RESOURCE ALLOCATION FOR UNDERLAY COGNITIVE RADIO NETWORKS

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RESOURCE ALLOCATION FOR UNDERLAY COGNITIVE RADIO NETWORKS

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Submitted by: **Muthana Hatem Dahham AL-JANABI**

Approval of the Graduate School of Natural and Applied Sciences, Çankaya University.

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ABSTRACT

RESOURCE ALLOCATION FOR UNDERLAY COGNITIVE RADIO NETWORKS

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Cognitive Radio (CR) has appeared as one of the solutions to mitigate the spectrum scarcity problem. One of areas that has suffered from spectrum scarcity is Wireless Body Area Networks (WBAN). It is possible to use CR with an adaptive power control and transmit scheme over the same channel as a licensed user. This is called the underlay approach. Since the number of applications that use the unlicensed bands is rapidly increasing, it is important to devise methods that utilize licensed bands without causing problems to the licensed user. Utilizing underlay CR in WBAN applications may help resource constrained sensors to operate even in cases where unlicensed bands are full. Another problem is the limited lifetime of sensors. Recently, energy harvesting has emerged as a topic of much attention to increase the lifetime of sensors. CR-WBANs can help us to build a healthcare system that is more reliable and efficient than traditional WBANs; however, many challenges still need to be investigated. In this thesis, we examine the minimum required power that must be transmitted from a specialized device called the hybrid access point (HAP) to have the network running indefinitely. A HAP is used both to transfer energy to the sensors and to gather sensor data and forward it to the higher layer in the WBAN.

Keywords: Underlay Cognitive Radio; Wireless Body Area Network (WBAN); Energy consumption; Energy harvesting; Convex optimization.

ÖZET

TABAN YAKLAŞIMLI BİLİŞSEL RADYO AĞLARINDA KAYNAK DÜZENLEMESİ

AL-JANABI, Muthana Hatem Dahham

Elektronik ve Haberleşme Mühendisliği Yüksek Lisans

Tez Danışmanı: Dr. Öğr. Üyesi Özgür ERGÜL

Ağustos 2019

Bilişsel radyo, radyo tayfındaki doluluk sorununa cevap olarak ortaya çıkmıştır. Bu sorunun yaşandığı alanlardan biri de kablosuz vücut alan ağlarıdır. Bilişsel radyolarda güç kontrolü yaparak lisanslı kullanıcının performansını etkilemeden onunla aynı bantta iletişim yapmak mümkün olmaktadır. Buna taban yaklaşımı denilmektedir. Lisans gerektirmeyen bantları kullanan uygulama sayısı hızla artmakta olduğundan, lisanslı kullanıcıyı etkilemeden lisanslı bantları kullanabilecek yöntemler geliştirmek önem kazanmıştır. Taban yaklaşımlı bilişsel radyoyu kablosuz vücut alan ağlarında kullanmak, kaynak sıkıntısı olan bu cihazların lisanssız bantların dolu olduğu bölgelerde bile işlevsel olmasını sağlayacaktır. Diğer bir sorun da sensörlerin sınırlı pil ömürleridir. Son zamanlarda, enerji harmanı sensörlerin pil ömürlerini artıracak bir çözüm olarak ortaya çıkmıştır. Bilişsel radyo kablosuz vücut ağları geleneksel yöntemlere kıyasla daha güvenilir ve daha verimli sağlık sistemleri yaratmamıza yardımcı olacaktır; ancak hala incelenmesi gereken pek çok zorluk bulunmaktadır. Bu tezde hibrit erişim noktası adı verilen özel bir cihazdan gönderilmesi gereken minimum enerji miktarı incelenmiştir. Hibrit erişim noktası hem sensörlere enerji transferi, hem de sensörlerden veri toplayıp sistemdeki daha üst birimlere iletme amacı ile kullanılmaktadır.

Anahtar kelilemer: Kablosuz vücut alanı ağları; taban yaklaşımlı bilişsel radyo; Veri iletim hızı; enerji harmanı; konveks optimizasyon.

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This has been a long and sometimes an arduous journey. It would have been longer or even impossible without the support from many individuals.

I would like to express my gratitude towards my Supervisor Dr. Instructor. Özgür ERGÜL for providing me complete freedom to pursue my research interests. I thank him for his invaluable guidance throughout my thesis.

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LIST OF ABBREVIATIONS

WBAN	: Wireless Body Area Network
EEG	: Electroencephalography
ECG	: Electrocardiography
CR	: Cognitive Radio
PS	: Portable Server
AP	: Access Point
PU	: Primary User
SU	: Secondary User
QoS	: Quality of Service
PSD	: Power Spectral Density
TDMA	: Time Division Multiple Access
RF	: Radio Frequency
WPCN	: Wireless Powered Communication Network
WET	: Wireless Energy Transfer
WIT	: Wireless Information Transfer
CE	: Channel Estimation
CH	: Cluster head
HAP	: Hybrid access point
WD	: Wireless device
PT	: Primary transmitter
PR	: Primary receiver
CM	: Cluster members

CHAPTER ONE

1.1 Introduction:

Technological advancement has brought a revolution to today's human life. It has changed how humans work in every field of life, such as home automation, smart cities, environment monitoring, and prediction [1-5]; nevertheless, there are a number of challenges, one of which is healthcare in a fast growing world population and decreasing number of healthcare facilities relative to the population.

According to the US Census Bureau, it had been predicted that the population of aged people in the world would double from 375 million in 1990 to 761 million in 2025 [6]. Generally, the elderly suffer from various chronic diseases, thus they require continuous medical care. Many are required to stay in hospitals or remain under the constant supervision of medical professionals, lest their lives may be at risk. Every year, thousands of people die due to fatal or chronic disease. The most common reason for such fatal diseases is the lack of timely diagnoses. Research has revealed that most of these diseases may be controlled if identified during their initial stages [7]. Therefore, there is an insistent need to develop proactive and affordable healthcare systems for continuous health monitoring without any attendants and to diagnose the early stages of any medical issues.

In recent years, the development in the medical field and in medical devices and healthcare systems has been insufficient. Medical facilities operated using wires this causes high complexity and makes it difficult to handle these facilities. However, nowadays the medical field is improving and the Wireless Body Area Network (WBAN) is the one of the key technologies in the medical field with the ability to change the landscape of the medical system [8].

The WBAN has the ability to change lifestyles in many areas, especially in the area of health monitoring. A WBAN consists of small, intelligent, low-power devices that can establish a wireless communication link and provide continuous monitoring health of patients to medical staff. These are placed in, on or around the body of the patient with collected medical data being received at the sink node. The received medical data of the patient are observed by the medical staff. These continuous measurements can improve the quality of treatment [9].

In general, WBANs can be used in medical and non-medical applications [10]. In medical applications, there are two types of devices: wearable medical devices and implantable medical devices, depending on the type of signal acquired from the patient (blood pressure, electroencephalography (EEG), electrocardiography (ECG), heart rate, blood glucose level, body temperature, body posture, blood oxygen saturation, etc.). Implantable medical devices are placed inside the human body, while wearable medical devices are worn or placed on the skin or very near to the patient. Biomedical sensor nodes sense or otherwise measure the different health signs of the body, and any medical data are then transmitted to the sink node. The sink node is situated on the human body or at a nearby location [11]. As Figure 1.1 shows, Wireless Body Sensor Networks (WBSNs) are used to show and measure different vital signs.

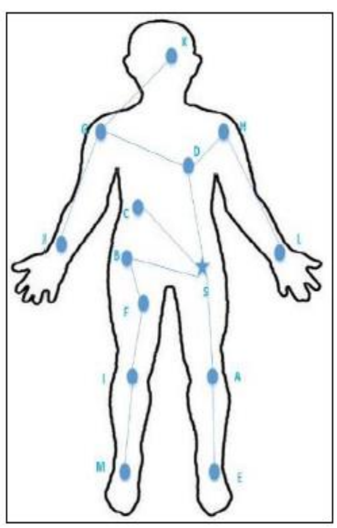

Figure 1.1: WBAN topology with 13 biosensors [11]

1.2 WBAN Architectures:

Figure 1.2 shows the general architecture of a WBAN health monitoring system. Through any wireless media connection (Bluetooth, etc.), these data are streamed remotely to a doctor's site, to a medical database for recording, or for an emergency alert issued to corresponding equipment. According to [12], WBAN communications can be classified into three tiers:

1.Tier-1 – Communication design (i.e., intra-BAN communication).

2. Tier-2 – Communication design (i.e., inter-BAN communication).

3. Tier-3 – Communication design (i.e., beyond-BAN communication).

These components cover multiple aspects ranging from low level to high level design issues and an efficient BAN system for a wide range of applications.

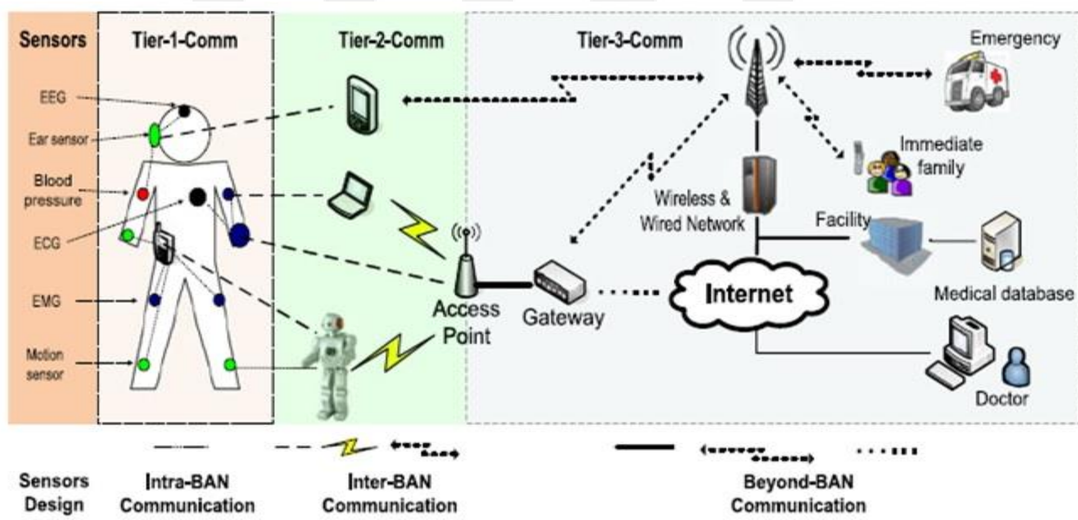

Figure 1.2 Tiers WBAN architecture [12].

1.2.1 Intra-BAN communications:

The radio communications in Intra-BAN range approximately 2 meters around the human body and they can be subcategorized as [12]:

-Communications that occur between sensors.

-Communications between sensors and nodes or portable server (PS).

The design of this tier is very critical since its battery operation and low bit rate make it a challenge to design an energy efficient protocol with QoS provisioning.

1.2.2 Inter-BAN communications:

Different from Wireless Sensor Network (WSN) that normally operate in independent system but the BAN hardly works alone. We can define this tier as the communication between the PS and one or more access points (APs).

The APs can be deployed as part of the infrastructure or placed in a dynamic environment for emergency situations. The implementation of this tier, as shown in Figure 1.2, is used to interconnect BANs with a network such as the Internet or cellular networks.

In [12], the paradigms of inter-BAN communication have been divided into two categories:

-Infrastructure based architecture; and

-Ad hoc based architecture.

While the former provides larger bandwidth, centralized control and flexibility, the latter has fast deployment when encountering a dynamic environment such as medical emergency care responses such as the Advanced Health and Disaster Aid Network [13].

