(ECG)	5		115
CR4(ECG)	8		184
CR5(ECG)	3		69

CR6 (Capsule endoscopy)	9		207
CR7 (Capsule endoscopy)	4		92
CR8 (Capsule endoscopy)	5		115
CR9 (Capsule endoscopy)	8		184
CR10 (Capsule endoscopy)	11		253

Table 4. 13 showed the total sensing, data, and Ack signals with the summation and total size in Kbps.

Table 4.13: Summation and total size for 10 CR signals

Active CR Nodes	Total Sensing signal with size	Total Data signal with size	Total Ack. signal with size	Summation in Bytes	Total size in Kb
CR1 (ECG)	6572	3724	299	10595	84.76
CR2 (ECG)	372	1064	92	1528	12.224
CR3 (ECG)	2356	1197	115	3668	29.344
CR4 (ECG)	496	1862	184	2542	20.336
CR5 (ECG)	1984	665	69	2718	21.744
CR6 (Capsule endoscopy)	620	1859	207	2686	21.488
CR7 (Capsule endoscopy)	744	676	92	1512	12.096

CR8 (Capsule endoscopy)	992	1014	115	2121	16.968
CR9 (Capsule endoscopy)	1364	1521	184	3069	24.552
CR10 (Capsule endoscopy)	496	2197	253	2946	23.568

While table 4.14 showed the data signals convert from Byte to Kilobits and find throughput.

Table 4.14: Throughput for the data signals of 10 CR nodes.

Active CR Nodes	Total Data signal with size in Bytes	Total size in Kb	Throughput in Kbps
CR1 (ECG)	3724	29.792	0.099307
CR2 (ECG)	1064	8.512	0.028373
CR3 (ECG)	1197	9.576	0.03192
CR4 (ECG)	1862	14.896	0.049653
CR5 (ECG)	665	5.32	0.017733
CR6 (Capsule endoscopy)	1859	14.872	0.049573
CR7 (Capsule endoscopy)	676	5.408	0.018027
CR8 (Capsule endoscopy)	1014	8.112	0.02704

CR9 (Capsule endoscopy)	1521	12.168	0.04056
CR10 (Capsule endoscopy)	2197	17.576	0.058587
Total Throughput in Kbps	0.420773 in Kbps		

Besides, Table 4.15, and Figure 4.2 showed Power Consumption and CR Life Time based on the total signals (Sensing, Data, Ack.)

Table 4.15: Power Consumption and CR Life Time of 10 CR case.

Active CR Nodes	Total size in Kbps	Power Consumption(mw)	CR Life Time(ms)
CR1 (ECG)	84.76	30.0898	69.9102
CR2 (ECG)	12.224	4.33952	95.66048
CR3 (ECG)	29.344	10.41712	89.58288
CR4 (ECG)	20.336	7.21928	92.78072
CR5 (ECG)	21.744	7.71912	92.28088
CR6 (Capsule endoscopy)	21.488	7.62824	92.37176
CR7 (Capsule endoscopy)	12.096	4.29408	95.70592

CR8 (Capsule endoscopy)	16.968	6.02364	93.97636
CR9 (Capsule endoscopy)	24.552	8.71596	91.28404
CR10 (Capsule endoscopy)	23.568	8.36664	91.63336

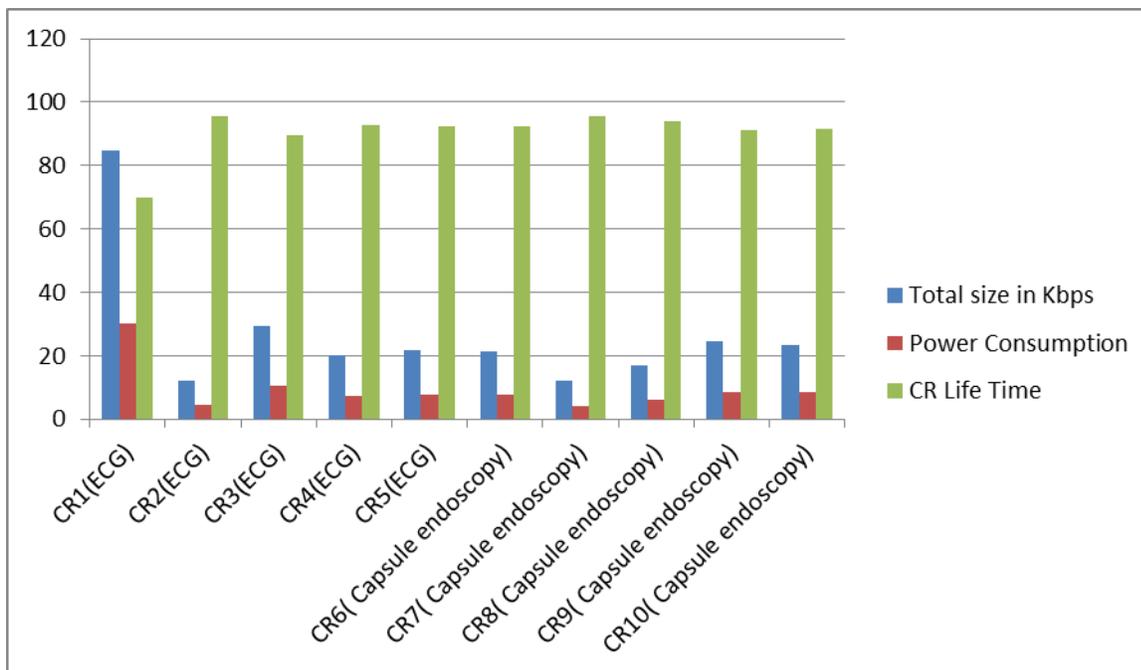


Figure 4.2: Power Consumption and CR Life Time of 10 CR nodes

Case3: 20 Cognitive Radio Nodes

The third state of the 20 CR nodes simulated with 10 PU and the evaluation parameters based on the different variables. The sensing signals details showed in Table 4.16.

Table 4.16: the Sensing signals details of the 20 CR nodes

Active CR Nodes	No. of Sensing signal	Size of each signal	Total size
CR 1(ECG)	16	124 Bytes	1984
CR 2(ECG)	3		372
CR 3(ECG)	6		744
CR 4(ECG)	3		372
CR 5(ECG)	5		620
CR 6(ECG)	2		248
CR 7(ECG)	3		372
CR 8(ECG)	4		496
CR 9(ECG)	5		620
CR 10(ECG)	2		248
CR11(Capsule endoscopy)	3		372
CR12(Capsule endoscopy)	3		372
CR13(Capsule endoscopy)	5		620
CR14(Capsule endoscopy)	3		372
CR15(Capsule endoscopy)	3		372
CR16(Capsule endoscopy)	4		496
CR17(Capsule endoscopy)	2		248
CR18(Capsule endoscopy)	1		124
CR19(Capsule endoscopy)	2		248

CR20(Capsule endoscopy)	4		496
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While the data signals details showed in Table 4.17.

Table 4.17: the data signals with total size in Bytes.

Active CR Nodes	No. of Data signal	Size of each signal	Total size
CR 1(ECG)	9	133 Bytes	1197
CR 2(ECG)	2		266
CR 3(ECG)	4		532
CR 4(ECG)	2		266
CR 5(ECG)	3		399
CR 6(ECG)	2		266
CR 7(ECG)	2		266
CR 8(ECG)	2		266
CR 9(ECG)	3		399
CR 10(ECG)	2		266
CR11(Capsule endoscopy)	1	169 bytes	169
CR12(Capsule endoscopy)	2		338
CR13(Capsule endoscopy)	4		676
CR14(Capsule endoscopy)	2		338
CR15(Capsule endoscopy)	3		507
CR16(Capsule endoscopy)	3		507
CR17(Capsule endoscopy)	2		338

CR18(Capsule endoscopy)	1		169
CR19(Capsule endoscopy)	1		169
CR20(Capsule endoscopy)	3		507

Besides, the Acknowledgement signals showed in Table 4.18.

