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أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Resource Allocation in OFDM-Based Cognitive Two-Way Relay Networks

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Resource Allocation in OFDM-Based Cognitive Two-Way Relay Networks

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Resource Allocation in OFDM-Based Cognitive Two-Way Relay Networks

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أ.د. فؤاد علي العاجز

ABSTRACT

Cognitive radio (CR), nowadays, is considered as one of the most promising techniques which introduce the flexible usage of radio spectrum and improve the spectral efficiency by enabling unlicensed users to exploit the licensed spectrum in an opportunistic manner. Moreover, the two-way relay communication has attracted a great attention as it introduces a relaying scheme with a bidirectional transmission to exchange information between two nodes. This strategy assumed to improve the overall capacity, since less time slots are needed than the one-way strategy, besides extending the radio coverage range of networks. Another common technique that improves the bandwidth efficiency and spectrum utilization is the orthogonal frequency division multiplexing (OFDM) technique which exhibits a distinctive efficiency in mitigating inter-symbol interference (ISI) and combating frequency selective fading. Therefore, two-way relay CR communication among OFDM terminals can take advantage of these three techniques to boost up the capacity together with the networks quality.

In this thesis, an OFDM-based amplify and forward (AF), cognitive two-way multiple-relay network is considered where two transceiver nodes exchange information via relay nodes. The full transmission happens in two time slots. In the first time slot, multiple access phase (MA), the transceiver nodes send their signals to the relay nodes while in the second time slot, broadcast phase (BC), the relay nodes broadcast the received signals to the transceivers.

In this dissertation, the problem to jointly optimize the network resources is considered. The first is the transmission power of transceivers and relay nodes to ensure suitable allocated power for best signals transmission besides ensuring no harmful interference is caused to the primary system. The other important resource to be optimized is the subcarrier pairing where the first and second time slots subcarriers have to be matched such that the subcarriers with the best conditions is reserved. The final tuned resource, in this work, is the relay selection where the relay node that assures the best transition of the received signal is selected.

The dual decomposition technique is applied to get the optimal resource allocation. Moreover, suboptimal algorithms are proposed to perform the resource allocation reducing, significantly, the computational complexity compared with the optimal solution with small performance degradation. Finally, simulation results of the suggested AF OFDM cognitive relaying network are shown to compare the performance gain of the different algorithms which reveals that the proposed suboptimal algorithm achieves good performance with much less computational complexity than the optimal one.

الملخص

تعتبر أنظمة الاتصالات الإدراكية في الوقت الراهن واحدة من أكثر التقنيات الواعدة ، والتي تتميز بخاصية الاستخدام المرن و الفعّال لنطاقات التردد الشاغرة وذلك من خلال تمكين مستخدمين غير مرخص لهم باستخدام نطاق ترددي معين من استغلاله بطريقة انتهازية تضمن عدم التسبب في حدوث تداخل ضار في موجات المستخدمين المرخصين، مما يُحسن كفاءة أنظمة الاتصالات خاصة في ظل التزايد المستمر للتطبيقات اللاسلكية ومحدودية الترددات المتاحة.

من ناحية أخرى ، فإن الاتصالات ذات الإتجاهين تحظى باهتمام كبير من قبل الباحثين نظراً لأن هذه التقنية تقترح تبادل كامل للمعلومات بين طرفي اتصال خلال وحدتين من الزمن بدلاً من أربع وحدات المتبعة في أنظمة الاتصالات أُحادية الإتجاه ، مما يُضاعف كفاءة استغلال النطاق الترددي ويزيد من عدد مستخدمي الشبكة مما يعمل على تحسين وتوسيع نطاق التغطية.

إضافة إلى ما سبق ، فإن تقنية التقسيم المتعامد للنطاق الترددي أثبتت أهميتها في زيادة نسبة الاستغلال الأمثل للنطاق الترددي المتاح ، إضافة لأهميتها في مقاومة الاضمحلال والتداخل بين أكواد الترميز.

بالنظر إلى التقنيات الثلاث المذكورة ، وأهمية كل واحدة منها في تحسين استغلال النطاقات الترددية فإن عملية دمجهم في شبكة اتصالات واحدة يسمح بالتحكم في استخدام وإدارة موارد الشبكة بدرجة عالية تُحقق أفضل كفاءة وسِعة استخدام ممكنة.

في هذه الرسالة ، نتناول بالبحث شبكة اتصالات لاسلكية مبنية على تطبيق تقنية التقسيم المتعامد للنطاق الترددي مع تقنية الاتصال ذي القدرة الإدراكية في شبكة اتصالات ثنائية الاتجاه ، حيث يعتمد الاتصال فيها على استغلال إحدى نقاط الشبكة المتوسطة مكانياً بين نقطتين ترغبان في تبادل المعلومات، كمرحل للبيانات بحيث تتكفل بتوصيل المعلومات بين النقطتين اللتين لا تملكان القدرة على الاتصال مباشرة. في مثل هذه الشبكة يتم الاتصال على مرحلتين: في الوحدة الزمنية الأولى (مرحلة الوصول المتعدد) تُرسل كل من النقطتين بياناتها للمُرحّل ثم يقوم المرحّل بدوره في الوحدة الزمنية الثانية (مرحلة البث) بجمع ودمج الإشارات المستلمة وبثها للمستخدمين إما بفك ترميز الإشارات وإعادة إرسالها ، أو الاكتفاء بتكبير الإشارة فقط.

التحدي الأكثر أهمية في هذه الدراسة هو الإدارة المتكاملة لموارد الشبكة والتي أهمها: القدرة الخاصة بنقاط الاتصال سواء كانت نقاط إرسال أو استقبال أو مرحلات بحيث تضمن استخدام القدرة المناسبة لتوصيل الإشارة مع ضمان عدم حدوث تداخل ضار مع إشارات المستخدمين المرخصين. المورد الثاني هو المزاوجة بين الموجات الحاملة الجزئية في كلا مرحلتي الاتصال لكي تضمن استخدام قنوات الاتصال ذات الظروف الأفضل.

المورد الأخير هو اختيار المرحّل الأمثل والذي يضمن أفضل انتقال للإشارة بين طرفي الاتصال. و لحل هذه المشكلة تقوم الأطروحة بتطبيق خوارزمية التحليل المزدوج والتي تضمن الحصول على حل هو الأمثل. بعد ذلك اقتُرحت خوارزميات تعطي حلولاً قريبة من الحل الأمثل لكنها تتميز بأنها أقل بكثير من ناحية التعقيد الحسابي من الحل بطريقة التحليل المزدوج. أخيراً تم عرض نتائج محاكاة لشبكة الاتصالات المقترحة المعتمدة على تقنية التقسيم المتعامد للنطاق الترددي في بيئة الاتصالات ذات القدرة الإدراكية التي تستخدم تقنية المرحّلات للتدليل على أداء الخوارزميات المختلفة والتي أظهرت أن الخوارزمية المقترحة القريبة من الأمثل تُعطي نتائج جيدة مع تميزها بأنها أقل بكثير من ناحية التعقيد الحسابي من الحل بطريقة التحليل المزدوج.

All praise goes to Allah, the Creator and Lord of the Universe

and the Cause of Every Success in My Whole life

This Work is dedicated to ...

My Great Parents,

My Dear Wife, and

Lovely Brothers and Kind Sister.

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LIST OF ABBREVIATIONS

AF	Amplify and Forward
BC	Broadcast
BS	Base Station
CP	Cyclic Prefix
CR	Cognitive Radio
CSI	Channel State Information
DF	Decode and Forward
FFT	Fast Fourier Transformation
FCC	Federal Communications Commission
IEEE	Institute of Electrical and Electronics Engineers
ISI	Inter-Symbol Interference
IFFT	Inverse Fast Fourier Transformation
LO	Local Oscillator
LTE	Long Term Evolution
MA	Multiple Access
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PAPR	Peak-to-Average Power Ratio
PU	Primary User
QoS	Quality of Service
SU	Secondary User
SNR	Signal to Noise Ratio
WLAN	Wireless Local Access Network

CHAPTER 1

INTRODUCTION

1.1 Introduction

In cognitive radio (CR) networks, a secondary, unlicensed, user (SU) coexists in the same geographical area with a primary, licensed, user (PU) exploiting the holes in the licensed spectrum band that is not occupied by any primary system node. The SUs are allowed to communicate using these frequency slots as long as they do not cause harmful interference to the PUs. This kind of communication exhibits an excellent utilization of the frequency bands that boosts up the bandwidth efficiency and spectrum utilization to much higher levels. The importance of CR technique rose to the surface considering the spectrum bands as a natural resource that has to be effectively managed.

A great technique that supports and enhances the control features in CR networks is the relaying process [5]-[9]. In relay networks, the direct link between the nodes that need to exchange information may not exists due to worse channel conditions, large distance, or the existence of obstacles. As a result, intermediate nodes act as relays by receiving the node signals and transmitting them again such that they guarantee that each node receives its desired signal. This technique assures better channel conditions and less transmission power which means low level of interference caused to PUs, when applied in CR systems, than the direct transmission case. Relay networks are, generally, divided into two categories: *one-way relaying* and *two-way relaying.* In one-way relay networks, the relay nodes receive information signal from a source node, in the first time slot and then in the second time slot, it retransmits the received signal to a destination node, using, in common, decode and forward (DF) or amplify and forward (AF) schemes. Consequently, four time slots are needed if two nodes want to establish full exchange of information since they cannot transmit in the same time. On the other hand, in the two-way relay scheme, the relay nodes receive information signals from transceivers in the first time slot, the multiple access phase (MA), and then in the second time slot, the broadcast phase (BC), they broadcast the received signals to the transceivers. This overcomes the one-way relay scheme and reveals the two-way relaying benefits by doubling the spectral efficiency, since only two time slots are needed to complete exchange of information between two nodes, besides increasing the network capacity.

Furthermore, in this work the orthogonal frequency division multiplexing (OFDM) technique is employed. This method increases the spectral efficiency by transmitting information over multiple orthogonal narrowband subcarriers besides being very effective in mitigating inter-symbol interference (ISI), combating frequency selective fading.

1.2 Contributions

1. The three techniques, mentioned in section 1.1, CR, two-way relaying and OFDM are combined to construct an OFDM-based AF CR two-way multiple-relay network.
2. The main network resources that affect the system throughput the nodes transmission power, subcarrier pairing between the two time slots, and the relay assignment are studied
3. The network resources are managed and jointly optimized to achieve maximum throughput while ensuring no harmful interference is introduced to the primary system using:
    1. Optimal solution based on the dual decomposition technique.
    2. Suboptimal algorithms with much less computational complexity compared to the optimal with small performance degradation.

1.3 Problem Definition and Motivation

In the recent years, the wireless communication systems have grown rapidly which increase, consequently, the number of users on the expense of the limited available bandwidth. So that, the optimal exploit of the network resources and bandwidth is considered, nowadays, as one of the most important search and development fields taking into account the best quality and performance. This vision has led to the CR systems that are considered as a smart way of exploiting every single hole in a spectrum of the primary network, in opportunistic manner, to be used in the secondary network.

The main issue to be considered in the CR systems is to ensure that the SU does not cause harmful interference to the PU by keeping the transmit power below a threshold limit. Considering this main and important condition the researchers suggested applying the CR idea in the relaying networks, where the communication between nodes is held via intermediate relay nodes which decrease, significantly the required power exploiting the spatial diversity. Moreover, deploying OFDM technique in the CR relaying environment, [8] and [9], boost the effective usage of the PU spectrum to higher percentage than single carrier system, where the frequency band is divided into N orthogonal narrow band subchannels.

Inspired by all of the above benefits, in this thesis, we propose an OFDM based CR AF two-way multiple- relay network, where the network main resources, power, subcarrier matching and relay assignment are jointly optimized to achieve the optimal capacity while keeping the interference to PU below a prescribed limit.

1.4 Objectives

The main objectives for this study can be summarized in the following points:

1. To study the main theoretical background required in this thesis.
2. To model an OFDM based CR AF two-way multiple- relay network and describe the system and the problem to be optimized by a set of efficient expressions and equations.

3. To introduce an optimal solution based on the dual decomposition technique where the dual variables are optimized using the subgradient method.
4. To propose suboptimal algorithm that has much less complexity than the optimal with small performance degradation.
5. To launch a simulation process that shows the results obtained and compares the performance of the optimal and suboptimal algorithms.