1.2.3 Beyond-BAN communication:

Tier-3 communication was designed for use in metropolitan areas. In order to connect two networks for inter-BAN and beyond-BAN communications, a gateway device, such as a portable device or laptop, can be employed to create a wireless link between these two networks. As shown in Figure 1.2, this tier can provide a further step to authorized personal healthcare (such as from a doctor or nurse) to remotely access a patient's medical information through a cellular network or the Internet. The database is an important part of beyond-BAN since it contains the user's profile and medical history and the doctor has the ability to access the user's information as needed. At the same time, automated notifications can be sent to relatives via network communications.

The design of Tier-3 communication is very important because if any abnormalities are found based on the up-to-date body information transmitted to the database, an alarm or notification can be sent to the patient or the doctor via short message service (SMS). The doctor can communicate anything important with the patient directly through video conference to give instructions or even call an ambulance.

The immediacy of a monitoring healthcare system in WBANs is a positive influence on human health. It encourages patient versatility, and for long-term treatment whether in a hospital or the patient's home, it lowers the cost [14]. It provides a far field monitoring for aged people and persons with chronic diseases. This helps them to continue their ordinary exercises [15]. Nevertheless, the expanding requests for utilizing WBANs in the healthcare insurance framework have brought new difficulties to the system, such as overlaps with other signals from different devices, spectrum scarcity, delay in the medium, and collapse of system transmission [15]. The previous challenges could affect people and put their lives at risk.

The Cognitive radio (CR) methodology is one of the solutions to reduce previous problems and to enhance network performance.

CR technology is an emerging model that gives flexibility plus efficient utilization of a radio spectrum. It permits illegitimate users to sharply access the spectrum without making any unsafe impedance authentic clients (i.e., primary users (PUs)). The CR methodology inserts cognition as a smart component into the radio spectrum to identify a nominee channel that unlicensed clients (secondary users (SUs)) could use in a manner to increase spectrum usage. The CR network can make a decision smartly, determine how to think about future objectives, provide information prioritization, and monitor any encompassing conditions [16]. Consequently, deploying CR in WBANs will improve framework execution and overcome any pre-referenced difficulties.

1.3 Related Works:

In [21], cognitive radio technology for BAN was suggested such that it was used and applied in medical and other environments to increase the efficiency of wireless resource utilization where the interference and spectrum scarcity had been overcome in wireless communication.

In [22], a dual band printed antenna was presented with a metal back-cover for WBAN applications operating at 2.45 GHz and 5.8 GHz in industrial, scientific and health (ISM) groups.

A performance analysis of the antenna flatbed body was used that adore physical body.

In [23], a delay limitation was studied with the MAC protocol applied in medical signals with respect to scaling back the packet loss and time delay in Time Division Multiple Access (TDMA) initially based on CSMA/CA surroundings.

The proposed protocol frame was considered a Bio MAC protocol super frame having the same type of structure and the method that had been proposed was aimed to enhance or decrease delay, hence its name was Decrease of Transmission Delay (DTD-MAC).

The Wireless Body Sensor Network (WBSN) was established as a star and a static environment was performed in a computer simulation in which the range of node devices had not been modified. At the end, it was found that DTD-MAC was more efficient than Bio-MAC.

In [24,] the studied deal with security in WBANs by proposed an autonomous mobile agent based on intrusion detection design.

Cooperative performance and mobile agent migration were used for intrusion detection in WBAN since the behavior of each node in WBAN was a computing node, so the intrusion detection of multiple mobiles was developed therefor decision creating and learning is distributed in the network among different nodes.

In [25] an advance health industry, technology and exploration was provided as safety of the future astronaut throughout area which gives plan around analysis on WBAN.

In a spacesuit health monitoring system, sensors and Bluetooth modules should be implemented on the interior aspect of the pressure suit to shield instrumentation from bad surroundings and with efficiency live important signal and the Bluetooth must connected to the antenna.

In the simulation part, a Perfect Electric Conductor (PEC) was used because the ground plane material improves the antenna output. However, having an air gap is the downside in a pressure suit therefore and to decrease this gap, a folded ground style was enforced.

In [26], a multi hop WBAN construction was proposed based on three operations:

1. Setup of clustered topology;
2. Mobility support; and
3. Transmission efficiency improvement.

The existing schemes that work on a 1-hop based star network were efficient for short varying networks, while the multi hop network had many benefits.

In [27], body topology was proposed and primarily based on spatial distribution of medical sensors which used two ad-hoc routing protocols, Ad hoc on-Demand Distance Vector Routing (AODV) and Destination-Sequenced Distance-Vector Routing (DSDV) for the model. Two of the protocols showed that AODV was more appropriate for the transmission of knowledge from the settings.

In [28], an algorithm to a time-free synchronization algorithmic rule was proposed in which the sensors changed once they transmitted their messages to the central node, so the last one known the sensing element node's time offset is at the intervals want level of time accuracy and the desire level of time accuracy at that point central communication if time offset is exceeds node answer sensing element node.

In [29], a wearable dual-band magneto-electric dipole antenna was proposed and set to be worn for the purpose of checking other antennas for human body performance below bending conditions.

The bending evaluation is performed by the mounted antenna simulating a vacuum cylinder with a varying radius. This antenna was produced to be compatible in terms of radiation, beam width and gain within a large operative waveband.

In [30], the researchers presented the heart rate, oxygen in the blood and body temperature for the implementation of WBAN. The nodes sensed and analyzed the received information to the server receiver with a spread of vary distances.

In [31], the researchers focused on the routing part in the WBAN, especially those occurring in the personal and native area of WBAN and to obtain an optimal solution, they used fuzzy logic as it required less power than other typical approaches. They proposed a protocol to this routing called a zone routing protocol with the following elements:

- a proactive routing protocol.
- a combination of reactive.
- a hybrid protocol.

1.4 Aim of study:

In this thesis, we propose a wireless body area network sensor by using underlay cognitive radio to minimize the power of hybrid access points acting as a secondary system with a pair of primary systems.

1.5 Thesis outline:

2. In Chapter 2, a Cognitive Radio is briefly introduced followed by the modes of cognitive radio and then the resource allocation of underlay cognitive radio ending with state-of-the-art cognitive radio based wireless body area networks and unopen issues and future research in cognitive radio based wireless body areas.
3. In Chapter 3, we present a brief description of convex optimization with a number of examples.
4. Chapter 4 presents a system model of the cluster-based cooperation protocol acting as a secondary system with the pair of primary systems and presents the calculations of all phases in the transmission round.
5. In Chapter 5, the conclusions of our study are presented.

CHAPTER TWO

COGNITIVE RADIO BASED BODY AREA NETWORK

2.1 Cognitive Radio Network:

The dramatic advancements in wireless technology in the last two decades have given birth to an enormous number of new wireless applications in both licensed and unlicensed frequency bands. The current spectrum regulations allow only licensed users to access licensed bands; however, the unlicensed bands are limited and thus becoming too overcrowded. Thus, the exponential growth in wireless applications at the backdrop of rigid spectrum assignment has created spectrum scarcity. Moreover, studies by regulatory bodies such as the Federal Communications Commission (FCC), have shown that the fixed allocation of a spectrum causes its inefficient use and thus underutilizes it in the space, time and frequency domains [80]. This has led to the flurry of research in devising efficient spectrum management policies.

Given the great variation in spectrum usage with respect to time and location, the most appropriate approach seems to be the dynamic spectrum access policies, as identified in [18], [19], [20], [34].

Out of this need to adjust to the surrounding dynamic radio environment was born the idea of cognitive radio [35]. Cognitive radio adapts its certain operating parameters (e.g., transmission power, carrier frequency, and modulation strategy) by learning in real time [18]. Using advanced radio and signal processing techniques along with flexible and novel spectrum allocation strategies, cognitive radio aims to accommodate new wireless applications in the crowded spectrum without degrading the performance of established wireless users [34].

Therefore, we can define the term cognitive radio thus [17]:

“A radio that can change its transmission parameters based on its interactions with the radio environment in which it operates”.

The frequency band for the primary users not being used is called a spectrum hole, as shown in Figure 2.1 as a function of time, power and frequency.

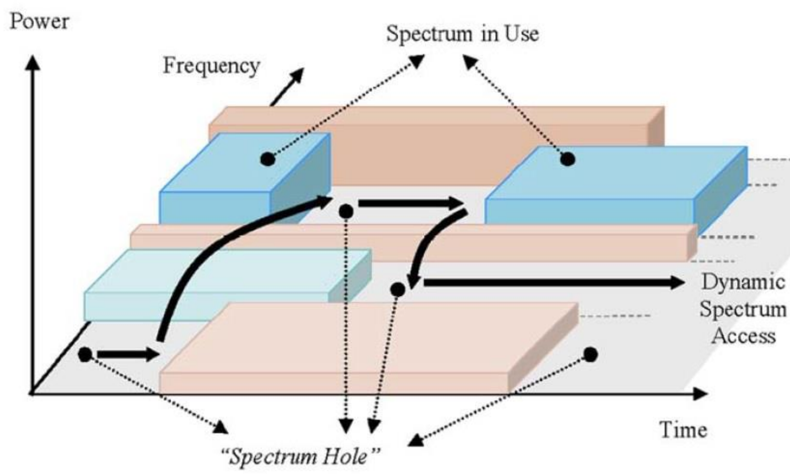

Figure 2.1 Spectrum holes [32].

2.1.1 Spectrum Sensing:

It shows as the availability of the spectrum holes in the spectrum so we can consider it to be the functionality key of CRNs because the throughput of the network depends on how many holes are available.

Spectrum sensing depends on continuous interactions with other network environments because it detects whether or not PUs are in the band, or it shows the activity of PUs and sometimes sees other spectrum holes [32]. Therefore, CRNs have to sense the spectrum periodically to avoid the interference of SUs with PUs. Figure 2.2 shows the functions of CRNs.

There are many studies on sensing.

In [36], the researchers provided an overview of spectrum sensing methods with techniques for sharing and allocation of parts in order to increase the efficiency of the spectrum in CR technology. However, the authors did not discuss any type of implementation.

The authors in [32] discussed a cooperative spectrum sensing and decision strategy for CRNs. However, they did not investigate the spectrum sensing techniques for distributed CRNs.

In [37], the authors proposed a new role-based approach for spectrum sensing working in both cooperative and non-cooperative spectrum sensing with CR.

In [38], the researchers studied spectrum sensing with an overview of the techniques with the present conventional and traditional spectrum sensing and made comparisons between them with state-of-the-art sensing techniques with which the researcher presented a cooperative approach for spectrum sensing studying the complexity, sensing interval and other issues.

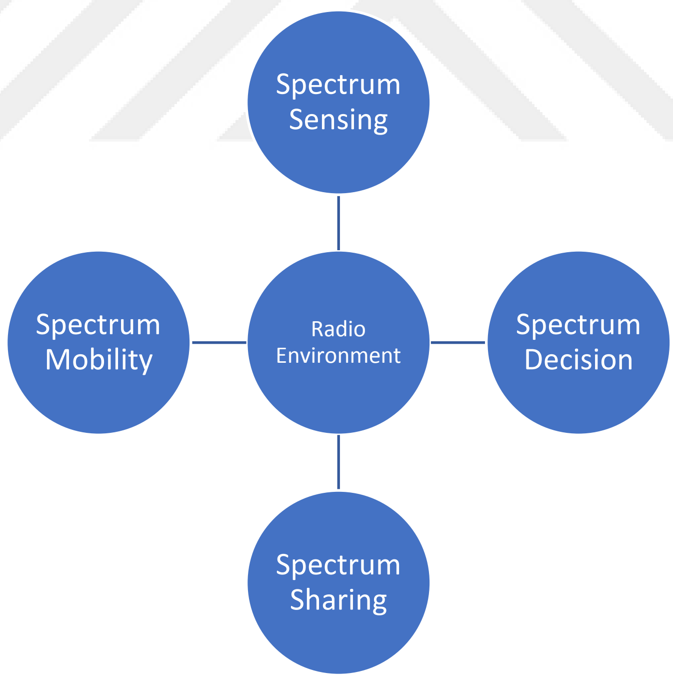

Figure 2.2 Cognitive radio functions.