Table 4.18: The Ack. signals of the 20 CR nodes.

Active CR Nodes	No. of Ack. signal	Size of each signal	Total size
CR 1 (ECG)	6	23 Bytes	138
CR 2 (ECG)	2		46
CR 3 (ECG)	3		69
CR 4 (ECG)	2		46
CR 5 (ECG)	2		46
CR 6 (ECG)	2		46
CR 7 (ECG)	2		46
CR 8 (ECG)	2		46
CR 9 (ECG)	2		46
CR 10 (ECG)	1		23
CR11 (Capsule endoscopy)	1		23
CR12 (Capsule endoscopy)	2		46
CR13 (Capsule endoscopy)	3		69
CR14 (Capsule endoscopy)	2		46
CR15 (Capsule endoscopy)	3		69

CR16 (Capsule endoscopy)	3		69
CR17 (Capsule endoscopy)	2		46
CR18 (Capsule endoscopy)	1		23
CR19 (Capsule endoscopy)	1		23
CR20 (Capsule endoscopy)	2		46

Table 4. 19 showed the total sensing, data, and Ack signals with the summation and total size in Kbps.

Table 4.19: Summation and total size for 20 CR signals

Active CR Nodes	Total Sensing signal with size	Total Data signal with size	Total Ack signal with size	Summation In Byte	Total size in Kb
CR 1(ECG)	1984	1197	138	3319	26.552
CR 2(ECG)	372	266	46	684	5.472
CR 3(ECG)	744	532	69	1345	10.76
CR 4(ECG)	372	266	46	684	5.472
CR 5(ECG)	620	399	46	1065	8.52
CR 6(ECG)	248	266	46	560	4.48
CR 7(ECG)	372	266	46	684	5.472
CR 8(ECG)	496	266	46	808	6.464
CR 9(ECG)	620	399	46	1065	8.52

CR 10(ECG)	248	266	23	537	4.296
CR11(Capsule endoscopy)	372	169	23	564	4.512
CR12(Capsule endoscopy)	372	338	46	756	6.048
CR13(Capsule endoscopy)	620	676	69	1365	10.92
CR14(Capsule endoscopy)	372	338	46	756	6.048
CR15(Capsule endoscopy)	372	507	69	948	7.584
CR16(Capsule endoscopy)	496	507	69	1072	8.576
CR17(Capsule endoscopy)	248	338	46	632	5.056
CR18(Capsule endoscopy)	124	169	23	316	2.528
CR19(Capsule endoscopy)	248	169	23	440	3.52
CR20(Capsule endoscopy)	496	507	46	1049	8.392

While table 4.20 showed the data signals convert from Byte to Kilobits and find throughput.

Table 4.20: Throughput for the data signals of 20 CR nodes.

Active CR Nodes	Total Data signal with size	Total size in Kb	Throughput in Kbps
CR 1(ECG)	1197	9.576	0.03192

CR 2(ECG)	266	2.128	0.007093
CR 3(ECG)	532	4.256	0.014187
CR 4(ECG)	266	2.128	0.007093
CR 5(ECG)	399	3.192	0.01064
CR 6(ECG)	266	2.128	0.007093
CR 7(ECG)	266	2.128	0.007093
CR 8(ECG)	266	2.128	0.007093
CR 9(ECG)	399	3.192	0.01064
CR 10(ECG)	266	2.128	0.007093
CR11(Capsule endoscopy)	169	1.352	0.004507
CR12(Capsule endoscopy)	338	2.704	0.009013
CR13(Capsule endoscopy)	676	5.408	0.018027
CR14(Capsule endoscopy)	338	2.704	0.009013
CR15(Capsule endoscopy)	507	4.056	0.01352

CR16(Capsule endoscopy)	507	4.056	0.01352
CR17(Capsule endoscopy)	338	2.704	0.009013
CR18(Capsule endoscopy)	169	1.352	0.004507
CR19(Capsule endoscopy)	169	1.352	0.004507
CR20(Capsule endoscopy)	507	4.056	0.01352
Throughput in Kbps	0.209093 Kbps		

Besides, Table 4.21, and Figure 4.3 showed Power Consumption and CR Life Time based on the total signals (Sensing, Data, and Ack.)

Table 4.21: Power Consumption and CR Life Time of 20 CR case.

Active CR Nodes	Total size in Kb	Power Consumption(mw)	CR Life Time(ms)
CR 1(ECG)	26.552	9.42596	90.57404
CR 2(ECG)	5.472	1.94256	98.05744
CR 3(ECG)	10.76	3.8198	96.1802
CR 4(ECG)	5.472	1.94256	98.05744
CR 5(ECG)	8.52	3.0246	96.9754
CR 6(ECG)	4.48	1.5904	98.4096

CR 7(ECG)	5.472	1.94256	98.05744
CR 8(ECG)	6.464	2.29472	97.70528
CR 9(ECG)	8.52	3.0246	96.9754
CR 10(ECG)	4.296	1.52508	98.47492
CR11(Capsule endoscopy)	4.512	1.60176	98.39824
CR12(Capsule endoscopy)	6.048	2.14704	97.85296
CR13(Capsule endoscopy)	10.92	3.8766	96.1234
CR14(Capsule endoscopy)	6.048	2.14704	97.85296
CR15(Capsule endoscopy)	7.584	2.69232	97.30768
CR16(Capsule endoscopy)	8.576	3.04448	96.95552
CR17(Capsule endoscopy)	5.056	1.79488	98.20512
CR18(Capsule endoscopy)	2.528	0.89744	99.10256
CR19(Capsule endoscopy)	3.52	1.2496	98.7504
CR20 (Capsule endoscopy)	8.392	2.97916	97.02084