1.5 Literature Review

In this study, the problem of resource allocation in OFDM based CR AF network is discussed. The resource allocation problem in relay networks has received much attention over the past years. Vu and Kong in [1] considered a two-way relay OFDM based DF system where they proposed an optimal subcarrier and power allocation algorithm that match the subcarrier in order of channel power gain. The transmission in their approach happens in three time slots. In the first and second time slots, the two transceivers transmit their signals to the relay node then in the third time slot the relay re-encode the received signals and broadcast them to the transceivers. The authors in [2] introduced a joint resource allocation in two-way relay AF OFDM based multi-relay network. They performed the allocation by solving the formulated problem using the dual decomposition algorithm to obtain an asymptotically optimal solution. Moreover, they proposed two suboptimal schemes to solve the problem with much less complexity than the dual decomposition and small performance degradation. He et al. proposed, in [3], a multi-subcarrier DF relay strategy, in two-way relay OFDM based network. Their proposed technique does not need to perform subcarrier pairing process between the first and second time slots transmission. Additionally, they introduced an optimal resource allocation to characterize the achievable rate region of their proposed system by dividing the main optimization problem into two first and second time slots subproblems then solve them utilizing the advantages of ellipsoid method and the Lagrangian duality optimization technique. The work in [4] considers a two-way relay OFDM based AF system in which the authors developed an efficient technique for power allocating by replacing the individual power constraints with the total power constraint where they were able to obtain the closed form solution of the node powers, which is not a trivial duty in individual power approach. Moreover, they proposed a two-step suboptimal approach in which the power is optimally assigned to each subcarrier first, and then at each subcarrier the assigned power is distributed to the three terminals. Their proposed method was shown to assign 50% of the total power to relay irrespective of the channels.

The authors in [1], [2], [3] and [4] did not consider the CR technique that has been applied in this thesis to serve the current researches in utilizing the spectrum bands. Furthermore, the relaying transmission process in this dissertation occurs in only two time slots, rather than three, which enhance the spectral efficiency by a very good percent. Additionally, the scenario in this work depends on individual power constraints approach since it is more general than the total power one, considered in [4]. The total power constraint approach is more suitable when the different network nodes have the same power source. Therefore, the individual power constraints approach is more realistic.

CR two-way multi-relay AF network was considered in [5], in which the power and relay selection are jointly optimized under individual power and primary system interference constraints to achieve the maximum throughput. Moreover, they presented a closed form solution of the optimal power allocation of the transceiver nodes, only, while the relays power are fixed to be the minimum between the available power upper bound and the interference threshold divided by the channel gain. In [6] the problem of relay selection and resource allocation for two-way multi-relay CR network was investigated assuming AF then DF schemes. They applied the dual decomposition technique and subgradient method to find the optimal power allocation, where a closed form solution is obtained in the same manner as [5]. Moreover, in [6], a suboptimal approach based on the genetic algorithm was proposed.

The authors in [5] and [6] did not consider the multicarrier technique which employed in this work in order to offer more flexibility in the resource distribution process besides supporting, to a great extent, the fact that CR operates in noncontiguous band.

The system in [7] presents an opportunistic spectrum sharing in two-way relay OFDM based network in which the secondary system tries to help the primary system to achieve its target rate when a low signal to noise ratio (SNR) is presented. The power and subcarriers were jointly optimized such that the sum rate is maximized. Moreover, their system considered a single relay with limited scenario where the secondary network is a primary network helper not a separated network that can be utilized in a different application rather than the primary system one. The work in this thesis is more general and can be applied to networks that provide different services than the primary network. In [8], Shaat and Bader studied the joint subcarrier matching and power allocation in OFDM based one-way single relay CR system in order to maximize the total system throughput under interference constraints that ensure no harmful interference caused to the PUs. Additionally, they proposed an efficient suboptimal scheme that has much less complexity than the asymptotically optimal one. The authors followed the one-way relaying approach which is half the spectral efficiency of the two-way relaying applied in this thesis. Additionally, they introduced a single relay model which has been extended to a multiple-relay scenario in this study to generalize the network and make the optimization process more flexible. In [9], the authors studied the power allocation for OFDM based two-way single relay link in CR environment in order to maximize the sum rate. They assumed individual power constraints for secondary source and relay nodes while the interference assumed to be aggregated of the secondary system. They solved the optimization problem using the dual decomposition method. Their approach considered only the power allocation without optimizing the subcarrier pairing. Moreover, they suggested a simple single relay model where no relay selection process is needed. Saliya et al. in [10] discussed the optimal power allocation for physical layer network coding two-way relay CR network where the sum rate is maximized under total power constraint and interference power threshold. The authors did not utilize the benefits of using the multicarrier technique. Moreover, they did not perform optimization for other network resources rather than nodes power.

1.6 Thesis Structure

This dissertation is organized in five chapters; the first one, the introduction, gives a smooth entrance to the topics studied throughout the rest chapters.

Chapter 2 describes the CR technique, shows its main contributions, common network architecture, characteristics, advantages, drawbacks, and the current main applications of this technique.

In Chapter 3, a brief background of the OFDM technique and the relaying networks is presented.

Chapter 4 describes the system model, problem formulation, the optimal and suboptimal algorithms that perform the resource allocation, and finally the simulation results and discussion.

Chapter 5 comes to a conclusion that summarizes the important issues drawn out from this study and the recommendations on future work to be carried on this subject.

A paper out of this thesis is submitted to IEEE International Workshop on Cognitive Cellular Systems (CCS 2014), attached at the end of the thesis.

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CHAPTER TWO

COGNITIVE RADIO SYSTEMS

2.1 Introduction

As the demand of enormous data rates in the wireless communication systems and applications grows rapidly, the requirement of efficient spectrum usage becomes an insistent need considering the natural frequency spectrum limitations. Surveys from the Federal Communications Commission (FCC) confirmed that 90 percent of the time, many licensed frequency bands remained idle [1]. Moreover, a large portion of the assigned spectrum is used intermittently as shown in Figure 2.1. Independent studies held in some countries confirmed this surveys, and concluded that spectrum utilization depends strongly on time and place. So that it becomes obvious that the current conventional static frequency allocation schemes cannot meet the actual needs of the increasing number of higher data rate devices, especially, considering that the recent communication systems are no longer voice only systems, but also includes multimedia applications.

As a result, CR networks have been proposed as a very useful and smart solution to a great extent that has the ability to overcome these spectrum barriers. In CR networks, SUs are permitted to use the same spectrum of the PUs in an opportunistic manner by dynamically senses for frequency holes, frequency channels that are not occupied by the PU, and then use the best available channel to establish their communication.

The CR concept has many definitions in several contexts but in this study, we use the definition adopted by Federal Communications Commission (FCC) [2]: "*Cognitive radio: A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating* *parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets.*".

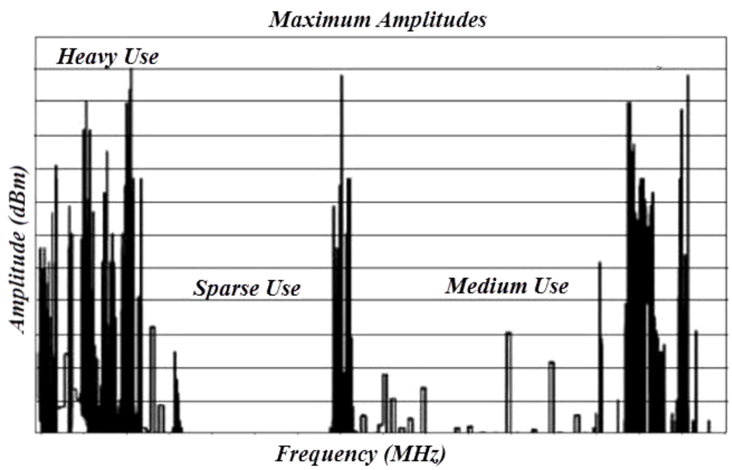

Figure 2.1 Spectrum utilization [3].

The main functions for CR networks can be summarized as follows:

• *Spectrum sensing*: Detecting idle channels in the licensed band and sharing the spectrum without causing harmful interference to the other users.

• *Spectrum decision*: Allocating the best available channels to meet user communication needs.

• *Spectrum mobility*: Guarantee soft transition to better spectrum (spectrum handoff).

• *Spectrum sharing*: Provide the best and fair spectrum scheduling among coexisting CR users.

These functions are to be discussed in details later in this chapter.

2.2 Cognitive Radio Network Characteristics

The CR systems must gain necessary information from the radio environment before they adjust their operating mode to environment variations. This is referred as the *cognitive capability*, which enables CR systems devices to be aware of the transmitted waveform, radio frequency (RF) spectrum, communication network type, geographical information, locally available resources and services, user needs, security policy, and so on then the CR devices can dynamically change their transmission and operating parameters according to the sensed environment variations and achieve optimal performance, which is referred to as *reconfigurability* [4].

2.2.1 Cognitive Capability

Cognitive capability refers to the ability of the radio technology to capture or sense the information from its radio environment. This capability cannot simply be realized by monitoring the power in some frequency bands of interest but more sophisticated techniques are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users. Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected [3].

The cognitive capability relies on the adaptive operation in open spectrum task, referred as the cognitive cycle, which will be discussed later in this chapter.

2.2.2 Reconfigurability

Reconfigurability is the ability of tuning the operating and transmission parameters, on the fly, without any need of modifications on the hardware components. Reconfigurability provides the basis for the following features [5]:

a) Adaptation of the radio interface so as to accommodate variations in the development of new interface standards.
b) Incorporation of new applications and services as they emerge.
c) Incorporation of updates in software technology.
d) Exploitation of flexible heterogeneous services provided by radio networks.

The most important challenge, in CR networks is to share the licensed spectrum without causing harmful interference to the licensed users. As shown in Figure 2.2. The CR enables the usage of temporally unused spectrum, which is referred to as spectrum hole or white space [6].

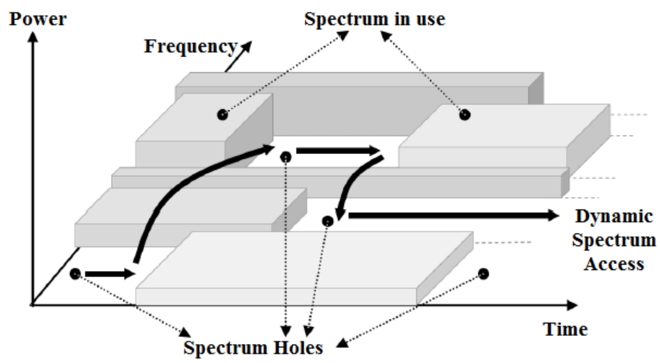

Figure 2.2 Illustration of spectrum white space [3].

2.3 Network Architecture and Applications

In CR systems, the network components include both SUs and PUs in the same geographical area, as shown in Figure 2.3 [4].

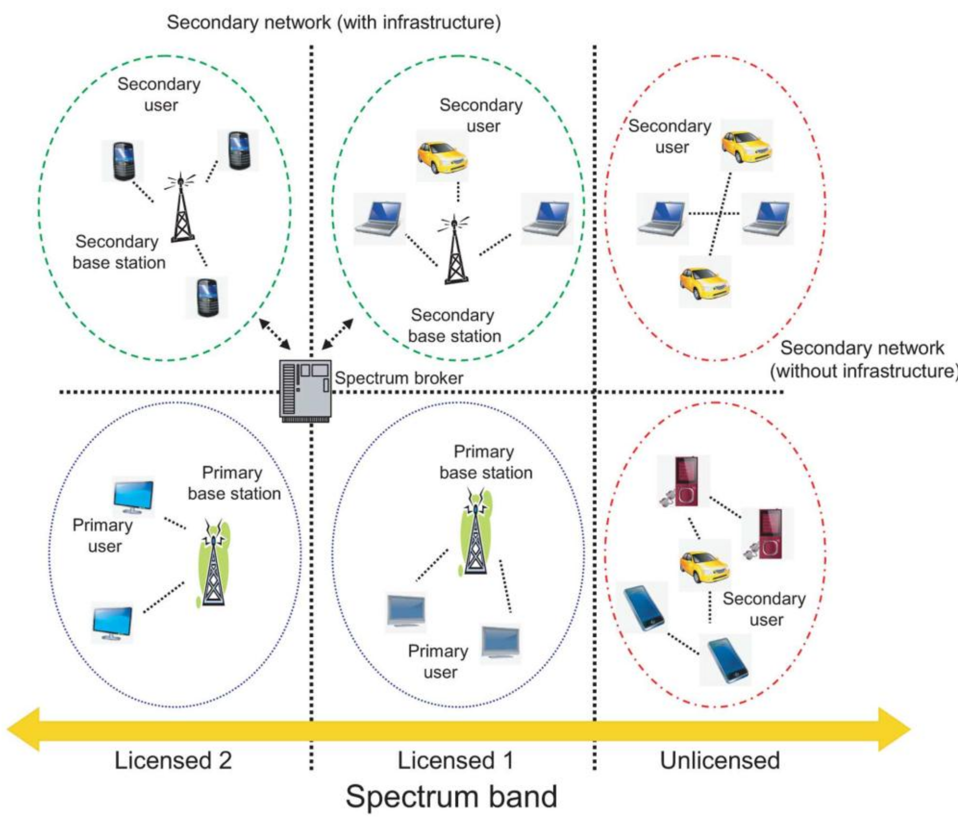

Figure 2.3 CR network architecture [4].