2.1.2 Spectrum Decision:

The sensing part the spectrum decision has the ability to select or detect the best spectrum band, such as a spectrum hole which is compatible with SU conditions. Therefore, a spectrum decision can mean the ability to select the best channel for SU requirements. Moreover, it can be referred to as a spectrum decision as a spectrum assignment because it assigns the best channel to CRNs.

Spectrum decision can be classified into three functions:

- Spectrum characterization;
- Spectrum selection; and
- Reconfiguration of the CR.

In [39], the spectrum decision was proposed as a framework and in general, the spectrum decision must be based on certain requirements such as interference. Therefore, the authors in [39] attempted to maximize the capacity of the network as a requirement and to take the adaptively of spectrum decision, they proposed a plan for dynamic resource management at the end the simulation to show the approach efficiency.

In [40], the methodologies of spectrum decision had been produced as a survey in CRNs, so they presented multiple implementations for spectrum decisions on many CR platform. The researchers gave a wide picture to the CR function of the spectrum decision, so it's only one side and the other like sharing or mobility as important management for spectrum was not discussed.

In [41], the study focused on spectrum decisions and sensing based on the method of online learning. The authors worked on both secondary users and primary users in the simulation model; however, the research did not contain more generic approaches across realistic models.

2.1.3 Spectrum Sharing:

We can define spectrum sharing as the ability to allow a number of SUs to use the same band as the primary user in order to avoid the interference or collision that may occur between multiple users with different users in the network. According to CRNs, there are two types of spectrum sharing: overlay spectrum sharing and underlay spectrum sharing. In the overlay mode, when there are different SUs sharing the spectrum, also referred to as open spectrum sharing, and in the underlay spectrum sharing mode, also referred to as the primary sharing technique for spectrum where the SUs share the spectrum with the PUs all the time under the constrain of threshold to avoid the interference between them [36]

In [42], through the transmission powers control in the SUs, the authors proposed a number of approaches, namely three algorithms in power allocation that focus on the interference area. The authors in this research aimed to maximize one of the CRN properties, such as energy efficiency, or sum data rate of the SUs. However, the authors only compared them among themselves and not with known works.

In [43] works with the number of PUs (multiple) and the number of SUs since they work on cooperative spectrum sharing. In their work, they based it on matching theory. The method that they proposed was based on two algorithms:

- The distributed matching algorithm; and
- The distributed matching algorithm with utility increasing.

The authors compared the performance of the two algorithms with each other and with previous known works and made an implementation for spectrum sharing.

In [44], the authors worked on spectrum sharing for underlay cognitive radio in the interference property. They proposed an algorithm for dynamic power allocation and worked to guarantee the Quality of Services (QoS) for the PUs. For that, they proposed an algorithm to minimize transmission power. However, the simulation results showed that it needed more investigation, especially in terms of interference to improve the QoS to the SUs.

2.1.4 Spectrum Mobility:

It can be considered that SUs act like visitors to the primary users band, so the CRNs need to monitor the spectrum band in continuous manner since sometime the SUs works on a spectrum band or on a channel and the parameter of network change like detect the PUs on the band so for not interrupt the sending data of SUs it might have the ability to change to another channel or seeking to another spectrum hole so it’s one of the important functionality of CRNs because it has the ability to switch to another band when the current channel become unavailable that called spectrum mobility and might QoS for SUs requirements [17]

In [45], by using fuzzy logic for spectrum decisions, the authors proposed an algorithm that worked on the effectivity for the selection of frequency channel for example make spectrum decision and make a backup for spectrum mobility so by using the Wi-Fi band. They compared the proposed algorithm with the conventional spectrum decision algorithm and the simulation showed from the results the advantage of the proposed algorithm noting that the Wi-Fi band was considered a secondary band. The authors did not clear the activity of the PUs.

In [46], spectrum mobility was studied by present analysis for CRNs and the paper contained simulations with the implementation of their works.

2.2 Cognitive Radio Modes:

Figure 2.3 shows the aforementioned three modes of cognitive radio. The *y*-axis corresponds to the power spectral density (PSD) of the PU and SU. As Figure 2.3 shows, the overlay and underlay modes allow both the PU and SU to coexist, while the interweave mode allows the SU to access only the vacant spectrum. The following section gives a brief overview of these three modes.

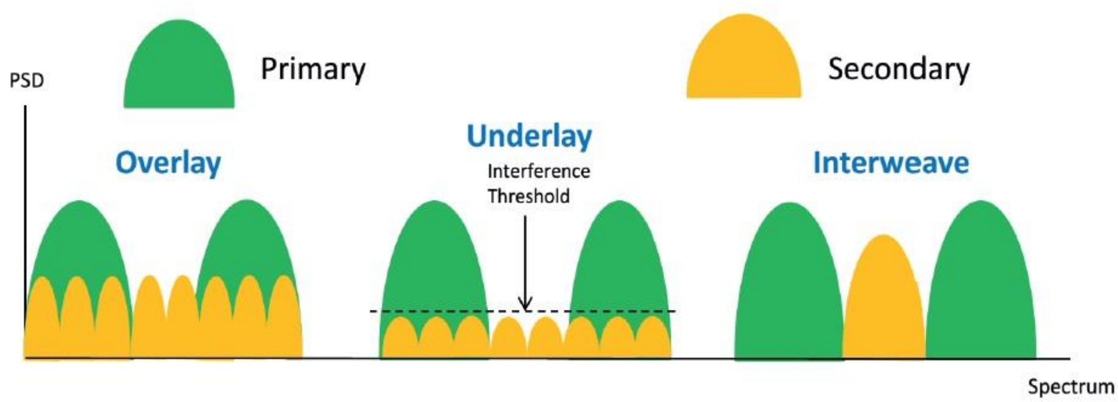

Figure 2.3: Three modes of spectrum sharing in cognitive radio.

2.2.1 Interweave Mode:

The interweave mode requires the SU to access the spectrum only if the PU is absent, i.e., the SU needs to access the spectrum opportunistically. Therefore, a major portion of the spectrum is unused in the time, frequency and space domains. Such a vacant spectrum is called a spectrum hole.

These spectrum holes vary with frequency, time and geographical location, and they can be used by the SU to access the spectrum without causing interference to legitimate users. For example, depending on the traffic, a PU can be busy or idle at a given time. If a PU is idle, an SU can access the spectrum for its communication. The prerequisite for such opportunistic access is the periodic detection of the spectrum hole. This process of detecting a spectrum hole is known as spectrum sensing.

Spectrum usage is thus enhanced through frequency reuse in the spectrum hole. Spectrum sensing needs to be accurate to avoid missing the detection of the PU as it causes interference to the active PU. Similarly, a false alarm denies the spectrum access opportunity to the SU even if the PU is absent, thus wasting the spectrum.

2.2.2 Overlay Mode:

In overlay mode, the SU has the knowledge of the PU's codebook or message. Information about the codebook can be obtained if the PU follows standard publicized codebooks for its communication. Moreover, the PU itself can periodically broadcast the codebook information. Thus, the SU can obtain a PU message by hearing it for some time and then decoding it. Basically, the enabling premise for the overlay mode is that the SU has the PU's message before its transmission begins. Exploiting such knowledge, the SU can coexist with the PU rather than competing with it for spectrum access.

For example, the knowledge of a PU message can be utilized to eliminate the interference at the Secondary Destination (SD) by using techniques such as Dirty Paper Coding (DPC) [46].

The other way to exploit PU message knowledge is to improve the quality of the PU's communication by transmitting (relaying) it to the primary destination (PD) using a part of the available power [47].

The remainder of the power can be used for the SU's own transmission. In this case, the SU cooperates with the PU to maintain or enhance the latter's QoS. As a reward of this cooperation, the SU can access the spectrum to transmit its own data. The scenario where an SU relays a PU message is also called a cooperative cognitive radio network (CCRN).

2.2.3 Underlay Mode:

The governing factor in underlay mode is the permissible interference level at the PD, which is assumed to be known to the SU. Thus, the SU can have concurrent transmission with the PU, provided that the interference caused to the PD by SU's transmission remains below a predefined threshold. To ensure that the interference threshold is met at the PD, the SU can spread the signal over a large bandwidth, as in ultrawideband systems. Moreover, multiple antennas can be used to steer the SU's signal away from the PD. As shown in Figure 2.4, due to the unavoidable interference constraint, an SU usually needs to transmit at low power, thus having a short communication range.

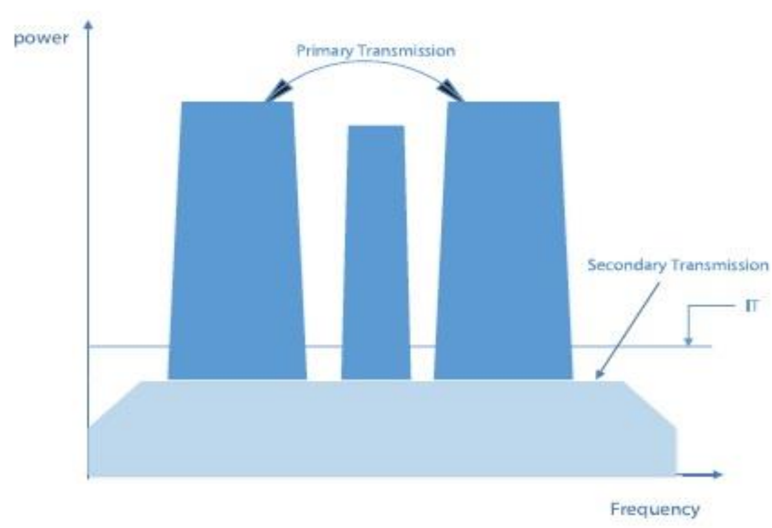

Figure 2.4 Underlay mode [48]

2.3 Underlay resource allocation:

Resource allocation (RA) can be considered the key function in communications for wireless network since wireless channel gains vary frequency and time so especially for CR, where spectrum access by SUs generate interference. Figure 2.5 shows resource allocation algorithm in underlay cognitive radio.

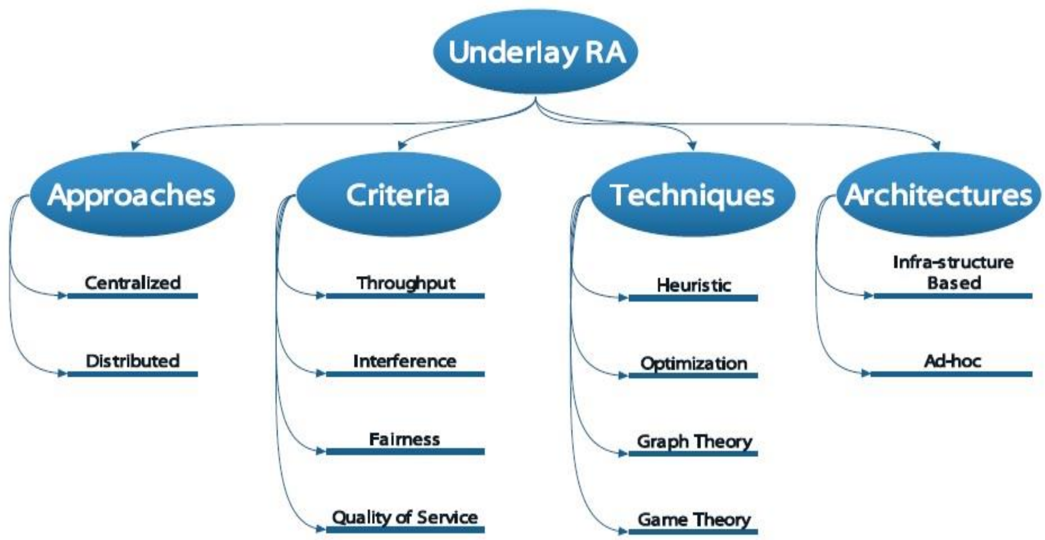

Figure 2.5 Underlay Cognitive Radio Resource Allocation

2.3.1 Approaches:

In underlay CRNs resource allocation there are two important approaches each of ones contain advantages and disadvantages according to the requirements problem and environments one of these must be use.