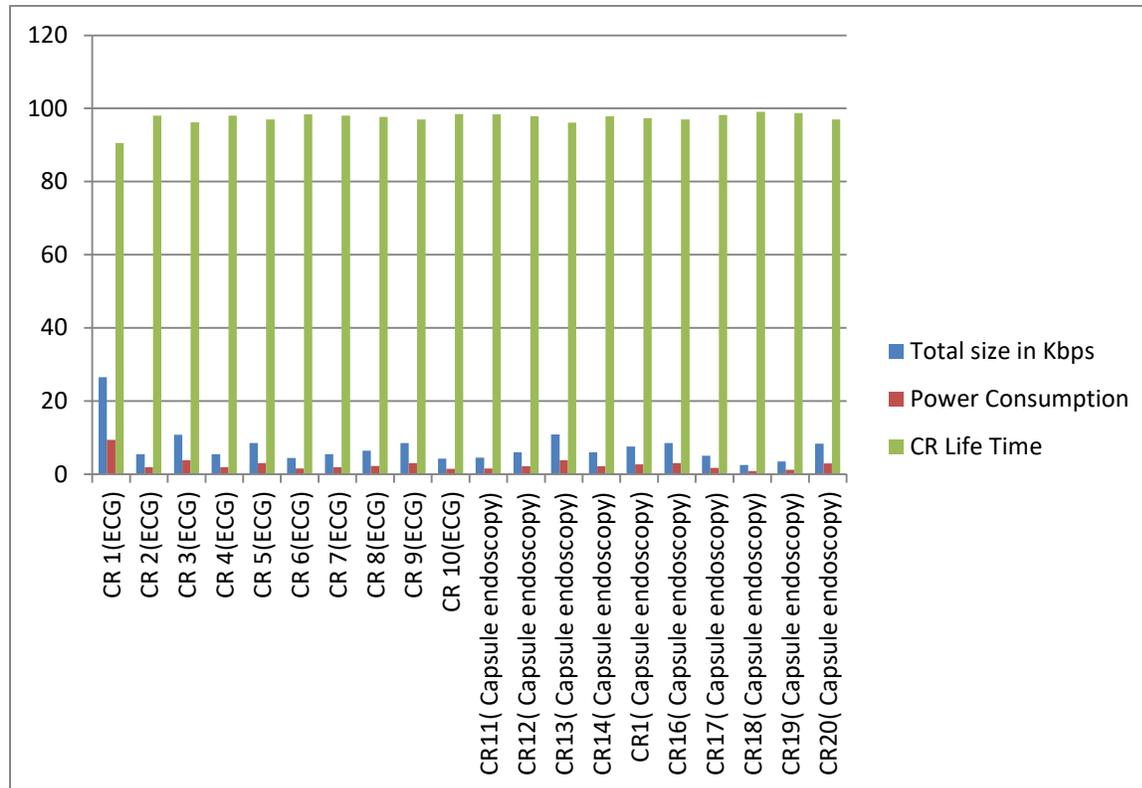


Figure 4.3: Power Consumption and CR Life Time of 20 CR nodes

4.3 Cooperative Spectrum Sensing with Group Manager

Case1: 6 Cognitive Radio Nodes

The second state of the 6 CR nodes simulated with 2 PU and the evaluation parameters based on the different variables, as the topology showed in Appendix A. The sensing signals details showed in Table 4.22.

Table 4.22: the Sensing signals details of the 6 CR nodes of 2nd case study.

Active CR Nodes	No. of Sensing signal	Size of each signal	Total size in Bytes
CR1(ECG)	11	124 Bytes	1364
CR2(ECG)	1		124
CR3(ECG)	4		496

CR4(Capsule endoscopy)	2		248
CR5(Capsule endoscopy)	4		496
CR6(Capsule endoscopy)	2		248

While the data signals details showed in Table 4.23.

Table 4.23: the data signals with total size in Bytes of 2nd case study.

Active CR Nodes	No. of Data signal	Size of each signal	Total size in Bytes
CR1(ECG)	41	133 Bytes	5453
CR2(ECG)	11		1463
CR3(ECG)	14		1862
CR4(Capsule endoscopy)	21	169 bytes	3549
CR5(Capsule endoscopy)	9		1521
CR6(Capsule endoscopy)	18		3042

Besides, the Acknowledgement signals showed in Table 4.24.

Table 4.24: The Ack signals of the 6 CR nodes of 2nd case study.

Active CR Nodes	No. of Ack. signal	Size of each signal	Total size in Bytes
CR1(ECG)	24	23 Bytes	552
CR2(ECG)	7		161
CR3(ECG)	10		230
CR4(Capsule endoscopy)	12		276

CR5(Capsule endoscopy)	6		138
CR6(Capsule endoscopy)	14		322

Table 4. 25 showed the total sensing, data, and Ack. signals with the summation and total size in Kbps.

Table 4.25: Summation and total size for 6 CR signals of 2nd case study.

Active CR Nodes	Total Sensing signal with size	Total Data signal with size	Total Ack. signal with size	Summation In Byte	Total size in Kb
CR1(ECG)	1364	5453	552	7369	58.952
CR2(ECG)	124	1463	161	1748	13.984
CR3(ECG)	496	1862	230	2588	20.704
CR4(Capsule endoscopy)	248	3549	276	4073	32.584
CR5(Capsule endoscopy)	496	1521	138	2155	17.24
CR6(Capsule endoscopy)	248	3042	322	3612	28.896

While Table 4.26 showed the data signals convert from Byte to Kilobits and find throughput.

Table 4.26: Throughput for the data signals of 6 CR nodes of 2nd case study.

Active CR Nodes	Total Data signal with size	Total size in Kb	Throughput in Kbps
CR1(ECG)	5453	43.624	0.145413
CR2(ECG)	1463	11.704	0.039013
CR3(ECG)	1862	14.896	0.049653
CR4(Capsule endoscopy)	3549	28.392	0.09464

CR5(Capsule endoscopy)	1521	12.168	0.04056
CR6(Capsule endoscopy)	3042	24.336	0.08112
Throughput in Kbps	0.4504 Kbps		

Besides, Table 4.27, and Figure 4.5 showed Power Consumption and CR Life Time based on the total signals (Sensing, Data, Ack.)

Table 4.27: Power Consumption and CR Life Time of 6 CR case of 2nd case study.

Active CR Nodes	Total size in Kb	Power Consumption(mw)	CR Life Time(ms)
CR1(ECG)	58.952	20.92796	79.07204
CR2(ECG)	13.984	4.96432	95.03568
CR3(ECG)	20.704	7.34992	92.65008
CR4(Capsule endoscopy)	32.584	11.56732	88.43268
CR5(Capsule endoscopy)	17.24	6.1202	93.8798
CR6(Capsule endoscopy)	28.896	10.25808	89.74192

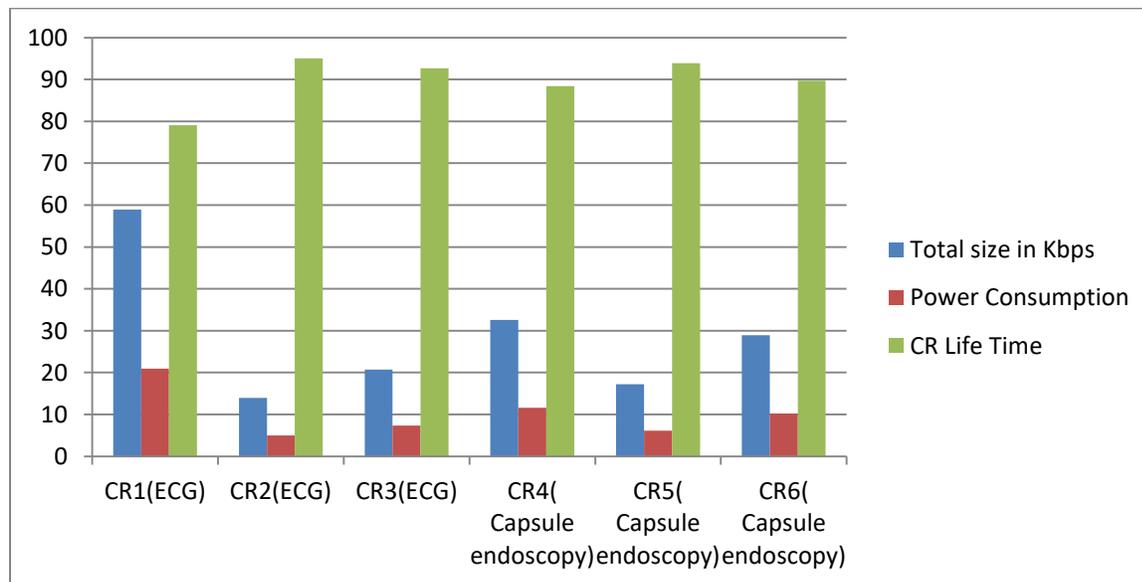


Figure 4.4: Power Consumption and CR Life Time of 6 CR nodes.

Case2: 10 Cognitive Radio Nodes

The second state of the 10 CR nodes simulated with 4 PU and the evaluation parameters based on the different variables, as the topology showed in Appendix B. The sensing signals details showed in Table 4.28.