A secondary network is a network that consists of a set of SUs with or without a secondary base station (BS). SUs can only access the licensed spectrum when it is not engaged by a PU while a primary network is consists of a set of PUs and one or more primary BS. Primary network users have the right to use specific licensed spectrum bands under the coordination of primary BS.

It should be noted that the PUs and the BSs are not, in common, equipped with CR functions. As a result, the secondary network is required to detect, immediately, the presence of a PU and transform the transmission to another available band so as to avoid interfering with primary transmission. This will be discussed later in details the spectrum mobility subsection. The spectrum broker is a central network component that has a main role in sharing the spectrum resources among different CR networks. It can be connected to every network and serve as a spectrum manager to enable coexistence of multiple CR networks.

2.4 Cognitive Cycle

The idea of cognitive cycle was first described by Mitola in [7]. The cognitive cycle, Figure 2.4, is continually run by the CR to observe spectral opportunities, create plans to adapt itself, decide, and act to explore the best opportunities. The main stages of a perfect cognitive cycle are: the spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility.

2.4.1 Spectrum Sensing

The spectrum sensing function enables the CR to monitor the available spectrum bands, captures their information, and then detects the spectrum holes. There are, generally, three different aspects of spectrum sensing, the interference temperature model, transmitter detection model and cooperative detection model. The chart in Figure 2.5 summarized the spectrum sensing techniques.

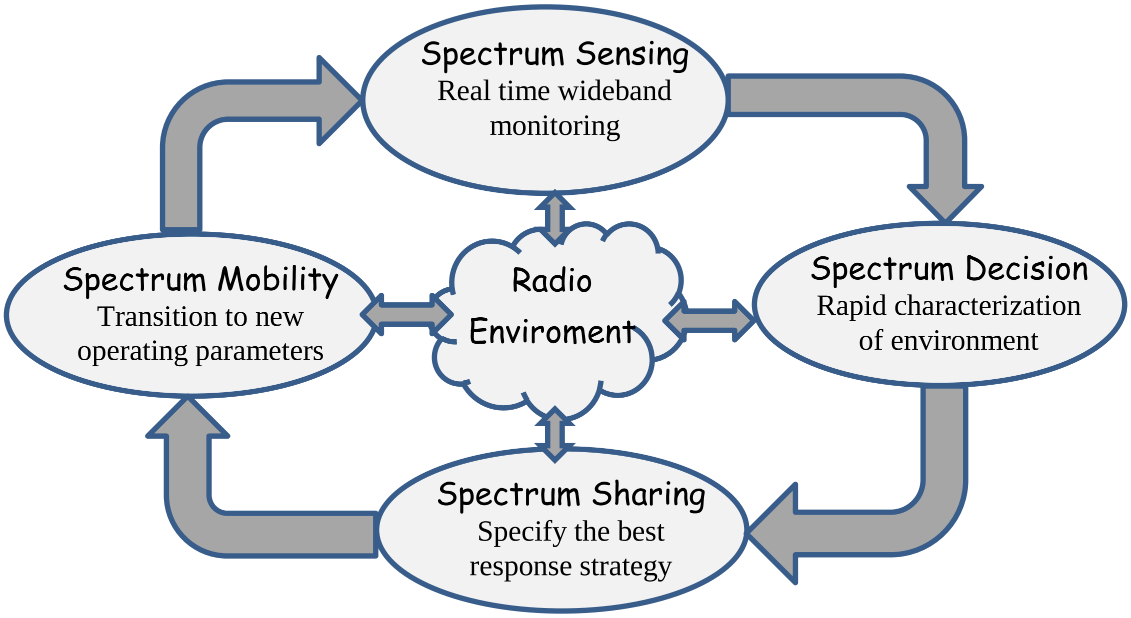

Figure 2.4 Cognitive Cycle.

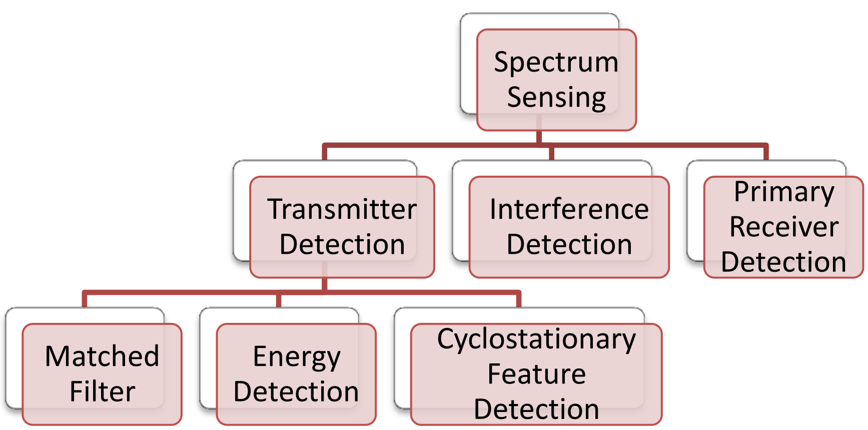

Figure 2.5 Spectrum sensing techniques.

2.4.1.1 Interference Temperature Model

The interference temperature model, shown in Figure 2.6, is a common way to measure and limit the interference perceived at PUs [8]. The interference temperature model manages interference at the PU receiver through the interference temperature limit, which is represented by the amount of new interference that the receiver could tolerate [3]. As long as the SUs do not exceed this limit by their transmissions, they can use this spectrum band.

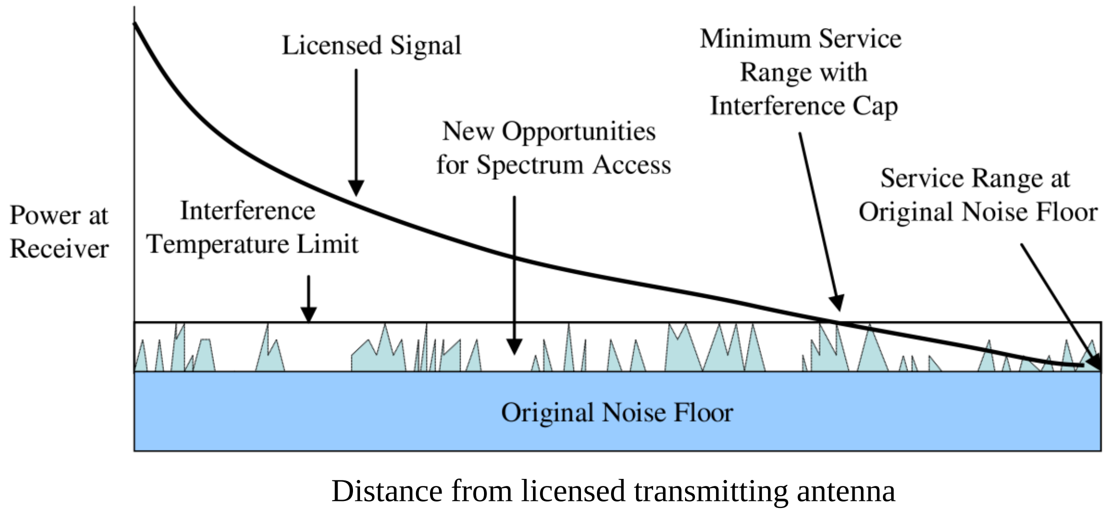

Figure 2.6 Interference temperature model [9].

The interference temperature model main limitation that affects its sensing ability are

1. No practical way for a CR to measure or estimate the interference temperature i.e. CR users cannot distinguish between actual signals from the PU and interferences.
2. Interference temperature limit should be location dependent of the PUs which is not easy to determine.
3. Increasing the interference temperature limit will affect primary network's capacity and coverage.

2.4.1.2 Transmitter Detection

The sensing, in this scheme, is performed over the weak signal received at the CR terminal from the primary transmitter. The increasing in the distance between the CR terminal and the primary transmitter as well as the shadowing degrades the performance of this type of sensing [10].

There are three different schemes, generally, used for the transmitter detection approach. The matched filter detection, energy detection and cyclostationary detection.

a) Matched filter detection

The matched filter detection technique, shown in figure 2.7, is obtained by correlating a known signal, also called a template, with an unknown signal to decide the presence of the template in the unknown received signal.

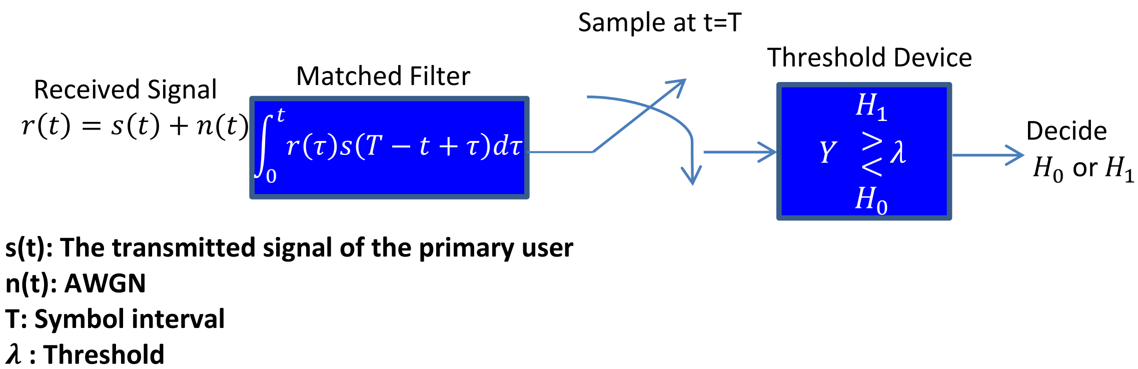

Figure 2.7 Matched filter detection technique.

To be applied, this technique requires a prior knowledge of the PU signal such as the modulation type and order, the pulse shape, and the packet format. Consequently, if this information is not accurate, then the matched filter performance is poor. However, owing to the knowledge that most of the wireless network systems have pilot, preambles, synchronization word or spreading codes, these can be used for the coherent detection. The main advantage of the matched filter detection is the less time required to achieve high processing gain due to coherency.

b) Energy detection

Energy detection is the most common type of spectrum sensing because of its simple implementation and the fact that no prior knowledge about the PU signal is required. In order to measure the energy of the received signal, the output signal of a bandpass filter, $r(t)$, with bandwidth W is squared and integrated over the observation interval T, that is

$$Y = \int_0^T r^2(t)\, dt \tag{2.1}$$

where T is the observation (sensing) time.

Finally, the output of the integrator, Y, is compared with a threshold, λ, to decide whether a licensed user is present or not [11].

Let P_d be the probability of detection and P_f the probability of false alarm, then if P_d is low then the probability of missing the presence of the PU is high which increases the interference to the PU while a high P_f would result in low spectrum utilization since false alarms increase the number of missed opportunities (white spaces).

The main drawbacks of the energy detector are the inability to differentiate signal types as it can only determine the presence of the signal, its prone to the false detection triggered by the unintended signals and the need to longer sensing time than the matched filter technique.

c) Cyclostationary detection

In general, modulated signals are coupled with sine wave carriers, pulse trains, repeating spreading, hopping sequences, or cyclic prefixes, which result in built-in periodicity. Therefore, cyclostationary detection uses the periodicity advantage in PU signals to detect the PU transmitter utilizing the spectral correlation function. It is robust to the noise power and uncertainty but it has a high computational cost and requires long time of observation [12].