Centralized:

This part majorly relies on the availability of the resource allocation process of central entity for management, so the Base Station (BS) should be the input for the purpose of control, which can be considered a server. This central node in centralized approaches collects the data from the other nodes and send them to the network.

This approach has been widely explored in papers such as [45]. It has been shown that the centralized strategy has many advantages. For a complete network, the general view and one of the advantages of a centralized approach is the ability to take the best solution of the metric performance, such as spectrum efficiency, reductions of interference or maximization of the minimal throughput, etc. Therefore, by taking this approach, network interference will be minimized in order to give better performance to the network. Moreover, it can be the optimal fairness because the information in the entire network at the main node is available. The achievement of this control may be through greedy nodes which estimate the resources that have a large portion of the other weak nodes at their expense.

In addition, the priorities in this approach are more efficient; however, on the other side, there are a number of disadvantages, one of which is that the entire network depends on one entity (the central node) when any drop occurs in the central node, which will drop the network that leads to more interference and greater loss of power.

2. Distributed:

In this approach, there are no central nodes that control the transmission, so each node in the network can depend on itself by taking the decision or the path to send the information through it by through cooperation by exchanging information with its neighbors where every node produces a number of observations and calculations which are sufficient for a decision or making a decision with its neighbors to find the best solution. This has been the consideration of many distributed approaches in many works such as [48]. One of the important advantages in this approach is flexibility from the central approach and another when any affect events in the network that will not need to be repair all the resource allocation in network just the effected part. Distributed approaches are more robust in communications and even produce fewer delays for exchanging data and have a lower overhead. Therefore, this approach is suitable for light networks. For high networks, the centralized approach is more effective.

2.3.2 Underlay standard (Criteria):

There are many standards which could be targeted by the problem of the allocation of resources. These standards can be incorporated as an objective principle of improvement or as a constraint that must continue.

1. Throughput:

Increasing the productivity of the network is a very common standard and typically an RA problem. This may be considered a problem in individual user productivity [49] or combined the sum-rate network [50] and also some considerations are maximizing the rate of the total number of each of the secondary and primary networks as a whole [51].

In the papers, many of the restrictions are applied to the problem of maximizing productivity, such as the maximum transmission capacity [52], and the minimum that indicates the interference ratio (SINR) [53].

In [54], multiple SUs are allowed to share or use the same PUs but give priority to primary networks. The system rate, R, is the performance criterion adopted by the scheduling algorithm. In particular, the definition of R, such as collecting the rates of activated secondary links, is as follows:

$$R = \sum_{p=1}^{M} \sum_{i \in S_p} R_i^{(p)} \tag{2.1}$$

where

M= the total number of available resource blocks.

S_p = the set of scheduled SUs on the p^{th} resource blocks.

The simulation showed that the algorithm to reveal things achieve productivity gains derived from the transfer of specific diversity. However, the algorithm suffers from the problem of unfairness.

2. Interference:

Interference in wireless communications is known to be a major obstacle that prevents reliable communication. Various techniques to reduce overlap in time, frequency and space, is proposed in [55]. Multiple access techniques include time division multiple access (TDMA), frequency division multiple access (FDMA), space division multiple access (SDMA) and code division multiple access (CDMA).

One of the oldest techniques used to coordinate access between users and the preservation of the broadcasts of the cross pointer [56]. In particular, can be mitigated by the overlap of an allocation transfer of different frequency ranges. Similarly, through the allocation of transmission decade different time slots, and spatial trends, or symbol respectively. Moreover, the easing of other interference, such as the Energy Control, to adapt the ray, and have access to the spectrum of opportunistic infections was also proposed in [55].

These techniques work in the underlay CRN where orthogonality between SUs and PUs for time and frequency is violated. Nevertheless, orthogonal access techniques can be exploited among the SUs themselves to coordinate their access.

To minimize or avoid is the key criterion for the problem of allocating resources to the CRN basis. This is due to the fact that the basis for the model is simultaneously sharing the same frequency channel between the secondary network and primary network. Based on this, we distinguish between the three sources of interference:

• Interference that occurs from secondary users to primary users.

• Interference that occurs from primary users to secondary users.

• Interference that occurs among the secondary users themselves.

The first source of the interference for the secondary user and primary user is usually the most important source that must be calculated until a solution to the problem is achieved. Therefore, the spectrum sharing operation in a CRN should protect the primary user and give it a high priority so the secondary user has to send the date under a condition and not access it. This is called an interference threshold or interference temperature (IT), which is usually the recipient being set in the Statute, and which should not violate the secondary user before the network in order to be able to participate with the licensed spectrum [57]. This can be done through strong power control techniques that guarantee protection and simultaneously do not significantly degrade the SINR of SUs.

3. Fairness:

A relationship between resource allocation and the fairness issue exists such that when the RA attempts to focus on boosting the throughout of the network, the unfairness problem grows. For example, some users attempt to allocate many resources while others cannot allocate anything, which is known as resource starvation. Therefore, covering the fairness trade off of many previous works, they evaluate the throughput/fairness criterion instead of only the throughput as it is done in [58].

In [59], two strategies of fairness are provided, these being maximum-minimum fairness and proportional fairness in which qualitative fairness measures are represented. This is due to the fact that these techniques or measures do not give an exact number representing the degree of fairness. Nevertheless, they provide a study which shows whether the operation of the resource allocation takes fairness into account. Maximum-minimum fairness works on the throughput of the worst node and attempts to maximize it. In proportional fairness, there are many works to prove that it is a better balance than maximum-minimum fairness.

4. Quality-of-Service (QoS):

Resource allocation algorithm must be considered for very important problem which it is QoS provisioning [50]. Although the nature of the spectrum in the wireless network is time-varying showing that the QoS for the secondary user is very important especially when we are talking in WBAN field for example when the delay happened for sending the data will making the life of the patient on risk so for that there are many of researches that provide the QoS for secondary users ([51]-[54])and the definition of QoS differ from one to another but in general can be refer to number of performance metric like delay, packet error rate, transmission rate and signal to noise radio (SINR).

2.3.3 Resource Allocation Techniques:

In this sub-section, we will highlight the techniques commonly used to solve the problem of resource allocation in underlay CRNs so we can categorize these techniques as being heuristic, optimization, graph theory and game theory.

1. Heuristic:

This can be considered one of the important search methods that gives reasonable solutions, not the best results but optimal ones since it is produced in an acceptable time and with space complexity. Moreover, they are less bound than optimization methods, and thus they can the use of models that are more representative of real-world issues [62].

2. Optimization:

This method attempts to find for the optimal solution for all possible nodes. It can minimize or maximize the specific objective function. This function objectivity is used to assess the quality of the solution output given the general mathematical infrastructure improvement problem thus [63]:

$$\text{minimize } f_0(x)$$

$$\text{subject to: } f_i(x) \leq b_i, \qquad i = 1, \ldots, m$$

where the problem components are as follows:

- $x = (x_1, \ldots, x_n)$: optimization variables
- $f_0 : R^n \rightarrow R$: objective function
- $f_i : R^n \rightarrow R, i = 1, \ldots, m$ constrain functions
- and the optimal solution x^* has the smallest value of f_0 among all vectors that satisfy the above constraints

3. Graph Theory:

Graph theory is a technique that is used widely to analyze and model interactions in networks. A graph *G* may include a set of vertices *V* and edges *E*, and is denoted by *G* = (*V*, *E*). These can be mapped to a network component according to a certain problem. Graph theory can then be applied to a wide range of networks, including mechanical, transportation and communication networks. It provides appropriate tools to solve network-related problems. Graph theory can be applied only to networks with previously known structures [64].

Wireless communications diagram theory is extensively utilized to unravel booking and resource allocation issues, particularly issues of high computational exertion [54].

For CRNs, the SUs as a rule can be mapped to the vertices and the edges being mapped vary depending on the model definition of the required relation between two vertices. For example, in a conflict or vertex-coloring graph model, an edge between two vertices (SUs' links) refers to the SUs overlapping each other [54].

For example, in a conflict or vertex-coloring graph model, an edge between two vertices (SUs' links) refers to the SUs overlapping each other [54].

The previously mentioned kinds of charts could be weighted/unweighted or directed/undirected [65]. In a weighted diagram, each edge is allotted a non-negative number called a weight [66]. The coordinated diagram, or digraph, is where the edges have bearings, or officially an edge being an arranged pair of vertices.

Figure 2.5 shows an example of constructing a vertex-coloring weighted graph, G = (V, E, W), to a network consisting of five users and four FBs. The graph components are the vertices V = {SU1, SU2, SU3, SU4, SU5} and edges E = {(SU1, SU4, FB 1), (SU1, SU3, FB 1), (SU1, SU3, FB 4), (SU1, SU5, FB 2), (SU3, SU4, FB 3), (SU2, SU4, FB 2), (SU2, SU5, FB 3), (SU2, SU5, FB 4)}.

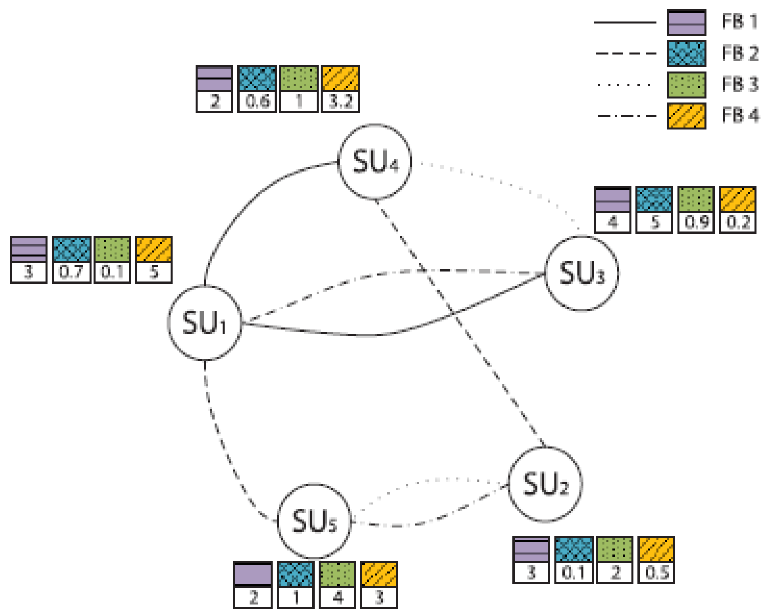

Figure 2.6 Vertex-coloring weighted graph for construction [48].

The documentation (SU1, SU4, FB 1) indicates that SU1 and SU4 are in the obstruction scope of one another on FB 1; thus, in the RA result, they ought not to be distributing the equivalent FB. Finally, the extra factor W means that the array of weights is distributed to every vertex on each FB.

