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Spectrum **H**andoff **S**trategies in **C**ognitive **R**adio **N**etworks

إستراتيجيات تسليم الطيف في شبكات الراديو الإدراكية

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أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Spectrum Handoff Strategies in Cognitive Radio Networks

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استراتيجيات تسليم الطيف في الشبكات الراديوية الإدراكية

Spectrum Handoff Strategies in Cognitive Radio Networks

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واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

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مساعد نائب الرئيس للبحث العلمي وللدراسات العليا

أ.د. فؤاد علي العاجز

ABSTRACT

Today, Cognitive Radio (CR) have a promising solution to both spectrum inefficiency and spectrum scarcity issues by enabling secondary users (SUs) to exploit the idle frequency bands temporarily in opportunistic manner as long as the primary users (PUs) do not occupy their spectrum.

The SUs must vacate these frequency bands when the PUs come back and reuse them. This is one of challenge in CR technology. In this case, the communication links of the SUs must be finding another idle frequency bands to resume their communication links. This is called spectrum handoff which is affecting to the performance of system by main factors such as: link maintenance probability, the number of spectrum handoff, switching delay.

Spectrum handoff may be happen more than once for a wide range of the spectrum available in CR. This switching change the characteristics of propagation transmission loss which is affects the overall system performance. Thus, in this thesis, the path loss and coverage area are essential factors studied to enhance the system performance and make it more immune to propagation losses.

In this dissertation, we aim to overcome these issues by proposing a systematic selection method to select and assign new appropriate frequency channels efficiently to achieve a better transmission performance. Additionally, the adaptation power technique is applied in order to control base station transmitted power and estimate the appropriate coverage area to reduce and avoid interference and also to conserve power dissipation in the system.

The combining of these approaches, selection method and power adaptation, is found to be helpful to achieve an efficient spectrum utilization, reduce power consumption, maintain the connectivity link, decrease the number of spectrum handoffs from failure which are very important to improve overall system performance. The simulation results show a comparison of the proposed strategy with other techniques by increasing the wide of frequency switching up to 70% and also studies the effect of the adaptation technique on the system performance.

الملخص

تعتبر أنظمة الاتصالات الإدراكية "الراديو الاداراكي" واحدة من أكثر التقنيات الواعدة والتي تتميز بخاصية الاستخدام المرن للطيف من خلال تمكين المستخدمين الغير المرخص لهم (المستخدم الثانوي) باستغلال النطاقات الترددية الغير مستعملة من قبل المستخدمين المرخصين (المستخدم الأساسي) بطريقة انتهازية دون إحداث أي تأثير سلبي على موجات المستخدمين المرخصين مما يعزز من كفاءة استخدام الطيف الترددي في زيادة تلبية احتياجات الشبكات اللاسلكية من نطاقات في ظل محدودية وندرة الطيف الترددي.

عندما يطلب من المستخدم الغير مرخص إخلاء النطاق الترددي فوراً في حال رجوع المستخدم المرخص لاستخدام الطيف الترددي الذي تركه سابقاً حيث تسمى هذه العملية بما يعرف "عملية تسليم أو انتقال الطيف" و تعتبر أحد التحديات في شبكات الاتصالات الإدراكية ، حيث في بعض الحالات لعملية انتقال الطيف قد يحصل فقدان للاتصال بين الشبكة والمستخدم النهائي حيث تم تصنيف عدة عوامل رئيسية توثر على أداء هذه الشبكات من خلال فقدان الاتصال منها : (احتمالية الحفاظ على الاتصال دون انقطاع - احتمالية استمرارية الاتصال -عدد عمليات انتقال الطيف خلال الاتصال).

اضمحلال المسار ومنطقة التغطية تعتبر من العوامل الأساسية التى تؤثر في تحسين الأداء والحفاظ على استمرارية الاتصال بين المحطة الرئيسية والمستخدم النهائي لأنظمة الشبكات الاداركية مما دفعنا في هذه الرسالة لدراسة هذه العوامل مع الأخذ بعين الاعتبار قضية تكرار حدوث عملية الانتقال للطيف كظهور واختفاء حركة المستخدم الأساسي للطيف .

في هذه الأطروحة تم اقتراح طريقة جديدة ذات منهجية لاختيار وتخصيص نطاق ترددي جديد ومناسب بالإضافة إلى تطبيق تقنية تكيف الطاقة على الطريقة المقترحة لتقدير الطاقة المناسبة لمحطة البث للحد والتقليل من حدوث تداخل والحفاظ على الطاقة من التبدد لتحقيق منطقة تغطية تؤدي لأنظمة أكثر كفاءة وأفضل أداء.

الجمع بين الطريقة المقدمة لاختيار النطاق الترددي وتكيف الطاقة يعتبر مهما جدا لتحسين أداء أنظمة الشبكات الإدراكية ككل حيث يزيد من الاستفادة من استخدام الطيف والحد من استهلاك الطاقة، وضمان حفظ الاتصال من الانقطاع وتقليل عدد عمليات انتقال الطيف.

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To my parents, wife, sons and daughters

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LIST OF ABBREVIATIONS

A/D	Analog /Digital
BS	Base Station
CDMA	Code Division Multiple Access
CPE	Customer Premises Equipment
CR	Cognitive Radio
CRS	Cognitive Radio System
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DSA	Dynamic Spectrum Access
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
IEEE-1900	ITU, Institute of Electrical and Electronics Engineers 1900
IF	Intermediate Frequency
ISM	Industrial, Scientific and Medical
ITU-R	ITU-Recommendation
ITU-R	ITU-Regulation
LAN	Local Area Network
LTE	Long Term Evolution
MAN	Metropolitan Area Network
Ofcom	Office of Communications
OFDM	Orthogonal Frequency Division Multiplexing
P2P	Peer-to-Peer

PAN	Personal Area Network
PU	Primary User
QoS	Quality of Service
RAN	Regional Area Network
RRS	Reconfigurable Radio Systems
SCC	Standards Coordination Committee
SDR	Software Defined Radio
SU	Secondary User
TC	Technical Committee
TV WS	TV White Space
WG	Working Groups
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WPs	Working Partys
WRAN	Wireless Regional Area Network
WRC	World Radio communication Conference
WRC-12	World Radio Communications Conference in 2012
WS	White Spaces

1

Introduction

1.1Introduction

The increasing demand for new wireless communication services and applications that is lead to increase demand for higher capacity wireless networks. The wireless networks become highly heterogeneous and the emerging technology which is cognitive radio (CR) motivating to use in order to find possible spectrum.

The demand of spectrum is not problem according to the outcomes of several studies have shown, but the radio resources are used inefficiently because the allocation of spectrum is static. Therefore, a functionality of CR is required to be built into future Equipment to have the cognitive capability to help with the Dynamic Spectrum Allocation (DSA). This is allowed more efficient utilization of radio resources by changing the spectrum allocation on demand [1].

A CR is a self-aware communication system that efficiently uses spectrum in an intelligent way. The most significant characteristic of a CR is the capability to sense surrounding radio environment such as information about transmission power, modulation, frequency, bandwidth, etc. and make a decision to adapt the parameters for maintaining the quality of service (QoS).

It self-coordinates the usage of spectrum in identifying unused radio spectrum on the basis of observing spectrum usage. Therefore, CR users are occupying the idle channel by opportunistic manner. The spectrum handoff occurs when a PU more activity to utilize this unused radio spectrum. In order to avoid service failure, the link maintenance procedures should perform by CR user in order to reconstruct the communication [2].

Regulatory bodies of various countries focusing on this promising technology (CR) and becomes a priority to research because the solution of the development of future wireless systems is considered and increasing of the spectrum utilization is contributed. This technology will play as principle due to the scarcity of unallocated spectrum.

Despite of a large temporal and spatial variation in the spectrum occupancy, a CR has the capabilities to sense the operating environment, learn and adapt in real time according to environment creating a form of mesh network. Also, CR supports to the direction of self-organizing systems where individual nodes can instantaneously establish ad hoc networks whose structure is changing over time, Instead of wireless communication systems, which is going of fully centralized systems. These reasons encourage many of organizations to be interested about CR technology [3].

CR can learn temporal characteristic of channels over time which can be exploited in channel selection scheme to improve the performance. Transmitter power adaptation needs to assure reliable communication in the changing environment without causing harmful interference to other users and reserve power consumption.

Frequency changing and power control selects suitable frequency bands and transmission power levels for the CR system. We have studied systematic channel selection for searching for a target frequency channel as starting search from the beginning to route the switching process, and to try mostly changing channel from high to low in order to minimize the number of handoff dropped or breaking, and harmful interference to other systems. This is the basis of proposed scheme [1].

This thesis presents an overview of CR system and network and lists enabling techniques for cognitive radios, main functionalities, and describes the state-of-the-art in CR standards, regulation, Frequency changing and power control selects suitable frequency bands and transmission power levels for the CR system.

We have studied systematic channel selection for searching for a target frequency channel as starting search from the beginning to route the switching process, and to try mostly changing channel from high to low in order to minimize the number of handoff dropped or breaking, and harmful interference to other systems architecture, and applications. CR tasks are reviewed with a more detailed discussion on spectrum handoff, changing frequency, adaptation power management functionalities and the impact of the path loss and coverage area which is an interested effect of transmission performance.

In addition to the related work of CRs, we present a system model for coexistence between primary system and secondary and propose new scheme to improve the classic random selection. So, the power control technique and evaluate the performance of scheme with and without transmitter power control, applying systematic frequency selection is used. The obtained results include computer simulations using Matlab.

In this work, we suppose the combining of frequency selection scheme and adaptation power technique to observe the impact of these jointly schemes using three case studies and evaluate the spectrum handoff process on performance of CR system.

1.2 Problem Statement

The spectrum handoff is one of the main tasks in the structure of the CR network. The CR system should be able to change the operating band in order to avoid a detected PU activity or in order to improve the overall system performance by transmitting on another spectrum hole with better conditions. Accordingly, the transmission parameters of the CR system should be adapted according to the new transmission band. The work in the thesis is focused on this important task in order to study its impact on the overall system performance and also investigate the different factors that affect its performance. Moreover, the work examines the existing algorithms and proposes an efficient algorithm in order to improve the performance of the CR network.

Simple and low complexity algorithm is proposed using frequency and power management control to solve the effect of frequent appearance of primary system to forcing the secondary system to vacate the occupied channel. The results produce more efficient handoff mechanism by decreasing number of spectrum handoff drop or break comparing to the conventional randomly selection and increasing the overall system performance by implementation of the power adaptation technique with compared to without adaptation use of power. This algorithm is approved to be more effective in many real and expected application parameter for possible coexistence environment using Matlab based simulator.

1.3 Motivation and Objectives

From the past ten years, the dramatic growth in wireless communication due to the popularity of smart phones and other mobile devices is considerable and great. Then, the demand for commercial spectrum has been mounting. Clearly limited spectrum is a critical barrier to continued growth of commercial wireless services. Similarly, increasing demand for unlicensed bandwidth, due to the continuing growth of as WiFi, and emergence of application domains, such as sensor networks for safety applications, smart grid control, medical wearable and other systems [4].

Meeting this huge demand for bandwidth is a challenge since most easily usable spectrum bands have been allocated. Many studies have shown that more than 90% of the allocated spectrum is unused or underutilized. This suggests that meeting future demands for wireless bandwidth will not only require new communication and networking technologies that use the spectrum more efficiently but also new techniques for increasing spectrum utilization. Until now, spectrum policy relies largely on static spectrum allocation, which is simple and encourages investments in infrastructure, so it is considered as main task in Palestinian ministry of telecommunication and information technology which encourages the research on this technology [4].

The objective of the aims to maximize spectral and power efficiency of the CR system based on power and frequency control and to use efficiently the network state information, which is partially given as external control information and partially estimated, reduced for transmission and combined.

The secondary system has to be spectrum aware in order to exploit the available spectrum efficiency. In this research, the four major tasks of CR are considered carefully which are spectrum sensing, spectrum management, spectrum sharing and concentrated on spectrum mobility. CR objective is to improve spectral efficiency by sensing the environment and filling the gaps in licensed spectrum by their own transmissions. Spectrum handoff is a critical task in a CR system.

The transmission of PUs has to be reliably detected and spectrum sensing should ensure adaptive transmission in wide bandwidths without causing interference to PUs.

However, it is also very important to know how to exploit the sensed available spectrum efficiently. Transmission parameters have to be adapted based on the sensed spectrum and the channel estimation. To maximize the spectral and energy efficiency. The power and the frequency have to be jointly controlled. This is a challenging task. Investigation of efficient adaptive transmission strategies in CR network is one of the main tasks presented in this thesis. In addition the proposed algorithm should be efficient in order to solve or improve the existing number of spectrum handoff schemes.

1.4 Contribution

The main contribution in the study of CR of the thesis can be summarized as follows:

- Having good performance of CR system with simple concepts and architecture.
- Propose an algorithm of systematic frequency selection scheme with power adaptation technique to improve spectrum handoff performance considering link maintenance probability, the number of spectrum handoff failure, and non-completion probability by reducing: the number of spectrum handoff dropping or breaking, overloaded the signaling and delay due to the running process of spectrum handoff.
- Combine the new scheme with power adaptation to enhance the coverage area and reserve power transmit consumption by eliminating the interference due to wide coverage area at changing frequency from high to low and also consume the power dissipated at changing frequency from high to low, all these according to propagation characteristics transmission losses.

- Measure the impact of spectrum handoff on the CR network and provide a simulated demonstration of the system performance considering the proposed algorithm, so the results approved the best overall performance at jointly new scheme selection frequency with adaptation power comparing with the classic method and without adaptation power management by increasing the wide of frequency range gain and also improving the flexibility of wide frequency switching in cell coverage size.

1.5 Organization of the Dissertation

The dissertation is divided into five chapters as detailed below:

- The first one, the introduction, gives a smooth entrance to the topics studied throughout the rest chapters. The problem statement, motivation and objectives, contribution and organization of the dissertation are displayed.
- In Chapter 2, the general framework for CR and CR networks is presented including the background, definitions and cycle of CR technology. DSA and SDR concepts and the functionalities, standards, architecture network and applications of the CR.
- In Chapter 3, spectrum handoff in CR networks, the main types of spectrum handoff, four famous strategies for spectrum handoff, procedure of spectrum handoff selection and challenges are explained.
- Chapter 4 presents the developed CR system model, characterizes the power and frequency control algorithms for CR systems and presents the results of three case studies in the proposed scheme.
- Finally, Chapter 5 summarizes the research conclusions as a focusing the spectrum handoff and impacts this process to overall performance system using proposed scheme. Also, some challenges may be addressed to be done in future works.

2

Cognitive Radio Background

The continuing growth of wireless communication systems is demanding an increased need for a more efficient use of spectrum. Advancements in technology are enabling the development of radio systems that have the potential to use the radio resources much more dynamically and efficiently.

Regulatory bodies in various countries (including the federal communications commission (FCC) in the United States, and office of communications (Ofcom) in the United Kingdom) found that most of the radio frequency spectrum was inefficiently utilized. For example, cellular network bands are overloaded in most parts of the world, but amateur radio and paging frequencies are not crowded.

Independent studies performed in some countries confirmed that observation, and concluded that spectrum utilization depends strongly on time and place. Moreover, fixed spectrum allocation prevents rarely used frequencies (those assigned to specific services) from being used by unlicensed users, even when their transmissions would not interfere at all with the assigned service. This was the reason for allowing unlicensed users to utilize licensed bands whenever it would not cause any interference (by avoiding them whenever legitimate user presence is sensed). This model of wireless communication is known as cognitive radio (CR) [4].

CR system could offer improved the efficiency of the overall spectrum use and provide additional flexibility. CR system is not a radio communication service, but is a technology that can be implemented in wide range of applications in the wireless communication. As any system of a specific radio communication service that uses CR system technology in a frequency band that is allocated to that service must operate in accordance the provisions of the Radio Regulations governing the use of this band.

CR systems are a focusing of research activity and applications under study and trial. Most of systems using some cognitive features have already been deployed and some administrations are authorizing these systems. The main definitions and key concepts technology of CR are remembered. In addition, the major functions and components architecture of cognitive radio and applications of cognitive radio are reviewed.

2.1 Definitions of Cognitive Radio System

CR is defined as an adaptive, intelligent radio and network technology that can automatically detect available channels in a wireless spectrum and change transmission parameters enabling more communications to run instantly and also improve radio operating behavior. CR uses a number of technologies including Adaptive Radio (where the communications system monitors and modifies its own performance) and software defined radio (SDR) where traditional hardware components including mixers, modulators and amplifies have been replaced with intelligent software [4].

There are many definitions of CR and definitions are still being developed both in academia and through standards bodies, such as International Telecommunication Union (ITU), Institute of Electrical and Electronics Engineers 1900 (IEEE-1900), FCC and others regulatory administrations.

In Academic, the idea of cognitive radio was first presented by Joseph Mitola III and Gerald Q. Maguire, Jr in 1999. It was a novel approach in wireless communications that Mitola later described as [3]:

"*The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context and to provide radio resources and wireless services most appropriate to those needs*".

Another academic definition by Haykin in [2]:"*Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding by building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind: highly reliable communications whenever and wherever needed and efficient utilization of the radio spectrum*".

In regulatory, the World Radio communication Conference (WRC) 2012 Agenda item 1.19, based on the results of ITU-Recommendation (ITU-R) studies, in accordance with Resolution 956 (WRC-07)", ITU-R Working Party 1B has developed definition of CR system and published in Report ITU-R SM.2152 as the following:

"Cognitive Radio System (CRS) *is a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained."[5].*

Another regulatory organization, the FCC defined as: "*CR is a radio that can change its parameters based on interaction with the environment in which it operates*" [6].

From the above definitions and concepts, CR has two main characteristics implementations as:

i. Cognitive Capability: This is the ability to acquire the radio parameters from its surroundings. CR should be able to determine the frequency occupancy by identifying the spectrum holes (or spectrum white space). The spectrum hole is defined as the frequency bands which are allocated to any service but not utilized in some location or not used all the time by the licensed system. Furthermore, depending on the system, CR might have information about the modulation and coding as well as the geolocation of the licensed system devices.

ii. **Reconfigurability:** this operation enables to rapidly adapt the transmit parameters, i.e. operating frequency, transmit power and communication technology, modulation and coding, according to the radio environment in order to achieve the optimal performance.

2.2 Cognitive Radio Concepts and Capable Technology

Currently, the most radio systems are not aware of their radio spectrum environment and operate in a specific frequency band using a specific spectrum access system.

Regulatory bodies in various countries (including the FCC in the United States, and Ofcom in the United Kingdom) found that most of the radio frequency spectrum was inefficiently utilized in the 0-6 GHz band varies from 15 to 85% depending on time, frequency and geographical location as shown in figure 2.1which the spectrum utilized very crowded in some bands (heavy use), medium use or free used (white space) [7].

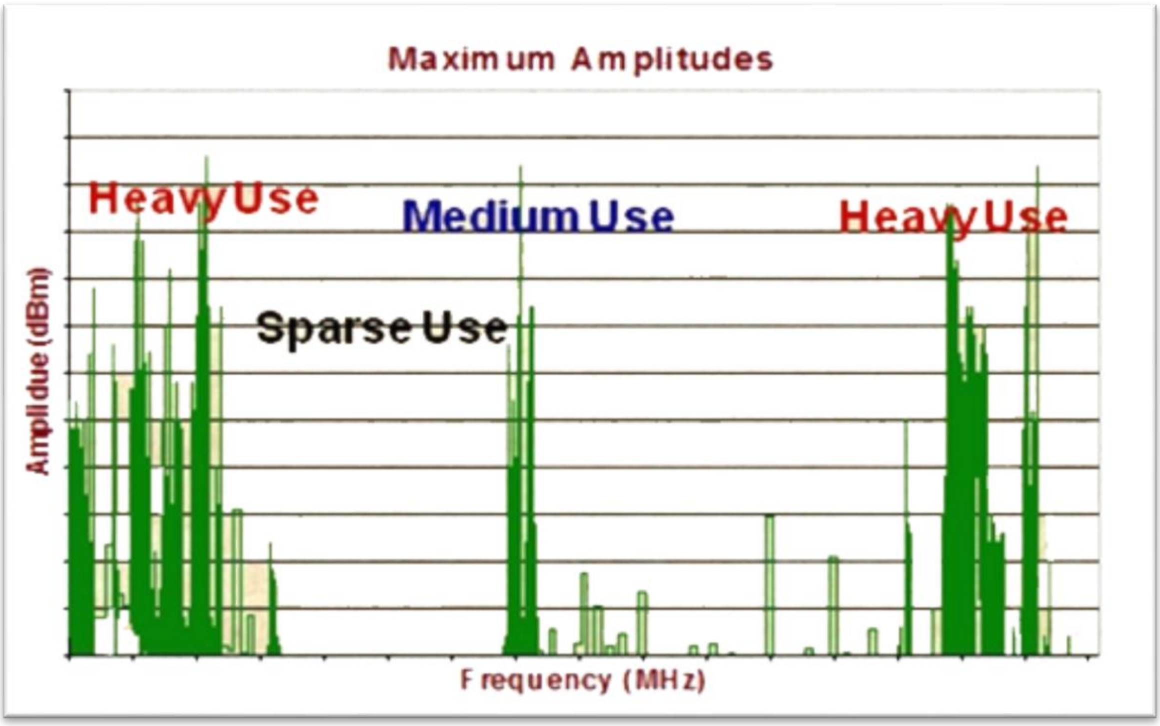

Figure 2.1: Spectrum occupancy blow 3 GHz [7].