The main limitations of the transmitter detection technique are the receiver uncertainty problem and the shadowing problem, Figure 2.8. The receiver uncertainty implies that the CR user cannot avoid the interference due to the lack of information of the primary receiver. The shadowing problem occurs when the CR user is located in the transmission range of the primary transmitter, but may not has the ability to detect the transmitter due to the shadowing, as shown in Figure 2.8 (b), which causes the received signal power to fluctuate about the path loss by a multiplication factor, thereby resulting in "coverage" holes.

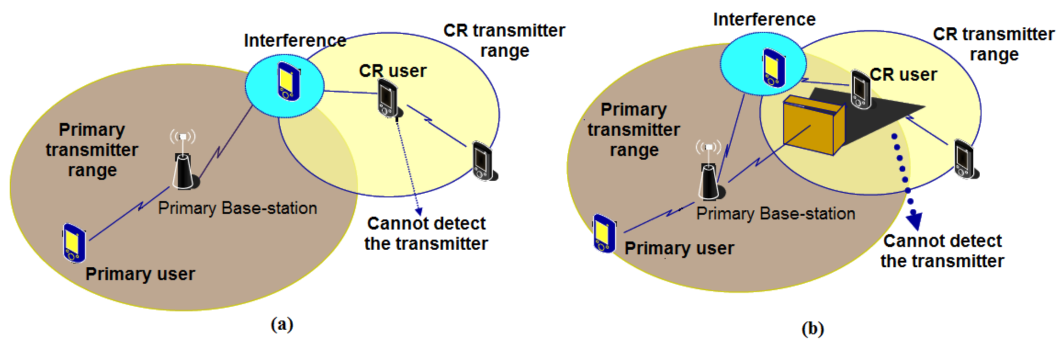

Figure 2.8 Transmitter detection problems: (a) Receiver uncertainty and (b) shadowing uncertainty [3].

2.4.1.3 Primary Receiver Detection

In this technique, the advantage of the fact that all RF receivers local oscillator (LO) emit leakage power is exploited to allow CRs to locate these receivers so the CR users detect the LO leakage power for the detection of PUs instead of the transmitted signals.

The LO leakage power can be detected following the same methods introduced to the transmitter detection [13], i.e., matched filter detection, energy detection or cyclostationary detection. Currently, the LO method is only feasible in the detection of the TV receivers [3].

The main advantage of the primary receiver detection is the ability to solve the receiver uncertainty problem inherited in the transmitter detection technique but the LO leakage signal weakness make the implementation of a reliable detector is not trivial. Table 2.1, [10] and [20], summarizes and compare between the advantages and drawbacks of the interference temperature, transmitter and primary receiver detection sensing techniques.

Table 2.1: Comparison between the interference temperature, transmitter and primary receiver detection schemes, [10] and [20].

Sensing technique		Advantages	Drawbacks
1- Interference temperature detection		- Recommended by FCC. - Ensure that the prescribed interference threshold to PU is not violated.	- Requires knowledge of the PU location.
2- Transmitter Detection	**Matched filter**	- Optimal Performance. - Fast detection with low cost. - Low number of samples are requires. - Best in Gaussian noise. - Needs shorter sensing duration, means, less power consumption.	- High complexity. - Requires a prior knowledge of the PU transmissions, and extra hardware on nodes for synchronization with PUs.
	Energy detection	- No prior information is required. - Low cost. - Simple to implement. - Requires the least amount of computational power on nodes.	- Unreliable in Low SNR regime - High False Alarm - Cannot differentiate PU signal from other SUs - Doesn't work for spread spectrum signals. - Requires longer sensing duration (high power consumption). - Accuracy highly depends on noise level variations.
	Cyclo-stationary	- Robust to noise uncertainty - Performs well in low SNR regimes. - Can differentiate between several types of transmissions.	- Partial knowledge of the primary signal - High computational complexity.
3- Primary receiver detection		- Most resilient to variation in noise levels.	- Requires a prior knowledge of PU transmissions. - Requires high computational capability on nodes.

2.4.2 Spectrum Decision

CR networks needs the capability to decide the best spectrum band among the available sensed bands; this is what so called *spectrum decision*, which depends, essentially, on the quality of service (QoS) requirements, spectrum characteristics and the PU activity. Considering the QoS and spectrum characteristics, the CR system have to be aware of data rate, acceptable error rate, delay bound, the transmission mode, and the bandwidth of the transmission. Additionally, the CR users have to follow the PU activity and take into account the number of spectrum handoffs, that happens in a certain spectrum band to be considered in spectrum decision. Moreover, the spectrum decision involves three main functions: spectrum characterization, spectrum selection and CR reconfiguration.

Many parameters such as the channel interference level, error rate, path loss, delay and holding time are important for efficient spectrum characterization. Once spectrum holes are characterized, the next major step is to select the best available spectrum suitable for the user's specific QoS requirements. In CR networks, the set of channels available for each node is not static due to dynamically changing topologies and varying RF propagation characteristics. This implies that spectrum selection techniques in CR networks should be closely coupled with routing protocols [15].

Based on spectrum characterization and spectrum selection, reconfiguration of parameters occurs. The radio parameters that commonly reconfigured in CR networks are modulation and coding scheme, transmission power, operating frequency, channel bandwidth and communication technology.

2.4.3 Spectrum Sharing

The idea of the spectrum sharing in CR networks is similar to the medium access control (MAC) principle in the existing classical systems. However, the case in CR networks differs in the fact of the coexistence with the licensed system in the same geographical area. The main three aspects of the spectrum sharing stage are the architecture assumption, spectrum allocation behavior, and spectrum access technique as depicted in the chart, Figure 2.9.

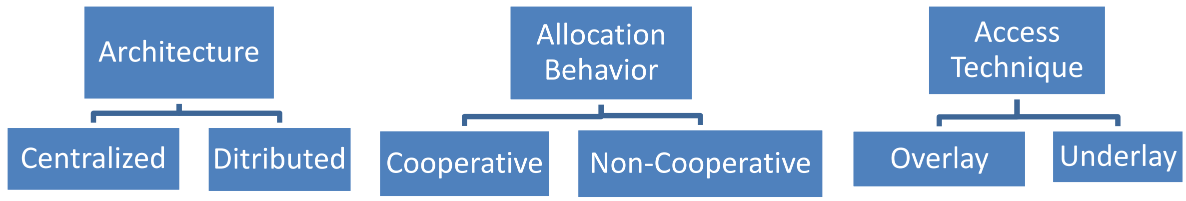

Figure 2.9 Spectrum sharing in CR networks.

The CR networks are divided, considering architecture, into centralized and distributed networks.

a) Centralized spectrum sharing

In this topology, a centralized unit controls the processes of the spectrum allocation and access in which each CR user in the network forwards their spectrum allocation data to the central unit which then constructs a spectrum allocation map [16].

b) Distributed spectrum sharing

When the infrastructure is not available each CR user performs the task of the spectrum allocation and the access is based on local protocols.

The next classification of the spectrum sharing techniques in CR networks is based on the allocation behavior where the spectrum can be cooperatively or non-cooperatively allocated.

a) Cooperative spectrum sharing

CR users, in this scheme, exchange their information with other neighboring users. In other words, the interference information of each CR user is shared among other users [17].

b) Non-cooperative spectrum sharing

Also referred as selfish spectrum sharing since it considers the node itself rather than any other user's parameters by selecting the channel with the objective of achieving maximum throughput. The main disadvantage of the non-cooperative networks is that it may result in reduced spectrum utilization.

The third, and final, classification of spectrum sharing in CR networks is based on the access technology described as

a) Spectrum Overlay

In this technique, the CR node accesses the network using only the portions of the spectrum that is not occupied by any PU [18]. Consequently, the interference to the primary system is minimized.

b) Spectrum Underlay

The SU, in this scheme, is permitted to transmit over the full licensed spectrum band such that the interference to the PU is less than the interference threshold tolerated by the primary system. This technique can utilize increased bandwidth compared to overlay techniques.

Figure 2.9 depicts the idea of the spectrum overlay and spectrum underlay access techniques.

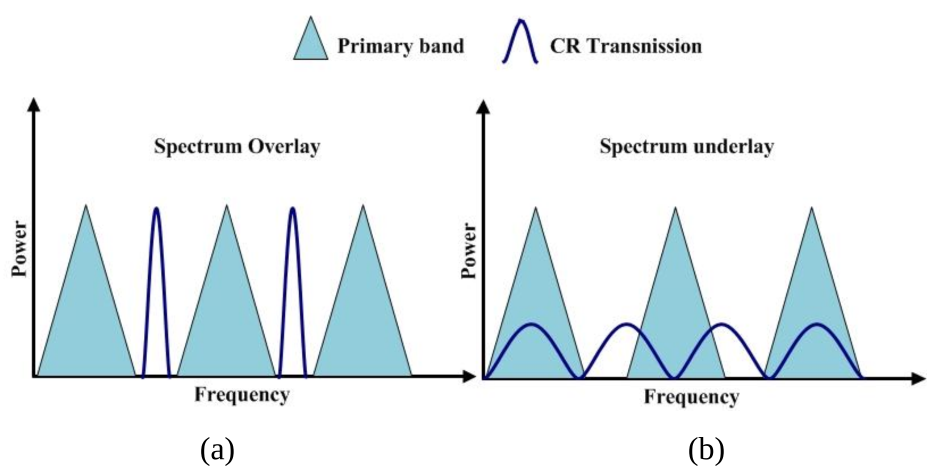

Figure 2.10 a) Spectrum overlay. b) Spectrum underlay

2.4.4 Spectrum Mobility (Spectrum Handoff)

In the classical cellular wireless networks, the handoff process occurs when the signal power becomes weak. This usually happens at the cell boundary when the mobile user moves from one cell to an adjacent one. In this case, the transition to a new suitable base station becomes an insistent need in order not to drop the call. On the other hand, in CR systems the handoff process, called spectrum handoff, takes place when a PU re-appears in the licensed band or the channel conditions become worse in order to provide the SU with smooth frequency transition with low latency. The transmission of the SUs is suspended during a spectrum handoff; so that they will experience longer packet delay.

A good way to alleviate the performance degradation due to long delay is to reserve a certain number of channels for potential spectrum handoff [18].

The main steps of the spectrum handoff are

1- PU detection: Accomplished following one or more, if possible, of the approaches described in spectrum sensing, subsection 2.4.1.
2- PU notification.
3- Channel switching: This depends, essentially, on the hardware switching efficiency.
4- Resume communication: By one of the sharing techniques depicted in subsection 2.4.3.

The spectrum handoff could be classified into two main categories, reactive and proactive handoff.

a) *Reactive handoff:* In this scheme, the CR user performs the handoff after detecting the PU.
b) *Proactive handoff:* The handoff is performed when the CR user predicts that a PU will access the current channel.

The main challenge in spectrum mobility techniques is to apply algorithms guarantee that no severe performance degradation is caused to the applications during the handoff process.

2.5 Applications

The ability of real-time decisions in networks decreases the burdens of centralized spectrum management. Therefore, CR networking can be used in different applications. It can provide military with adaptive, seamless, and secure communications. Moreover, a CR network can also be implemented to enhance public safety and homeland security. A natural disaster or terrorist attack can destroy existing communication infrastructure, so an emergency network becomes indispensable to aid the search and rescue [4]. Another important and promising application is the sensor networks such as home monitoring, factory automation and disaster relief operations.

2.5.1 Public Safety Networks

Public safety networks are one of the applications that can exploit CR technique. Police officers and fire and paramedic personnel use such networks for communication among them. The public safety personnel do not have the technology to dynamically operate across the different spectrum segments. Recall that public safety licensees have a wide variety of bands available (VHF-Low, VHF-Hi, UHF below 800, UHF-800, etc.) [21]. The CR technique can offer public safety networks more bandwidth through opportunistic spectrum access. Moreover, a public safety CR network can provide a substantial communication improvement by allowing the interoperetability across different public safety services while adapting, smartly, to the high peak-to-average nature of the traffic carried out by such networks.