A bipartite matching problem is widely used for spectrum mapping and RA in CRNs, as in [67]. As a rule, the two partitions of a bipartite graph are mapped to the SUs and the frequency bands available for assignment. Figure 6 shows an example of establishing a bipartite graph for the RA operation of a network of five SUs and four FBs. It can be seen from the figure that the SU1 contends only for FB1 and FB3. Similarly, from tracking the edges drawn in the figure, one may undoubtedly obtain the FBs for which each SU is sized.

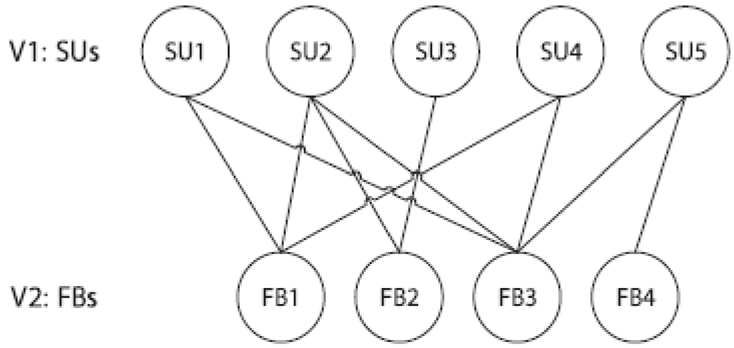

Figure 2.7 Bipartite graph for construction.

3. Game Theory:

Game Theory can be defined as a mathematical infrastructure used to design models and investigate the interactions between many units affecting one another or which possibly have conflicts of interest [68]. For the most part, a game is planned by thinking about many players (choice creators) who take the choices (or activities) to amplify their results (utility). Despite the fact that it had been initially created for financial matters, game theory is used in various fields, including design, science, political theory, physiology, etc. [69], due to its advanced theoretical foundations making it a powerful tool in decision making.

		P1	
		W	A
P2	W	(0,0)	(0,1–C)
	A	(1–C,0)	(-C,–C)

Figure 2.8. A game model for two users [68].

To illustrate the thought behind game theory, a straightforward model telling the best way to build a game model for a variety of ways to reach the framework with two players p1 and p2 is delineated in Figure 2.8. The figure demonstrates that both players have two activities either to get to the channel (An) or to pause (W). In light of the selected activities of the two players, the adjustments of the players are resolved, accepting that the expense of directing a transmission is $0 < C << 1$ and the advantage of transmission is 1. At that point, the result is the distinction between the advantage and the cost. The figure demonstrates that if the two players transmit simultaneously, then both will lose the expense of transmission, and along these lines, the adjustments are spoken to by $(-C, -C)$. Additionally, on the off chance that the two players pause, at that point, no result is accomplished (i.e., (0, 0)). The main situation where a genuine result of $1-C$ is accomplished is when either p1 transmits and p2 pauses or when p2 transmits and p1 pauses.

2.3.4 Architectures:

1. Infra-Structure Based:

This model incorporates the presence of a base station and various clients associated with it. In general, the network can be worked in one of two phases, namely a downlink phase and an uplink phase, and it gives one-bounce correspondences. According to the condition of the work of the infra-structure-based network, the centralized approach of this model is followed to utilize the focal element. The user's measurements and observations proceeds to the central point or node to take the final decision. As a result, being infrastructure based is useful for establishing a permanent network. In the figure below, part (a) shows the model of infra-structure based networks.

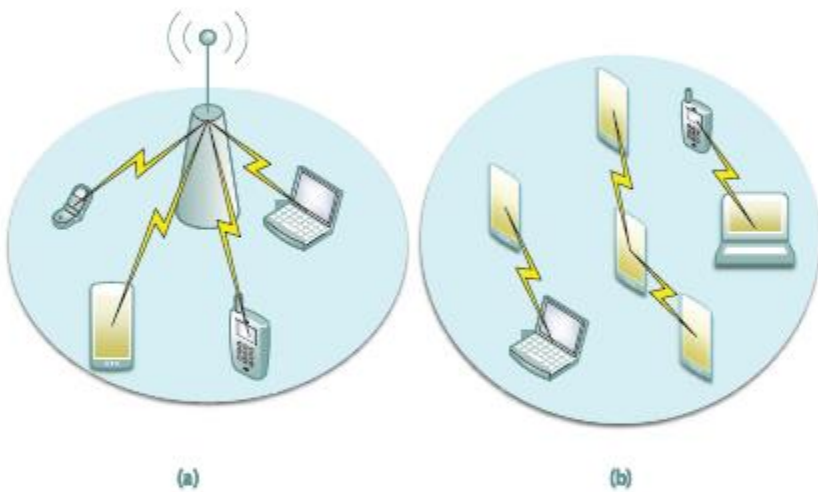

Figure 2.9 (a) Infrastructure-based network (b) Ad-hoc network.

2. Ad-Hoc:

In the ad-hoc model, also called the infrastructure-less model, the connection occurs between the CR hubs without the need for the central node or a base station. In an infrastructure, the connection occurs by allowing all the nodes to be connected by the central node (base station); however, here the nodes can connect through a single-hop or multi-hop. In a multi-hop network, the main function of the routing play is to find the best way to send the data. Therefore, ad-hoc by its nature is similar to a distributed algorithm [70], [71]. However, this adds another challenge: every node must depend on itself to determine the best path to send the data. Therefore, [70] contains a brief survey in the MAC protocol for Ad-hoc.

The ad-hoc contains several advantages including nodes being easily set up since they do not require a central node. Alternatively, a node can directly connect without an access point and this also allows for the ad-hoc to be more suitable to use than infrastructure, especially in military environments and military sensor networks [70]. Figure 2.9 (b) shows the structure of ad-hoc networks.

2.4 Cognitive Radio based WBANs:

It is of importance for CR-WBANs to combine the two important technologies of Cognitive Radio and Wireless Body Area Networks to make healthcare systems more efficient and flexible. CR-WBANs help to overcome issues that conventional WBANs experience by reducing energy consumption, increasing throughput, decreasing latency and reducing the interference applied by CRs in WBANs.

The architectures of CR-WBANs and WBANs are very similar except for the intelligent components that are embedded in the network.

As explained earlier, the architecture of WBANs consist of three tiers, so it would not add any cognition to the sensors in the first tier since the sensors would consume power and expose patients' bodies to harmful electromagnetic fields. Additionally, the need for frequent battery replacement would be problematic, especially for sensors that work inside the human body.

It is more suitable to add the cognition to the Cognitive Body Controllers (CBCs) since they contain higher-capacity, longer-life batteries. The CBC is also responsible for the communication between tier one and tier two also in addition to its enhancing the performance of the network in terms of transmission, retransmission and increases in the efficiency of the spectrum [14].

2.4.1 CR-WBANs the-state-of-the-art:

There are many reviews of WBAN applications; however, a small number that are state of the art are individually put into account with CR-WBANs. This section presents the most recent applications of CR-WBANs to cooperate more study in CR field and provides different categorizations for these applications with regard to their main targets, performance of metrics, and layers.

Figure 2.10 shows an analysis of state-of-the-art CR-WBAN applications with respect to the system's goals, metric performance and applied layers. Most state-of-the-art applications are focused on deploying CR technology in the sublayer of the media access control (MAC) and physical layer. Additionally, many studies focus on reducing latency and power consumption and increasing throughput.

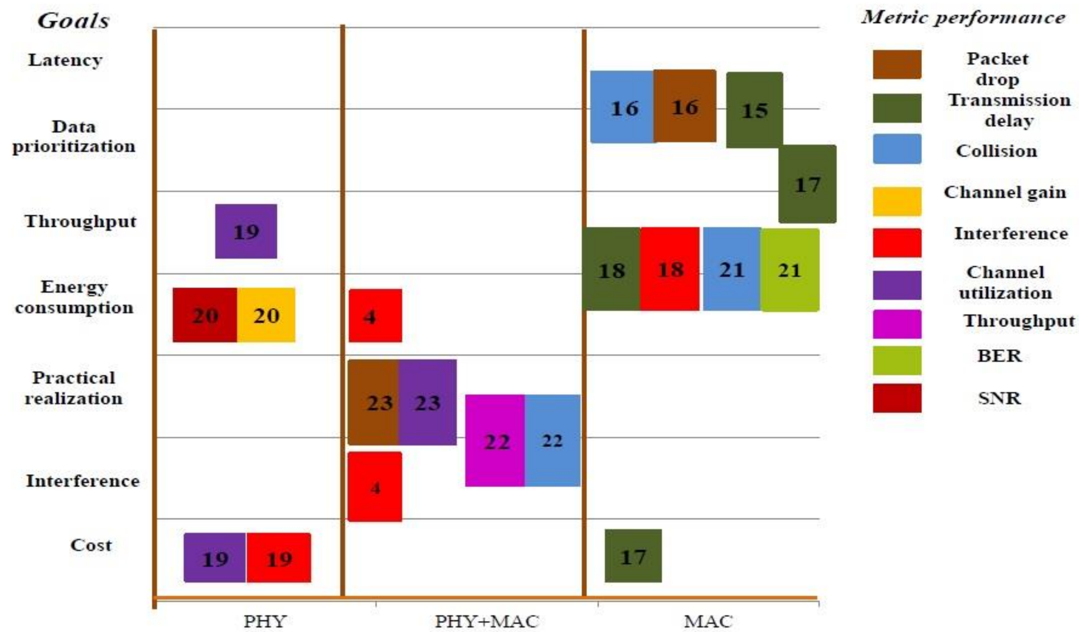

Figure 2.10: Analysis of the-state-of-the-art applications [46]

2.4.2 Open issues and future research direction in CR-WBANs:

Expanding CRs in WBAN improves the performance of certain systems. However, this may bring difficulties for certain networks. Many problems should be explored and examined. In this section, we will present a brief overview of a number of important issues pertaining to CR-WBAN and suggest some guidelines for future work.

- Consumption of Power: Consuming power in sensor networks was, and still is, an open issue that needs to be considered. It is known that sensors in WBANs have some limitation in power and applying cognitive functional capability will consume power.

Various techniques can be applied to avoid power consumption:

1. Designing power-efficient methods reduce the lost power caused by collisions, numbers of retransmissions and idle listening.

2. Deploying artificial intelligence tools helps to enhance the performance of cognitive radio networks. However, there is a lack in the proposed literature, as long as research, in expanding Artificial Intelligence (AI) in CR-WBANs.

3. In the future, energy harvesting will play an important research role in CR-WBANs, especially for implanted devices, whereby power can be gathered from outside sources

and put away in self-governing tools. In the medication field, the body of a human and its organs are outside energy sources, which are called enzymatic bio-energy components. These ecologically friendly cells convert synthetic energy into a fuel source.

-Safety and confidentiality: expanding the CR in WBANs could add safety problems to the system, such as PU emulation attacks. CR-WBANs face many safety challenges which consider a patient’s data in dangerous more than traditional WBAN because of the circumstance of the operating environment such as sensing etc. Because there are few security algorithm proposals in the literature, this area of research needs more investigation.

- The performance of QoS: of the system has to be high by increasing the rate of transmission. On the other hand, the PU should not be affected. Thus, an SU should accurately sense the presence of a PU. This could be done by designing sensing mechanisms that can detect the presence of a PU.

-Channel acquisition: In order to provide CR-WBANs with appropriate services, acquiring a channel with high accuracy and reliability is a major factor. Designing a channel acquisition model can include various parameters such as sensing performance and data prioritization. Even though channel acquisition is an influential element in the performance of CR-WBANs, there is a lack in the literature with regard to designing such models.

-Communication among multiple body controller units (multiple CR-users): has a significant role in building an adequate universal healthcare system with efficient and reliable performance. A few studies are focused on communications among multiple BCUs on the same network. Thus, this area is still an actual challenge and needs further investigation to build a robust pervasive healthcare system.