A radio, therefore, that can sense and understand its local radio spectrum environment, to identify temporarily vacant spectrum and to use it, has the potential to provide wider bandwidth, increase spectrum efficiency and minimize the need for centralized spectrum management. This could be achieved by a radio that can make independent decisions about how it accesses spectrum intelligently [7].

2.2.1 Dynamic Spectrum Access (DSA)

One of characteristics of CR is a capability, which identifies the spectrum portions available in a specific moment and place through the interaction with the environment. These available spectrum portions are called spectrum holes or white spaces (WS) as in a figure 2.2. This characteristic is important to the implementation of CR system technology, since it is considered additional capabilities to radio communication systems will provided, such as dynamic spectrum access (DSA) [7].

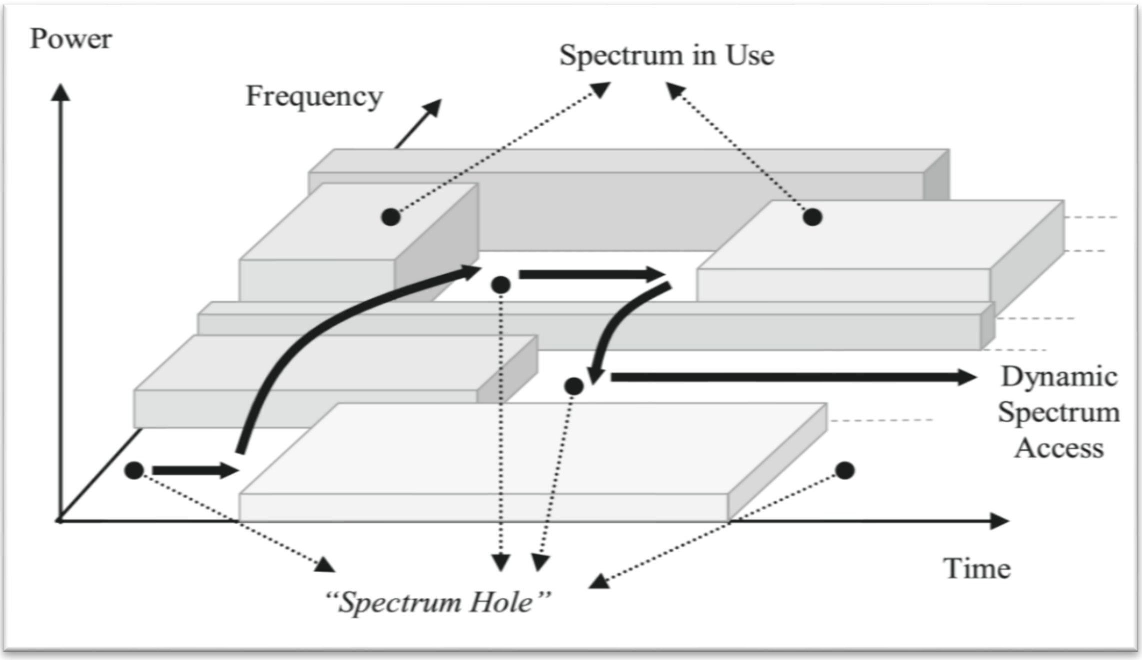

Figure 2.2: White Space (Spectrum Hole) [7].

Therefore, DSA techniques permit the cognitive radio to operate in the best available channel and the CR system uses this technique to enable the users to determine which portions of the spectrum are available and detect the presence of PUs when a user operates in a licensed band (spectrum sensing), select the best available channel (spectrum management),coordinate access to this channel with other users (spectrum sharing), and vacate the channel when a licensed user is detected (spectrum mobility).There are three main models of DSA, namely, open sharing (general use), hierarchical access (shared-use), and exclusive use (private-use) models as shown in figure 2.3.

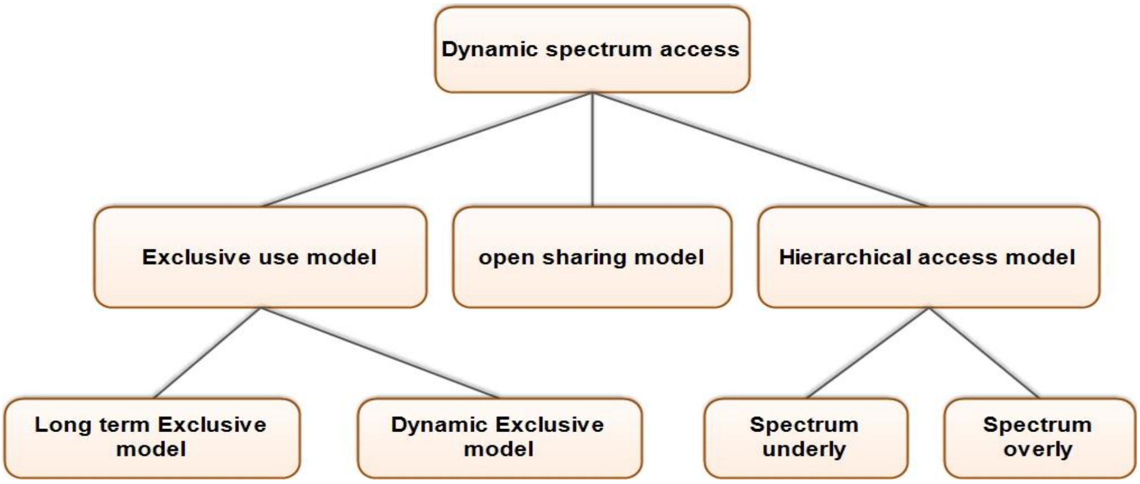

Figure 2.3: A taxonomy of dynamic spectrum access.

In the open use model, the spectrum is open for access to all users. This model is already been used in the industrial, scientific and medical(ISM) band. In the hierarchical use model, PUs (licensed users) are allocated the frequency bands, which are opportunistically accessed by the SUs (unlicensed users) when the PU does not occupy them.

In the exclusive use model, a PU agrees to access of a particular frequency band to a secondary user (SU) for a certain time. This model is more flexible than the spectrum licensing model related with traditional command and control, because the type of use and the spectrum license is able to change dynamically. In opportunistic spectrum access SU can exploit idle in band sections without causing interference to the active PUs[7].

Spectrum overlay and spectrum underlays are the two approaches for opportunistic spectrum access. The spectrum overlay approach (or opportunistic spectrum access) does not essentially force any strict constraint on the transmission power by SU. It allows SU to identify and utilize the spectrum holes defined in space, time and frequency. This approach is well matched with the existing spectrum allocation thus the PU systems can continue to work without being affected by the SUs.

The spectrum underlay approach limits the transmission power of SU so that they work below the interference temperature limit of PU. One possible approach is to transmit the signals in an ultra-wide frequency band (UWB) transmission in order that a high data rate is achieved with very low transmission power. It is the worst-case hypothesis that the PU transmits all the time. Thus, probably it does not utilize spectrum holes [7].

In the open use model, dynamic sharing can be between homogenous networks (IEEE 802.11a uses in the 5 GHz band) or between heterogeneous networks (coexistence between IEEE 802.11b and 802.15.1 Bluetooth networks).

When all the networks in a heterogeneous environment have cognitive or adaptive capabilities, it is referred to as symmetric sharing. On the other hand, when there is one or more network without cognitive/adaptive capabilities (e.g. coexistence of primary technology with CR technology, coexistence of powerful 802.11 networks with low-power 802.15.4 networks) is referred to as asymmetric spectrum sharing. DSA is divided into two major parts, i.e. spectrum investigation (sensing and analysis) and spectrum utilization (decide and handoff) [7].

2.2.2 Software Defined Radio (SDR)

The other characteristic of cognitive radio ability is a reconfigurability, which it should also be possible to transmit and receive through different frequency values using different access technologies. That is why the parameters of a CR can be modified to adapt to the environment and use the best frequency band.

SDR can act as a key enabling technology for a variety of other reconfigurable radio equipment's commonly discussed in the advanced wireless market and it's also a novel definition in Agenda Item 1.19 proposed for the work of world radio communications conference in 2012 (WRC-12) just to discuss the possibility of a harmonized action and is published in report ITU-R SM.2152 as [5]:

a radio transmitter and/or receiver employing a technology that allows the RF operating parameters including, but not limited to, frequency range, modulation type, or output power to be set or altered by software, excluding changes to operating parameters which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard [5].

A SDR is a reconfigurable radio in which the transmission parameters such as modulation mode, frequency band, and protocol may be adapted dynamically. This adaptability function is obtained by software-controlled signal processing algorithms.

Block diagram as shown in Figure 2.4 clear a general structure and ability of the SDR transceiver. It has the radio being assembled with a radio frequency front end, a down converter to an intermediate frequency (IF) or base band processing, an analog/digital (A/D) converter, and then a processor. The capacity of processing limits the complexity of the signal that can be holds [8].

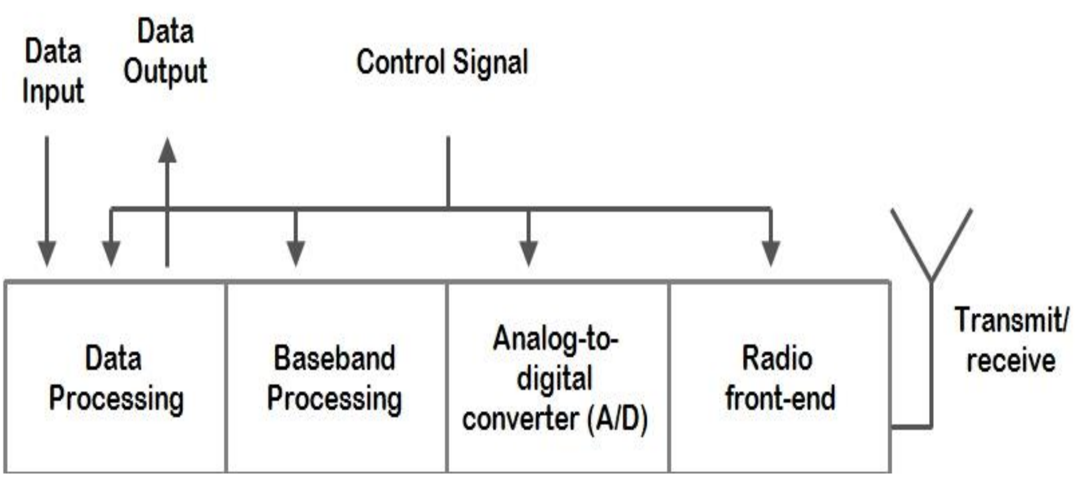

Figure 2.4: SDR transceiver [8].

SDR is a main part to implementing CR and the major functions of SDR are as multiband function since the SDR will carry wireless data transmissions over a different frequency spectrum used by different wireless access systems (e.g. cellular band, ISM band, TV band), the second function is multiple standard which it will support various standards such as global system mobile (GSM), wireless fidelity (WiFi), worldwide interoperability for microwave access (WiMAX). Multiple services is a third function so the SDR will be able to work on various types of services such as cellular telephony or broadband wireless Internet access. The fourth function is a multi-channel access since the SDR will be able to work on multiple frequency bands simultaneously [8].

As shown in Figure 2.4, the transmission parameters in a SDR transceiver may be reconfigured according to the communication requirements and specifications. The radio parameters such as standard to be operated and frequency band can be set before the device is delivered to the user. However, the parameters cannot be changed when the device is configured once.

Even though dynamic reconfiguration of the device is not supported in SDR. The parameters can be seldom reconfigured, when the network infrastructure modified or added on a connection basis. For example, when a user wants to start a wireless internet connection, the transceiver parameters can choose from the availability of different wireless access networks such as GSM, WiFi or WiMAX, based on performance and cost.

The radio parameters can also be dynamically changed on a basis of time slot. For example, the transmission power can be changed when the level of interference varied. The SU can change the operating band of frequency when the activity of the PU is detected [8].

SDR technologies are essential to the benefits of which can help to reduce cost and increase system efficiencies and it provided these types of radio with the flexibility necessary for them to achieve their full potential. CR is considered as a revolutionary technology that aims for remarkable improvements in efficiency of spectrum usage and it will change the way to the radio spectrum regulation, but also requires some of new enabling techniques [8].

2.3 The Cognitive Radio Cycle

In CR cycle, the CR system, monitors spectrum bands, captures their information, and then detects the spectrum spaces .The characteristics of the spectrum spaces is estimate using spectrum sensing to detect and choose the appropriate spectrum band according to the spectrum characteristics and user requirements. At the operating spectrum band is determined, the communication can be performed over this spectrum band [7].

In order to achieve these objectives, CR is required to adaptively modify its characteristics and to access radio spectrum without causing excessive interference to the primary licensed users. Cognitive cycle of CR operation as secondary radio system is shown in Fig. 2.5. Steps of the cognitive cycle are: spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility as explained in details in section 2.4 [7].

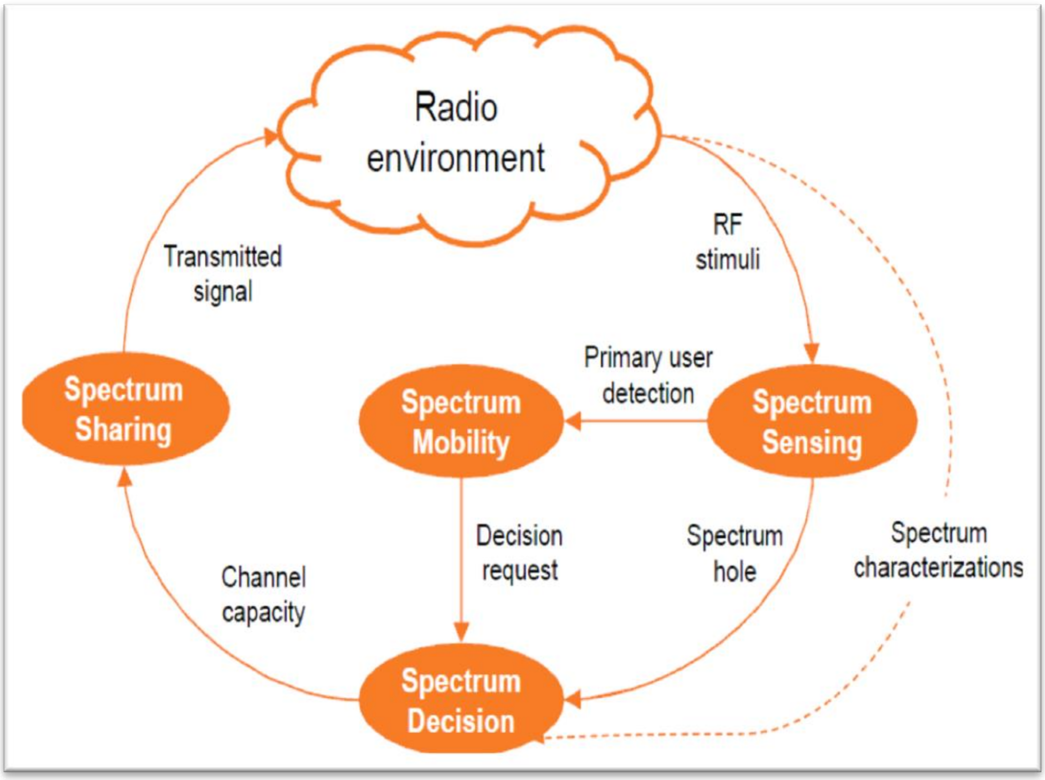

Figure 2.5: Cognitive cycle of cognitive radio [7].

2.4 Main Functionalities of Cognitive Radio

This section describes the functions and components of cognitive radio which provide adaptability to wireless transmission through dynamic spectrum access so that the performance of wireless transmission can be optimized, as well as enhancing the utilization of the frequency spectrum [9].The major functionalities of a CR system include spectrum sensing, spectrum management, spectrum sharing and spectrum mobility.

The components typically of a cognitive radio is depicted in Figure 2.6 since through spectrum sensing, the information of the target radio spectrum (e.g. the type and current activity of the licensed user) has to be obtained so that it can be utilized by the cognitive radio user. The spectrum sensing information is exploited by the spectrum management function to analyze the spectrum opportunities and make decisions on spectrum access. If the status of the target spectrum changes, the spectrum mobility function will control the change of operational frequency bands for the cognitive radio users [7].

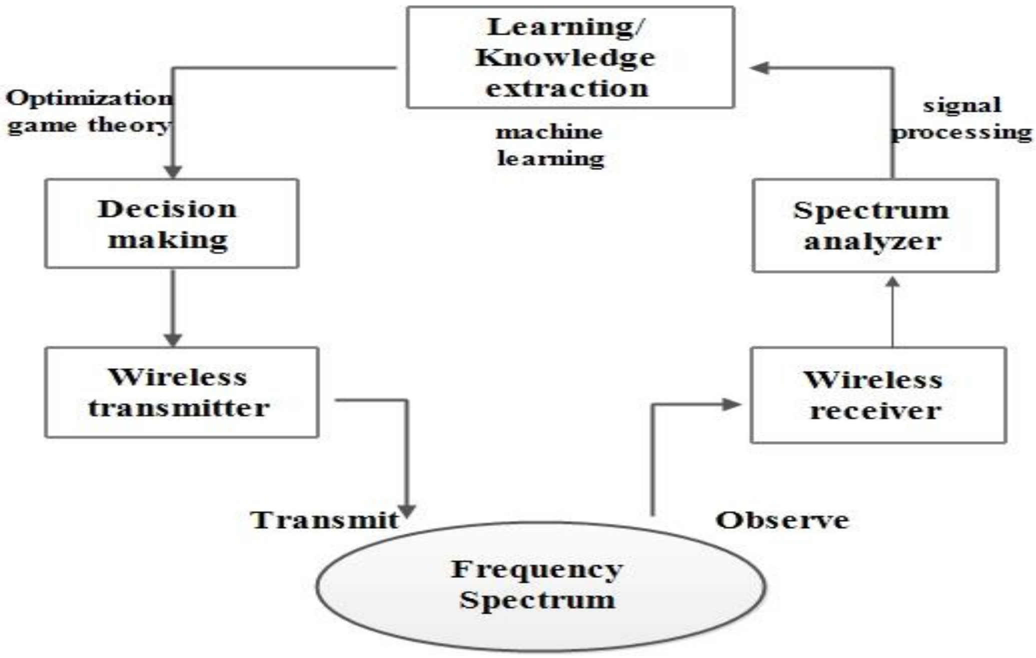

Figure 2.6: Components in a cognitive radio [7].

The Main functions of Cognitive Radios are described as:

2.4.1 Spectrum Sensing

Detecting the unused spectrum and sharing it without harmful interference with other users and it is an important requirement of the CR network to sense spectrum holes, where detecting primary users is the most efficient way to detect spectrum holes. Spectrum sensing techniques can be classified into three main categories as [10]:

i. **Transmitter Detection (non-cooperative detection)**: CR must have the capability to determine if a signal from a primary transmitter is locally present in a certain spectrum, there are several approaches proposed: matched filter detection, energy detection, cyclostationary feature detection.

ii. Cooperative Detection: refers to spectrum sensing methods where information from multiple Cognitive radio users is incorporated for primary user detection.

iii. **Interference Based Detection:** refers to the interference temperature model as the signal of a radio station designed to operate in a range at which the received power approaches the level of the noise floor .The noise floor is the level of noise introduced by the system, below which the signal that is being captured cannot be isolated from the noise. [10, 37].