2.5.2 Disaster Relief and Emergency Networks

The communications infrastructure, usually, collapsed as a result of natural disasters such as hurricanes, earthquakes, wild fires, or other unpredictable phenomena. This results in partially or fully damaged networks. Therefore, there is an urgent need for a means of communications to facilitate the rescue team's duty to be well organized help. The CR networks can be used for such emergency networks [22].

The use of CR technique in disaster relief networks can provide a significant amount of bandwidth that can deal with the expected huge amount of voice and multimedia traffic e.g. transmitting videos locate a specific position of a survivor. It is worth to mention the contribution of using wireless local access network (WLANs) in the relief of the Haiti earthquake. However, the communication over such a network was unreliable and suffered significant delays [23].

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CHAPTER THREE

OFDM TECHNIQUE AND RELAYING NETWORKS

3.1 Introduction

CR networks require efficient physical layer. Therefore, the OFDM technique, known to be suitable for the physical architecture, has been recommended for the CR systems because of its capability to perform underlying sensing besides the ability to occupy the empty gaps left by the primary system users. The OFDM flexibility provides opportunities to be used in advanced systems such as CR networks.

OFDM divides the target spectrum into orthogonal narrowband subchannels where the signal values are modulated on the subchannels in frequency domain. Interference to the PUs is avoided by simply nullifying the subchannels in the occupied spectrum segments and modulating only the subchannels in the unused spectrum segments. With a sufficient number of subchannels, an OFDM-based CR system can operate efficiently in any target PU spectrum regardless of its channelization scheme [1].

Employing OFDM technique in the CR environment decreases the overall sensing time since if a PU appears at a single carrier, sensing in other carriers is not necessary. Furthermore, OFDM based CR networks have the ability to use multiple spectrum bands, simultaneously, for the transmission.

Another factor that, significantly, increases the OFDM based CR network efficiency when coupled with the cooperative networks principal. Cooperative communications emerged to exploit the spatial diversity gains inherited in the multiuser wireless systems without the need of multiple antennas at each node. This is achieved by having the users relay each other’s messages and thus forming multiple transmission paths to the destination [2].

The relay-assisted wireless networks ensure better channel conditions, increase coverage and less transmission power than the direct link transmission case which means low level of interference is caused to PUs.

In this study, the CR principal is deployed in an OFDM based two-way multiple-relay network.

3.2 Orthogonal Frequency Division Multiplexing (OFDM) System

3.2.1 OFDM System Design and Benefits

The concept of OFDM dates back to 1960s. In OFDM, the entire band is divided into many narrowband orthogonal subchannels, which are transmitted in parallel to maintain high data rate transmission and, at the same time, increase the symbol duration to combat ISI, a form of distortion of a signal in which one symbol interferes with subsequent symbols because of multipath fading, [3]-[6]. Additionally, orthogonal subcarriers offer the ability to be decoded separately.

The basic idea of OFDM modulation is to divide the transmitted bitstream into many different substreams and send these over many different subchannels. Typically the subchannels are orthogonal under ideal propagation conditions. The orthogonality requires that the sub-carrier spacing is $\Delta f = \frac{k}{T}$ Hertz, where T is the symbol duration, and k is a positive integer, typically equal to 1. Moreover, the data rate on each of the subchannels is much less than the total data rate, and the corresponding subchannel bandwidth is much less than the total system bandwidth [7].

The duration of the OFDM symbol is longer than the single carrier modulation and its bandwidth is narrower. Consequently, the OFDM systems are more robust to frequency-selective fading, in which different frequency components of the signal experience uncorrelated fading, by driving each subcarrier to be exposed to flat fading rather than frequency selective fading. On the other hand, OFDM is more sensitive to the time-varying impairment of channels.

In OFDM systems, the frequency spectrum of the subcarriers are overlapped with minimum frequency spacing and the orthogonality is achieved between the different subcarriers [8]. As shown in Figure 3.1, the QAM modulated OFDM input symbol stream is passed through a serial to parallel converter to be splitted into N parallel symbol stream. The parallel data is then passed through an inverse fast Fourier transformer (IFFT) to generate time sequence of the symbol stream.

The OFDM symbol obtained by applying the IFFT algorithm consists of the sequence $x[n] = x[0], \ldots, x[N-1]$ of length N, where [8]:

$$x[n] = \sum_k \sum_{l \in Z} X_{k,l} g_T(n - lT) e^{j2\pi(n-lT-C)k/N}, \quad (3.1)$$

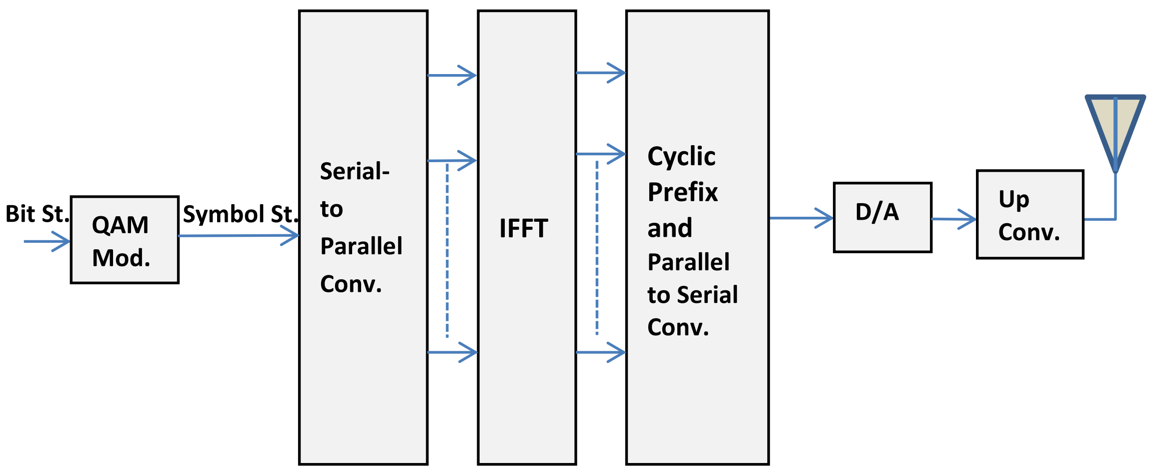

Figure 3.1 OFDM transmitter.

where k is the subcarrier indices and is a subset of the set $\{0, 1, \cdots, N-1\}$, C is the length of the cyclic prefix (CP), N is the number of subcarriers, $T = C + N$ is the length of the OFDM symbol, l denotes the l_{th} OFDM symbol and $g_T(n)$ is a rectangular pulse shape where $g_T(n) = 1$ if $n \in \{0, 1, \ldots\ldots, T-1\}$ and equals 0 otherwise.

Furthermore, a CP, a copy of the last part of the symbol determined by the expected duration of the multipath channel in the operating environment such that C is greater than the channel delay spread, is then added to the beginning of the OFDM time sequence which acts as guard interval to combat ISI from the previous symbol. The cyclic prefix serves to eliminate ISI between the data blocks, because the first C samples of the channel output affected by this ISI can be discarded without any loss relative to the original information sequence. Moreover, it allows the linear convolution of a frequency-selective multipath channel to be modeled as circular convolution [7]. The resulting digital signal is ordered by a parallel to serial converter then turned into an analog signal, through digital to analog converter, upconverted and finally passed to the antenna to be transmitted through the channel.

At the OFDM receiver, Figure 3.2, the received signal is downconverted then sampled by the analog to digital converter (A/D) to get the digital form again and filtered to remove the high frequency components. The CP is then removed. The resulting signal is serial to parallel converted and passed through the FFT. The output parallel signal of the FFT is then gathered into a serial stream, as the original transmitted signal, which passed through a demodulator to extract the required signal.

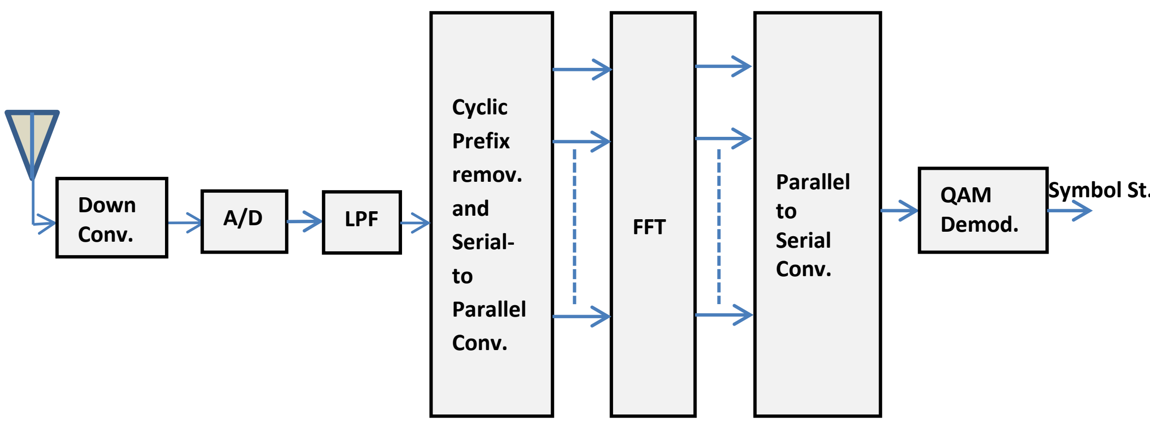

Figure 3.2 OFDM receivers.

3.2.2 Peak to- Average Power Ratio

One of the main OFDM system problems is the peak to average power ratio (PAPR) which caused because of the linear combination of the transmitted symbols which means a Gaussian like form, from the central limit theorem. The OFDM transmitted signal has a very large PAPR compared with the single carrier modulation. The PAPR problem may cause nonlinear distortion of the amplifier at the transmitter.

Many approaches have been proposed to reduce the PAPR of OFDM signals. Back off the operating points of nonlinear power amplifiers is a classical method of reducing the large PAPR. However, this method severely reduces the efficiency of the power amplifiers. Clipping and filtering, [9], selected mapping (SLM), [10], and partial transmit sequence (PTS) are also another methods that reduce the PAPR problem. The clipper method could be, directly, used to reduce the PAPR of an OFDM signal but it may cause in-band distortion and out-of-band radiation due to nonlinearity [11].
The SLM and PTS techniques are distortionless compared with the clipping and filtering techniques but they are with heavy computational complexity.

3.2.3 OFDM Applications

OFDM has been applied in several wireless communication applications, because of its efficient features, such as terrestrial digital video broadcasting and European digital audio broadcasting. Moreover, OFDM has been exploited in many IEEE standards, e.g. IEEE 802.11a/g/n, IEEE 802.15.3a, and IEEE 802.16d/e. Furthermore, the orthogonal frequency division multiple access (OFDMA), achieved by allocating a group of subcarriers to a specific user, is considered, currently, as one of the most promising radio transmission techniques for long term evolution (LTE) wireless communication systems.

In this thesis, we apply the OFDM technique in a CR two-way multiple-relay network which supports the underlying sensing that decrease the overall sensing time of the system. The OFDM can be used to construct the transceiver of CR networks by virtue of its flexibility for subchannel assignment and power allocation [12].

3.3 Relaying Networks

Relay communication systems are important, in general, when reliable communication cannot be guaranteed by using a conventional direct link communication. The spatial diversity of relay networks and space-time codes, both, can be used to improve the transmitted signal quality, thereby enhancing the channel capacity. Moreover, the relay communications are a promising technique that combat signal fading due to multipath radio propagation. It also improves the system performance and coverage area.

The concept of relaying has also been integrated into major specifications for next generation wireless communications such as the IEEE 802.16j [18]. The relay networks are divided, generally, into two categories: one-way and two-way relay networks, which will be discussed in sections 3.3.1 and 3.3.2, respectively. In the relay networks, the relay node retransmits the signal received following two basic schemes, [13]-[16], AF and DF. In the AF scheme, the relay received a signal in the first time slot and then retransmits an amplified version of the received signal in the second time slot. The main advantage of this technique is the simple implementation and significant efficiency in high signal to noise ratio (SNR) regimes. On the other hand, the main drawback is the amplification of the noise signal which degrades the performance in low SNR regimes. In DF the relay decodes the received signal, in the first time slot, before transmitting a fresh version of the signal in the second time slot. The DF technique is efficient in low SNR regimes.

3.3.1 One-Way Relay Networks

Consider the three-node relay system shown in Figure 3.3. Let S be the source node that intends to transmit a message to the destination node D while R is an intermediate node serves as relay node. There is no direct link between S and D due to poor channel conditions. Consequently, the relay R assists the source to destination transmission in order to increase the system coverage and achievable capacity.