CHAPTER THREE

3.1 Convex optimization:

The meaning of convex optimization is the optimization the convex function, which simply means that if we can draw a segment line between two points on the graph of a function such that there are no points in the graph above a segment line, the second term optimization becomes in general a set of techniques that reduces the complexity of the algorithms. Therefore, it can be called a repeated process of minimizing the loss function or objective function.

To obtain the term of objective function, it's a function that we want to minimize or maximize depend on the application. If we want to minimize the function then called loss function and the term of constrain, it's the certain conditions which we have to minimize or maximize the objective function.

For example, to explain what we discussed, suppose we want to minimize $f(x) = x^2 + 3$, $f(x)$ will be our objective function and x our optimization variable. We assume that the minimal value $x = 3$, so the value of the function will be $f(x) = 12$ and to minimize the function, we must calculate the gradient of the function, which will be $\frac{d}{dx} = 2x$, inputting the value of x, it will give 6. Our gradient is positive, so we have to decrease the value of x since we want to minimize the function; and if we increase it, the value of the function will be maximized. Therefore, we assume $x = -1$ and we get $f(x) = 4$ and for the calculation of the gradient from $\frac{d}{dx} = 2x$, we get $\frac{d}{dx} = -2$ and our gradient is negative, so we have to increase the value of x to 0, $f(x) = 3$ and $\frac{d}{dx} = 2x = 0$, which means the global minimum of the above function is $x = 0$.The mathematical optimization problem form [63]:

$$\text{minimize} \quad f_0(x) \tag{3.1}$$

$$\text{subject to} \quad f_i(x) \leq b_i, \quad i = 1, \dots, m$$

where

The vector $x = (x_{1,\dots,} \ x_n)$ is the optimization variable of the problem.

The $f_0 : \mathbf{R}^n \rightarrow \mathbf{R}$ is the objective function.

The $f_i : \mathbf{R}^n \rightarrow \mathbf{R} \ \ i = 1, \dots, m$ are constrain functions.

The $b_1, \dots, b_m$ are the limits or bounds for the constrains.

So, we can say that x^* is optimal if the value of it gives the smallest objective value between all the vectors which that satisfy the above constraints.

3.2 Convex sets:

3.2.1 Line segment:

Suppose we have two points $a_1 \ and \ a_2$ where these points are not equal and in $\mathbf{R}^n$ belong to the form:

$$y = \theta a_1 + (1 - \theta)a_2 \tag{3.2}$$

Where the value of $\theta \ \in \mathbf{R}$ from 0 to 1 and can consider that θ is a line segment passing through $a_1 \ and \ a_2$. When the $\theta = 0$, $y = a_2$ and when the $\theta = 1$, $y = a_1$.

3.2.2 Affine sets:

We can define as a set $S \ \subseteq \ \mathbf{R}^n$ is a affine if the line that pass through any two points in S lies in S in other words if any two points $a_1 \ and \ a_2 \ \in S$ and the $\theta \ \in \mathbf{R}$ under the form $y = \theta a_1 + (1 - \theta)a_2 \in S$ which it contain the linear combination of any two points. The idea of affine sets is to generalized the problem for more than two points. So, we can refer to it as affine combination to the points $a_1 + \dots + \ a_n$:

$$\theta_1 a_1 + \dots + \ \theta_n a_n \tag{3.3}$$

$$\text{Where } \theta_1 + \cdots + \theta_n = 1$$

If the S is an affine set and $a_0 \in S$ then we can consider V is a subspace under the form below:

$$V = S - a_0 = \{a - a_0 \mid a \in S\}$$

So, let suppose that two points v_1 *and* $v_2 \in V$ and $\alpha, \beta \in \mathbf{R}$ we can have that $v_1 + a_0 \in S$ and $v_2 + a_0 \in S$, the form can be written as :

$$\alpha v_1 + \beta v_2 + a_0 = \alpha(v_1 + a_0) + \beta(v_2 + a_0) + (1 - \alpha - \beta)a_0 \in S \quad (3.4)$$

3.2.3 Convex sets:

We can say that a set S is convex if any line segment that connect between two points in S. Figure 3.1 shown the difference between convex and non-convex sets. Let suppose two points a_1 *and* $a_2 \in S$ and the value of θ is $0 \le \theta \le 1$ so we can have:

$$\theta a_1 + (1-\theta)a_2 \in S$$

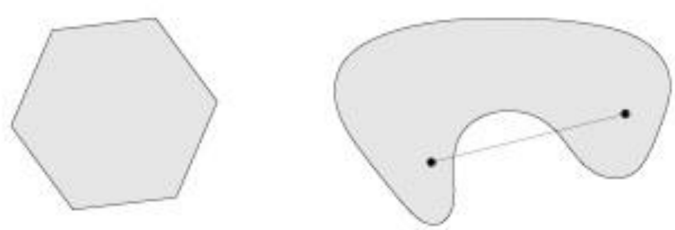

Figure 3.1 convex, non-convex [63]

In figure 3.1 the left side is convex since we can connect any two points in the shape but the right side is non-convex because we cannot connect the segment line between the dots points as it's appeared.

3.2.4 Cones:

We can say that the set S is cones or nonnegative homogenous if every point in S with $\theta \geq 0$ we must have the result of multiplying belong to S like $\theta a \in S$ so a set S is convex cones if it's convex and cone according to form below:

$$\theta_1 a_1 + \theta_2 a_2 \in S$$

The form above called conic combination with $\theta_1, \dots, \theta_n \geq 0$ of $a_1, \dots, a_n$. For that if any a_i are in the convex cone then every conic combination of a_i in S. In other word the set S is convex conic if and only if it contains all the conic combinations. So, the conic hull of the set S can be define as the set of all combinations of the points in S like form below

$$\{\theta_1 a_1 + \cdots + \theta_n a_n \mid a_i \in S, \theta_i \geq 0, i = 1, \dots, n\} \qquad (3.5)$$

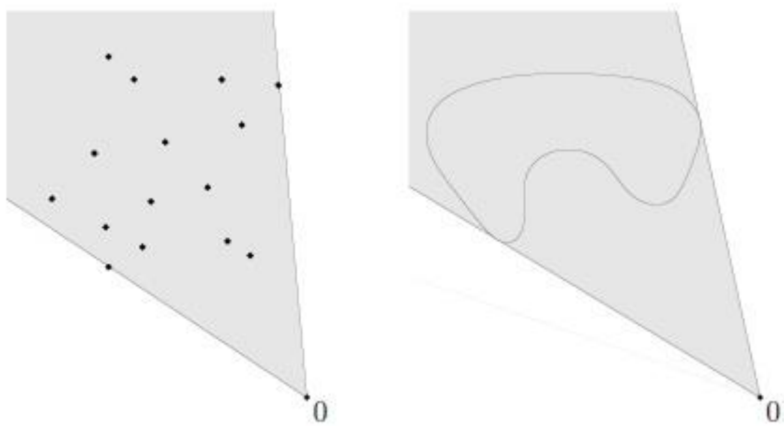

Figure 3.2 shows the conic hulls of the two shapes in previous figure [63]

3.3 Convex functions:

A function $f\ :\ \mathbf{R}^n \to \mathbf{R}$ is convex if $\mathbf{dom}\, f$ is a convex set if all $x, y\ \in \mathbf{dom}\, f$ and the $0 \leq \theta \leq 1$ we have:

$$f(\theta x + (1-\theta)y) \leq \theta f(x) + (1-\theta)f(y) \qquad (3.6)$$

In other word that mean the line segment between $(x, f(x))$ and $(y, f(y))$ it can be the from x to y shows in figure (3.3).

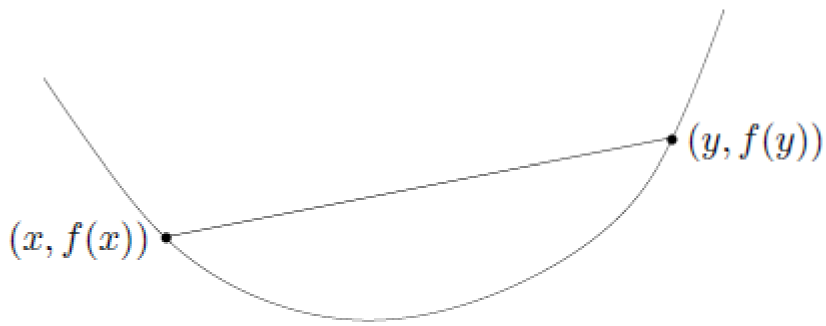

Figure 3.3 convex function [63].

When $x \neq y$ with the $0 < \theta < 1$ then the function called strictly convex and if the inequality holds in the form above, it also called concave if the value of the function equal to $-f$ and it convex.

Note that affine function always satisfies the form above so any function is convex and concave at the same time affine.

So, any function is convex if and only if it is convex when it is limited to any line that cross through its domain.

In mathematical way we can say:

f is convex if and only if for all $x \in \mathbf{dom}\, f$ and all v

$$g(t) = f(x + tv) \text{ is convex on its domain}$$

$$\{t \mid x + tv \in \mathbf{dom}\ f\} \quad (3.7)$$

3.4 Convex optimization problems:

The basic terminology that we mention before:

$$\begin{aligned} &\text{minimize} \quad f_0(x) \\ &\text{subject to} \quad f_i(x) \leq 0, \;\; i = 1, \dots, m \\ &\qquad\qquad\quad h_i(x) = 0, \quad i = 1, \dots, p \end{aligned} \tag{3.8}$$

The form above try to find the value of x to minimize the $f_0(x)$ through all the others values which satisfy the two conditions $f_i(x) \leq 0,\; i = 1, \dots, m$ and $h_i(x) = 0, \quad i = 1, \dots, p$.

Where:

$x \in \mathbf{R}^n$ = optimization variable.

$f_i(x) \leq 0$ = inequality constraints.

$h_i(x) = 0$ = equality constraints.

$h_i : \mathbf{R}^n \rightarrow \mathbf{R}$ = equality constraint functions.

So, for a set of points where the objective of function and all the constrains defined above the form, the domain can be written:

$$D = \bigcap_{i=0}^{m} \mathbf{dom}\, f_i \;\cap\; \bigcap_{i=1}^{p} \mathbf{dom}\, h_i \tag{3.9}$$

The term $x \in D$ is feasible if it satisfies all the objectives in the form (3.8). The form (3.8) became a feasible if there is at least one term (x) feasible and otherwise it can be called infeasible.

Note that the set of all feasible points called feasible set. To find the optimal value of the form (3.8) can be written:

$$p^* = \inf\{f_0(x) \mid f_i(x) \le 0, i = 1, \dots, m, h_i(x) = 0, i = 1, \dots, p\} \quad (3.10)$$

The above form extends the values of p^* from $-\infty\ to + \infty$. If the problem infeasible then the value of p^* is ∞ but if there is a feasible point in the problem then $f_0(x_k) \to -\infty$ as $k \to \infty$ so the problem then called unbounded below.

3.4.1 Optimal and locally optimal points:

We can say that x^* is an optimal point if x^* is feasible and $f_0(x^*) = p^*$. If we have a set of x^* then it called optimal set, denoted by the form below:

$$X_{opt} = \{x \mid f_i(x) \le 0, i = 1, \dots, m, h_i(x) = 0, i = 1, \dots, p, f_0(x) = p^*\} \quad (3.11)$$

If there is an optimal point to the form (3.8) then we can say that the optimal value is attained or achieved and there is a "solvable" to the problem and if the value of X_{opt} is empty than we can say that the optimal value is not attained.