2.4.2 Spectrum Management

Capturing the best available spectrum to meet user communication requirements. CR should decide on the best spectrum band to meet the QoS requirements over all available spectrum bands, therefore spectrum management functions are required for CR. The main mechanisms optimized of spectrum management functions can be classified as:

i. Spectrum Analysis: The SUs use the information obtained from spectrum sensing to schedule and plan spectrum access. In this case, the transmission requirements of SUs have to be optimizing the transmission parameters and analyzed this information to get knowledge concerning the spectrum holes such as interference estimation, duration of availability and collision probability with a PU due to sensing error. Then, a decision to access the bandwidth, frequency, transmit power, modulation mode, time duration and location of spectrum is made by optimizing the system performance given the preferred objective i.e. maintain the interference caused to PUs lower the target threshold and maximize the throughput of the SUs [11] .

ii. Spectrum Decision: Before a decision is made on spectrum access based on spectrum analysis, the unlicensed users access the spectrum holes. Spectrum access is carried out based on a cognitive medium access control (MAC) protocol to avoid conflict with PUs and also with other SUs.

The CR transmitter is also required to make compromise with the CR receiver to synchronize the transmission in order that the transmitted data received successfully. A cognitive MAC protocol either is based on a fixed allocation MAC such as frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA) or a random access MAC such as ALOHA, or carrier sense multiple access with collision avoidance (CSMA/CA)[11].

2.4.3 Spectrum Sharing

Providing the fair spectrum scheduling method among coexisting CR users, one of the major challenges in open spectrum usage is the spectrum sharing. It can be regarded to be similar to generic media access control MAC problems in existing systems .The spectrum sharing function is classified into three main categories as shown in figure 2.7 according to Architecture, Allocation behavior and Access technique [12].

In the spectrum sharing Architecture**,** there are two configurations as *a* centralized architecture; sharing decisions are made at one node. In contrast, for distributed architecture, each SU node independently accesses the spectrum based on its observations and decisions. The major difference is the second architecture does not need an infrastructure as the first one does.

The spectrum sharing allocation behavior works as co-operative or non-cooperative. The co-operative behavior considers the impact on other SUs. The non-cooperative behavior creates a competition among the SUs.

The spectrum sharing access techniques follow three schemes: overlay, underlay, and underlay with interference avoidance.

The overlay scheme occurs when the SU transmits power similar as the PU does. If the SU transmits at the same time as the PU transmission, the SU signal overlays the PU signal. Similarly, the underlay scheme occurs when the SU spreads its power into the whole available bandwidth, as in CDMA or UWB.

If the instantaneous transmission occurs, the SU signal underlay the PU signal. The underlay with interference avoidance scheme is similar to the underlay scheme, but it avoids the band where the PUs exist, as in the orthogonal frequency division multiplexing (OFDM) technique [13].

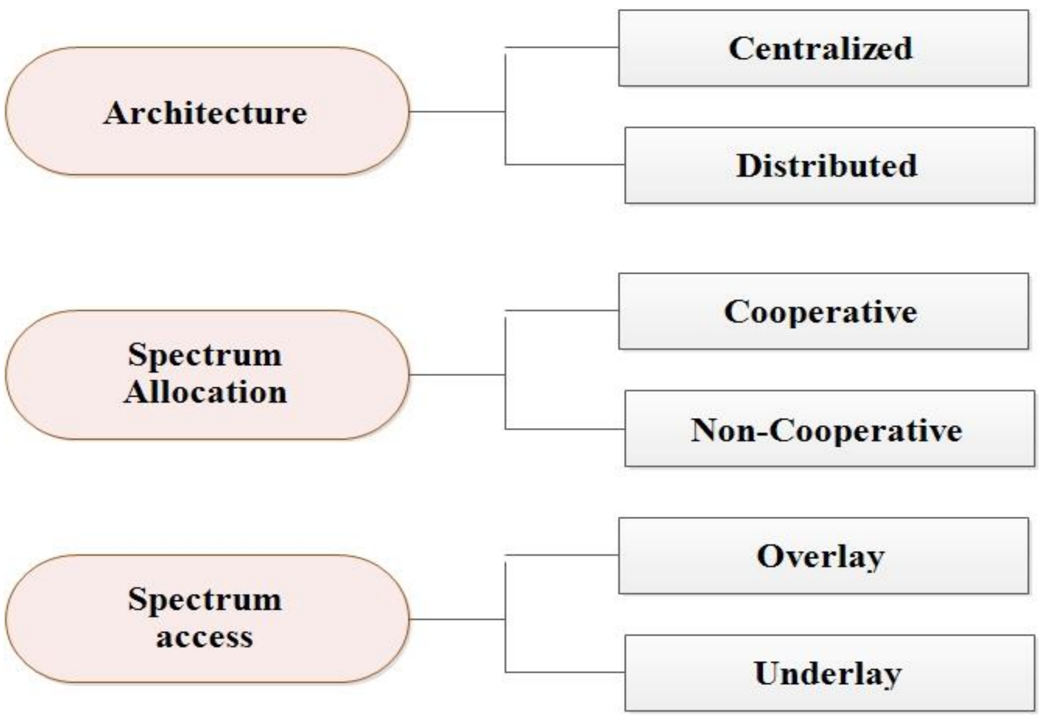

Figure 2.7: Spectrum Sharing Function Categories.

2.4.4 Spectrum Mobility

This is defined as the process when a CR user exchanges its frequency of operation. CR networks target to use the spectrum in a dynamic manner by allowing the radio terminals to operate in the best available frequency band, maintaining seamless communication requirements during the transition to better spectrum, and arises when current channel conditions become worse or when a primary user appears. Each time a CR user changes its frequency of operation, the network protocols are going to shift from one mode of operation to another. The spectrum mobility can be categorized into the time, the space as follows [14]:

i. **Spectrum mobility in time domain**. The available channels change with respect to time, which is to maintain QoS in this environment. The physical radio goes through the spectrum to fulfill the QoS requirements. Spectrum mobility (spectrum handoff) in time can be categorized according to the target channel selection methods into two main types: proactive-sensing spectrum handoff and reactive-sensing spectrum handoff [15].

ii. **Spectrum mobility in space.** As user changes its position from one place to another, the available bands also changes and assign a new frequency to the CR networks. So, if CR user moves to another place in the same network, the spectrum mobility called intercell handoff but if spectrum mobility occurs between different network, its referred to vertical handoff. For more details about spectrum mobility and specifically spectrum handoff will be in the next chapter [15].

2.5 The Architecture of Cognitive Radio Network

Some part of the wireless spectrum is licensed for different tasks and few bands are still unlicensed. In this section, there is discussion about all the possible scenarios for a better description of the communication protocols. The cognitive radio architecture is illustrated of components as in figure 2.8 and it is become clear that there are two main groups, the primary networks and the CR networks.

2.5.1 Primary Network

The primary networks have special rights to specific bands. The primary network includes the PU and the primary base-station.

i. **Primary User**: PUs may be called licensed users, operate in specific spectrum bands. This process is entirely controlled by the primary base-station only. This PUs do not require any further enhancements for the coexistence of the primary base stations and the other PUs.

ii. Primary Base-Station: The primary base station has a fixed infrastructure. Primary networks do not have the ability of CR for sharing the spectrum with SUs but it can be requested to have both legacy and CR protocols for primary network access of SUs.

2.5.2 Cognitive Radio Network

CR networks do not have the permission to operate in the required band. The CR networks can be deployed both with infrastructure and without infrastructure networks as illustrated in figure 2.8. The components of the network are as follows:

i. Cognitive Radio User: The CR user (secondary or the unlicensed user) has no spectrum license, so extra functionalities are needed for sharing the spectrum band.

ii. **Cognitive Radio Base Station**: The CR base station (secondary or unlicensed base station) has a fixed infrastructure component with CR abilities. CR can access the different networks by providing the single hop network connection to CR user. Single hop connection is used to reduce the propagation delay; it has now become essential to have single hop network connection which connects the user terminals [10].

The CR network architecture in figure 2.8 shows different types of networks primary network access, with infrastructure based CR network, without infrastructure based CR network (ad hoc network). The CR networks operate both in licensed and unlicensed bands (mixed spectrum environment). There are three access types are:

i. Primary Network Access: The licensed bands are means for the CR users through which they access the primary base station. Networks with access right to certain spectrum bands, e.g. common cellular systems and TV broadcast networks and users of these networks are referred to as PUs. They have the right to operate in licensed spectrum and users of certain primary network do not care of other primary or secondary networks users [10].

ii. CR Network Access: The CR users can access the CR base station not only the licensed bands but also the unlicensed spectrum bands and do not have license to operate in the spectrum band they currently use or aim at using a opportunistic spectrum access . Users of these networks are referred to as SUs and additional functionalities are required to share licensed spectrum bands with other secondary or primary networks [10].

iii. CR Ad hoc Access: The CR users communicate with different CR users through the ad hoc connection on licensed and unlicensed bands and it is allows unlicensed users to opportunistically access available licensed spectrum bands for data communication under an intelligent and cautious manner.

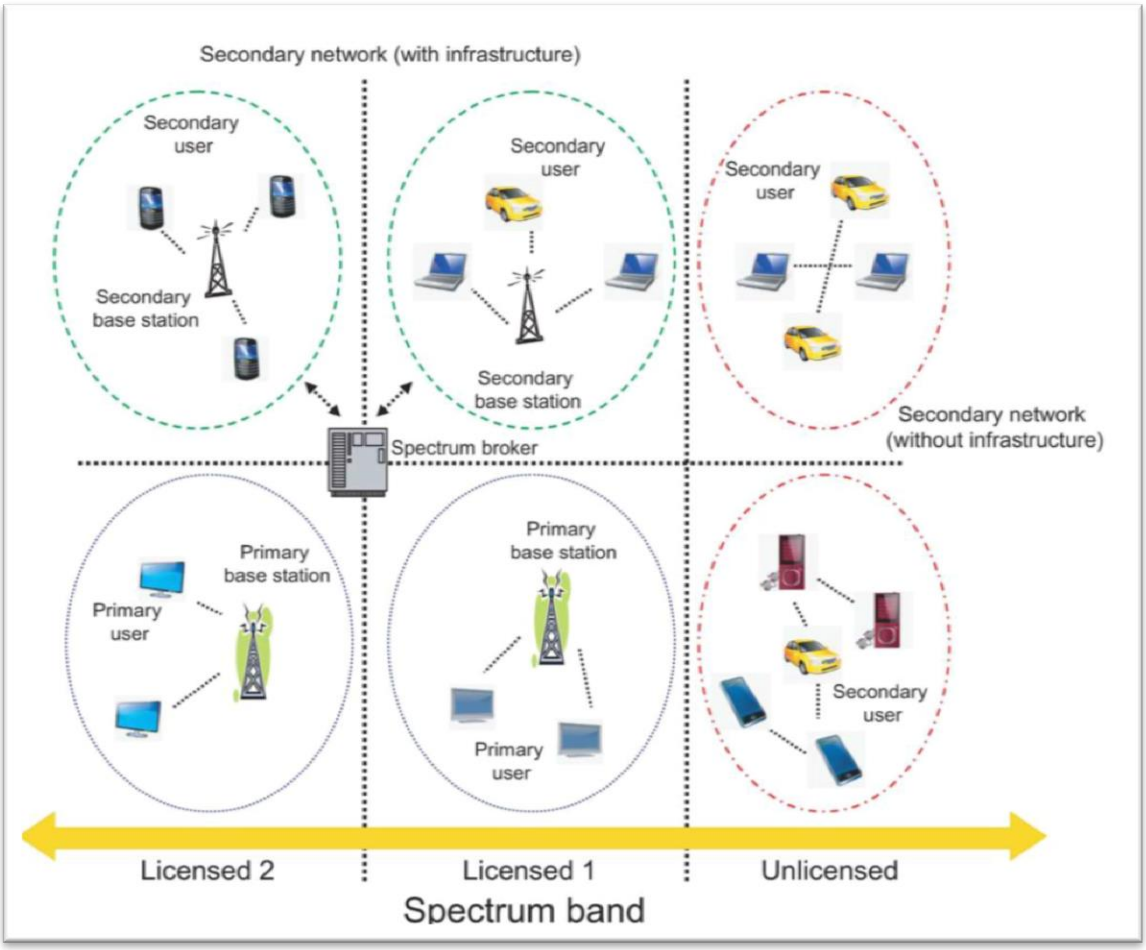

Figure 2.8: Cognitive Radio Architecture [10].

2.6 Cognitive Radio Standardization

The standardization is a key aspect of the success of the current and future CR system performed on all levels, including IEEE, ITU, ETSI, SDR forum and ECMA [15].

- **In IEEE,** it is started the development of the first international CR standard in 2006 and it have several working groups (WG) in standards coordination committee (SCC) 41 on DSA Networks and the 802 LAN/MAN standards committee are standardizing CR Systems and their component to improve the current standards to support the cognitive capability. There are two major standards in the IEEE on CR which are IEEE 802.22 and IEEE P1900 [15].

- **IEEE 802.22:** this standard is the first worldwide standard on CR technology. The main target of this standard is to enable the sharing of the TV spectrum with broadcast service in the low population rural areas. In this standard, not only the PHY and MAC layers are considered. But unlike other standards, it addresses additional functions like the spectrum sensing functions and the geo-location one.

  Using the spectrum sensing function, the spectrum holes are identified while the geo-location one is determining the location of the cognitive devices. The location information is combined with a database of the primary transmitters to determine the available channels. The network BS is covering a geotropical area with 30 km radius and can support a maximum of 255 fixed units of customer premises equipment (CPE). The minimum downlink (BS to CPE) throughput is 1.5 Mb/s while the minimum in the uplink (CPE to BS) is 384 kb/s [16, 17].

- **IEEE P1900:** this standard focuses on the next generation radio and spectrum management [18]. The standard considers the advanced radio system technologies such as the CR systems, policy defined radio system, adaptive radio systems and related technologies.

  The standards consists of six working groups: IEEE P1900.1 to define the glossary of the terms, IEEE P1900.2 for the interference coexistence analysis, IEEE

P1900.3 for the evaluation of software modules in SDR to guarantee the compliance in the software part, IEEE P1900.4 is the major working group which relates to coexistence support for the reconfigurable heterogeneous air interface, IEEE P1900.5 for the definition of the policy language and policy architectures, and finally, IEEE P1900.6 to define the spectrum sensing interfaces as well as data structures for DSA systems. An extensive review on the standardization activity within IEEE and other organization can be found on [15, 19, 20].

- **In ITU**, the ITU-Regulation (ITU-R) working parties (WPs) 1B and 5A currently release reports describing the CR System concept and the regulatory measures required to introduce the CRS since WP 1B is considering the international radio regulation implications of the SDR and CRS, as well as, methods to satisfy WRC-12 agenda item 1.19 and WP 5A is currently developing the working document toward a preliminary new draft report, "Cognitive Radio Systems in the Land Mobile Service" [22].

- **In ETSI** (European Telecommunications Standards Institute), technical committee (TC) on reconfigurable radio systems (RRS) has been developing reports describing different components of the CR system, as well as reports on the CR system concept and the regulatory aspects of the CR system.

Currently, ETSI TC RRS is developing draft technical specification, "Coexistence Architecture for CR networks on UHF white space frequency bands." This draft specification will define system architecture for spectrum sharing and coexistence between multiple CR networks. The coexistence architecture is targeted to support secondary users in UHF white space frequency bands [24].

- **In ECMA** (European association for standardizing information and communication) systems, Task Group 1 of technical committee 48 has standardized a CR system for television (TV) white space.ECMA-392 specifies a number of incumbent protection mechanisms that may be used to meet regulatory requirements. Summary of international standardization on CRS you can see the following figure 2.9 [21-29].

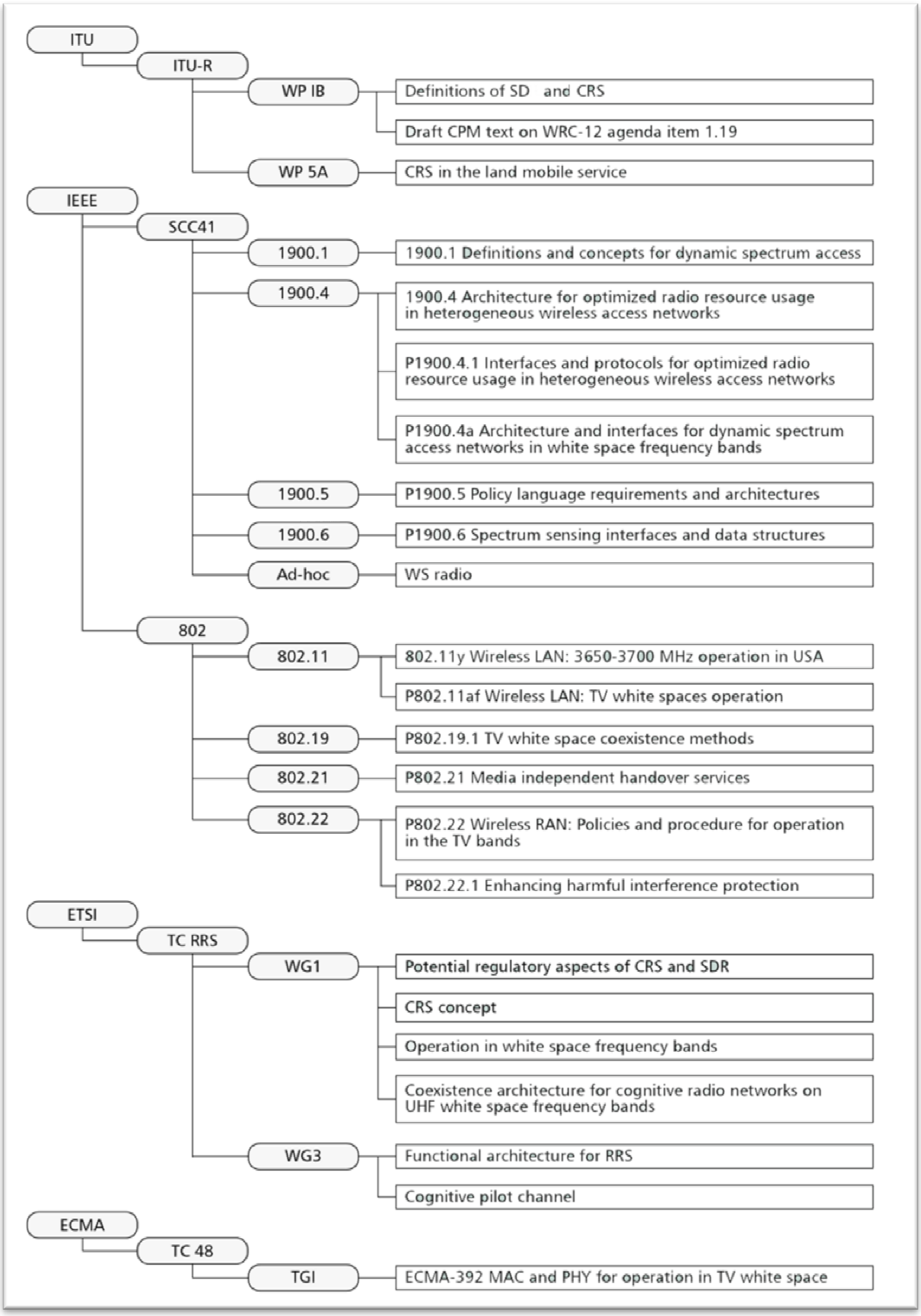

Figure 2. 9: Summary of international standardization on CR system [26].

2.7 Applications of Cognitive Radio

More flexible and efficient use of spectrum in the future open up exciting opportunities for cognitive radio to enable and support a variety of emerging applications, starting from smart grid, public safety and broadband cellular, to medical applications. This section displays a brief explanation about how cognitive radio would support such applications and figure 2.10 shows an example of the CR network applications [21]:

- **Next generation wireless networks***:* CR is expected to be a core technology for next generation heterogeneous wireless networks. This will provide intelligence to both the user part and service part equipments to manage the network and air interface efficiently.