In the first time slot, S transmits its signal to R. The received signals at the relay node, Y_R, can be expressed as [17]:

$$Y_R = h_{SR}\sqrt{P_S}\,X_S + Z_R, \qquad (3.2)$$

where, X_S is the source transmitted symbol, P_S is the source transmitted power, h_{SR} is the complex channel coefficient of the $S-R$ link and Z_R is the independent complex Gaussian noise.

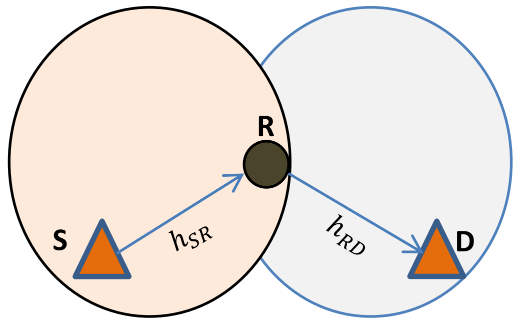

Figure 3.3 One-way Relay Network.

In the second time slot, the received signal is retransmitted to the destination following one of the schemes discussed, previously in this chapter, AF or DF techniques.

If the AF is adopted, the received signal at the relay node has to be multiplied by an amplification factor β, Then, the received signal at the destination node, Y_D, can be expressed as:

$$Y_D = \beta h_{RD}\sqrt{P_R}Y_R + Z_D, \tag{3.3}$$

Where, h_{RD} is the complex channel coefficient of the $R-D$ link and Z_D is the independent complex Gaussian noise at the destination side. The destination is then extracts the desired signal.

On the other hand, if the DF scheme is adopted the received signal at the destination edge is expressed as [18]:

$$Y_D = h_{RD}\sqrt{P_R}X_R + Z_D, \tag{3.4}$$

where X_R is the relay transmitted symbol. No amplification factor is needed and the only noise presented is the destination receiver noise.

3.3.2 Two-Way Relay Networks

Two-way relay wireless communication networks has attracted a great deal of concern because of using the relaying principal with two-way transmission, [14]-[16], to exchange information between two transceiver nodes T_1 and T_2 as shown in Figure 3.4. This strategy may enhance the overall system capacity and coverage due to the fact that two time slots, only, are required for full transmission which doubles the capacity compared to one-way approach.

The system in Figure.3.4 consists of two transceiver nodes T_1 and T_2, and one relay node R in the first time slot, also denoted as the multiple access phase (MA), T_1 and T_2 transmit their messages to R. The signal received at the relay can be expressed as:

$$Y_R = h_1\sqrt{P_{T1}}\ X_1 + h_2\sqrt{P_{T2}}\,X_2 + Z_R, \quad (3.5)$$

where, X_i $k \in \{1,2\}$ is the unit power transmitted symbol of the terminal node T_k, P_{Tk} is the average transmission power, and Z_R is the independent complex Gaussian noise with zero mean and variance σ^2.

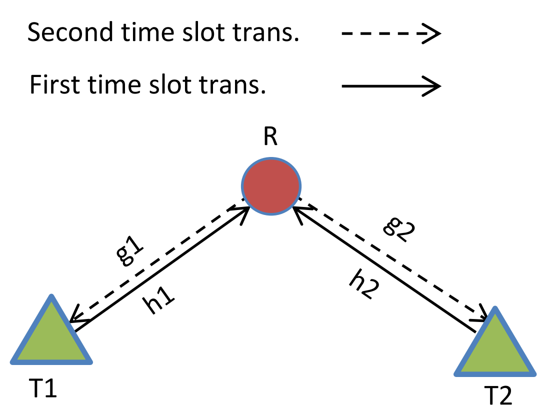

Figure 3.4 Two-way relay network.

Again, if the AF scheme is deployed, the signal received at T1 and T2 are:

$$Y_1 = Ag_1\sqrt{P_R}Y_R + Z_1, \quad (3.6)$$

$$Y_2 = Ag_2\sqrt{P_R}Y_R + Z_2, \qquad (3.7)$$

where, P_R denote the average transmission power of the relay node R and Z_k is the independent complex Gaussian noise with zero mean and variance σ^2 $k \in \{1, 2\}$.
A is the amplification factor expressed as

$$A = \frac{1}{\sqrt{P_1 h_1 + P_2 h_2 + \sigma^2}} \qquad (3.8)$$

After receiving the signals, each transceiver node is then extracts the desired signal by canceling the self-interference.

Now, if the DF scheme is applied, the received signal at each node edge is given by:

$$Y_1 = h_1\sqrt{P_R}X_R + Z_1, \qquad (3.9)$$

$$Y_2 = h_2\sqrt{P_R}X_R + Z_2, \qquad (3.10)$$

where X_R denotes the unit-power transmitted symbol. No amplification factor is used and the only noise faced is the independent complex Gaussian noise Z_k, $k \in \{1,2\}$.

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CHAPTER FOUR

RESOURCE ALLOCATION IN OFDM-BASED COGNITIVE TWO-WAY MULTIPLE-RELAY NETWORKS

4.1 Introduction

This chapter presents the main contribution of this thesis where a joint resource allocation problem in AF OFDM based two-way multiple-relay CR network is considered. Two transceiver nodes exchange information via relay nodes due to large distance, existence of obstacles or worse channel conditions, between the two transceiver nodes. The full transmission occurs in two phases MA and BC phases. Considering individual power and interference constraints, the power allocation, subcarrier pairing and relay assignment are jointly optimized to maximize the sum-rate.

In this study, the dual decomposition technique is applied to obtain the optimal resource allocation. Additionally, suboptimal algorithms are introduced to perform the allocation with much less complexity, compared to the optimal solution, and small performance degradation. Simulation results and discussion are shown at the end of this chapter to demonstrate the performance gain of the proposed algorithms.

4.2 Constrained Optimization

4.2.1 Duality Theory

In the communication systems, the duality theory concept is frequently used. The main benefit of the dual algorithm is that it can be used to bound a non-convex problems or decompose the main problem into a number of subproblems. Consider the following primal problem:

$$\max_x f(x)$$
$$\text{subject to} \tag{4.1}$$
$$g(x) \le A$$

The functions f and g are not necessarily convex or concave functions, A is a constant and x is the variable to be optimized and p^* is the optimal value.

The first step in the dual problem construction is finding the Lagrangian function of a dual variable λ:

$$L(x,\lambda) = f(x) - \lambda(g(x) - A) \tag{4.2}$$

Then, the maximum value of the Lagrangian function is called the Lagrange dual function which can be expressed as:

$$D(x,\lambda) = max_x \;\; L(x,\lambda) \tag{4.3}$$

The Lagrange dual function gives an upper bound on the optimal value p^* of the problem (4.1) for every $\lambda \ge 0$. Therefore, to find the lowest upper bound, the dual problem is formed by minimizing the Lagrangian dual function as follows [4]:

$$D^o = \min_\lambda D(x,\lambda)$$
$$s.t \qquad \lambda > 0 \tag{4.4}$$

Thus, the inequality $D^o \ge p^*$ is always holds even if the original problem is not convex.

The *duality gap* is defined as the difference $D^o - p^* \ge 0$ which defines the gap between the optimal solution of the primal problem and the lowest upper bound on it that can be obtained from the Lagrange dual function. The duality is called *weak duality* when the original primal problem is not convex. The *strong duality* takes place if $D^o = p^*$, i.e. the optimal duality gap is zero. If the primal problem is convex, the strong duality usually holds.

For problem (4.1), when $f(x)$ is concave and $g(x)$ is convex, and there exists a strictly feasible point in the constraints set, the primal and dual problems have the same solution [5]. When the primal problem is not convex, the zero duality gap cannot be guaranteed but if a non-convex problem satisfies the time sharing condition, the strong duality holds.

4.2.2 Time Sharing Condition

Theorem 1 in [3] indicates that if an optimization problem satisfies the time-sharing condition, then it has a zero duality gap, i.e., the primal problem and the dual problem have the same optimal value.

The time sharing condition can be summarized as follows [3]: Assume that x^* and y^* are the optimal solutions of the optimization problem (4.1) with $A = A_x$ and $A = A_y$ respectively. The optimization problem (4.1) satisfies the time sharing condition if for any $A = A_x$, $A = A_y$ and for any $0 \leq b \leq 1$, there is always exists a feasible solution c, such that $g\ (c) \leq bA_x + (1 - b)\ A_y$ and $f\ (c) \geq bf\ (x) + (1 - b)\ f\ (y)$.

For many practical optimization multicarrier problems, the time-sharing condition is satisfied. Our problem, in this study, is satisfying the time sharing condition for, sufficiently, large number of subcarriers regardless of the problem convexity implies that the duality gap approaches zero. The dual problem can be solved instead of the primal one when it is easier to be solved or when a closed form solution cannot be found. Thus, in section 4.4 the dual method is used to solve the primal problem by discussing its dual problem rather than itself.

4.2.3 Subgradient Method

The subgradient method is a very simple algorithm for minimizing a non-differentiable convex function. The subgradient method can be used to solve inequality constrained optimization problems e.g.

$$\min f^o(x)$$
$$s.t \tag{4.5}$$
$$g_i(x) \le 0, \;\; i = 1, \dots\dots, m$$

where g_i are convex.

The subgradient of any function f at the point x is any vector v that satisfies the inequality [8]:

$$f\,(y) \ge \; f\,(x) + \; v^T\,(y \; - \; x)\,, \forall y \tag{4.6}$$

When f is differentiable, v is the gradient of f at x, i.e. $\nabla f\,(x)$

In order to solve (4.5) the subgradient performs the following update, at each iteration, on the maximization variable x

$$x^{k+1} = x^k + \alpha_k v(x^k), \tag{4.7}$$

where k denotes the number of iterations, α_k is the k^{th} step size, and v is a subgradient of the objective or one of the constraint functions at x^k and is given by [8]:

$$v(x^k) = \begin{cases} \partial f^o(x^k) & g_i(x^k) \le 0, \quad i = 1, \dots\dots, m \\ \partial f_u(x^k) & \text{for some } u's \text{ such that } f_u(x^k) > 0 \end{cases} \tag{4.8}$$

where $\partial f(x)$ denotes the set of subgradients of f at x. From (4.5), if it is found that the current point is a feasible solution, the objective subgradient is used. On the other hand, if it is infeasible the subgradient of any violated constraint is chosen.

Moreover, the step size, which has to be set before the algorithm starts, has many different types like constant step size with $\alpha_k \; = \; \alpha, \forall k$, and diminishing step size rule e.g. example of the diminishing step size rule is $\alpha_k = \frac{a}{\sqrt{k}}$, where $a \; > \; 0$.

4.3 OFDM-Based CR Two-way Relay System Model and Problem Formulation

4.3.1 System Model

In this section, an OFDM-based two-way multi-relay CR network will be investigated. As shown in Figure 4.1 a CR relay system coexists with the primary system in the same geographical area. Due to the bad channel conditions, large distance or the existence of obstacle, there is no direct link between the two transceiver nodes T_1 and T_2 so they try to exchange their information through M relay nodes. The network frequency spectrum is divided into N orthogonal subcarriers each having a Δf bandwidth. Perfect channel state information (CSI) of all links is available and the subcarriers and power can be feasibly allocated by a centralized scheduler or by one of the transceiver nodes. Moreover, all sub-channels are assumed to experience independent, frequency-selective fading.