Table 4.28: the Sensing signals details of the 10 CR nodes.

Active CR Nodes	No. of Sensing signal	Size of each signal	Total size in Bytes
CR1(ECG)	8	124 Bytes	992
CR2(ECG)	1		124
CR3(ECG)	3		372
CR 4(ECG)	1		124
CR5(ECG)	2		248
CR6(Capsule endoscopy)	1		124
CR7(Capsule endoscopy)	2		248
CR8(Capsule endoscopy)	1		124
CR9(Capsule endoscopy)	1		124
CR10(Capsule endoscopy)	2		248

While the data signals details showed in Table 4.29.

Table 4.29: the data signals with total size in Bytes.

Active CR Nodes	No. of Data signal	Size of each signal	Total size in Bytes
CR1(ECG)	30	133 Bytes	3990
CR2(ECG)	9		1197

CR3(ECG)	10		1330
CR 4(ECG)	16		2128
CR5(ECG)	6		798
CR6(Capsule endoscopy)	13	169 bytes	2197
CR7(Capsule endoscopy)	5		845
CR8(Capsule endoscopy)	8		1352
CR9(Capsule endoscopy)	11		1859
CR10(Capsule endoscopy)	14		2366

Besides, the Acknowledgement signals showed in Table 4.30.

Table 4.30: The Ack. signals of the 10 CR nodes.

Active CR Nodes	No. of Ack. signal	Size of each signal	Total size in Bytes
CR1(ECG)	15	23 Bytes	345
CR2(ECG)	5		115
CR3(ECG)	6		138
CR 4(ECG)	9		207
CR5(ECG)	4		92
CR6(Capsule endoscopy)	11		253
CR7(Capsule endoscopy)	5		115
CR8(Capsule endoscopy)	6		138
CR9(Capsule endoscopy)	9		207
CR10(Capsule endoscopy)	12		276

Table 4. 31 showed the total sensing, data, and Ack signals with the summation and total size in Kbps.

Table 4.31: Summation and total size for 10 CR signals of 2nd case study .

Active CR Nodes	Total Sensing signal with size	Total Data signal with size	Total Ack. signal with size	Summation In Byte	Total size in Kb
CR1(ECG)	992	3990	345	5327	42.616
CR2(ECG)	124	1197	115	1436	11.488
CR3(ECG)	372	1330	138	1840	14.72
CR 4(ECG)	124	2128	207	2459	19.672
CR5(ECG)	248	798	92	1138	9.104
CR6(Capsule endoscopy)	124	2197	253	2574	20.592
CR7(Capsule endoscopy)	248	845	115	1208	9.664
CR8(Capsule endoscopy)	124	1352	138	1614	12.912
CR9(Capsule endoscopy)	124	1859	207	2190	17.52
CR10(Capsule endoscopy)	248	2366	276	2890	23.12

While table 4.32 showed the data signals convert from Byte to Kilobits and find throughput.

Table 4.32: Throughput for the data signals of 10 CR nodes of 2nd case study.

Active CR Nodes	Total Data signal with size	Total size in Kb	Throughput in Kbps
CR1(ECG)	3990	31.92	0.1064
CR2(ECG)	1197	9.576	0.03192
CR3(ECG)	1330	10.64	0.035467

CR 4(ECG)	2128	17.024	0.056747
CR5(ECG)	798	6.384	0.02128
CR6(Capsule endoscopy)	2197	17.576	0.058587
CR7(Capsule endoscopy)	845	6.76	0.022533
CR8(Capsule endoscopy)	1352	10.816	0.036053
CR9(Capsule endoscopy)	1859	14.872	0.049573
CR10(Capsule endoscopy)	2366	18.928	0.063093

Besides, Table 4.33, and Figure 4.6 showed Power Consumption and CR Life Time based on the total signals (Sensing, Data, Ack.)

Table 4.33: Power Consumption and CR Life Time of 10 CR case of 2nd case study.

Active CR Nodes	Total size in Kbps	Power Consumption	CR Life Time
CR1(ECG)	42.616	15.12868	84.87132
CR2(ECG)	11.488	4.07824	95.92176
CR3(ECG)	14.72	5.2256	94.7744
CR 4(ECG)	19.672	6.98356	93.01644
CR5(ECG)	9.104	3.23192	96.76808
CR6(Capsule endoscopy)	20.592	7.31016	92.68984
CR7(Capsule endoscopy)	9.664	3.43072	96.56928
CR8(Capsule endoscopy)	12.912	4.58376	95.41624
CR9(Capsule endoscopy)	17.52	6.2196	93.7804
CR10(Capsule endoscopy)	23.12	8.2076	91.7924

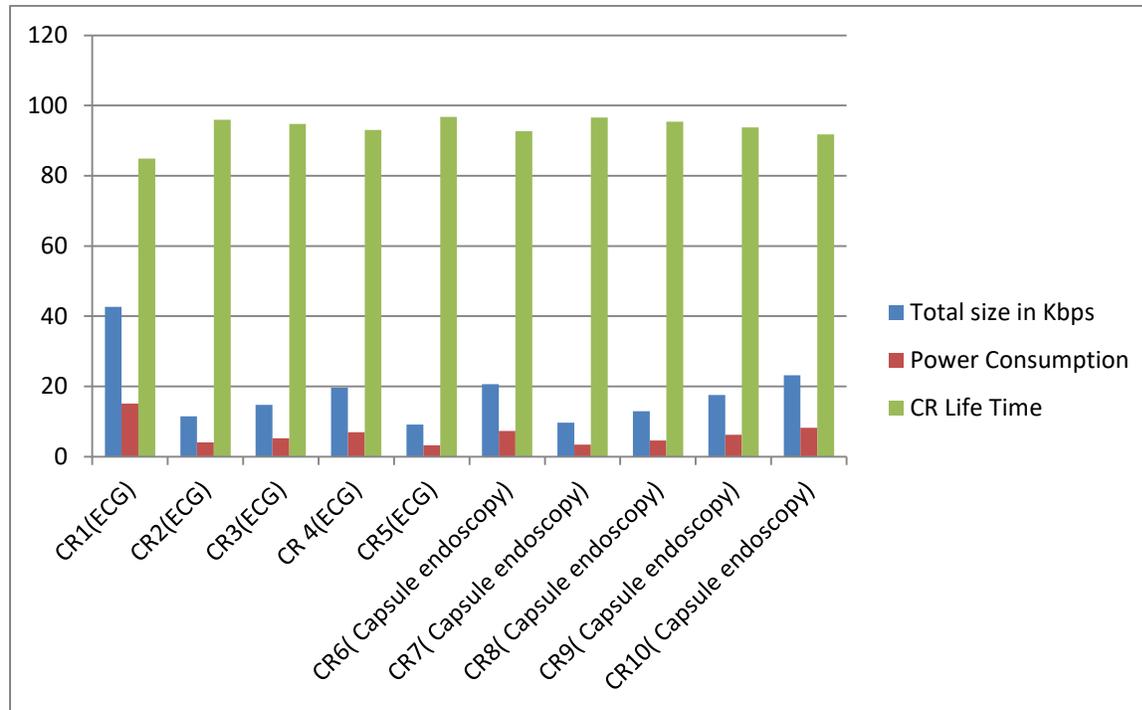


Figure 4.5: Power Consumption and CR Life Time of 10 CR nodes of 2nd case study.

Case3: 20 Cognitive Radio Nodes

The third state of the 20 CR nodes simulated with 10 PU and the evaluation parameters based on the different variables, as the topology showed in Appendix C. The sensing signals details showed in Table 4.34.

Table 4.34: the Sensing signals details of the 20 CR nodes of 2nd case study.