  At the user-part, mobile equipment with multiple air interfaces (e.g. cellular, WiFi and WiMAX) can observe the condition of the wireless access networks (e.g. transmission quality, delay, throughput, and congestion) and make a decision on selecting the access network to connect according to cost.

  At the service-part, radio resource from multiple networks can be optimized for the given set of mobile users and their QoS requirements. Based on the mobility and traffic outline of the users, efficient load balancing systems can be implemented at the infrastructure of service provider to allocate the traffic load among multiple available networks to reduce network congestion [21].

- **Coexistence of different wireless technologies***:* New wireless technologies are being developed to reuse the radio spectrum allocated to other wireless services such as TV service. CR is a solution to provide coexistence between these different technologies and wireless services.

  IEEE 802.22 based wireless regional area network (WRAN) users can opportunistically use the TV band when a TV station is not broadcasting. Spectrum sensing and spectrum management will be critical mechanism for IEEE 802.22 standard WRAN technology to avoid interference to TV users and to maximize throughput for the WRAN users [21].

- **Intelligent transportation system** (ITS): it is a widely used in different wireless access technologies to improve the safety and efficiency of transportation by vehicles.

- **Emergency networks***:* Emergency and public safety networks can take advantages of the CR concepts to provide flexible and reliable wireless communication. In the case of disaster situation, the infrastructure of standard communication may possibly not exist, and then, a CR network as an emergency network may require to be established to carry disaster recovery [21].

- **Military networks***:* With CR, the parameters wireless communication can be dynamically adapted based on the location and time as well as the mission of the militaries. Suppose, if some frequencies are noisy or jammed, the CR transceiver can search for and access another frequency bands for communication. Furthermore, location aware CR can manage the transmitted waveform in a particular area to keep away from interference to the high priority military communication systems [21].

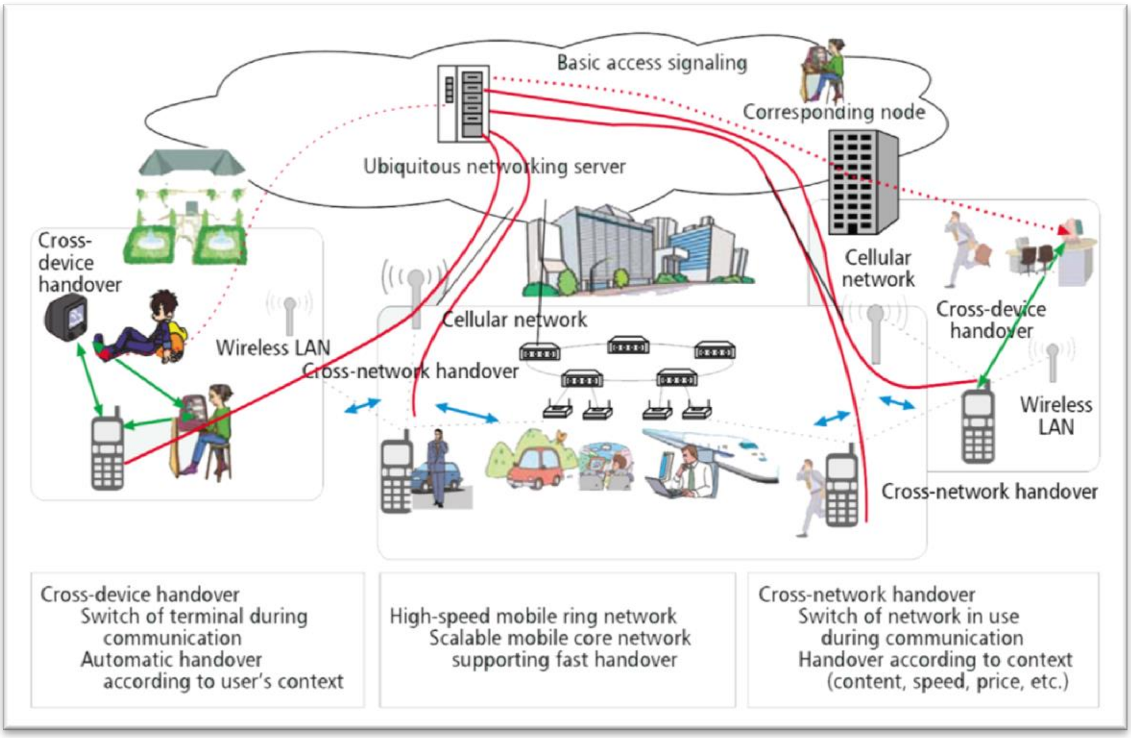

Figure 2.10: Multi-service Network Application [21].

3

Spectrum Handoff in CR Network

Spectrum mobility is one of the most important functionalities of CR networks, which enables SUs to change the operating frequencies based on the availability of the spectrum. Spectrum mobility gives rise to a new type of handoff called spectrum handoff, which refers to the process that when the current channel used by a SU is no longer available, the SU needs to pause its ongoing transmission, vacate that channel, and determine a new available channel to continue the transmission.

3.1 Spectrum Handoff Overview

As CR networks have capability to support flexible usage of wireless radio spectrum and it is a technique have attracted increasing attention in recent years. In CR networks, SUs may dynamically access underutilized spectrum without interfering with PUs, which is called spectrum handoff. Spectrum handoff refers to the procedure mentioned by the SUs when they users want to transfer their connections to an unoccupied spectrum band [30].

The CR users monitor the entire unused spectrum continuously during the transmission. If the specific portion of the spectrum in use is required by a primary user, the communication needs to be continued in another vacant portion of the spectrum, then spectrum handoff occurs, and they move to the "best matched" available spectrum band.

Compared with other functionalities (spectrum sensing, spectrum management, and spectrum sharing) of CR networks, spectrum mobility is a very important and evidences from the significant number of interactions that the spectrum management functions necessitate a cross-layer design approach as shown in figure 3.1. Thus, each spectrum management function cooperates with application, transport, routing, medium access and physical layer functionalities with taking into consideration the dynamic nature of the underlying spectrum.

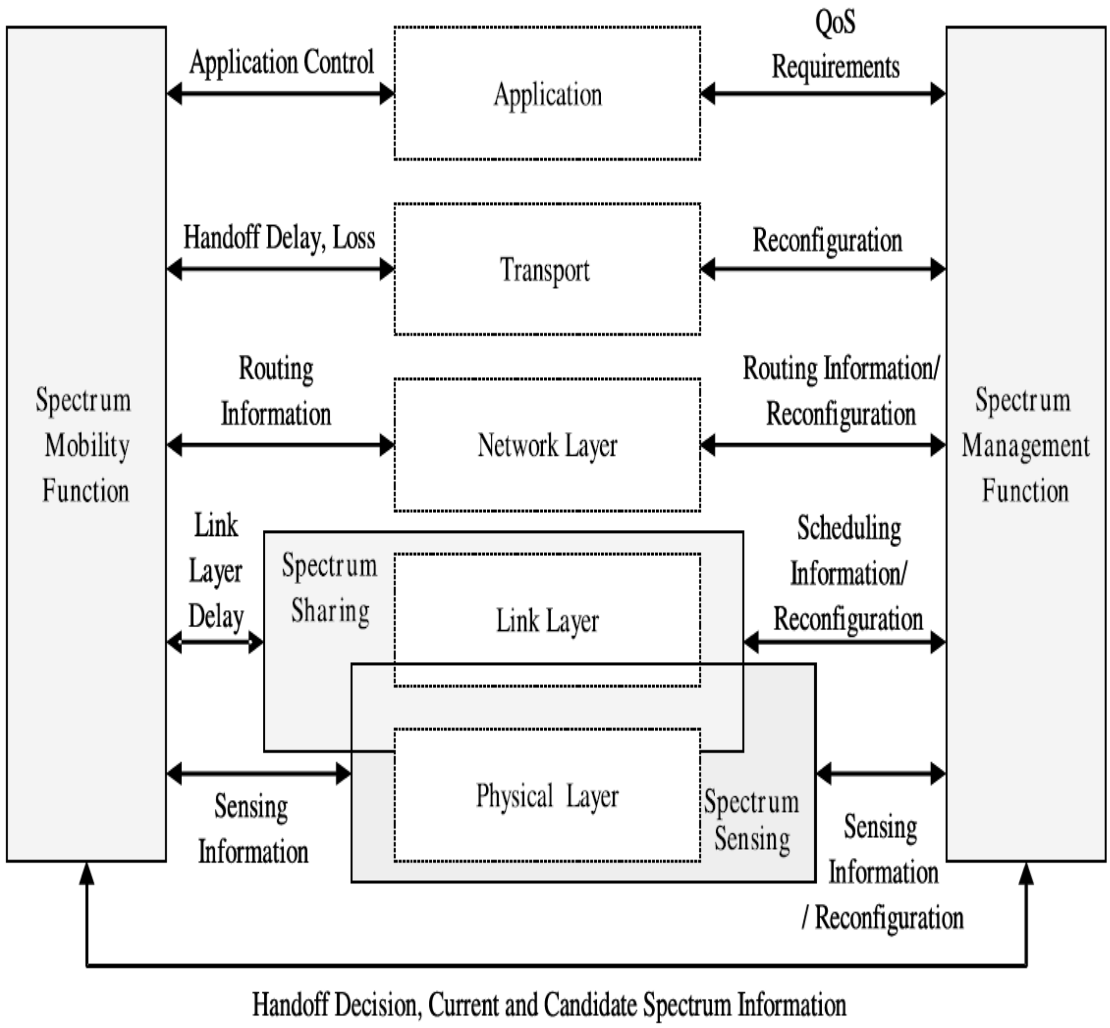

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Figure 3.1: CR network communication functionalities [7].

Hence, spectrum handoff method focuses on the seamless transition with minimum quality degradation and it occurs when primary user is detected, secondary user moves from one place to another, or current spectrum condition becomes worse.

Figure 3.2 shows the cyclic spectrum handoff process which consists of two phases: the first phase is evaluation phase and the second is link maintenance phase.

In first phase, SU observes the environment and analyzes whether handoff triggering events occur. Once SU decides to perform spectrum handoff, it goes into link maintenance phase. In the link maintenance phase, SU first pauses the ongoing transmission. Then, SU hands over the reclaimed channel to PU and resumes data transmission session over another free channel. Finally, SU leaves link maintenance phase and resumes the cycle [32].

Note that backup target channel can be searched either in evaluation or in link maintenance phase depending on whether proactive or reactive handoff is used. There are two important factors impact for the efficient spectrum handoff which is sensing speed and accuracy in spectrum sensing. The trade-off between them is need, because fast sensing speed would lead to less accuracy rate output.

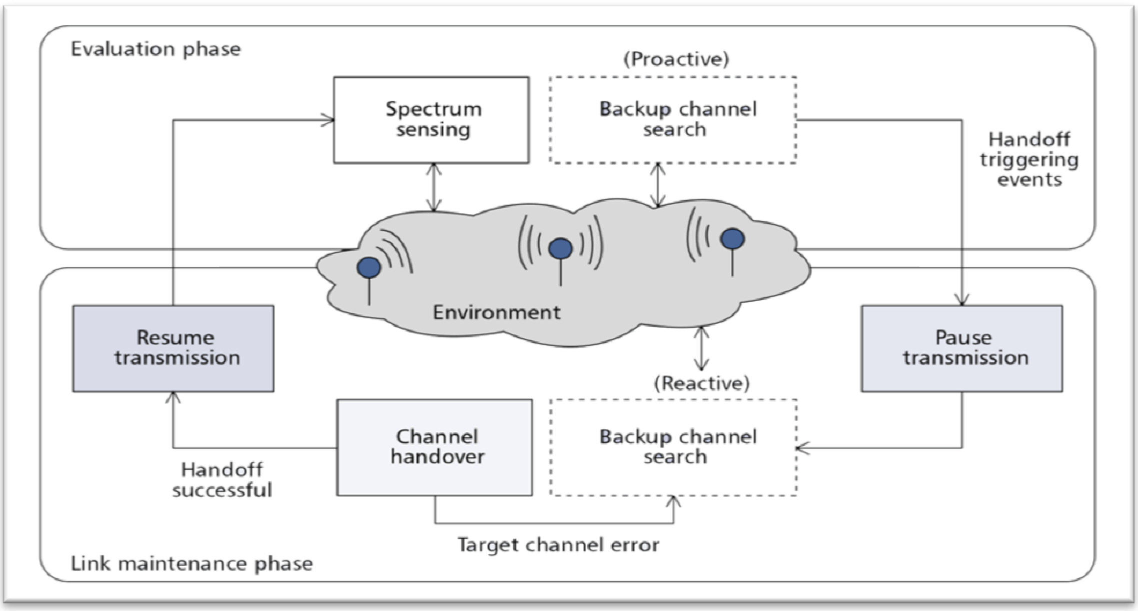

Figure 3.2: Spectrum handoff process [33].

From the previous mentioned , we note various spectrum handoff strategies are classified regard to sense and event (time and latency), which is a two famous main types: proactive-sensing and reactive-sensing, whereas categorized spectrum handoff according to heterogeneous network, availability spectrum and movement user from place to another is defined by the spectrum pooling (space and spectrum availability) which is spectrum mobility, user mobility, quality degradation since it moves between spectrum bands, frequencies, cells, systems. From all of these categories, we will explain and discuss more details in the next sections.

3.2 Spectrum Handoff Strategies

Spectrum availability in CR networks varies over time and space, making it more difficult to provide seamless and reliable communications to secondary users traversing across multiple change of band. So, under such a different environment, the available channels change over time while the available bands also change as a user moves from one place to another.

Spectrum handoff strategy is considered as the main part and it is important role to compensating the disorder of the system best performance. The spectrum handoff schemes can be categorized according to the target channel selection methods and handoff triggering event occurrence into two main types: proactive-sensing spectrum handoff by which the secondary users make the target channels for spectrum handoff ready before its transmission (predetermined), and the other type is reactive-sensing spectrum handoff where the target channel for spectrum handoff is selected or sensed only after the spectrum handoff request is made(on demand manner) [14].

Spectrum sensing can be executed either before or after spectrum handoff triggering events happens, and so can be handoff action. The combination of the two parameters above, gives an extended four spectrum handoff strategies: non-handoff, pure reactive handoff, pure proactive handoff, and hybrid handoff strategy as shown in figure 3.3 and discuss in the following sub-sections [33]:

3.2.1 Non-Handoff Strategy

In non-handoff strategy, the SU selects the licensed channel to transmit, if PU is active, then the SU keeps staying in original channel and being idle until the channel becomes free again from PU to use as the next target channel and the SU resumes the data transmission again.

The higher waiting latency to SU is a major disadvantage of this approach because the delay is as long as PU is active in the corresponding channel. This approach is not efficient for delay sensitive applications and the probability of channel failure increase according to the PU activity. Also, it is obvious that time is badly wasted during SU waiting period [33].

3.2.2 Pure Reactive Handoff Strategy

In pure reactive handoff strategy, SU adopted reactive spectrum sensing and reactive handoff action approach. At a handoff triggering event occurs, SU executes spectrum sensing to determine target backup channel. Then, link communication is transferred to the new target channel. Meaning that, both target channel selection and handoff action are executed reactively after a triggering event happens.

This strategy is an advantage of that SU can get an accurate target channel since spectrum sensing is executed in the most relevant spectrum environment, but it comes at a cost of longer handoff latency due to on demand spectrum sensing. Therefore, spectrum sensing becomes the major delay in the handoff process in this strategy because the SU executes spectrum sensing after detecting the handoff event [33].

3.2.3 Pure Proactive Handoff Strategy

The SU run both spectrum sensing and handoff action proactively approach in this handoff strategy before the triggering event happens. SU executes spectrum sensing to determine a backup target channel before a handoff triggering event happens. Based on the knowledge of PU traffic model, SU is able to predict PU arrival so that SU evacuates the channel beforehand [33].

There are many features by using the pure proactive approach. The first feature, handoff latency can be very short because everything can be planned in advance. The second, the possibility of multiple spectrum handoffs can be minimized by considering future target channel usage when selecting backup target channel. While, the disadvantages of this approach is that backup target channel can remain issue because it is no updated instantaneously.

There is a chance that prepared backup channel is already occupied by other users at handoff time. Additionally, choose PU traffic model accurately also becomes a key factor in this approach. Poor predictions caused by incorrect PU traffic model may worsted degrade the overall spectrum mobility performance [33].

3.2.4 Hybrid Handoff Strategy

Hybrid handoff strategy incorporates pure proactive and pure reactive strategy by applying proactive spectrum sensing and reactive handoff action. Target channel selection is prepared beforehand or during SU data transmission while, spectrum handoff is executed after a handoff triggering event happens. Hybrid handoff approach is a reasonable compromise between pure reactive and pure proactive strategy.

Despite the fast of spectrum handoff time which can be executing the spectrum sensing time during the handoff process. However, target channel can stay its time is over as it does in pure proactive approach [33].

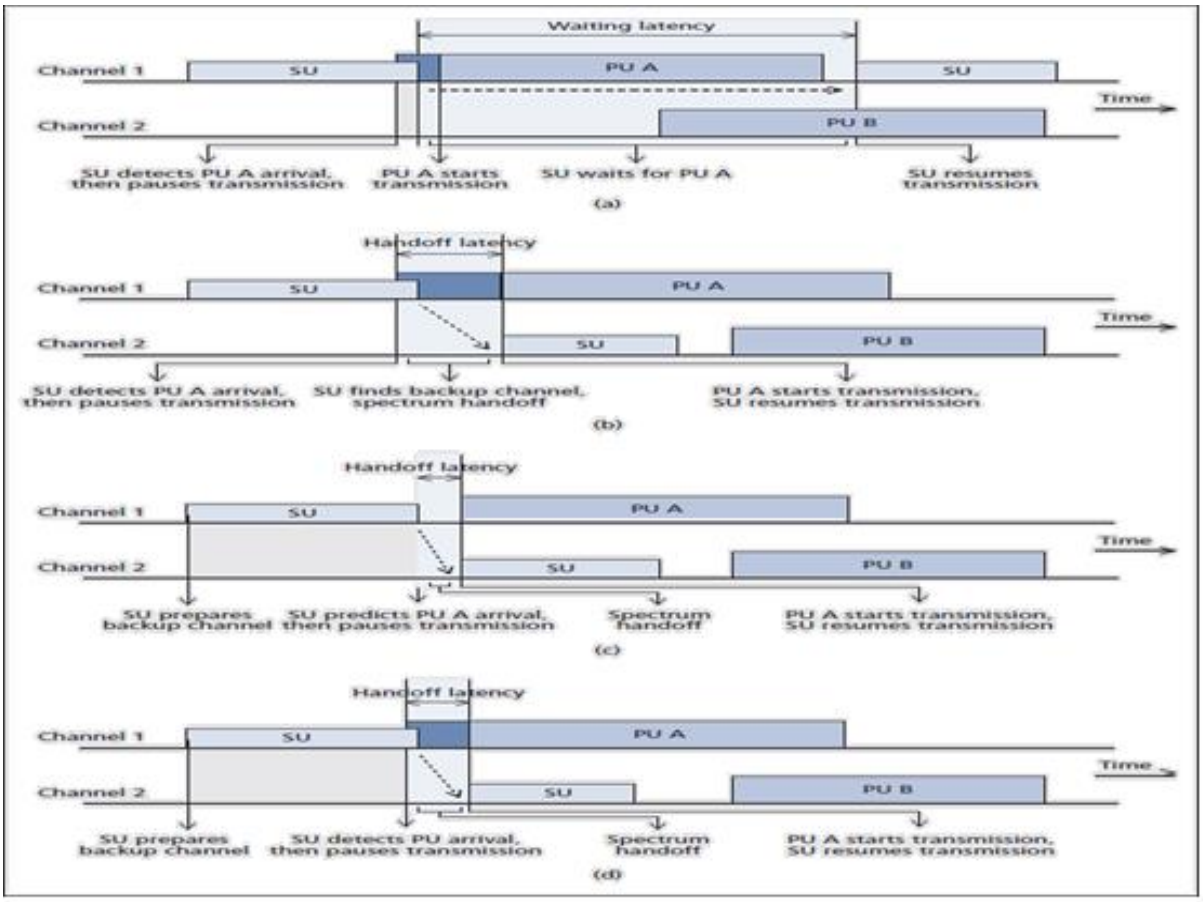

Figure 3.3: Spectrum handoff strategies: a) non-handoff; b) pure reactive handoff; c) pure proactive handoff; and d) hybrid handoff [33].