If x is a feasible point with the $f_0 \le p^* + \epsilon$ where $\epsilon > 0$ then called $\epsilon - suboptimal$ and the set of that called $\epsilon - suboptimal\ set$ for the form (3.8).

We can say if x is feasible point a locally optimal if there is an $R > 0$ such that:

$$f(x) = \inf\{f_0(z) \mid f_i(z) \le 0, i = 1, \dots, m, \quad (3.12)$$

$$h_i(z) = 0, i = 1, \dots, p, \|z - x\|_2 \le R\}$$

The form (3.12) means that x try to minimize the f_0 through the nearby points in the feasible sets. Some time the term of globally optimal is used to distinguish between optimal and locally optimal.

3.4.2 Maximization problems:

The maximization problem can be written as below [63]:

$$\begin{aligned} &\text{maximize} && f_0(x) \\ &\text{subject to} && f_i(x) \leq 0, \quad i = 1, \dots, m \\ & && h_i(x) = 0, \quad i = 1, \dots, p \end{aligned} \tag{3.13}$$

The above can be done by minimizing the function $-f_0$ with the same constrains above. Even we can define all the terms above for example the optimal value can be written as below:

$$p^* = \sup\{f_0(x) \mid f_i(x) \leq 0, i = 1, \dots, m, h_i(x) = 0, i = 1, \dots, p\} \tag{3.14}$$

When we are working in maximization problem, the objective is called utility or satisfaction level instead of the cost in the minimization problem.

CHAPTER FOUR

4.1 Background:

Battery life is an important problem in wireless devices (WDs). When the energy of a battery is low, the batteries in WDs need to be manually replaced, which would be costly, especially for sensors inside the human body, leading to interruptions in their operation. Recent research and development present wireless energy transfer (WET) technology which enables wireless powered communications network (WPCN) [73-75]. Therefore, using WET normally reduces the costs of changing batteries and increases the quality of communication by increasing node lifetime.

A special node can be placed separately as a hybrid access point (HAP) in a WPCN [76]. In our study we used the HAP for both energy transfer and data reception.

In [77], the researchers propose a protocol of harvest-then-transmit which consists of two phases. In the first phase, the HAP broadcasts the energy via a radio frequency (RF) to the sensors in a downlink. Then, the WDs transfer their information to the HAP through an uplink.

In [79], a cluster-based user cooperation in WPCN was proposed where the multi-antenna HAP applies the energy transfer to the cluster and then receives the data transmissions from it. This study is similar to the wireless sensor network (WSN) where one of the sensors works as a monitor called the cluster head (CH) and the others are cluster members (CMs) to the HAP, and the CH forwards the information transmission of the other CMs.

In our thesis, we assume the cognitive wireless powered communication network (CWPCN) of the cluster-based cooperation is a SUs and attempt to send the data transmission over a PU channel by using underlay CR, as shown in Figure 4.1. Of importance is the fact that the CH consumes more energy than the other nodes since it transmits the messages of every user, including its own messages, and for the network to contain a large number of WDs, the CH would be considered the bottleneck of the network.

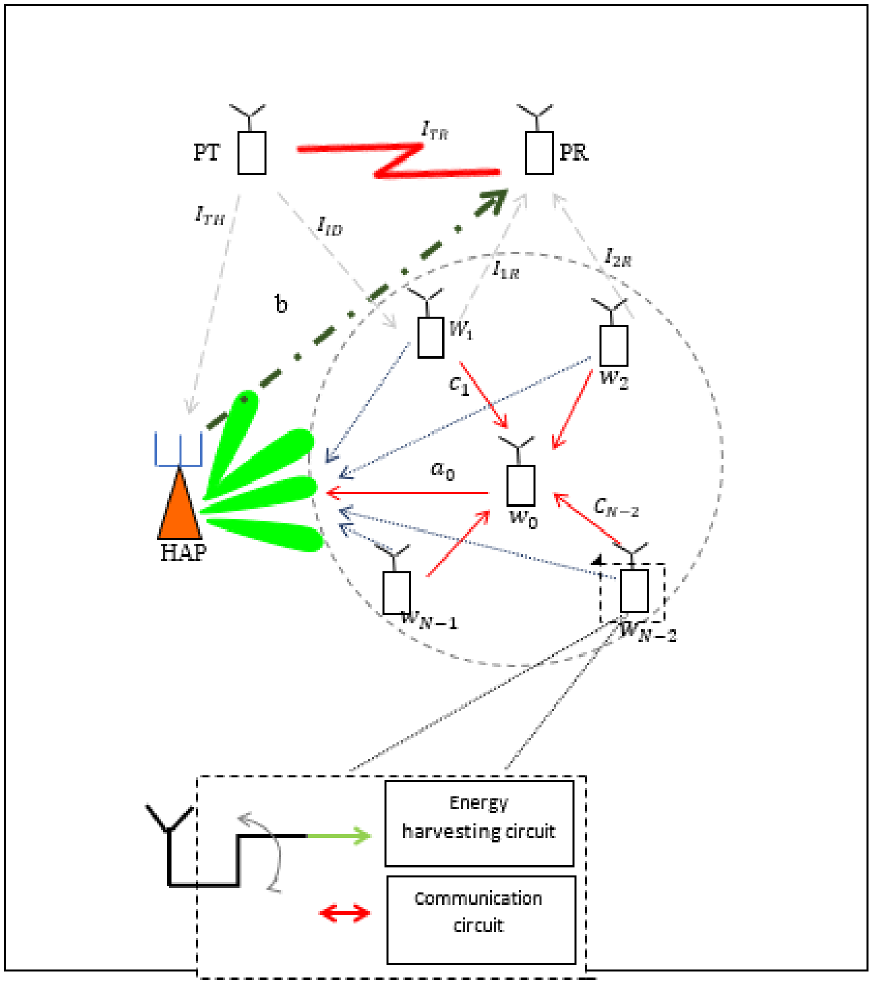

Figure 4.1 Schematic of cluster-based cooperation in underlay CWPCN

4.2 System model:

4.2.1 Channel model:

As shown in figure 4.1, we consider CWPCN primary transmitter (PT) and primary receiver (PR) and the CWPCN consist of one HAP and N WDs (eg. Medical devices).

The HAP broadcast the wireless energy in wireless energy transfer (WET) phase to all WDs and receive the data in wireless information transfer (WIT) from all WDs. We assume that all PUs and SUs operate on the same frequency band. We use TDMA as shown in figure 4.2, in order to separate the energy phase and the transmission phase.

The CH is used to help relay the information of the other CMs. As shown in figure 4.1 the CH is denoted by W_0 and the other CMs $\mathrm{W}_1, \dots, \mathrm{W}_{N-1}$.

The channel coefficient between the HAP and W_i is denoted by $\mathrm{a}_i \in \mathrm{C}^{M\times 1}$ where $\mathrm{a}_i \sim \mathcal{CN}(0, \sigma_i^2)$ and the term σ_i^2 average channel gain $i = 0,1, \dots, N-1$.

The channel coefficient between j −th CM and the CH are denoted by $\mathrm{c}_i \sim \mathcal{CN}(0, \delta_i^2)$ $j = 0,1, \dots, N-1$.

The channel coefficient between PT and PR are denoted by $\ell_{TR} \sim \mathcal{CN}(0, \delta_{TR}^2)$.

The channel coefficient between PT and HAP are denoted by $\ell_{TH} \sim \mathcal{CN}(0, \delta_{TH}^2)$.

The channel coefficient between HAP and PR are denoted by $\mathrm{b} \sim \mathcal{CN}(0, \sigma^2 \mathbf{I})$.

The channel coefficient between PR and WDs are denoted by $\ell_{iR} \sim \mathcal{CN}(0, \delta_{iR}^2)$.

The channel coefficient between PT and WDs are denoted by $\ell_{iD} \sim \mathcal{CN}(0, \delta_{iD}^2)$.

We use $h_i \triangleq |a_i|^2$, $g_i \triangleq |c_i|^2$, $h_{iR} \triangleq |l_{iR}|^2$, $h_{iD} \triangleq |l_{iD}|^2$, $h_{TR} \triangleq |l_{TR}|^2$, $h_{TH} \triangleq |l_{TH}|^2$ correspond to the gains of channel where $|\,.\,|$ denote the 2-norm operator.

4.2.2 Cooperation protocol:

Figure 4.2 depicts the transmission time block for cluster-based cooperation. At the starting of the block, channel estimation (CE) starts with the fixed amount of time τ_0.

Therefore, it is assumed that the HAP knows the channel state information (CSI) for the links between PU transmitter and itself. We also assume that as in [78], the interference between the PUs and the SUs can be estimated by the HAP and WDs. We do not assume any knowledge about the channel between the PT and PR.

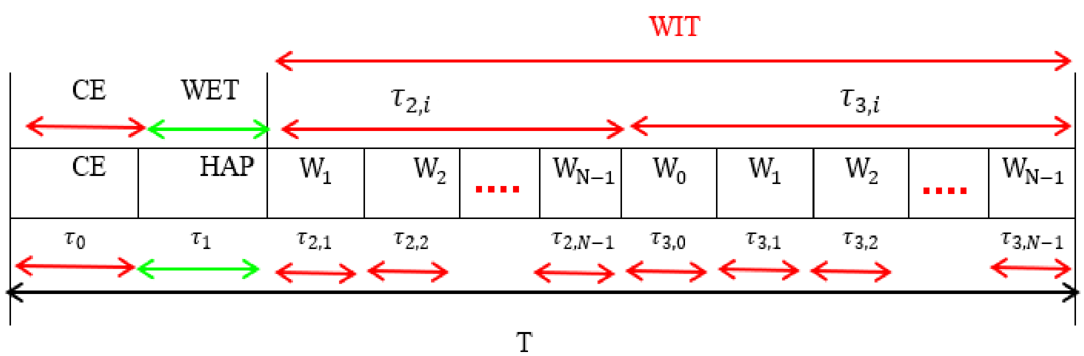

Figure 4.2 Block transmission round

After that the WPCN operate in three phases. In the first phase, the HAP broadcast energy to all WDs. In the second phase CMs transmit their information to the CH with duration $\tau_{2,i}$ for $i = 1, \ldots, N-1$. Finally, in phase three, the CH sends the decoded messages for $N-1$ CMs including own message to the HAP with the duration $\tau_{3,i}$ $i = 1, \ldots, N-1$,. So, the time allocation for one transmission block can be written as below:

$$\tau_0 + \tau_1 + \sum_{i=1}^{N-1} \tau_{2,i} + \sum_{i=0}^{N-1} \tau_{3,i} \leq T \tag{4.1}$$

In our work we assumed that the value of $T = 1$ as in [79].

4.2.3 Underlay cognitive radio transmission:

WDs harvest the energy form the HAP in WET phase and store the energy in rechargeable battery in downlink and use it in WIT phase in uplink to transmit their data. We assume that the HAP and the CH have stable power supplies and the PT transmit with the constant power P_P, the HAP with maximum power is P_{max}.

4.3 Secondary system analysis:

In this part, we will illustrate the calculations of three phases for the cluster-based cooperation in underlay CWPCN.

Phase I:

In this phase, the HAP send wireless power to the sensors by transmitting random energy signals and the transmit power of HAP is P_H as:

$$E[|w(t)|^2] \leq P_H \tag{4.2}$$

The received energy by the $i-$th sensor is [11]:

$$H_i = \eta \, \tau_1 \, A_i \tag{4.3}$$

Where $\eta \in [0,1]$ the energy harvesting energy and it assumed equal for all sensors, $A_i \triangleq a_i a_i^H$.