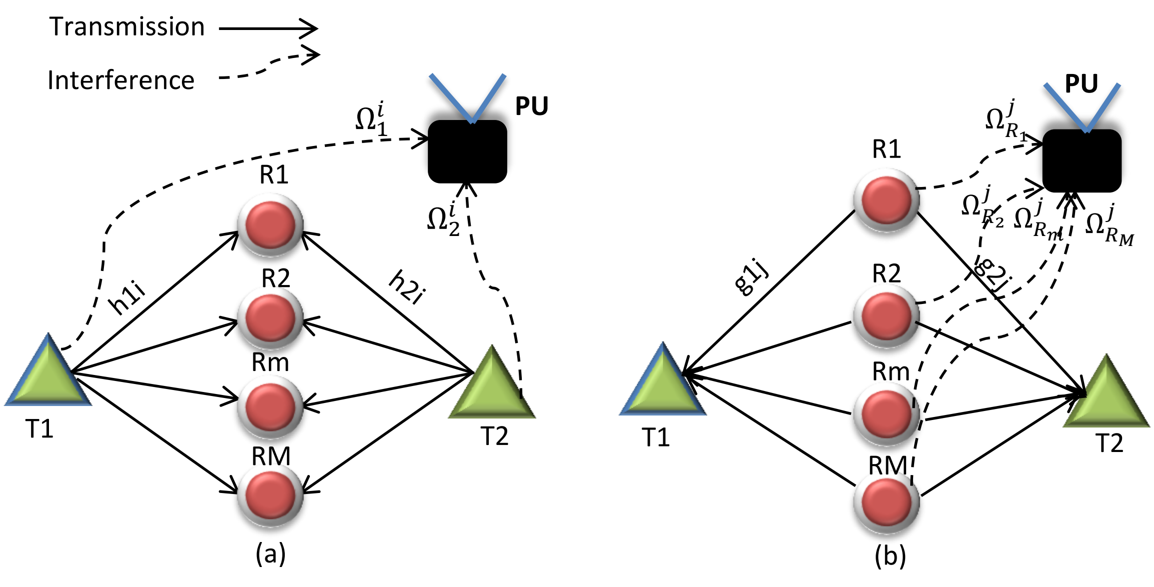

Figure 4.1 two-way relaying OFDM based CR network System model
a) Multiple-access phase (MA) b) Broadcast phase (BC)

The CR system can use the temporarily unused primary system bands guaranteeing that the total interference introduced to the PUs does not exceed the maximum interference threshold described by the primary system I_{th}.

The relay is assumed to be half-duplex, thus receiving and transmitting in two different time slots. To complete a full exchange of information, two phases are considered, the MA phase and the BC phase. In the MA phase, T_1 and T_2 transmit their data, simultaneously, to the selected m^{th} relay using the same subcarrier. In the BC phase, the selected relay amplifies the received signals, and broadcasts them to the two transceiver nodes. Once received, T_1 and T_2 can extract the required information by canceling self-interference.

The relay node, R_m, receives the combined signal on subcarrier i in the MA phase and then amplify and broadcast it on another subcarrier j in the BC phase so subcarrier-pairing scheme between the two phases is deployed where subcarrier i in the first time slot and its corresponding subcarrier j in the second time slot will form a subcarrier pair $\langle i, j \rangle$. Let $h_{1\,i}^{m}$ and h_{2i}^{m} denote the channel coefficients over the i^{th} subcarrier from T_1 and T_2 to the relay node R_m, respectively. Similarly g_{1j}^{m} and g_{2j}^{m} denote the channel coefficients over the j^{th} subcarrier from the selected relay node to T_1 and T_2, respectively. Moreover, Ω_k^i and $\Omega_{R_m}^j, k = \{1,2\}$ are channel complex coefficients between the transceiver nodes T_k relay node R_m and the PU, respectively. In order to avoid the interference among the relays, each subcarrier pair is only allowed to be allocated to one relay node, but not vice versa. Accordingly, more than one pair of subcarriers may be assigned to a relay node.

In the MA phase, the received signal at the m^{th} relay over subcarrier i $Y_{m,i}$ can be expressed as:

$$Y_{mi} = h_{1i}^{m}\sqrt{p_{1i}^{m}}\ X_{1i} + h_{2i}^{m}\sqrt{p_{2i}^{m}}\,X_{2i} + Z_{mi}, \tag{4.9}$$

where X_{ki}, $k \in \{1,2\}$, is the unit power transmitted symbol of the terminal node T_k over subcarrier i, p_{ki}^{m} is the average transmission power, and Z_{mi} is the independent complex Gaussian noise with zero mean and variance σ_{mi}^2.

The received signal by the m^{th} relay is then multiplied by amplification factor D expressed as [1]:

$$D = \frac{1}{\sqrt{p_{1i}^{m} h_{1i}^{m^2} + p_{2i}^{m} h_{2i}^{m^2} + \sigma^2}} \tag{4.10}$$

The signal is then broadcasted to the transceivers. Once received the signals, the transceiver nodes extract the desired signals by cancelling self-interference.

The received signals at the terminal nodes T_1 and T_2 over subcarrier j in the BC phase are given by

$$Y_{1j} = D g_{1j}^{m} \sqrt{p_{Rj}^{m}}\, Y_{mi} + Z_{1j} \tag{4.11}$$

$$Y_{2j} = D g_{2j}^{m} \sqrt{p_{Rj}^{m}}\, Y_{mi} + Z_{2j} \tag{4.12}$$

Where p_{Rj}^{m} denote the average transmission power of the relay node R_m over subcarrier j. Moreover, Z_{kj} is the independent complex Gaussian noise with zero mean and variance σ_{kj}^2 at T_k, $k \in \{1, 2\}$ on each subcarrier includes the noise caused by the PUs transmission. Based on the central limit theorem, the PUs noise could be considered as Gaussian noise. Without loss of generality, the noise variance is assumed to be constant for all subcarriers, i.e. $\sigma_{mi}^2 = \sigma_{kj}^2 = \sigma^2$.

The received end-to-end signal to noise ratio (SNR) at T_1 and T_2 through R_m over the subcarrier pair $\langle i, j \rangle$ can be given by the following equations [2]

$$SNR_1 = \frac{p_{2i}^{m} p_{Rj}^{m} f_2 f_3}{\sigma^2 \left(p_{Rj}^{m} f_3 + p_{1i}^{m} f_1 + p_{2j}^{m} f_2 + \sigma^2 \right)} \tag{4.13}$$

$$SNR_2 = \frac{p_{1i}^{m} p_{Rj}^{m} f_1 f_4}{\sigma^2 \left(p_{Rj}^{m} f_4 + p_{1i}^{m} f_1 + p_{2j}^{m} f_2 + \sigma^2 \right)} \tag{4.14}$$

respectively. Where $f_1 = |h_{1i}|^2$, $f_2 = |h_{2i}|^2$, $f_3 = |g_{1j}|^2$ and $f_4 = |g_{2j}|^2$.

The total end-to-end AF data rate on a given subcarrier pair $\langle i, j \rangle$ that is allocated to the m^{th} relay, $R_{AF}^{m,i,j}$, is expressed as [9]

$$R_{AF}^{m,i,j} = \frac{1}{2}\, log_2(1 + SNR_1) + \frac{1}{2} log_2(1 + SNR_2) \tag{4.15}$$

The pre-log factor of (½) in equation (4.15) above, is due to the fact that two times slots are required for the complete transmission process.

4.3.2 Problem Formulation

Let $\boldsymbol{p} \triangleq \left(p_{1i}^{m}, p_{2i}^{m}, p_{Rj}^{m}\right)$ represents the average transmission power of nodes T_1, T_2 and the selected relay R_m, respectively. All channel gains for the network can be adopted by assuming classical channel estimation approach and all the noise variances assumed to be equal σ^2. Denote $\psi_{m,i,j} \in \{0,1\}$ as the relay selection indicator with $\psi_{m,i,j} = 1$ represents that the subcarrier pair $\langle i, j \rangle$ is allocated to the relay R_m otherwise $\psi_{m,i,j} = 0$. Moreover, denote $\theta_{i,j} \in \{0,1\}$ as the subcarrier-pairing indicator, that is, if subcarrier i in the first time slot is paired with subcarrier j in the second time slot, then $\theta_{i,j} = 1$ otherwise $\theta_{i,j} = 0$.

Our objective is to jointly optimize the power, relay assignment and subcarrier pairing to maximize the throughput of the multi-relay two-way OFDM CR system, previously described, such that the instantaneous interference introduced to the primary system is below the maximum tolerable threshold, I_{th}. The primal optimization problem of our system is expressed as:

$$\max_{\theta_{i,j}, \psi_{m,i,j}, \boldsymbol{p} > 0} \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{m=1}^{M} \theta_{i,j} \psi_{m,i,j} R_{AF}^{m,i,j}$$

$$S.t$$

- (C1:Subcarrier pairing constraint):

$$\sum_{i=1}^{N} \theta_{i,j} = 1, \qquad \forall\, j; \quad \text{and} \quad \sum_{j=1}^{N} \theta_{i,j} = 1, \qquad \forall\, i$$

- (C2:Relay assignment constraint):

$$\sum_{m=1}^{M} \psi_{m,i,j} = 1 , \qquad \forall\, i,j$$

- (C3:Transceivers T_1 and T_2 power constraint):

$$\sum_{i=1}^{N}\sum_{m=1}^{M} p_{ki}^{m} \le P_k , \qquad k = \{1,2\}$$

- (C4:Relays individual power constraints):

$$\sum_{j=1}^{N} p_{Rj}^{m} \le P_R \quad , \quad \forall m$$

- (C5:Interference constraint at the first time slot (MA)):

$$\sum_{i=1}^{N}\sum_{m=1}^{M} (\Omega_1^i p_{ki}^m + \Omega_2^i p_{2i}^m) \le I_{th} \;, \quad k = \{1,2\}$$

- (C6: Interference constraint at the second time slot (BC)):

$$\sum_{m=1}^{M}\sum_{j=1}^{N} \Omega_{R_m}^{j}\, p_{Rj}^{m} \le I_{th}$$

$\boldsymbol{\theta} = \{\theta_{i,j}\}_{N\times N}$, $\boldsymbol{\psi} = \{\psi_{m,i,j}\}_{M\times N\times N}$ and $\boldsymbol{p} = \{p_{1i}^m , p_{2i}^m , p_{Rj}^m\}$ are the total variables to be optimized. (C1) expresses the subcarrier pairing constraint implies that each subcarrier in the MA phase paired with one, and only one, subcarrier in the BC phase. (C2) represents the relay selection constraint which indicates that each subcarrier pair can be assigned to one relay only. (C3) and (C4) express the individual power constraints in the transceivers and different relays, respectively. I_{th} is the maximum tolerable interference to the PUs expressed by constraints (C5) and (C6).

4.4 Optimal Resource Allocation Based On Dual Method

4.4.1 Optimal Resource Allocation

The dual problem of the primal problem, which satisfies the time sharing condition for large number of subcarriers N, is expressed as

$$\min_{\lambda \geq 0} D(\boldsymbol{\lambda}) \tag{4.16}$$

with $\boldsymbol{\lambda} = [\lambda_{T_1}, \lambda_{T_2}, \lambda_{R_1}, \dots\dots, \lambda_{R_M}, \lambda_{I_1}, \lambda_{I_2}]$ is the dual variables vector, where $(\lambda_{T_1}, \lambda_{T_2})$ and $(\lambda_{R_1}, \dots\dots, \lambda_{R_M})$ are non-negative dual variables associated with individual power constraints (C3) and (C4). Moreover, the dual variables $(\lambda_{I_1}, \lambda_{I_2})$ are associated with the tolerated interference to the PU constraints (C5) and (C6).

The dual function $D(\boldsymbol{\lambda})$ is defined as

$$D(\boldsymbol{\lambda}) = \max_{\theta_{i,j}, \psi_{m,i,j}, \boldsymbol{p} > 0} \mathbf{L} \tag{4.17}$$

where L is the Lagrangian function of the primal problem, given by (4.18).

In order to solve the dual problem (4.16), a two phase solution is presented. First we need to solve the Lagrangian in (4.18) to optimize the resources variables $\{\theta, \psi, \boldsymbol{p}\}$ for a given feasible dual variables vector $\boldsymbol{\lambda}$, then a subgradient method is applied to optimize $\boldsymbol{\lambda}$ where each of the resource variables is refined at every iteration.

$$\begin{aligned} \mathrm{L} = & -\sum_{m=1}^{M}\sum_{i=1}^{N}\sum_{j=1}^{N}\theta_{i,j}\psi_{m,i,j}R_{AF}^{m,i,j} + \sum_{k=1}^{2}\lambda_{T_k}\left(P_k - \sum_{i=1}^{N}\sum_{m=1}^{M}p_{ki}^{m}\right) \\ & + \sum_{m=1}^{M}\lambda_{R_m}\left(P_R - \sum_{j=1}^{N}p_{Rj}^{m}\right) + \lambda_{I_1}\left(I_{th} - \sum_{i=1}^{N}\sum_{m=1}^{M}\Omega_1^i p_{ki}^{m} + \Omega_2^i p_{2i}^{m})\right) \\ & + \lambda_{I_2}\left(\left(I_{th} - \sum_{m=1}^{M}\sum_{j=1}^{N}\Omega_{R_m}^{j}p_{Rj}^{m}\right)\right) \end{aligned} \tag{4.18}$$

1- Optimizing the transmit power $\boldsymbol{p}^*$:

Starting by assuming initial feasible values of the dual variables assuming that $\langle i, j \rangle$ is an available subcarrier pair that is already matched and assigned to a relay node R_m so that $\theta_{i,j}\psi_{m,i,j} = 1$.