3.2.5 Comparison of Handoff Strategies

These strategies are examining to the handoff latency factors, so that pure proactive handoff strategy has the lowest handoff latency, while hybrid handoff and pure reactive handoff strategies have moderate and non handoff strategy the long handoff latency respectively as shown in figure 3.4.

These features will determine their suitability for various applications in PU networks. It gives an overall description of the various factors. In non-handoff strategy, PU data transmission becomes a major delay source to SU. While handoff decision task completion can be estimated, it is not the case for PU activity where its completion tends to be random in nature [33].

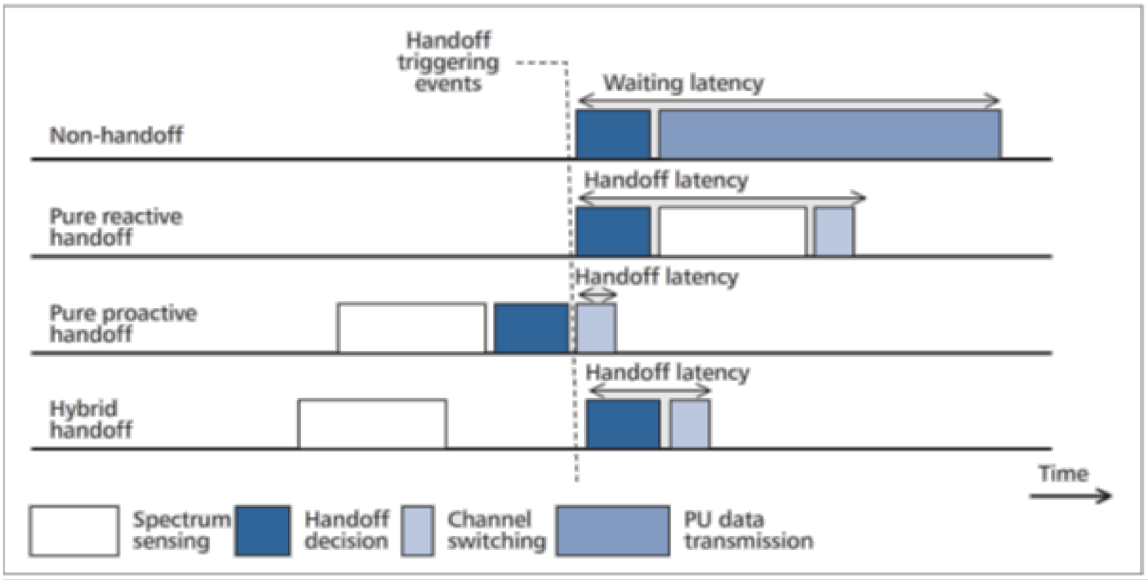

Figure 3.4: Handoff latency factors [33].

Therefore, non-handoff strategy suffers from unpredictable waiting latency. For other spectrum handoff schemes, major delay sources to SU come from spectrum sensing, handoff decision, and channel switching task; among which spectrum sensing is considered the most time-consuming.

In pure reactive handoff strategy all three tasks are executed during the handoff phase. Conversely, in pure proactive handoff strategy spectrum sensing and handoff decision task are excluded from handoff phase. In hybrid handoff strategy, spectrum decision and channel switching tasks are executed during handoff phase, while spectrum sensing is excluded from handoff phase. As a result, pure proactive handoff strategy features the fastest response in spectrum mobility, whereas pure reactive handoff strategy displays relatively slow response and hybrid handoff strategy has moderate response.

Comparison between various spectrum handoff strategies is summarized in Table 3.1 and it is important to note that the application of spectrum handoff strategy depends on unique characteristics of the PU network.

Non-handoff strategy can be suitable for the PU network with short data transmission pattern, for example a public safety service, and in the situation where other licensed spectrum bands are highly crowded.

In the case of well, under primary networks, pure proactive strategy would be the best, so most of classical handoff schemes are based to it and the moving user from place to another and overload cell is considered as examples. Furthermore, pure reactive handoff strategy and hybrid handoff strategy are good for CR networks in general PU networks where PU arrival is considered to be random, such as in battlefield and natural disaster evacuation [33].

Table 3.1. Comparison of spectrum handoff strategies [33].

Strategy	**Non-handoff**	**Pure reactive**	**Pure proactive**	**Hybrid**
Main idea	stay and wait	Reactive sensing Reactive action	Proactive sensing Proactive action	Proactive sensing Proactive action
Advantages	Very low PU interference	Accurate target channel selection	Fastest response Smart target channel selection	Fastest response
Disadvantages	Very high SU interference	Slow response	Outdates target channel selection	Outdates target channel selection
Handoff latency	Unpredictably high latency	Medium latency	Very low latency	Low latency
Dependency	PU activity	Spectrum sensing	Backup channel relevancy Accurate PU traffic model	Backup channel relevancy
Best suited environment	Short data transmission PU network	General PU network	Well-modeled PU network	General PU network

3.3 Types of Spectrum Handoff

For efficient mobility management, CR networks need to mitigate this dynamic spectrum availability by performing mobility management adaptively dependent on the heterogeneous network conditions.

The main difference between classical and CR cellular networks lies in spectrum mobility, which gives rise to a new type of handoff in CR cellular networks, the so-called spectrum handoff. Compared to the classical wireless network, the CR network requires more complicated mobility management functionalities due to the dynamic spectrum environment and heterogeneous handoff types, as shown in figure 3.5. These functionalities are initiated by three different events: user mobility, spectrum mobility, and quality degradation [34].

User mobility is defined as the event that a mobile CR user transfers an ongoing connection from one base station (BS) to another as it approaches the cell boundary. Conversely, spectrum mobility is referred to as the event that CR users switch their spectrum due to the PU activity. Each BS detects one of these events by monitoring current spectrum availability and the quality variation of current transmissions and performs a proper mobility management function accordingly.

To solve the problem in spectrum mobility, we modify a conventional spectrum pooling concept, known as the most suitable structure to adapt to the dynamic radio environment in CR networks for handling both spectrum and user mobilities in a multicell environment[34].

The spectrum pool consists of a main subparts which are defined as below and figure 3.5 shows these components in different cell based to CR assignment [35, 36]:

i. **Spectrum pool:** A set of contiguous licensed spectrum bands, each of which consists of multiple channels.
ii. **Spectrum band:** A basic bandwidth unit for operating a certain wireless access technology such as 5 MHz WiMAX band operating at 2.5 GHz.
iii. **Channel:** A minimum part unit of wireless resource that mobile users can access through multiple access schemes. Each channel has the identical capacity.

By taking into account both mobility events based on spectrum handoff strategies as mentioned above, can defined and modeled four different types of handoff schemes as shown in figure 3.5:

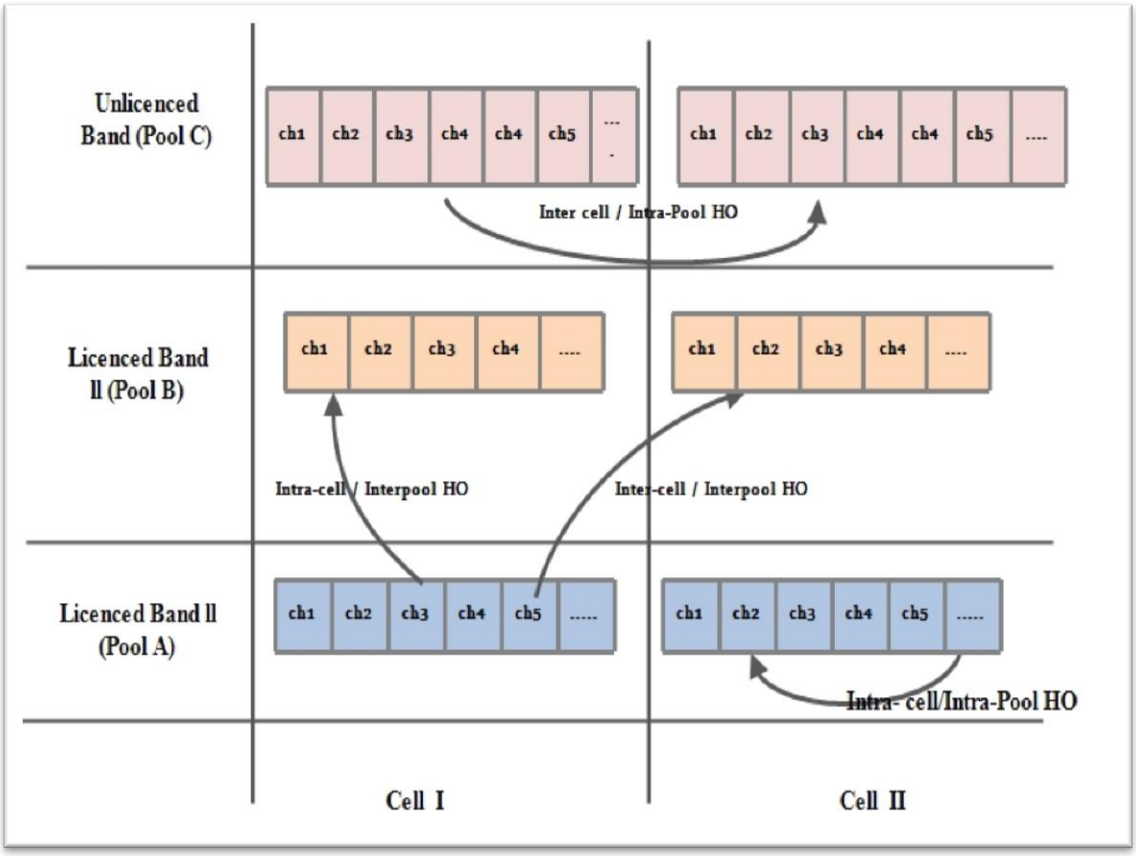

Figure 3.5: Different handoff types in CR networks.

3.3.1Intracell/Intrapool Handoff

When PUs are detected in the spectrum, Intracell/intrapool handoff occurs. Thus, it is mostly implemented in are reactive approach. The First procedure in this handoff approach is requiring a preparation time to determine the handoff type (d_{prep}). Next, the sensing process is scanning to identify the idle channel; CR users need to wait for the next sensing cycle, called a sensing synchronization time (d_{syn}^{sen}). Then, they sense the spectrum bands in the pool (d_{sen}) and determine the proper spectrum (d_{dec}). Finally, CR users move to a new spectrum band and resume transmission after the synchronization to the transmission schedule on that spectrum (d_{syn}^{tx}).CR users can switch the spectrum without reconfiguring their RF front-end (d_{recfg}), because spectrum bands in the pool are neighbors, and hence the physical spectrum switching delay is negligible. In summary, the latency for intracell/intrapool handoff (Type 1) can be illustrated as follows formula [34]:

$$D_1 = d_{prep} + d_{syn}^{sen} + d_{sen} + d_{dec} + d_{syn}^{tx} \qquad 3.1$$

3.3.2Intracell/Interpool Handoff

Intracell/interpool handoff may occur, if CR BSs can exploit multiple spectrum pools or if the current spectrum pool does not have enough spectrum resource due to PU activity. CR users detecting PU activities and hop to another spectrum pool in the same current cell and it is also at reactive handoff. Thus, its handoff latency is similar to that of the intracell/intrapool handoff (Type 2) as follows formula [34]:

$$D_2 = d_{prep} + d_{recfg} + d_{syn}^{sen} + d_{sen} + d_{dec} + d_{syn}^{tx} \qquad 3.2$$

Note that the intracell/intrapool handoff not the same type 1, because of each spectrum pool is placed in the different frequency range, and needs the reconfiguration of RF front end. Generally, reconfiguration process takes longer time than other delay components.

3.3.3 Intercell/Interpool Handoff

This handoff type is identical to that in classical cellular networks, which is occur when CR users moving to other cells. A mobile CR user needs to note the signals from neighbor cells during its transmission to determine a suitable target cell. If the neighbor cells use different spectrum pools, the mobile CR user should stop its transmission and reconfigure its RF front-end in every observation of neighbor cells, which is a major overhead in handoff. Thus, a network-controlled approach is more feasible for intercell/interpool handoff (Type 3) instead of mobile station controlled method, because the BS determines the target cell based on the stochastic user information. As a result, mobile CR users need a single reconfiguration time.

In this case, the BS prepares the handoff in advance according to user mobility. Thus, this is a proactive handoff and does not need the handoff preparation time d_{prep} that is use in previous reactive handoff types as follows formula [34]:

$$D_3 = d_{recfg} + d_{syn}^{sen} + d_{sen} + d_{dec} + d_{sych}^{tx} \qquad 3.3$$

3.3.4 Intercell/Intrapool Handoff

This handoff occurs when mobile CR users in cell successfully switch to other neighbors since a new target cell is that uses the same spectrum pool as the same current cell. Then, reconfiguration process is not required and this is also a proactive handoff. Therefore, the latency for intercell/intrapool handoff (Type 4) can be expressed as follows formula [34]:

$$D_4 = d_{syn}^{sen} + d_{sen} + d_{dec} + d_{syn}^{tx} \qquad 3.4$$

The latency in this handoff is significantly decreased and more advantageous to mobile CR users compared to that in other cases which is improves mobility in CR networks.

3.4 Selection Handoff Type in Cognitive Radio Network

Spectrum handoff due to transition between pools and classical intercell handoff due to physical user mobility are the main two different handoff types for CR networks and required to initiate and determine the suitable scheme for making handoff [34].

Spectrum handoff is the unique characteristic in CR networks. When PUs appear in the spectrum, CR users generally change its spectrum band without switching the base station. However, since CR networks have time varying spectrum availability, each cell may not have enough spectrum bands to support current users.

CR users can have another option, cell switching. So, when the PU activity is detected in the cell, the base station needs to check if it has enough spectrum resource for intracell/intrapool handoff. If the cell has enough spectrum resource, the base station executes the intracell/intrapool handoff or all users requiring new spectrum bands (Type1). Otherwise, some of current users are forced to move to the neighbor cells [34].

If the PU activity is detected, all users in cell need to execute intracell/interpool handoff (Type 2) regardless of current spectrum resource since they cannot find other available spectrum bands for switching in that cell. After the user selection, the selected users need to find the proper target cell. Unlike the classical handoff, CR users cannot observe the signal strength from other neighbor cells while maintaining the connection to current cells.

Another main reason to initiate handoff in CR networks is the intercell user handoff (moving mobility), which happens at the boundary of either cells. So, when CR users approach the boundary of cell, starting go to check the feasibility of intercell/intrapool handoff (Type 4). Unlike the intercell/interpool handoff, CR users can measure the signal strength from other base station directly, which is exactly same as classical handoff schemes.

If CR users cannot find a proper target cell for intercell/intrapool handoff, they need to perform the intercell/interpool handoff to find a cell having a different spectrum pool. This procedure is same as the cell selection scheme but does not require a preparation time (Type 3) [34].

For mobile users, larger cell coverage is generally known to be much more useful since it reduces the number of handoffs. However, in CR networks, the large cell coverage is not always desirable for mobile users. As the cell coverage becomes larger, the PU activity becomes higher since it is more highly probable to include multiple PU activity regions.

The PU activity in cell results in a significantly long switching latency. In addition, since CR users in cell are allowed to have a higher priority in channel access, cell overload also influences the use of extended spectrum band. As a result, CR networks need an advanced algorithm to select the best handoff type for mobile users at the boundary of cell .When CR users become closer to the boundary; the base station initiates the handoff procedures and gathers the neighbor cell information from a central network entity [34].

3.5. Spectrum Handoff Challenges

The randomness due to from the appearance of PUs which always has higher priority in using licensed spectrum than SUs, it is extremely difficult to achieve fast and smooth spectrum transition leading to minimum interference to license users and performance degradation of secondary users during a spectrum handoff.

Also, the latency caused by spectrum sensing, decision and handoff procedures, quality degrades during spectrum handoff. These problems become even more challenging in ad hoc networks where there is no centralized entity to control the spectrum mobility. Some open research challenges for efficient spectrum handoff in CR are the following [10]:

i. The available channels change with respect to time which defined as spectrum handoff in time domain that is required to maintain QoS in this environment is considered a challenge. Thus, the physical radio goes through the spectrum to achieve the QoS requirements.

ii. When the user changes its position from one place to another, the available bands also a change which is spectrum handoff in space and to assign a new spectrum, it is a major issue in the CR networks. So the required spectrum handoff scheme should integrate intercell handoff. The spectrum handoff in different networks is referred as vertical handoff which takes place in the CR networks.

iii. At a particular instance, there are many frequency bands that are available for a CR user. For the selection of the best available spectrum, algorithms are required to determine the routing scheme (selection route).

iv. When the operational frequency becomes busy in the communication by a CR user. Then the user applications have to move to other available frequency bands.

v. Designing a new mobility management, to reduce or minimize the loss and the delay in a handoff.

4

Proposed Spectrum Handoff Scheme

4.1 Introduction

Cognitive Radio (CR) technology is considered a solution for the efficient usage of RF spectrum. The CR can communicate on the channel selected only as long as it is available, it will need to vacate the channel when the owner of the channel which is the licensed user arrives back on the channel. This is the spectrum mobility.

The CR device is a SU that operates in the band licensed to the PU. Here the SU in CR has to make sure that it avoids any harmful interference with the licensed channels at all costs. The SU will make evacuate the channel upon the arrival of PU. After vacating the channel, the SU will need to resume its transmission to complete it. In order to do that, the SU needs to suspend its transmission temporarily and handoff to another vacant channel; this kind of handoff is termed as spectrum handoff. Handoff here means switching to another channel to resume transmission [21].

Spectrum handoff is a very challenging issue in CR networks because it plays a key role in deciding the next target channel, i.e., the channel on which the SU will resume its transmission after vacating its current operating channel for the PU. The activity of PUs is arrivals randomly; it makes it very difficult and urgent to accomplish a seamless transition which is fast and smooth with minimum performance degradation during the spectrum handoff process.

Performance degradation issue is basically associated with the amount of delay caused during the spectrum handoff process. The more delay caused and compromised will be needed on the performance of transmission. Spectrum handoff delay depends on the handoff scheme used in spectrum handoff process as shown in previous chapter.

The performance requirements for CR system are: reliable spectrum hole and PU detection, accurate link estimation between users, fast and accurate frequency control and power control method that assures reliable communication between CR terminals and non-interference to PUs.

In a CR, adaptations to the physical layer will ensure a communication channel with certain guarantees for bandwidth use and data throughput. To know the performance of our whole system as well as the performance of parts of it we need to decrease number of handoff as important impact factor performance of systems.

4.2 Related Work

The major purposes of spectrum handoff for CR system are to reduce interference to PUs and to avoid service block and even connection loss for SUs. Thus, when PUs appear, SUs must vacate licensed bands and sense idle bands. If SUs cannot find an available band in a cell, their transmission may be interrupted. Otherwise spectrum handoff happens.

Additionally, when PUs appear frequently, spectrum handoff may result in degraded system performance due to the excess of spectrum sensing and spectrum handoffs. For that reason, some researchers proposed algorithms to reduce the number of spectrum handoff and to increase the capacity of SUs while others focus on the channel switching algorithms and switching time delay.

A novel spectrum handoff scheme is proposed considering a power control based spectrum handover scheme which intelligently adjusts the transmit power of the SU, greatly reduce the spectrum handover ratio and improve the effective data rate of the transmission efficiency by avoiding some of the handoffs [37].

The effect of the different path loss on the different frequencies used in the spectrum handoff and develop an algorithm that try to overcome the limitations of this effect [38]. The QoS can degrade significantly due to a change of frequency which reduced the outage probability. The spectrum access scheme of unlicensed channels as backup improves and characterizes the spectrum handoff performance: link maintenance probability, the number of spectrum handoff, and switching delay [29, 32].

The spectrum decision algorithm based on prediction is proposed to decrease spectrum handoff probability which can achieve fewer disruptions to primary transmissions by letting SUs proactively predict the future spectrum availability and perform spectrum handoffs before a PU occupies the current spectrum[39,40].

Wang et al. in [14] and Zhang et al. in [41] use queuing network model to discuss the effect of proactive sensing and reactive sensing on spectrum handoff to characterize the spectrum usage behaviors between primary and secondary users in CR networks dependent of sensing time.