Active CR Nodes	No. of Sensing signal	Size of each signal	Total size in Bytes
CR 1(ECG)	7	124 Bytes	868
CR 2(ECG)	1		124
CR 3(ECG)	2		248
CR 4(ECG)	1		124
CR 5(ECG)	1		124
CR 6(ECG)	2		248

CR 7(ECG)	2		248
CR 8(ECG)	1		124
CR 9(ECG)	1		124
CR 10(ECG)	1		124
CR11(Capsule endoscopy)	1		124
CR12(Capsule endoscopy)	2		248
CR13(Capsule endoscopy)	1		124
CR14(Capsule endoscopy)	1		124
CR15(Capsule endoscopy)	2		248
CR16(Capsule endoscopy)	1		124
CR17(Capsule endoscopy)	2		248
CR18(Capsule endoscopy)	2		248
CR19(Capsule endoscopy)	1		124
CR20(Capsule endoscopy)	1		124

While the data signals details showed in Table 4.35.

Table 4.35: the data signals with total size in Bytes of 2nd case study.

Active CR Nodes	No. of Data signal	Size of each signal	Total size
CR 1(ECG)	10	133 Bytes	1330
CR 2(ECG)	3		399
CR 3(ECG)	5		665
CR 4(ECG)	3		399

CR 5(ECG)	4		532
CR 6(ECG)	3		399
CR 7(ECG)	4		532
CR 8(ECG)	3		399
CR 9(ECG)	5		665
CR 10(ECG)	3		399
CR11(Capsule endoscopy)	2	169 bytes	338
CR12(Capsule endoscopy)	2		338
CR13(Capsule endoscopy)	5		845
CR14(Capsule endoscopy)	3		507
CR15(Capsule endoscopy)	4		676
CR16(Capsule endoscopy)	4		676
CR17(Capsule endoscopy)	3		507
CR18(Capsule endoscopy)	3		507
CR19(Capsule endoscopy)	2		338
CR20(Capsule endoscopy)	4		676

Besides, the Acknowledgement signals showed in Table 4.36.

Table 4.36: The Ack signals of the 20 CR nodes of 2nd case study.

Active CR Nodes	No. of Ack. signal	Size of each signal	Total size in Bytes
CR 1(ECG)	7		161
CR 2(ECG)	2		46

CR 3(ECG)	4	23 Bytes	92
CR 4(ECG)	2		46
CR 5(ECG)	3		69
CR 6(ECG)	3		69
CR 7(ECG)	2		46
CR 8(ECG)	2		46
CR 9(ECG)	3		69
CR 10(ECG)	2		46
CR11(Capsule endoscopy)	2		46
CR12(Capsule endoscopy)	2		46
CR13(Capsule endoscopy)	3		69
CR14(Capsule endoscopy)	3		69
CR15(Capsule endoscopy)	4		92
CR16(Capsule endoscopy)	3		69
CR17(Capsule endoscopy)	3		69
CR18(Capsule endoscopy)	2		46
CR19(Capsule endoscopy)	2		46
CR20(Capsule endoscopy)	2		46

Table 4. 37 showed the total sensing, data, and Ack. signals with the summation and total size in Kb.

Table 4.37: Summation and total size for 20 CR signals of 2nd case study.

Active CR Nodes	Total Sensing signal with size	Total Data signal with size	Total Ack. signal with size	Summation In Byte	Total size in Kb
CR 1(ECG)	868	1330	161	2359	18.872
CR 2(ECG)	124	399	46	569	4.552
CR 3(ECG)	248	665	92	1005	8.04
CR 4(ECG)	124	399	46	569	4.552
CR 5(ECG)	124	532	69	725	5.8
CR 6(ECG)	248	399	69	716	5.728
CR 7(ECG)	248	532	46	826	6.608
CR 8(ECG)	124	399	46	569	4.552
CR 9(ECG)	124	665	69	858	6.864
CR 10(ECG)	124	399	46	569	4.552
CR11(Capsule endoscopy)	124	338	46	508	4.064
CR12(Capsule endoscopy)	248	338	46	632	5.056
CR13(Capsule endoscopy)	124	845	69	1038	8.304
CR14(Capsule endoscopy)	124	507	69	700	5.6
CR15(Capsule endoscopy)	248	676	92	1016	8.128
CR16(Capsule endoscopy)	124	676	69	869	6.952
CR17(Capsule endoscopy)	248	507	69	824	6.592
CR18(Capsule endoscopy)	248	507	46	801	6.408
CR19(Capsule endoscopy)	124	338	46	508	4.064

CR20(Capsule endoscopy)	124	676	46	846	6.768
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While table 4.38 showed the data signals convert from Byte to Kilobits and find throughput.

Table 4.38: Throughput for the data signals of 20 CR nodes of 2nd case study.

Active CR Nodes	Total Data signal with size	Total size in Kb	Throughput in Kbps
CR 1(ECG)	1330	10.64	0.035467
CR 2(ECG)	399	3.192	0.01064
CR 3(ECG)	665	5.32	0.017733
CR 4(ECG)	399	3.192	0.01064
CR 5(ECG)	532	4.256	0.014187
CR 6(ECG)	399	3.192	0.01064
CR 7(ECG)	532	4.256	0.014187
CR 8(ECG)	399	3.192	0.01064
CR 9(ECG)	665	5.32	0.017733
CR 10(ECG)	399	3.192	0.01064
CR11(Capsule endoscopy)	338	2.704	0.009013
CR12(Capsule endoscopy)	338	2.704	0.009013
CR13(Capsule endoscopy)	845	6.76	0.022533
CR14(Capsule endoscopy)	507	4.056	0.01352
CR15(Capsule endoscopy)	676	5.408	0.018027
CR16(Capsule endoscopy)	676	5.408	0.018027

CR17(Capsule endoscopy)	507	4.056	0.01352
CR18(Capsule endoscopy)	507	4.056	0.01352
CR19(Capsule endoscopy)	338	2.704	0.009013
CR20(Capsule endoscopy)	676	5.408	0.018027
Total Throughput in Kbps	0.29672 Kbps		

Besides, Table 4.39, and Figure 4.7 showed Power Consumption and CR Life Time based on the total signals (Sensing, Data, Ack).

Table 4.39: Power Consumption and CR Life Time of 20 CR case of 2nd case study.

Active CR Nodes	Total size in Kb	Power Consumption	CR Life Time
CR 1(ECG)	18.872	6.69956	93.30044
CR 2(ECG)	4.552	1.61596	98.38404
CR 3(ECG)	8.04	2.8542	97.1458
CR 4(ECG)	4.552	1.61596	98.38404
CR 5(ECG)	5.8	2.059	97.941
CR 6(ECG)	5.728	2.03344	97.96656
CR 7(ECG)	6.608	2.34584	97.65416
CR 8(ECG)	4.552	1.61596	98.38404
CR 9(ECG)	6.864	2.43672	97.56328
CR 10(ECG)	4.552	1.61596	98.38404
CR11(Capsule endoscopy)	4.064	1.44272	98.55728
CR12(Capsule endoscopy)	5.056	1.79488	98.20512

CR13(Capsule endoscopy)	8.304	2.94792	97.05208
CR14(Capsule endoscopy)	5.6	1.988	98.012
CR15(Capsule endoscopy)	8.128	2.88544	97.11456
CR16(Capsule endoscopy)	6.952	2.46796	97.53204
CR17(Capsule endoscopy)	6.592	2.34016	97.65984
CR18(Capsule endoscopy)	6.408	2.27484	97.72516
CR19(Capsule endoscopy)	4.064	1.44272	98.55728
CR20(Capsule endoscopy)	6.768	2.40264	97.59736