The interference in this phase can be written:

$$h_{HR} P_H \leq I_{max} \tag{4.4}$$

Where h_{HR} the channel gain between HAP and PR

Phase II:

The transmit power of $i-$th CM $P_{2,i}$ is limited by:

$$\tau_{2,i} P_{2,i} \leq E_i \;\; i = 1, \dots, N-1 \tag{4.5}$$

The received signal at the CH can be written as below:

$$y_{0,i}^{(2)}(t) = c_i \sqrt{P_{2,i}} S_i^{(2)}(t) + n_i^{(2)}(t) \tag{4.6}$$

Where $n_i^{(2)}(t)$ the receiver noise N_0 and the primary link $h_{0D} P_P$ generate interference signal so the total interference noise power can be written below:

$$E\left[\left|n_i^{(2)}(t)\right|^2\right] = N_0 + h_{0D}P_P \tag{4.7}$$

In the worst-case, with the maximum interference and the given noise power, the minimum rate that the CH can decode the $i-$th CM message can be written as:

$$R_i^{(2)} = \tau_{2,i}\log_2\left(1+\frac{g_iP_{2,i}}{N_0+h_{0D}P_P}\right), i = 1, \dots, N-1 \tag{4.8}$$

From (4.8) the transmitted power in this phase can be written as:

$$P_{2,i} = \frac{\left(2^{R_i^{(2)}/\tau_{2,i}}-1\right)(N_0+h_{0D}P_P)}{g_i} \geq P_{req,i} \tag{4.9}$$

The interference constrain in this phase can be written as:

$$I_i^{CM}P_{2,i} \leq I_{max} \quad i = 1, \dots, N-1 \tag{4.10}$$

Phase III:

In this phase, the CH tries to send the messages of all CMs including its own message, one by one to the HAP. We assume that CH can transmit with the maximum allowable power, which is limited by the interference to the primary system. Each sensor has a rate requirement:

$$R_{3,i} = \tau_{3,i}\log_2\left(1+\frac{h_iP_{3,i}}{N_0+h_{TH}P_P}\right), i = 1, \dots, N-1 \tag{4.11}$$

The transmit power in this phase can be written:

$$P_{3,i} = \frac{I_{max}}{h_{oR}} \tag{4.12}$$

The interference constrain in this phase can be written:

$$I_i^{CH}P_{3,i} \leq I_{max} \quad i = 0, \dots, N-1 \tag{4.13}$$

Optimization problem:

$$\text{Min } P_H$$

$$\text{s.t. } \tau_0 + \tau_1 + \sum_{i=1}^{N-1} \tau_{2,i} + \sum_{i=0}^{N-1} \tau_{3,i} \leq T$$

$$\tau_{2,i} P_{2,i} \leq E_i \quad i = 1, \dots, N-1$$

$$h_{iR} P_{2,i} \leq I_{max} \quad i = 1, \dots, N-1$$

$$h_{oR} P_{3,i} \leq I_{max} \quad i = 0, \dots, N-1$$

$$P_{2,i} = \frac{\left(2^{R_i^{(2)}/\tau_{2,i}} - 1\right)(N_0 + h_{0D} P_P)}{g_i} \geq P_{req,i}$$

$$P_{3,i} = \frac{\left(2^{P_{req,i}/\tau_{3,i}} - 1\right)(N_0 + h_{TH} P_P)}{h_{oR}}$$

4.4 Simulation results:

In the all simulation of our work we set the efficiency of the receiver energy harvesting $\eta = 0.5$ and the noise power $N_0 = 10^{-12}$. The threshold constrain of interference with vary values $I_{max} = -70, -60, -50 \; and - 40 \; dbm$. The maximum power assumed to be $P_{max} = 3 \; W$, the power of primary user changes between $P_P = 0.2 \; W$ to $1 \; W$.

Between any two nodes, the mean channel gain follows a path-loss model. Let the distance between the HAP and all the sensors denoted by $d_{H,i}$ so the average of the channel gain can be calculated like below:

$$\delta_{H,i}^2 = G_A \left(\frac{3 \times 10^8}{4 \pi \, d_{H,i} f_c} \right)^{\alpha}$$

Where $G_A = 4$ the antenna gain, $\alpha = 3$ the path loss factor and the carrier frequency $f_c = 915 \; MHz$.

The distance between PT and $i-th$ WD denoted by $d_{PT,i}$.

The distance between PR and $i-th$ WD denoted by $d_{PR,i}$.

The distance between CH and $i-th$ CM denoted by $d_{CH,i}$.

The distance between PR and HAP denoted by $d_{PR,H}$.

The distance between PT and HAP denoted by $d_{PT,H}$.

The distance between PT and PR denoted by $d_{PT,PR}$.

We assume that we have 4 WD distributed uniformly on a circle with the radius $r = 2\,meters$ and the center of the circle far away from the HAP $d = 6$ as shown in figure below.

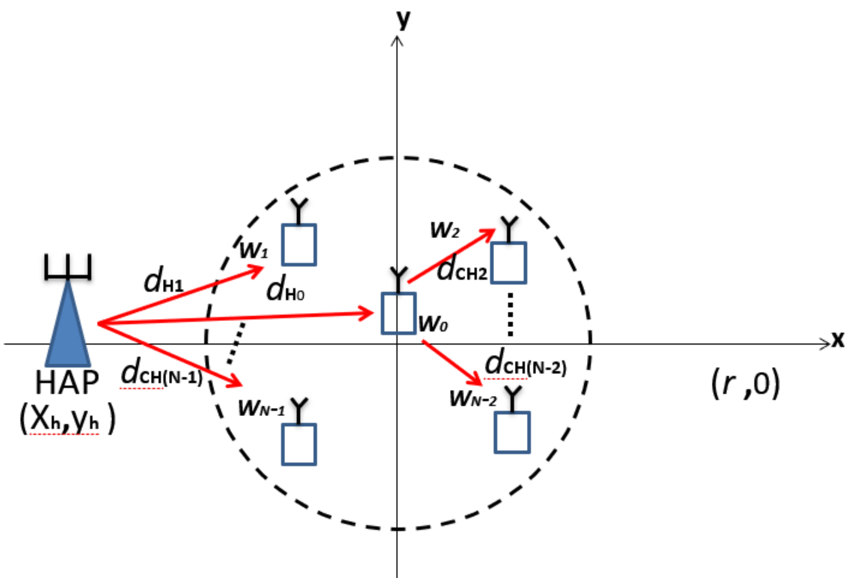

Figure (4.3) Deployment HAP and WDs

We take the distance between PT and PR as 200 meters as in [79]. Figure (4.4) shows how minimum HAP power changes as primary user transmission power changes from 0.2W to 1W. Both axes are in dBm scale. As the PU transmit power increases, PU interference in sensor to HAP communication increases. To meet the required rate, sensors must transmit with more power. Therefore, more HAP power is required to feed the sensors.

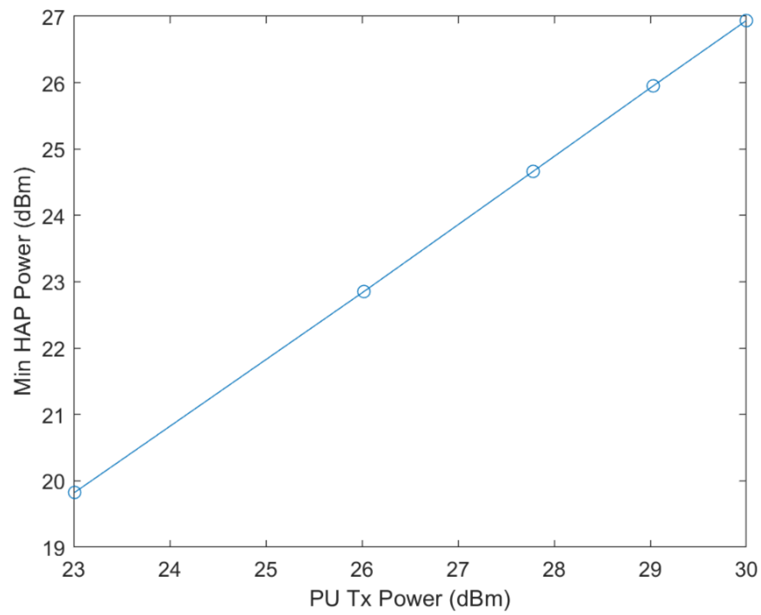

Figure (4.4) minimum HAP power

In figure (4.5), we show how minimum HAP power changes as maximum allowable interference power to the primary user changes between 10^{-2} to 10^{-6} W. Again, the axes are in dBm scale.

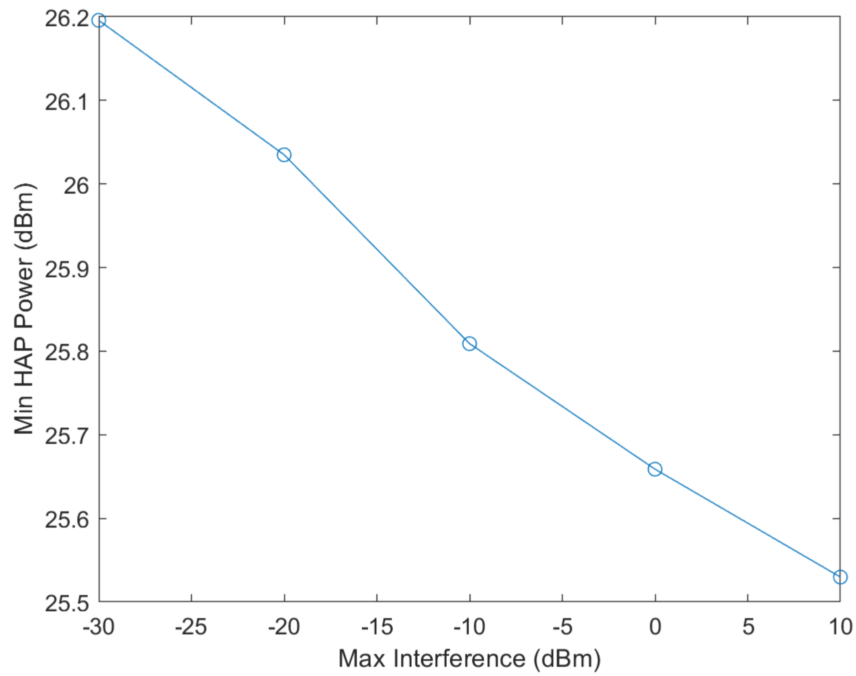

Figure (4.5) minimum HAP power

As the maximum allowable interference to the PU increases, CH can transmit to HAP with more power. Since required date rate for each sensor is fixed, to forward the sensor data CH now needs less time in phase 3, i.e. less T_3 durations. This in turn, leaves more time for sensors to transmit their data to the CH in phase 2, which this allows sensors to transmit with less power to the CH. Therefore, they require less power from the HAP.

CHAPTER FIVE

Conclusion:

Most of the research in the literature about energy harvesting WBANs is about determining the maximum data rate for the sensors. However, in reality, these sensors have a certain (usually very low) data rate requirement, and their transmission rate does not change in time. Therefore, one of the important questions is what is the minimum energy that should be transmitted by the HAP so that the WBAN operates with sensors transmitting at the required data rates. Since WBAN is located on a human body, exposure to unnecessary RF power may be harmful to the body. In this sense, it is important to determine the required minimum HAP wireless energy transfer power. In this work, we used a cluster-based WPCN as a secondary system and sent the data through a primary system by using underlay cognitive radio. In particular, the CH is used to manage the information by sending the transmission information of every cluster member to the HAP. To ensure the interference between the secondary WPCN and the primary system is below the tolerable limit, we used an interference temperature constraint. We determined the minimum required power that must be supplied by the HAP to the sensors under different conditions solving the related optimization problems and we verified our results via simulations.

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