Voluntary spectrum handoff is used to reduce temporary communication disruption time. The proposed approach is based on a fixed sensing window, a variable history window and the reduced forced spectrum handoffs. Using this approach, SUs can have longer undisrupted connection [42].

In this proposed strategy, we present the systematic frequency selection scheme joint with adaptation power of transmitter base station to optimal usage of spectrum resource. Also, improvement the overall performance CR system, reducing spectrum handoff from failure and decreasing the interference and power dissipated will be presented.

4.3 System Model

This section presents the CR system model. So, instead of a large multi-hop mesh network. It is reasonable to simplify situation to a single-hop wireless network and concentrate mainly to the CR concept.

In the CR system model the PUs do not need to know anything about CR devices, and there is no need to modify existing systems, which is thought to be a basic prerequisite to a CR system. It is important that the licensed PUs can still operate in the conventional way even in the presence of the CR system.

4.3.1 System Model Description

In this work, the general CR system model for our studies is presented in Figure 4.1. The cognitive radio system model includes PUs and SUs and it coexists with a CR each to other. Assuming the primary links is operating in any channel in the primary coverage area. Then the SUs are allowed to use the channels other than channel occupied inside the coverage of the primary transmitter base station. In the figure 4.1, the dimensions are illustrated only for the systems, the numbers and locations of the users.

At the beginning of network operation, the locations of PUs and SUs are chosen randomly in the network area using uniform distribution and it is a possible for SU to detect the presence of PU.

There are number of methods to achieve and detect the unoccupied channel (spectrum hole) such as sensing process using the SUs or / and geo-location database which updated from national body regulators since a SU would only need to report its location to the database and in return receive information regarding the spectrum availability and associated constraints.

When the current spectrum hole conditions become worse, or the PU appears and reclaims his assigned channel, SUs need to stop transmitting data and find other available channels to resume their transmission.

Since the transmissions of SUs are suspended during a spectrum handoff, they will experience longer packet delay. Therefore, a good spectrum handoff mechanism should provide with secondary users with smooth frequency shift with the least latency. When SUs need to switch to another frequency, they can immediately pick one channel from the reserved bands. Whenever a handoff becomes a must, SUs can switch their frequency to one of the candidate channels depending on their locations.

Proactive decision spectrum handoff is adopted in this work, so it is considered based on the moment when SUs carry out spectrum handoffs and it makes the target channels for spectrum handoff ready before data transmission according to the long-term observation outcomes. The proactive decision spectrum handoff may be capable to reduce handoff delay because the time consuming wideband sensing is not required.

Furthermore, it is easier to let both transmitter and receiver have an assent on their target channel for the proactive decision spectrum handoff than for the reactive decision spectrum sensing. Nevertheless, when the spectrum handoff process is initiated, the proactive decision spectrum handoff needs to account the issue of pre-selected target channel may no longer be available.

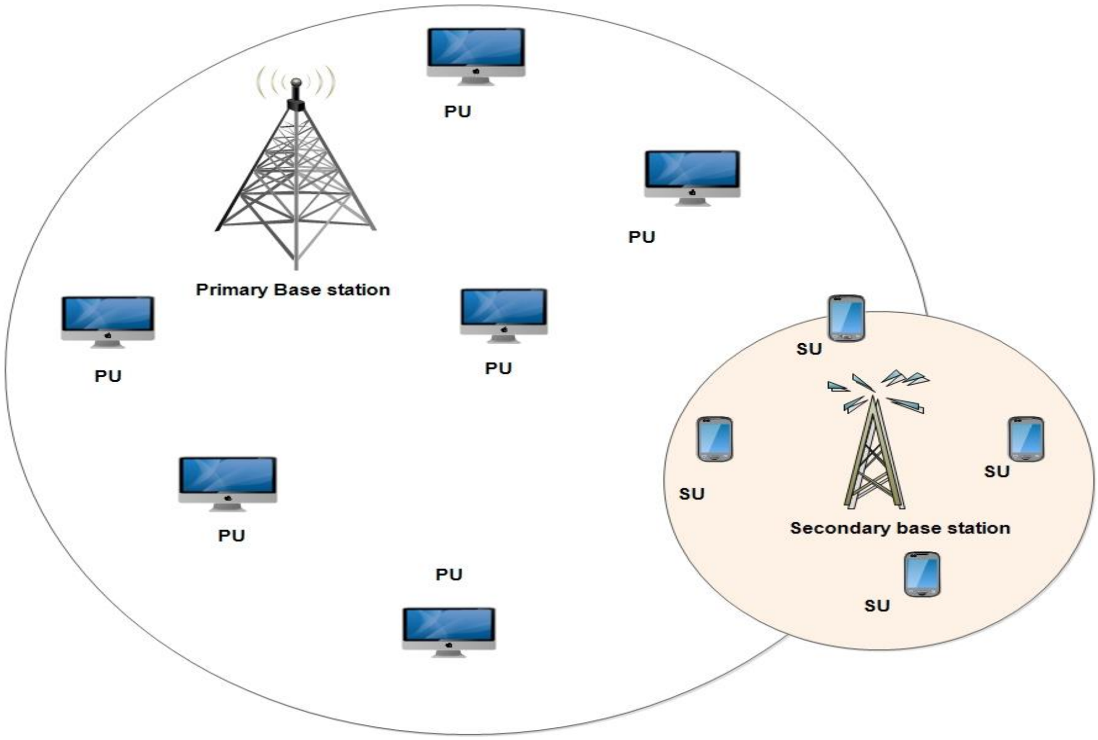

Figure 4.1: The Coexistence system model of PU and SU.

The tasks of the CR base station include spectrum sensing at the receiver for identification of spectrum holes, transmission of the sensing information to the transmitter side of the link via the feedback link. Also the base station control channel, and frequency and power control at the transmitter via the feedback information from receiver and control information from the base station [40].

The role of CR base station differs from conventional access point because it has now cognitive capability and the communication between SUs is peer-to-peer (P2P) type communication. The locally sensed spectrum information of SUs will be sent to a common control channel, combined in the secondary base station, and then broadcasted to the CR users in the network [43].

4.3.2 Frequency Changing and Path Loss

CR system has emerged as a new solution to the increasing demand of wireless communications and improved the spectrum utilization, so that the available list of frequency channel is extended which is obtained from the sensing operation. In this wide spectrum frequency (pool), the frequency is changed from a higher to lower or from lower to the higher one as shown in figure 4.2.

The cell coverage (dashed cell is new state) will be reduced or expanded because of the larger path loss or smaller, since the frequency is significant factor to impact the path loss. The changing of frequency (spectrum handoff) considered as a significantly affect QoS of secondary users due to signaling overhead and different path loss [38].

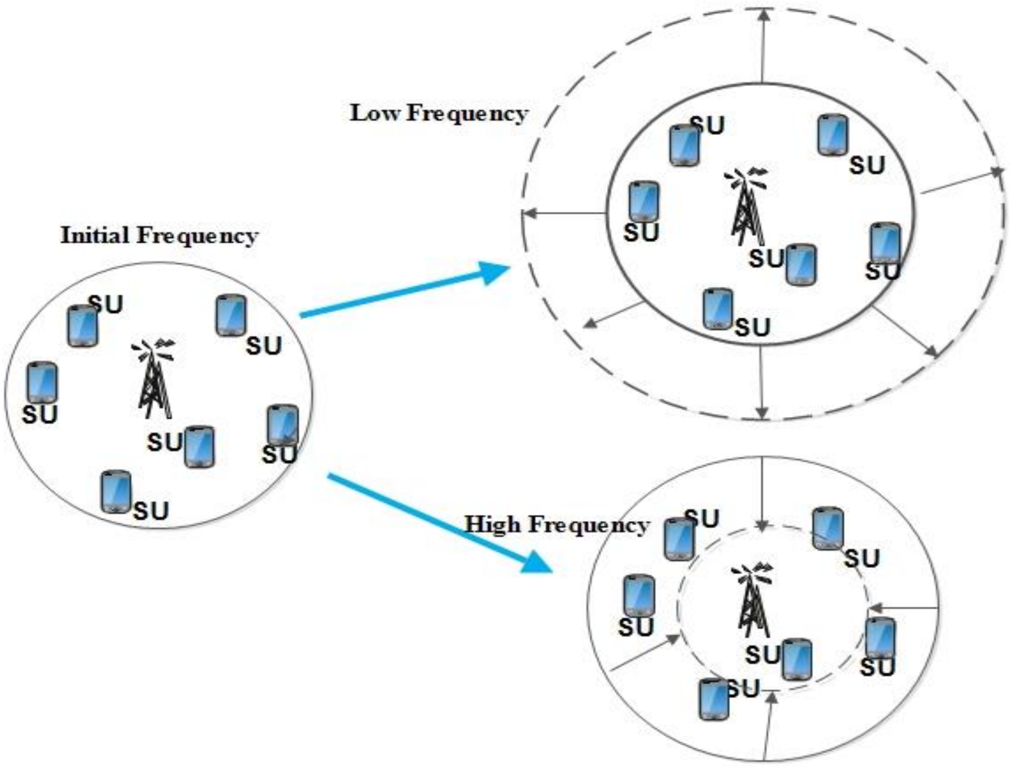

Figure 4.2: Cell Coverage due to changing frequency (spectrum handoff).

Generally, a high frequency band has large path loss, and a low frequency band has relatively small path loss. Thus, the propagation characteristic according to the operating frequency should be significantly considered in CR systems. On the other hand, it has not been significantly considered in conventional communication systems;

because the switching of channel frequency is transit to the same assign band, not widely band.

Clearly, it matters in CR system with the wide range of frequency band. There are several of path loss models, for examples, Okumura, Hata, Cost-231, Walfish, simplified free space and using based to environment area which may be urban, suburban, or rural. Suppose, we used as example, Okumura-Hata path loss model in urban areas, which is a one of the most popular models, shows the effect of center frequency on the amount of path loss as follows[38]**:**

$$L_{dB} = \alpha + \beta \log_{10} d - \gamma \qquad 4.1$$

Where

$$\alpha = 69.55 + 26.16 \log_{10} f_c - 13.82 \log_{10} h_b \qquad 4.1a$$

$$\beta = 44.9 - 6.55 \log_{10} h_b \qquad 4.1b$$

$$\gamma = 3.2(\log_{10}(11.7554 h_r))^2 - 4.97 \qquad 4.1c$$

Above equation shows the path loss is very dependent on many factors such as center frequency (f_c), distance (d), height of base station (h_b), and height of receiver station (h_r). Especially, α describes the effect of frequency on the amount of path loss.

The frequency operating and distance (coverage area) are very important propagation characteristics. Suppose the height of base station (h_b) equal 10 meter and height of receiver station (h_r) equal 3 meter to calculate the effect both frequency and distance on the path loss. First, for a given frequency the path loss increases with increased distance [38].

For example, put a frequency is a 450 MHz, the path loss increases from 151.86 dB at 10 kilometers to 178.67 dB at 50 kilometers. This difference of 26.8 dB can have a significant impact on the quality of the received signal in the system. Notice that for a factor of two increases in distance, the loss increases by 6 dB; again, this is characteristic of the path loss formula. It should also be noted at this point, there is a commonly used expression resulting from the path loss equation above that the free space path loss increases with the square of the distance between the two terminals.

The second important factor is that for a given distance the path loss increases with increased frequency. For example, put distance for 30 kilometers, the path loss increases from 156.5 dB at 100 MHz to 180.85 dB at 1700 MHz. Again, the 24.3 dB difference could have a potentially significant and detrimental impact on communications. Also, it should be noted that a factor of two increases in frequency will result in a 6 dB increase in the loss for the fixed distance. As another expression, path loss increases with the square of the increase in frequency.

4.3.2 Adaptation of Power Control in Secondary Base Station

In order to utilize the available spectrum more efficiently, a power control scheme is applied and incorporate into the proposed spectrum handoff selection scheme to reduce the number of spectrum handoffs and enhance the spectral efficiency.

In this work, by using the power control algorithm, CR station can determine not only primary channel's availability at its current location. Also it adjusts the power transmitter according to the check of the new frequency assign from handoff process is higher or lower to maintenance link. Moreover, it estimates a suitable coverage area to keep connection with the SUs; otherwise it switches to an idle frequency or the worst case the SUs blocking and out of service.

Frequency and power management is important and a suitable scheme to enhance the frequency bands and transmission power cost for the CR system. Thus, we have studied systematic channel selection and low complexity of power adaptation and incorporated to consume the power transmitter, reduce the number of spectrum handoff from failure and enhance the spectral efficiency.

4.4 Spectrum Handoff Proposed Scheme

When the PU appears and asks for his assigned channel, SUs need to stop transmitting data and find other available channels to resume their transmission. This kind of handoff in CR networks is termed as spectrum handoff. Since the transmissions of SUs are suspended during a spectrum handoff; they will experience longer packet delay. Therefore, a good spectrum handoff mechanism should provide with secondary users with smooth frequency shift with the least latency.

When SUs need to switch to another frequency, they can immediately pick one channel from the reserved bands (pool). Figure 4.3 shows the spectrum band (pool), for example, TV broadcasting band and the process of changing channel frequency as randomly. So, initially, the SU chooses a channel that is not occupied.

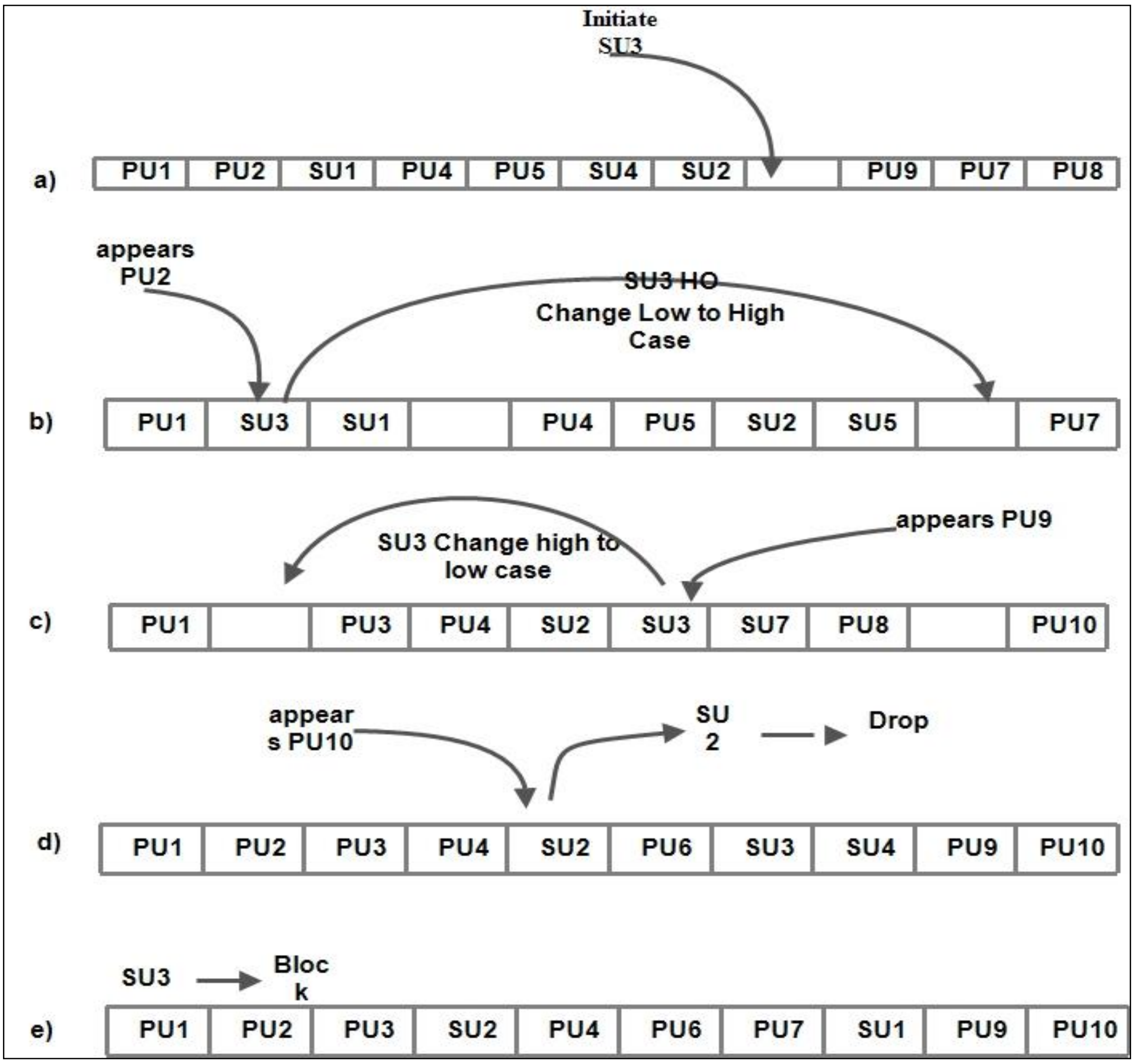

Figure 4.3: Spectrum Band (pool) random Selection (classic) a) Initial state select; b) Low to High HO; c) High to Low HO; d) Drop HO; e) Block HO.

If PU is detected, then the SU vacate the channel as the PU has high priority and choose other from the pool randomly which may be higher or lower than the current state .The status of obtained new channel is either unoccupied, dropped or blocked as shown in the figure 4.3.

4.4.1 Systematic Selection with Power Adaptation

Using the estimation of the cell coverage as a basis in CR network , we propose a combined systematic selection channel frequency and power adaptation scheme that can reduce not only the total number of handoffs, but also reserve the power consummation and improve the overall performance of the system.

The proposed algorithm spectrum handoff can be summarized into two stage scenario: the first stage is Channel frequency Selection, so it chooses between two paths which are systematic selection or random selection to pick the available new frequency due to spectrum handoff.

The second stage is power transmitter adaptation (power control), the decision of this stage is to apply the power adaptation or not and branching into four paths, each path produces the result based changing frequency and power adaptation.

The results in the first stage may be changing from a low frequency to a high frequency (Low to High case), or spectrum handoff from a high frequency to a low frequency (High to Low case). In the Low to High case, coverage would be reduced, while in the High to Low case, it would be expanded.

Therefore, it is more difficult to guarantee QoS in the Low to High case, because it is possible that cell outage will occur. In the Low to High case, we try to avoid cell outage by optimizing the power adaptation. Moreover, for the High to Low case, we propose another efficient scheme to reserve power transmitter overhead required that coverage area and avoiding interference with others networks.

In figure 4.4, the flowchart describes the algorithm in details, since we suppose any spectrum band service for primary system in real environment and if proposed another secondary system coexists in same area to exploit the spectrum band and efficiently improve the utilization of spectrum allocation scarcity. At detection of PU, the spectrum handoff decision needs to select any frequency to change it.