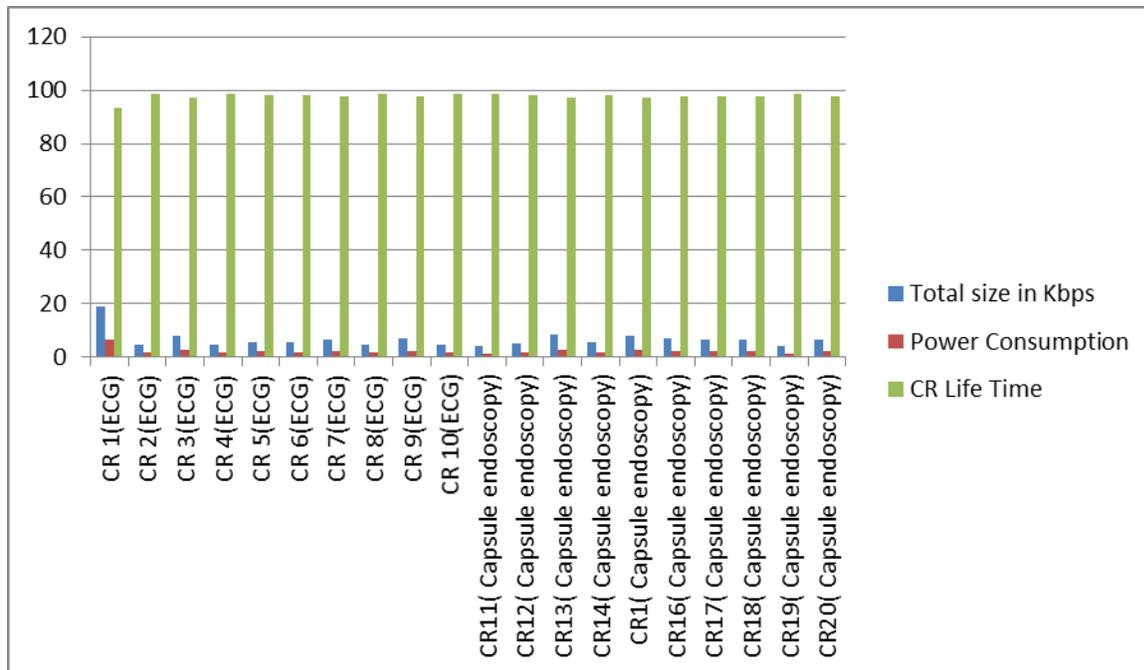


Figure 4.6: Power Consumption and CR Life Time of 20 CR nodes of 2nd case study.

4.4 System Comparison

The proposed system compared with the case study of without Group Manager node (GM) and with other related works as showed in Table 4.40.

Table 4.40 : The 1st case study of without group manager and the 2nd case study of group manager with (6, 10, 20) CR nodes .

Without GM				
CR Nodes	Avg. Total size in Kbps(Signals traffic)	Avg. Power Consumption	Avg. CR Life Time	Total Throughput(Data) in Kbps
6 CR Nodes	43.2106	15.33773	84.65317	0.422693 Kbps
10 CR Nodes	26.708	9.48134	90.51866	0.420773 in Kbps
20 CR Nodes	7.4596	2.648158	97.351842	0.209093 Kbps
With GM				
CR Nodes	Avg Total size in Kbps (Signals traffic)	Avg Power Consumption	Avg CR Life Time	Total Throughput(Data) in Kbps
6 CR Nodes	28.72666667	10.19796667	89.80203333	0.4504 Kbps
10 CR Nodes	18.1408	6.439984	93.560016	0.481653 Kbps
20 CR Nodes	6.6028	2.343994	97.656006	0.29672 Kbps
[11], ECG	/	/	/	0.1065 Kbps
[11], Capsule endoscopy	/	/	/	0.35322 Kbps

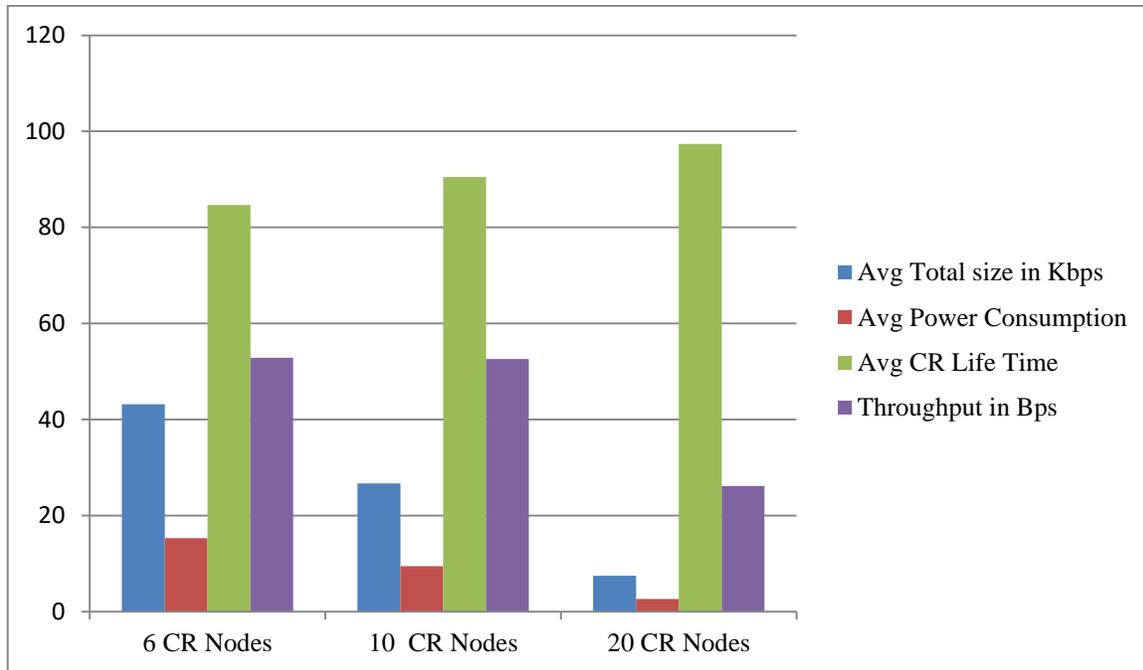


Figure 4.7: Avg. Total size, Avg. Power Consumption, Avg. CR Life Time, Total Throughput of the 1st case study.

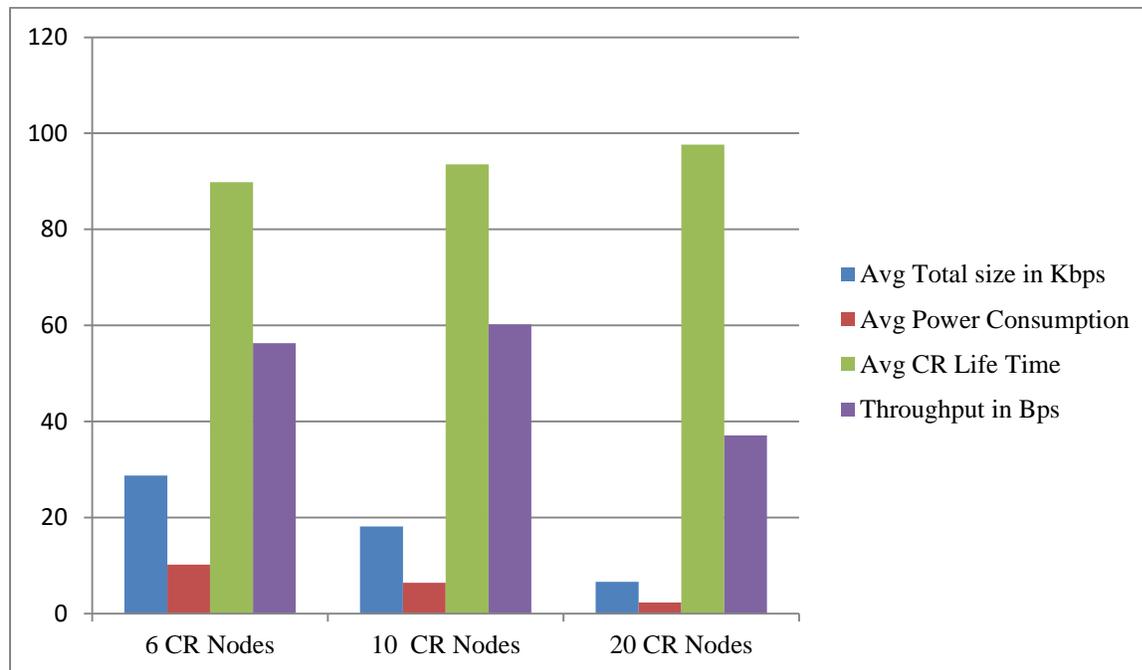


Figure 4.8: Avg. Total size, Avg. Power Consumption, Avg. CR Life Time, Total Throughput of the 2nd case study.

CHAPTER FIVE

Conclusions and Future Works

5.1 Conclusions

This chapter explains the proposed system conclusions and the main suggestions for future works they can be summarized as:

1. The wireless communication is a backbone for a development of a nation. But spectrum is finite resource and issues like spectrum scarcity, loss of signal quality, transmission delay, raised in wireless communication system due to growth of wireless applications and exponentially increased number of users.
2. Cognitive Radio (CR) is used to solve the problem of radio frequency scarcity. It is an intelligent and dynamically reconfigurable radio.
3. In a cognitive radio network with an increase in the number of secondary users, cooperative spectrum sensing may become impractical because in the time interval one CR must send its local sensing decision to the common receiver for the purpose of separating the decisions easily at the receiver end.
4. The proposed Cognitive Radio (CR) system is based on the simulation parameters: Throughput, power consumption, CR life time simulation parameters.
5. The proposed cooperative sensing system of Group Manager (GM) enhanced throughput as 1.066% for 6 nodes, 10.655% for 10 nodes, and 14.191% for 20 nodes compared with the case of without GM.
6. The power consumed decreased for better results as 66.489%, 67.923% and 88.514%. For the case of 6 CR, 10 CR, and 20 CR respectively.
7. The CR life time increase for better results as 10.608%, 10.336%, and 10.031. For the case of 6 CR nodes, 10 CR, and 20 CR respectively.

5.2 Suggestions for Future Works

1. Implementation of the proposed approach based on SDR by using a suitable platform.
2. Using another sensing techniques such as match filter detection.
3. Studying the impact of the proposed approach on security.
4. Developing the implemented approach to work as CSS optimization for CR in 6 G networks
5. Applying the proposed approach on other types of data type such as video, voice and files within other application such as Military application.

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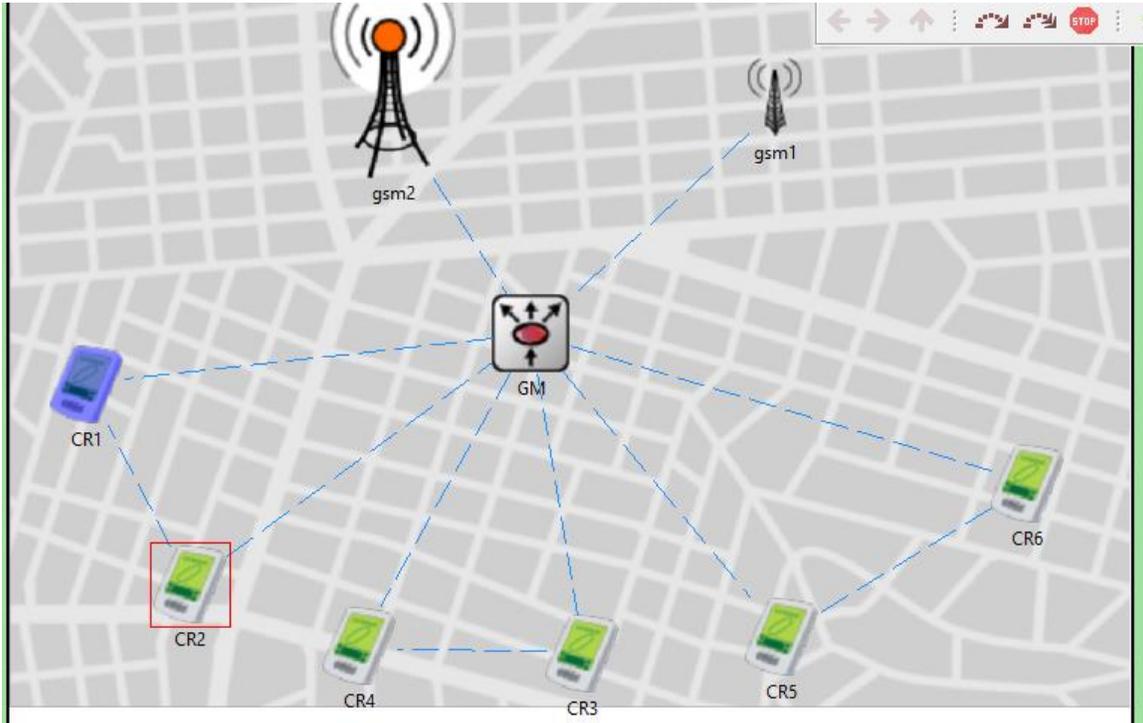
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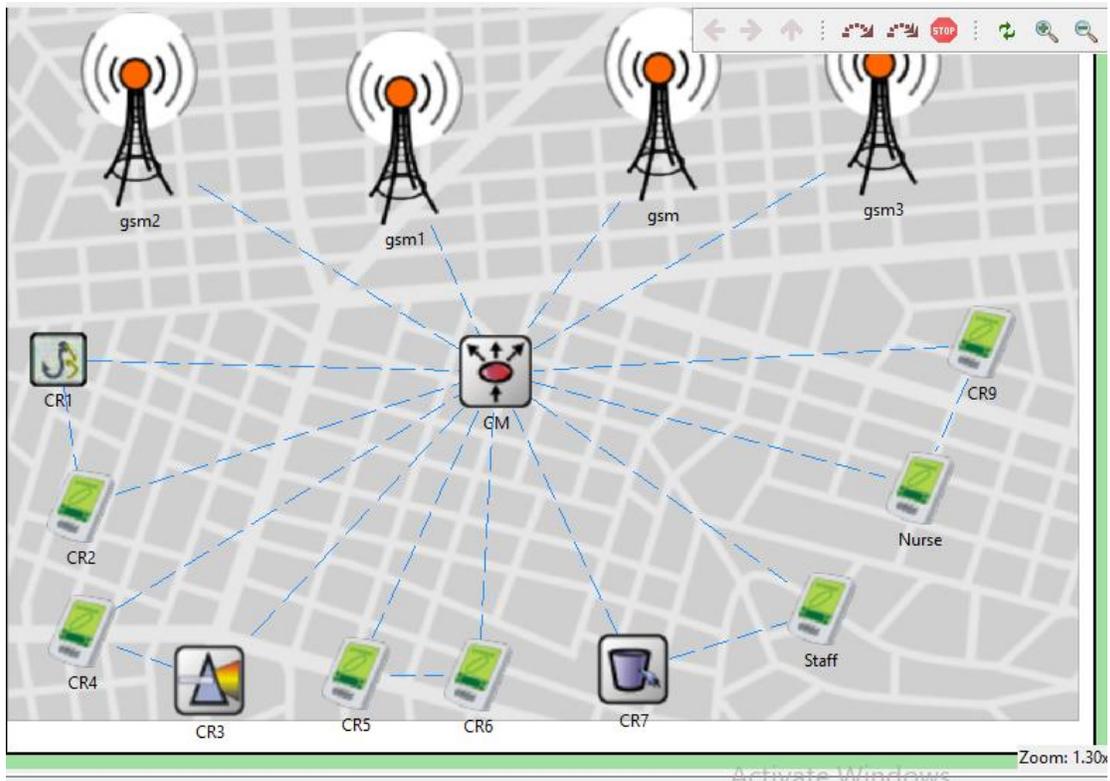
Appendix of Chapter 4