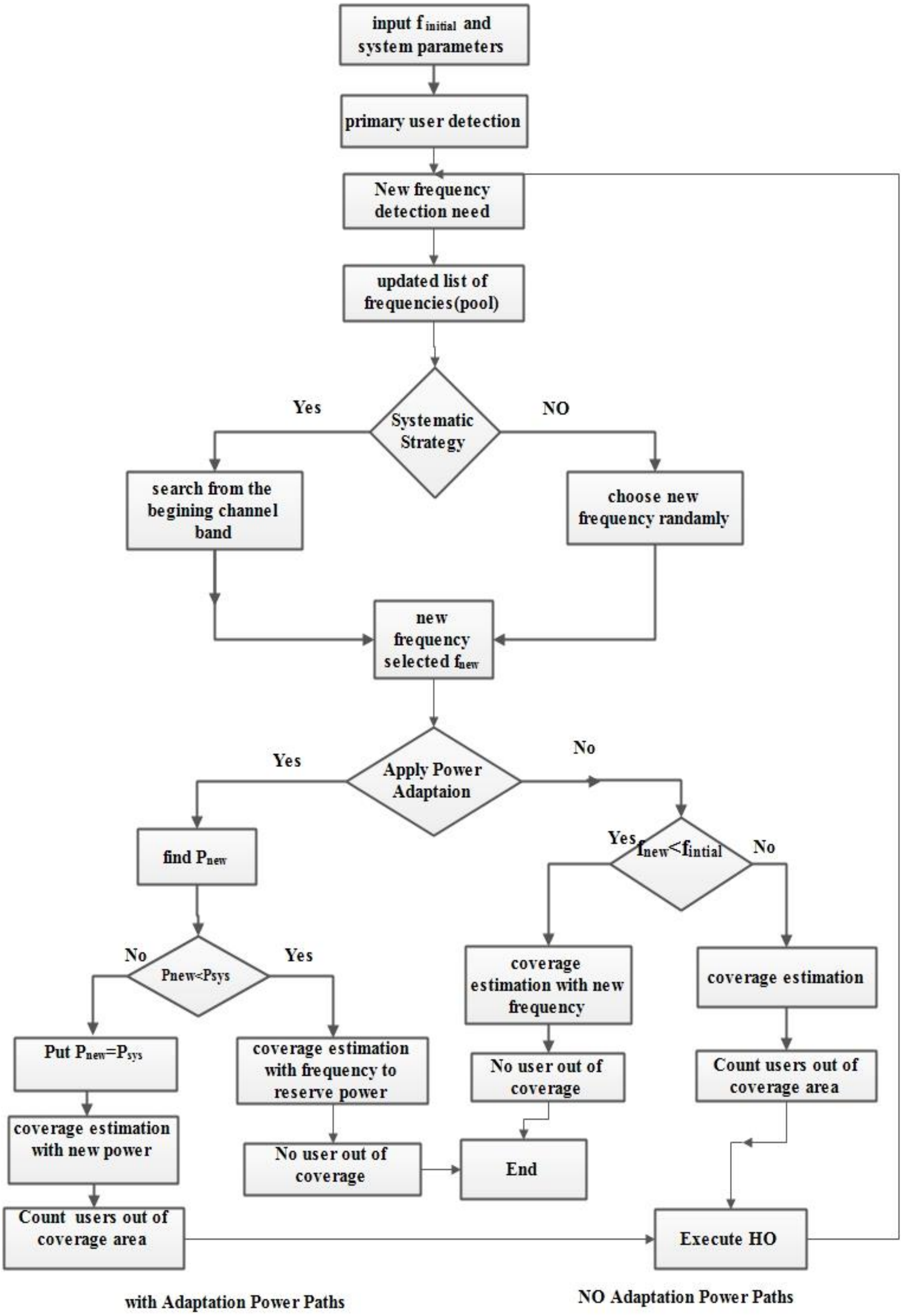

Figure 4.4: Flowchart Algorithm Proposed Scheme.

We can apply one of the two scenarios which systematic selection (proposed scheme) which is search from the beginning of the spectrum band (pool) to select the first unoccupied channel of the pool, while the other which is a randomly selection (classical scheme) is to obtain the new frequency randomly.

After selecting of the new frequency, the condition of power adaptation is applied. There are four paths which can be called power adaptation stage. So, the probability of new frequency selection may be low or high.

If it apply the adaptation power, then it calculate the power at new frequency and compared with maximum value of power system; if yes, estimate the coverage area at this frequency and adjust the power of transmitter bas station; if no, put transmit power equal the maximum value power of the system and estimate the coverage area and force all SUs to execute the handoff.

At no apply the power adaptation; there are other two paths to comparing only with respect to changing new frequency to low or high. It estimate the coverage area according to new frequency selection and execute the handoff if any SUs out of cell.

4.4.2 Algorithm Procedures

From the previous, the algorithm can be executed in two stages. The first stage is channel frequency selection process, where consists of two approach, systematic selection (proposed) that is the proposed approach where the search selection channel begins from the first channel pool and moves to neighbor channel until the obtaining an available channel free to assign as channel handoff as shown in figure 4.5.The approach is random (classic) selection, presents in figure 4.3.

In the second stage, the algorithm consists of the need for the power adaptation or not to apply that on the result from selection scheme (may be high or low). With no power adaptation, the check is about new frequency selection only, since the coverage area is a reduced or expanded according to new frequency selection (spectrum handoff).

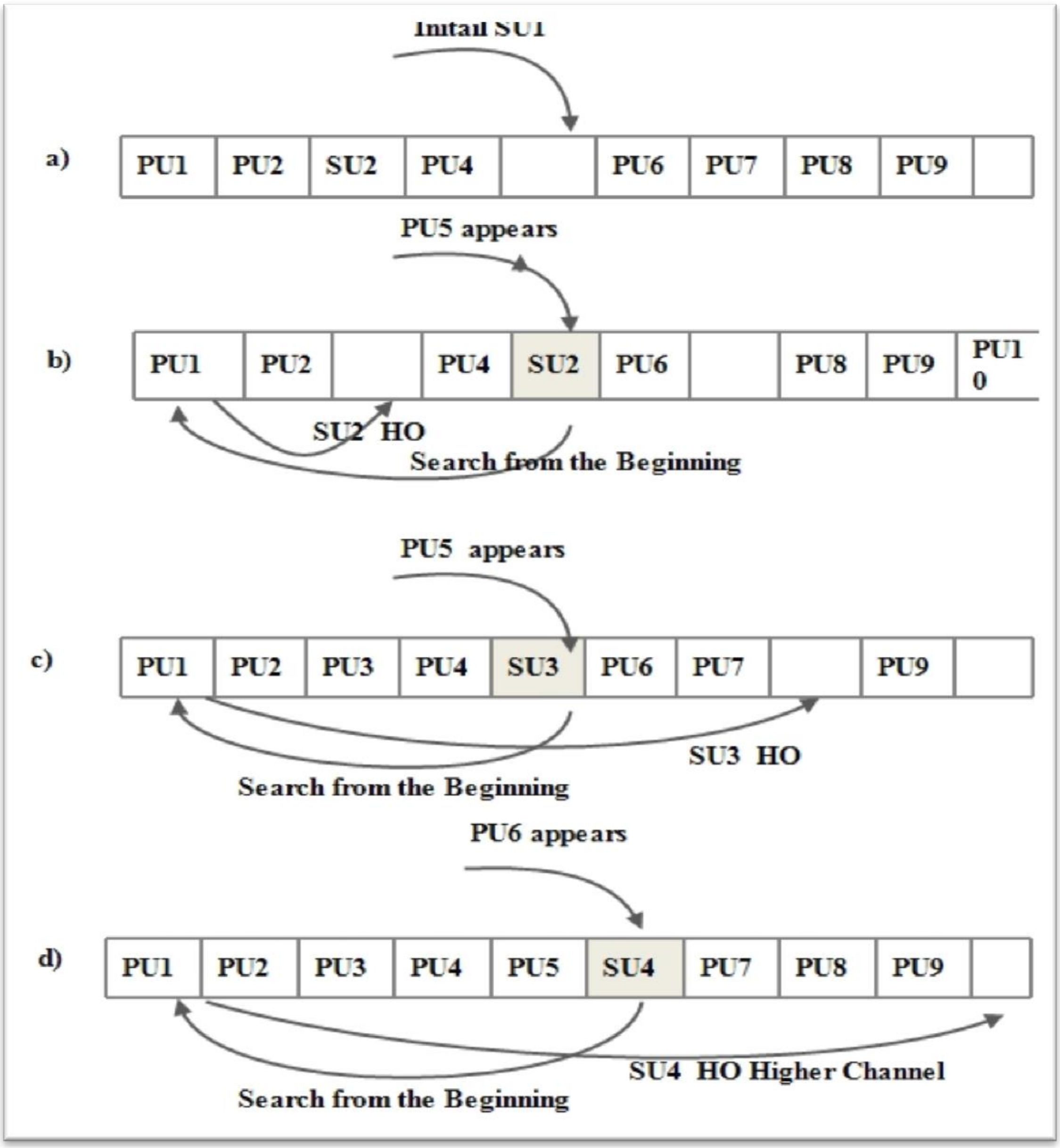

Figure 4.5: Spectrum Band (pool) Systematic Selection a) Initial state; b) Low to High; c) High to Low; d) Highest HO (waste case for availability).

This approach do not put any solution or condition to overcome the majority of number a handoff generate from changing low to high and also, the interference creates from big cell coverage at switching from high to low. Thus, the adaptation power approach is considered to overcome the SUs of cell outage and eliminate the interference by optimizing the transmitted power of the cell coverage.

In power adaptation approach, the algorithm calculates the new transmitted power based on new frequency selection using the famous formula of power transmission which is the transmit power equal the receive power (power sensitivity) subtract path loss value. Then, estimate this value to coverage all SUs in the cell area (high to low case); otherwise use the maximum power of the system to estimate the cell coverage (low to high). From this approach, the reserved power is achieved and the number of handoff is decreased as shown in the simulation results in next section.

4.5 Performance and Simulation Results

In order to investigate the performance of the proposed scheme in this section, the system environment was based on many applications to reflect to real coverage area and environment, since the IEEE organization classified as shown in 5.6 according to coverage area as well as network type into personal area network (PAN), local area network (LAN), metropolitan area network (MAN), and regional area network (RAN). We can categorize these standards based on cell size into small, medium, and large cells [43].

Based on criteria of TVWS (TV White Space) in the regulations[44,45] which are both regulatory organizations and stakeholders have been very focused on this band because it is an extremely valuable band in terms of propagation and in-building coverage . Each CR user is uniformly distributed in the cell is assumed, the intracell / intrapool type of handoff is adopted in our work simulation.

We obtained the updated holes of white space spectrum from the list of proactive prediction which is prepared by sensing function in CR system. Assume that the outage probability of SU is measured at the same power sensitivity of conventional real applications. Thus, the decision handoff is executed to avoid the dropping or breaking of link maintenance communication and enclose a more efficient QoS.

We present three cases to evaluate the performance of the proposed system in the following subsections and comparing the performance with classic random selection scheme, and also we will study the impact of power adaptation technique.

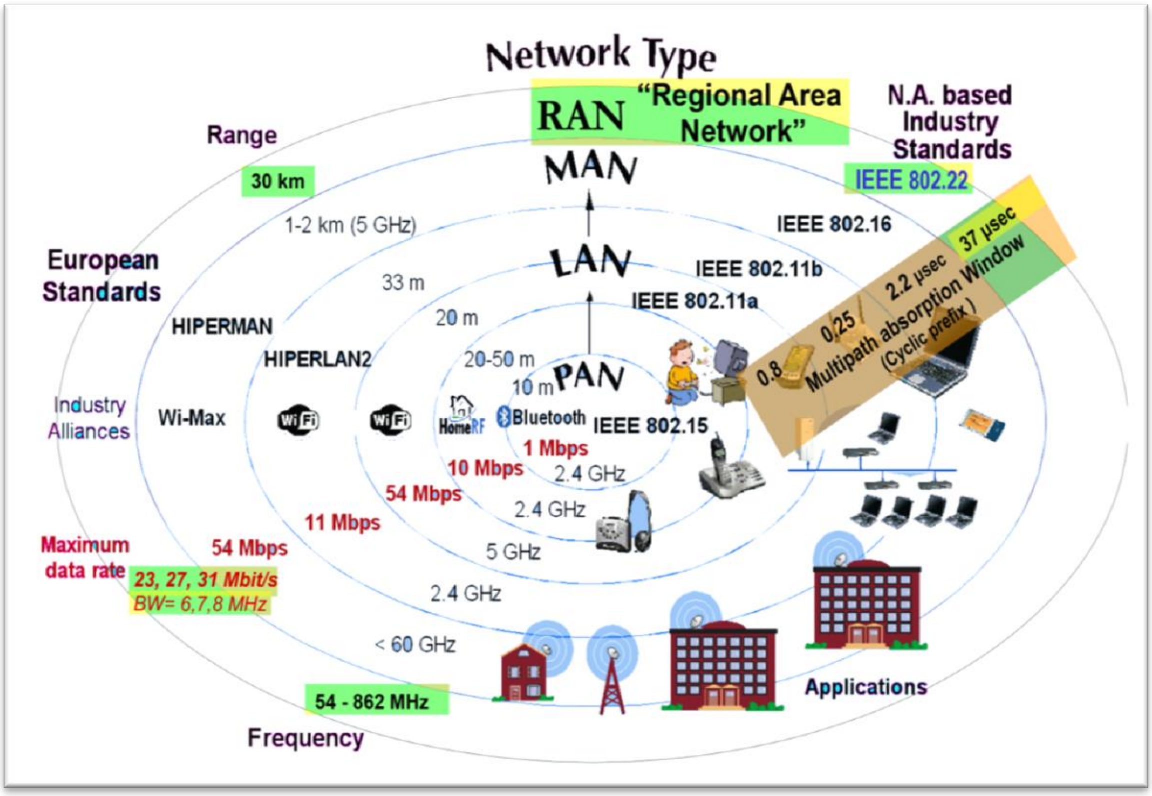

Fig. 4.6: IEEE wireless standards classification [43].

4.5.1 Case I: Small Cell Application to CR

We simulate the characteristics of Femtocell and Wi-Fi [46] as example applications from real environment in small cell. The simulation parameters are given in following Table 4.1.

Table 4.1 System parameters in small cell size

Parameters	**Femtocell**	**Wi-Fi**
Available Frequency Range MHz	From 54 to 700 MHz (TV WS)	
T_x Power Adaptation (dBm)	10-20	20-23
Height h_b (m)	3-6	3-12
Cell Size Coverage (m)	20-50	100-200
number of User in Cell	3-10	10-30
Power sensitivity (dBm)	-62	-62
Channel Model	Okumora -Hata	Okumora -Hata

4.5.1.1 Simulation Analysis and Discussion

In this simulation, the frequency of the BS means that it is before a primary user was detected (handoff switching). At handoff, the BS frequency may be switch to higher or lower frequency. We need to measure the possibility of this operating frequency of the BS on the option of having the frequency increased/decreased to lower or higher one in order to make successful handoff.

We should reduce that the possibility of having users outside the cell boundary, so no outage probability is occurred. The outage probability is defined as ratio between the number of SUs cannot connect to cell BS (out of cell) and the total number of SUs in the cell affected from switching frequency (handoff).This defines a wide frequency switching range which is used to evaluate the schemes. At any level of outage probability, we can know the expanding frequency switching in the range as operate currently in Base station (BS) to make a handoff process (low or high). Then, the outage probability decreases because the Low to High transition probability decreases as well as the frequency of the BS increases as shown in figure 4.7.

This is because the probability of transition from high to low is gradually getting higher. Thus, the coverage area is expanded, because most of frequency transition range probability switches to new frequency less than the operating frequency state.

This reduces the availability according to state of the current frequency of the used BS. So, we suppose that at any level of outage probability as a reference (for example 0.1), we need to monitor and measure the characteristics and the behavior of switching frequency range.

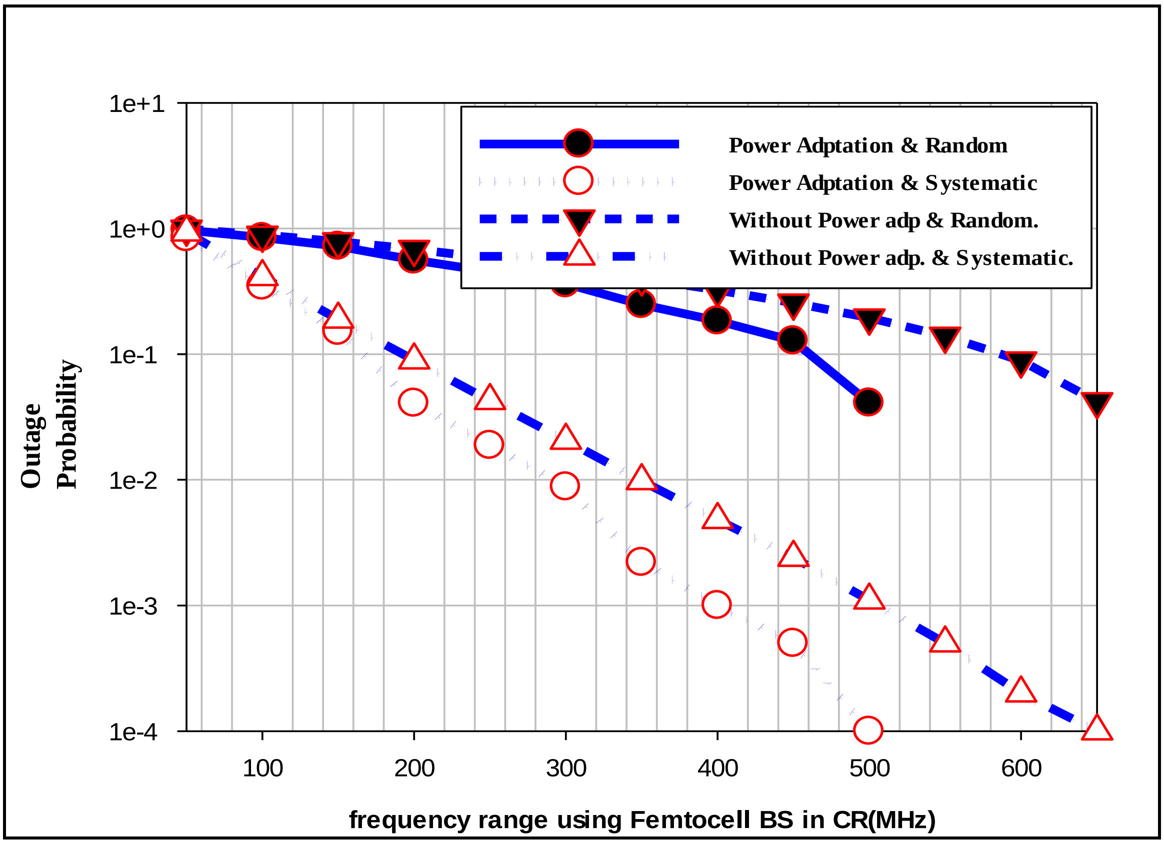

Figure 4.7: Outage probability of Femtocell CR application vs. TVWS frequency range.

At 0.1 outage probability, we can see from figure 4.7, since the random selection scheme without adaptation is reaching at frequency 580 MHz. This frequency means that, the frequency of BS lower than 580 MHz is not efficient because, all the switching frequencies (low or high) are lower than the reference probability. In the other words, the outage probability increases if we use any frequency BS lower than this value which means that most the switching frequency transit from high to low.

This schedule is a repeated again on the random without power, Systematic without power and Systematic with power adaptation. In the systematic selection (proposed) with power, the frequency range at 180MHz is crossed with reference outage probability. Then, the frequency range gain is increased up to 400MHz using proposed algorithm comparing to worst case which is random with no power adaptation to improve the flexibility wide frequency switching (spectrum handoff).

From these result, we investigate from the proposed scheme is more efficient and the overall system performance is enhanced and can be adopted to fit perfectly with the selection frequency scheme. The discussion in this sub- section is considered the same concepts as all following applications in our work.

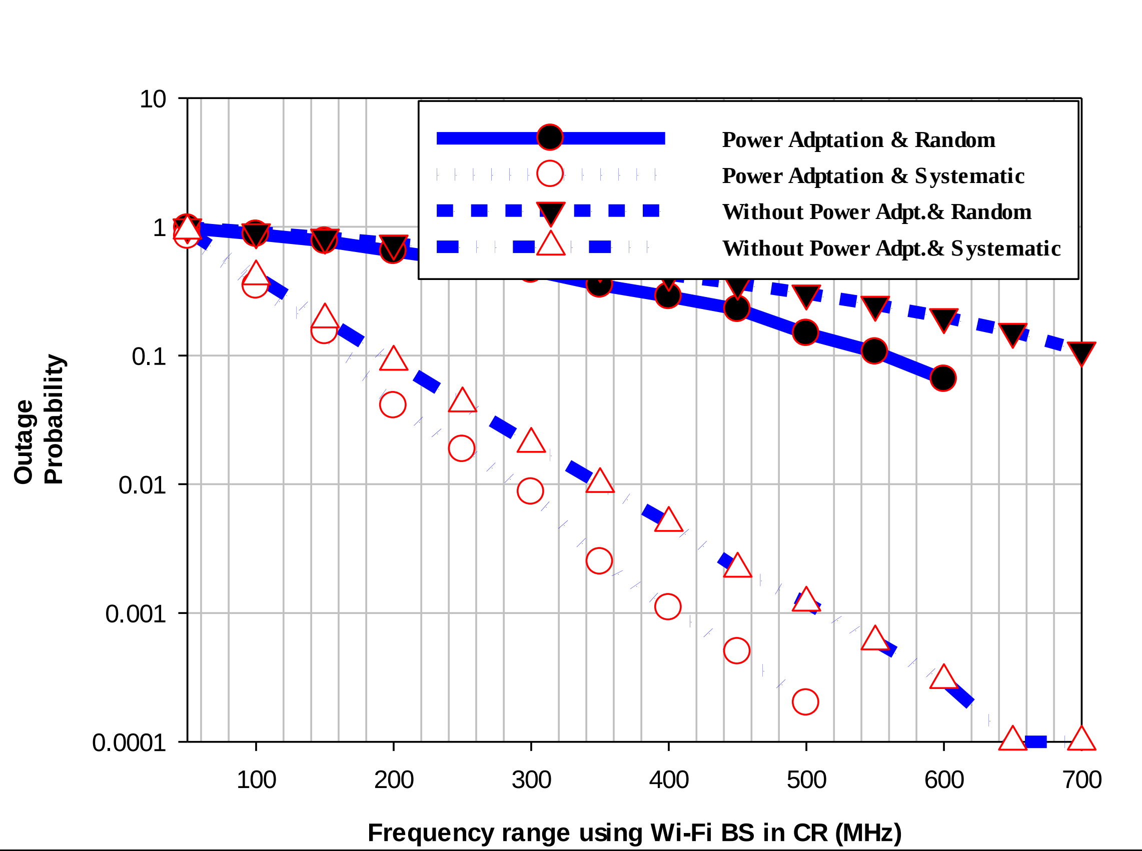

Figure 4.8: Outage probability of Wi-Fi CR application vs. TVWS frequency range.