Appendix A



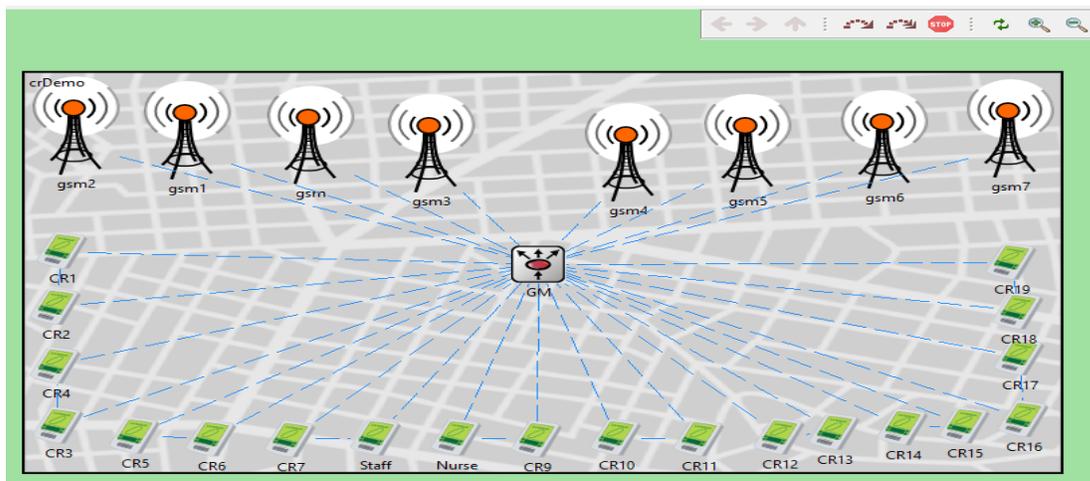
The case of 6 Cognitive Radio Nodes

Appendix B



The case of 10 Cognitive Radio Nodes

Appendix C



The case of 20 Cognitive Radio Nodes

Appendix D

Browse Data

Here you can see all data that come from the files specified in the Inputs page.

All (114 / 114) Vectors (6 / 6) Scalars (108 / 108) Histograms (0 / 0)

runID filter module filter statistic name filter

Ex...	R...	Module	Name	Vec...	Count	Mean	StdDev	Max	Min time	Max time
Ge...	#0	crDemo.CR1.specSensor	sensingSignal:vector	0	1204	1.500830564784...	0.50020708...	2.0	0.548863502...	0.90005
Ge...	#0	crDemo.CR2.specSensor	sensingSignal:vector	1	2	1.5	0.70710678...	2.0	0.549046835...	0.800283333333
Ge...	#0	crDemo.CR3.specSensor	sensingSignal:vector	3	1115	1.499551569506...	0.50022416...	2.0	0.844315744...	0.90001574409
Ge...	#0	crDemo.CR4.specSensor	sensingSignal:vector	2	1	1.0	n.a.	1.0	0.900065744...	0.90006574409
Ru...	#0	crDemo.CR1.specSensor	sensingSignal:vector	0	196	1.505102040816...	0.50125431...	2.0	0.548863502...	0.64965
Ru...	#0	crDemo.CR2.specSensor	sensingSignal:vector	1	2	1.5	0.70710678...	2.0	0.549046835...	0.600283333333

module filter statistic name filter

Name	Vector id	Count	Mean	StdDev	Max	Min time	Max time
sensingSignal:vector	0	196	1.505102040816...	0.50125431...	2.0	0.548863502...	0.64965
sensingSignal:vector	1	2	1.5	0.70710678...	2.0	0.549046835...	0.600283333333

The sample of statistics from OMNET++ of the proposed system.



جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة بابل
كلية تكنولوجيا المعلومات
قسم شبكات المعلومات

نهج استشعار متطور في شبكات الراديو الادراكي التعاوني

رسالة مقدمة

إلى مجلس كلية تكنولوجيا المعلومات في جامعة بابل والتي هي جزء من متطلبات
الحصول على درجة الماجستير في تكنولوجيا المعلومات / شبكات المعلومات

من قبل الطالبة

دعاء عايد محمد ياسين

باشرف

أ.د ستار بدر سدخان

م 2021

هـ 1443

الخلاصة

الراديو المعرفي هو حل لمشكلة الازدحام الطيفي من خلال إدخال الاستخدام الانتهازي لنطاقات التردد التي لا تشغل بشدة من قبل المستخدمين المرخص لهم. ان استشعار الطيف مهم في الراديو المعرفي لتجنب الاصطدامات مع المستخدمين المرخص لهم ولتحسين كفاءة استخدام الطيف المرخص له. إن اشارة جهاز الارسال الاولي لا يمكن اكتشافها بسبب مواقع الاجهزة (مشكلة المستخدم الاولي المخفية). ويمكن أن يكون سببه العديد من العوامل بما في ذلك تلاشي شديد متعدد المسارات أو التباطؤ الذي يلاحظه المستخدمون الثانويون. وتسمح شبكة الراديو المعرفي التعاونية لمستخدمي الراديو المعرفي المختلفين بتقاسم معلومات الاستشعار وزيادة دقة الكشف الأولي للمستخدمين ، ولكن التعقيد ازداد مع زيادة عدد المستخدمين وبالتالي زيادة عدد رسائل الاستشعار التي تسببت في استهلاك الطاقة ، والتي تؤثر على مدى حياة الراديو المعرفي. وتتناول هذه الأطروحة مشكلة استهلاك الطاقة و تحسين نهج الاستشعار باستخدام عقدة خارجية للقيام بعملية استشعار الطيف.

ويحاكي النظام المقترح نوع بيانات الرعاية الصحية (ECG) و(Endoscopy) في بيئة الشبكات اللاسلكية المعرفية. وعلاوة على ذلك ، تم تطبيق النظام المقترح باستخدام أداة محاكاة OMNET++. فقد عمل نظام الاستشعار التعاوني المقترح التابع Group Manager على تعزيز الإنتاج بنسبة 1.066% ل6 عقد ، و 10.655% ل10 عقد ، و 14.191% ل20 عقدة مقارنة بحالة عدم وجود Group Manager. وانخفضت الطاقة المستهلكة لتحقيق نتائج أفضل حيث بلغت 66.489% و 67.923% و 88.514%. بالنسبة لحالة 6 CR node ، و 10 CR node ، و 20 CR node على التوالي. إن الزيادة الزمنية في عمر الCR من أجل تحقيق نتائج أفضل بلغت 10.608% ، 10.336% ، 10.031%. بالنسبة لحالة 6 عقدة و 10 عقدة و 20 عقدة ، على التوالي.