According to the simulation analysis and discussion previously explained in subsection 4.5.1.1, Figure 4.8 shows the performance gain of the proposed scheme using Wi-Fi BS in frequency range of TV WS, so the proposed systematic selection scheme improves the performance of frequency range gain (handoff) up to 520MHz related to classic scheme.

Comparing the gain of wide frequency from two application Femtocell and Wi-Fi perspective in this case according to all wide range of frequency. We show that the proposed systematic scheme is more efficient and can improve the switching range availability up to 70% from all range of frequency band.

4.5.2 Case II: Medium Cell Application to CR

We considered characteristics of WiMAX [47] and LTE 700[48] as example applications from real environment in medium cell size, and simulation parameters are given in following Table 4.2.

Table 4.2 System parameters in medium cell size

Parameters	**Fixed WiMAX**	**LTE 700**
Available Frequency Range MHz	From 54 to 700 MHz (TV WS)	
T_x Power Adaptation (dBm)	36-40	40-42
Height h_b (m)	18-30	18-30
Cell Size Coverage (km)	Up to 15	Up to15
number of User in Cell	50-150	50-150
Power sensitivity (dBm)	-107	-107
Channel Model	Okumora -Hata	Okumora -Hata

As to the simulation analysis and discussion provided in subsection 4.5.1.1, Figure 4.9, 4.10 shows the performance gain of the proposed scheme using two application in medium cell size WiMAX and LTE in frequency range to note the impact frequency selection in this case.

Generally, the proposed systematic selection scheme improves the performance of wide frequency switching gain (spectrum handoff) for WiMAX and LTE up to 450MHz, 460 MHz respectively comparing with classic random scheme.

Comparing the gain of wide frequency for two applications WiMAX and LTE in this case and measured in all range of frequency, we show that the proposed systematic scheme is more efficient and can improve the switching range availability up to 64% from all range of frequency band.

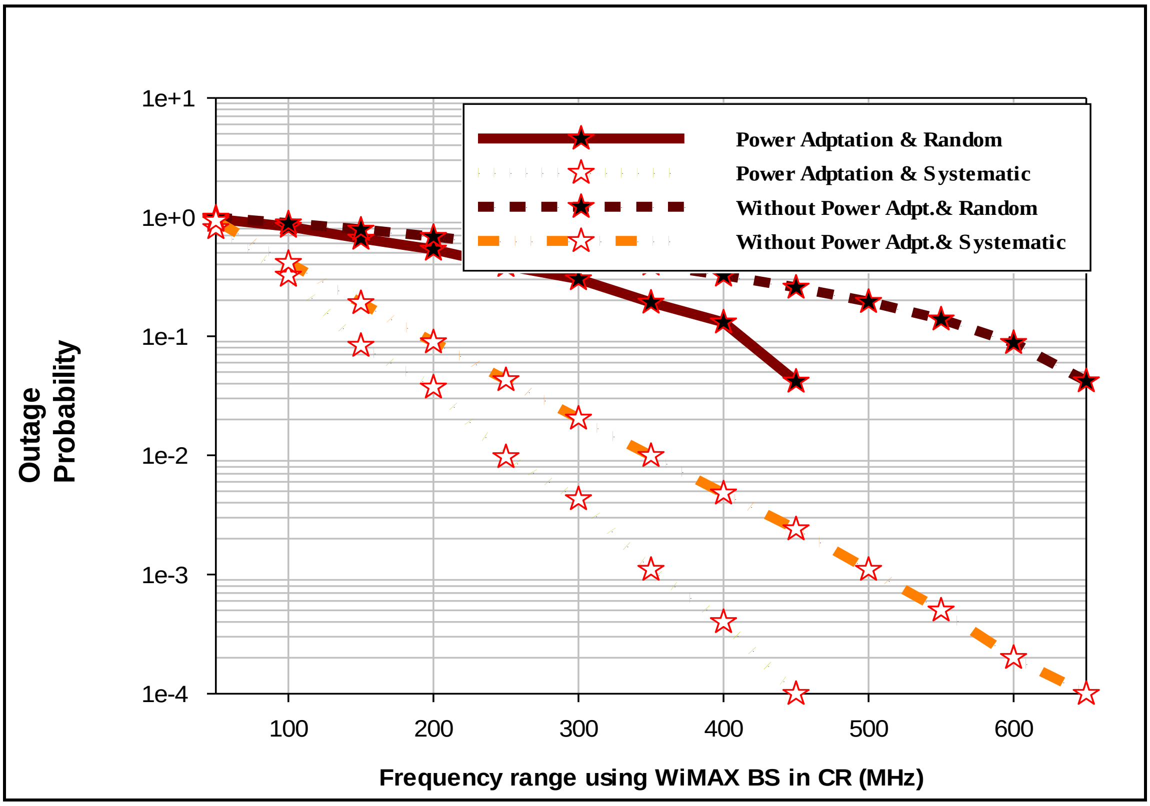

Figure 4.9: Outage probability of WiMAX CR application vs. TVWS frequency range.

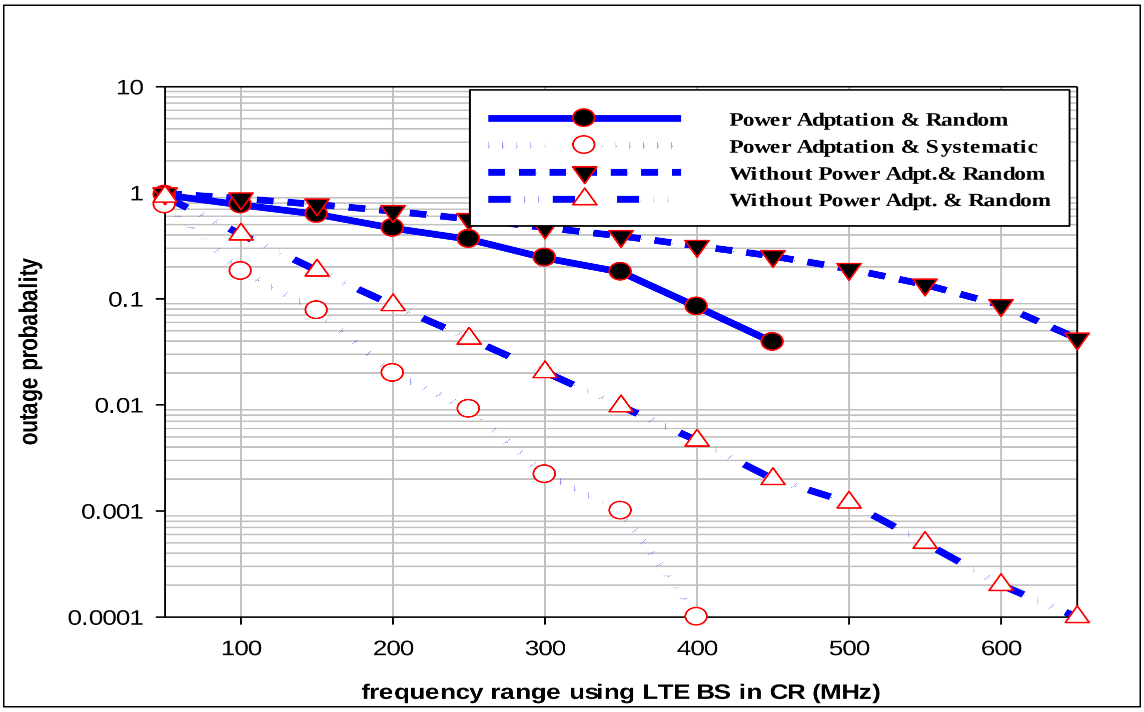

Figure 4.10: Outage probability of LTE700 CR application vs. TVWS frequency range.

4.5.3 Case III: Large Cell Application to CR

We considered characteristics of Public Safety [49] and IEEE 802.22 [43] as example applications from real environment in large cell size. The simulation parameters are given in following Table 4.3.

Table 4.3 System parameters in large cell size

Parameters	Public safety	IEEE802.22
Available Frequency Range MHz	From 54 to 700 MHz (TV WS)	
T_x Power Adaptation (dBm)	42-45	40-46
Height h_b (m)	18-30	18-30
Cell Size Coverage (km)	10-30	20-40
number of User in Cell	50-150	70-150
Power sensitivity (dBm)	-119	-114
Channel Model	Okumora -Hata	Okumora -Hata

Figure 4.11, 4.12 shows the performance gain of the proposed scheme using two applications in medium cell size public safety and IEEE 802.22 in frequency range to note the impact frequency selection in this case.

Generally, the proposed systematic selection scheme improves the performance of wide frequency switching gain (spectrum handoff) for Public Safety and IEEE 802.22 up to 410MHz, 440 MHz respectively comparing with classic random scheme.

Comparing the gain of wide frequency from two applications Public Safety and IEEE 802.22 in this case referred to all range of frequency. We prove that the proposed systematic scheme is more efficient and improve the switching range availability up to 57% from all range of frequency band.

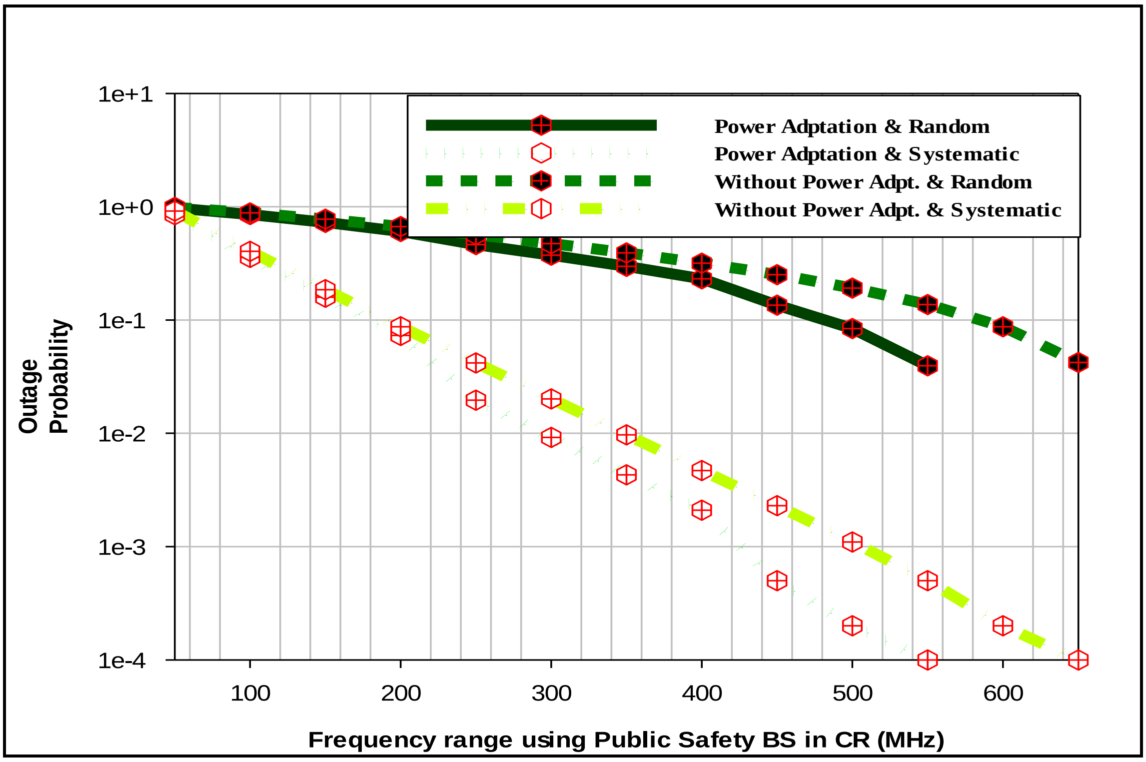

Figure 4.11: Outage probability of Public Safety CR application vs. TVWS frequency range.

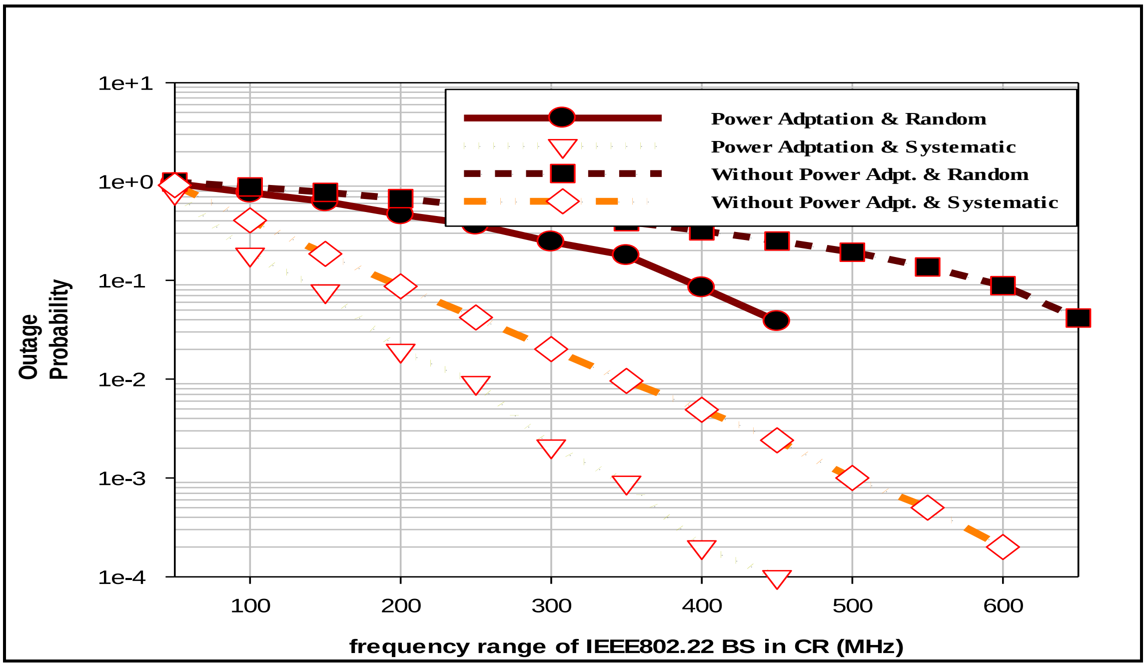

Figure 4.12: Outage probability of IEEE802.22 CR application vs. TVWS frequency range.

4.5.4 Comparison the Gain of wide frequency switching Results between Schemes

Table 4.4 shows the gain of a wide frequency transition (handoff) range in details. First, we display the impact of applying adaptation power in both classic random and proposed systematic schemes.

We note that the effect is considered acceptable to expand the range of frequency switching (handoff), since it is reach up to 190 MHz in classic scheme while 70MHz in proposed scheme in three cell coverage sizes (small, medium, large)cases.

Second, we present the gain value of proposed scheme up to 520 MHz which is considered as the worst classic scheme (No Adaptation power and random), also in three cell coverage size cases.

Table 4.4 Comparison the Gain of wide frequency switching Results between Schemes

Parameters		**Small Cell Coverage**		**Medium Cell Coverage**		**Large Cell Coverage**	
		Femtocell	**Wi-Fi**	**WiMAX**	**LTE**	**Public safety**	**IEEE 820.22**
Effect power to Gain wide frequency (MHz)	Random Classic	120	130	180	190	103	190
	Proposed Systematic	30	35	45	70	40	60
Gain wide frequency between Proposed and Classic scheme (MHz)		400	520	450	460	410	440

In summary, the expand in the frequency switching range at any frequency channel which operates currently in Base station (BS) in order to make a handoff process (low or high) is important because this expansion in the range permits the BS more flexibility to move to another frequency in the allowed range without having any of user out from boundary of the cell coverage area.

This leads to maintain a suitable availability of the frequency channel to guarantee the success of spectrum handoff process.

The number of handoff as well as preventing the link communication from dropping becomes more efficient using the proposed scheme which enhances the overall performance of the CR system.

Accordingly, the proposed scheme increases the wide of the frequency range by about 70%, 64%, 57% approximately in the three cases of cell coverage size .This ensures that the proposed scheme can be adopted in many applications and in different cell sizes and environments.

5

Conclusion and Future Works

5.1 Conclusion

The concept of cognitive radio (CR) is a promising technique to use the frequency spectrum efficiently. CR networks are being developed to solve current wireless network problems resulting from the limited available spectrum and the inefficiency in the spectrum usage.

The fundamental concept about CR characteristics, functionality, network architecture and applications are presented. Spectrum handoff is one of the most important issues in CR networks and to preparing this issues, we require to PU detection, target channel selection, routing recovery, handoff decision, and spectrum handoff strategy.

We studied the different handoff strategies which are classified into four models: non-handoff, pure reactive, pure proactive, and hybrid handoff strategy. Specific comparison between the four models is made in terms of handoff latency performance and the latency factor shows that pure proactive handoff strategy has the lowest handoff latency, while hybrid handoff and pure reactive handoff strategies have moderate and long handoff latency, respectively.

These features will determine their suitability for various applications in PU networks. Also, we defined the CR handoff based on the spectrum pooling concept which illustrate the spectrum channel availability and display mobility management framework according the event of handoff which it is occur from mobility user(intercell handoff) or spectrum mobility (spectrum handoff).

This thesis is focusing on spectrum mobility and more specifically on spectrum handoff task in the CR network and we proposed algorithm to make an efficient spectrum handoff that will improve the performance of the CR networks and overcome the drawback and reduce the number of spectrum handoff from falling, dropping, or breaking, so channel assignment in CR networks is especially challenging because wide spectrum band available.

It may be changing the channel from lowest band to highest, so this is the worst case based on transmission propagation loss. In contrast, if the assignment channels change from highest to lowest, the interference is considered as negative effect to the networks. From these problems we join the systematic channel selection scheme and power adaptation technique to solve these issues.

The first stage of algorithm permits to choose the selection method which is systematic or classic random and the stage apply the power adaptation or no adaptation approach. The simulation compares the result from four approaches which is systematic with adaptation, systematic without adaptation, classic with adaptation and classic without adaptation.

The best results was using systematic with adaptation which minimized the number of spectrum handoff and reserved the power dissipation produced from changing channel frequency and vary the coverage area of system. The simulation results prove that the proposed scheme have better performance when compare to other cases and we conclude that, the overall performance system is optimized to be more efficient using proposed scheme.

5.2 Future Works

There are many challenges that may be addressed to be done in the future work

- Predictive models to address the proposed algorithm adapted and hybrid of spectrum handoff strategy to choose the best holes that are needed to minimize the delay of the process and avoid the overloaded of signaling since the strategy selection currently specifically according the environment of primary system.

- Propose an algorithm considered the mobility handoff in cellular secondary system and compare and hybrid that with this scheme or may be explore novel scheme suitable to the new technique.

- Research and focus on the power control and an arrange control signaling between neighboring users in a rapid, robust and efficient way to limited time period when the spectrum holes are vacant and aiming to minimizing the use of resources such as energy and computations.

- According to my work in regulatory organization, we must focusing to this technology and expected that the transition to a new spectrum management approach and will have differences in different administrations both in scope, and the timeframe /roadmap for accomplishing the transition.

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