Then, the dual function in (4.17) can be rewritten as follows

$$D(\lambda) = \max_{\psi_{m,i,j},\theta_{i,j},\boldsymbol{p}>0}\left(-\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{m=1}^{M}\theta_{i,j}\psi_{m,i,j}W_{m,i,j} + \sum_{k=1}^{2}\lambda_{T_k}P_k + \sum_{m=1}^{M}\lambda_{R_m}P_R + I_{th}(\lambda_{I_1}+\lambda_{I_2})\right) \tag{4.19}$$

where

$$W_{m,i,j} \triangleq R_{AF}^{m,i,j} - \sum_{k=1}^{2}\lambda_{T_k}p_{ki}^{m} - \lambda_{R_m}p_{Rj}^{m} - \lambda_{I_1}(\Omega_1^i p_{1i}^m + \Omega_2^i p_{2i}^m) - \lambda_{I_2}\Omega_{R_m}^j p_{Rj}^m \tag{4.20}$$

Therefore, the optimal power allocation can be determined by solving the following sub-problem (4.21) for every (m,i,j).

$$\begin{aligned} &\max_{p_{1i}^m,p_{2i}^m,p_{Rj}^m} W_{m,i,j} \\ &s.t \\ &p_{1i}^m, p_{2i}^m, p_{Rj}^m \geq 0 \end{aligned} \tag{4.21}$$

The power allocation problem in (4.21) is neither convex nor concave, so that finding a closed form solution is not trivial. Furthermore, the multicast users which share the same resources are subject to different radio link conditions. For this reason, there are several possibilities for performing the power allocation, e.g., according to the best or worst user within each subchannel, or taking into consideration the requirements of each individual user [6]. Based on that, the optimal power allocation can be obtained via exhaustive search over the power of T_1, T_2 and R_m taking into consideration that each takes discrete values over a number of power levels L and that the interference constraint does not violated.

2- Optimal Relay Selection ψ^*

The optimal relay selection ensures that the transceiver nodes T_1 and T_2 choose the best relay node that have the preferable channel conditions. Substituting the optimal power values $\boldsymbol{p}^* = \{p_{1i}^m, p_{2i}^m, p_{Rj}^m\}$, calculated in step1, in equation (4.20). The optimal relay selection can be obtained solving the following maximization sub-problem

$$\max_{\psi_{m,i,j}} \; W_{m,i,j}$$
$$s.t \tag{4.22}$$
$$\sum_{m=1}^{M} \psi_{m,i,j} = 1\,, \qquad \forall\, i,j$$

Based on the maximization problem (4.22) we determine the optimal relay selection $\boldsymbol{\psi}^*$ at every possible subcarrier pair $\langle i,j \rangle$, so that $\theta_{i,j} = 1$. The optimal relay should be selected for $\langle i,j \rangle$ pair that maximizes $W_{m,i,j}$ therefore; the optimal relay selection can be expressed as

$$\psi_{m,i,j}^* = \begin{cases} 1, & m = m(i,j) = \underset{m}{argmax}\, W_{m,i,j}, \;\; \forall \langle i,j \rangle \\ 0, & \text{othewise} \end{cases} \tag{4.23}$$

3- Optimal subcarrier pairing θ^*

The optimal subcarrier pairing is considered as a linear assignment problem which can be solved, efficiently, by the Hungarian algorithm, summarized in Table 4.1, with a complexity of $O(N^3)$ [12]. Substituting each of $\boldsymbol{p}^*$ and $\psi_{m,i,j}^*$ into (4.20), we obtain:

$$\max_{\theta_{i,j}} W_{i,j}$$
$$s.t \tag{4.24}$$
$$\sum_{i=1}^{N} \theta_{i,j} = 1, \qquad \forall\, j; \;\; \text{and} \;\; \sum_{j=1}^{N} \theta_{i,j} = 1, \qquad \forall\, i$$

where

$$W_{i,j} = \underset{m}{argmax}\, W_{m,i,j} \qquad , \quad \forall \langle i,j \rangle \qquad (4.25)$$

Let W be a matrix such that:

$$W = \begin{bmatrix} W_{1,1} & W_{1,2} & \dots & W_{1,N} \\ W_{2,1} & W_{2,2} & \dots & W_{2,N} \\ \vdots & \vdots & \vdots & \vdots \\ W_{N,1} & W_{N,2} & \dots & W_{N,N} \end{bmatrix} \qquad (4.26)$$

where W is a $N \times N$ profit matrix. The objective in (4.24) can be maximized by picking elements from the matrix W such that the sum of profits is as large as possible.

Table 4.1 Hungarian Algorithm

Hungarian Algorithm
1. Subtract the elements in each row from the maximum number in the row, and subtract the minimum number in each column from the whole column.
2. Cover all zero-elements in W as few lines as possible;
3. If the number of lines equal to the size of W, the optimal solution is found. Otherwise, find the minimum number that is uncovered. Subtract this minimum number from all uncovered elements and add it into values at the intersections of lines, then go to Step 2.

The optimal subcarrier pairing can be expressed as

$$\theta^*_{i,j} = \begin{cases} 1, & j = j(i), \quad \forall i \\ 0, & \text{otherwise} \end{cases} \qquad (4.27)$$

The next stage is to optimize the dual variables $\boldsymbol{\lambda}$ taking the advantage of the three steps described above. As we have seen in subsection 4.2.1, the dual function is always convex so that iterative method, such as subgradient method can be used to minimize (4.16) with guaranteed convergence.

4.4.2 Subgradient Method to Calculate the Optimal $\boldsymbol{\lambda}^*$

Through the steps described in subsection 4.4.1, the optimal resource allocation $\{\boldsymbol{p}^*, \psi^*, \theta^*\}$ have been obtained, for a given initial values of the dual variable vector $\boldsymbol{\lambda}$. Substituting each of $\{\boldsymbol{p}^*, \psi^*, \theta^*\}$ into (4.17), we obtain the dual function then solving the optimization problem of the dual problem in (4.16), the optimal dual vector $\boldsymbol{\lambda}^*$ can be found by the subgradient method. The sub-gradient method can be used to solve the dual problem with guaranteed convergence, [8], since a dual function is always convex. Based on initially selected dual variables vector, $\boldsymbol{\lambda}^{\mathbf{0}} = [\lambda_{T1}^0, \lambda_{T2}^0, \lambda_{R1}^0, \ldots\ldots, \lambda_{Rm}^0, \lambda_C^0, \lambda_{RC}^0]$, $\boldsymbol{\lambda}$ can be updated at the $(t+1)^{th}$ iteration by as shown in the equations (4.28)-(4.31) below

$$\lambda_{T_k}^{(t+1)} = \lambda_{T_k}^{(t)} - \delta^{(t)}\left(P_k - \sum_{i=1}^{N}\sum_{m=1}^{M} p_{ki}^{m^*}\right); \quad \forall k \in \{1,2\} \tag{4.28}$$

$$\lambda_{R_m}^{(t+1)} = \lambda_{R_m}^{(t)} - \delta^{(t)}\left(P_R - \sum_{j=1}^{N} p_{Rj}^{m^*}\right); \ \forall m \tag{4.29}$$

$$\lambda_{I_1}^{(t+1)} = \lambda_{I_1}^{(t)} - \delta^{(t)}\left(I_{th} - \left(\sum_{i=1}^{N}\sum_{m=1}^{M}(\Omega_1^i p_{1i}^{m^*} + \Omega_1^i p_{2i}^{m^*})\right)\right) \tag{4.30}$$

$$\lambda_{I_2}^{(t+1)} = \lambda_{I_2}^{(t)} - \delta^{(t)}\left(I_{th} - \sum_{j=1}^{N}\sum_{m=1}^{M}\Omega_{R_m}^j p_{Rj}^{m^*}\right) \tag{4.31}$$

Where δ^t, step size of the t^{th} iteration which can be updated according to the non-summable diminishing step size policy [8].

The iterations are repeated until convergence. As a result, the optimal solution of the primal problem is achieved. It should be noted that all the resources $\{\boldsymbol{p}^*, \psi^*, \theta^*\}$ have to be recalculated for every single iteration, under $\lambda^{(t)}$, in terms of the steps described in subsection 4.4.1.

4.5 Suboptimal Algorithms

In fact, the significant weight of complexity in the optimal solution is, essentially, in the power allocation and in the Hungarian algorithm. As a result, three suboptimal algorithms are proposed based on this knowledge. In the three algorithms, the power of the relays and transceivers is fixed to be uniformly distributed over subcarriers, rather than the optimal allocation obtained in the previous section. Moreover, it is assumed that the interference introduced to the PU by every subcarrier is uniform. Therefore, the single subcarrier maximum allowable power should be the minimum between the interference threshold and the node power upper bound divided by the total number of subcarriers, i.e.

$$p_{ki}^{m*} = min\left(\frac{P_K}{N}, \frac{I_{th}}{\Omega_k^i N}\right), \qquad k = \{1,2\} \tag{4.32}$$

Similarly,

$$p_{Rj}^{m*} = min\left(\frac{P_R}{N}, \frac{I_{th}}{\Omega_{Rm}^j N}\right) \tag{4.33}$$

In the first suggested suboptimal, a greedy suboptimal algorithm is proposed in which the subcarriers are matched by ordering the subcarriers in the first and second time slots according to maximum achieved rate R_{AF}. The subcarrier pairing, in the next suggested algorithm is obtained using the Hungarian method. Finally, in the third suboptimal algorithm the pairing is done using the same subcarrier in, both, the first and second time slots.

4.5.1 Proposed Suboptimal Greedy Algorithm (Proposed Suboptimal)

The subcarrier matching in this algorithm is performed in an efficient way depending on the value of the rate $R_{AF}^{m,i,j}$ in (4.15). Once the power levels are determined, equations (4.32) and (4.33), the algorithm searches for the best second time slot subcarrier, j, and relay m that maximizes the product of SNR_1 and SNR_2 in the rate equation (4.15). By defining $\mathcal{A}$ and $\mathcal{B}$ sets that include all the non-assigned subcarriers in the MA and BC phases, respectively. This is an efficient greedy suboptimal algorithm that equivalent, in complexity, to a sort type algorithm. The proposed suboptimal algorithm is summarized in table 4.2.

Table 4.2 Proposed Suboptimal Algorithm

Greedy algorithm (Proposed Suboptimal)
1- Perform the power allocation of the transceivers T_1 and T_2 using distribution $p_{ki}^{m^*} = min\left(\frac{P_K}{N}, \frac{I_{th}}{\Omega_k^i N}\right)$, $k = \{1,2\}$.
2- For every subcarrier j and relay m, evaluate the relays power via $p_{Rj}^{m^*} = min\left(\frac{P_R}{N}, \frac{I_{th}}{\Omega_{Rm}^j N}\right)$.
3- For every subcarrier $j \in \mathcal{B}$ and relay m, evaluate the product of the SNRs, $Q = SNR_1 * SNR_2$ where both of SNR_1 and SNR_2 are given by (4.13) and (4.14), respectively.
4- Determine $j^* \in \mathcal{B}$ and m^* satisfying $(j^*, m^*) = argmax_{j,m} Q$.
5- Remove j^* from the set $\mathcal{B}$ and repeat the previous procedures until the set $\mathcal{A}$ is empty.

4.5.2 Hungarian Pairing Suboptimal Algorithm (Suboptimal + Hungarian)

In this algorithm, the optimal relay selection and subcarrier paring are obtained in the same methods described in the previous section while the nodes power is uniformly distributed over the subcarriers. Now, each of the calculated $p_{ki}^{m^*}$ and $p_{Rj}^{m^*}$ is substituted in the rate equation (4.15) then we proceed to steps 2 and 3 in subsection 4.4.1 to determine $\psi_{m,i,j}$ and evaluate the optimal subcarrier pairing matrix $\theta_{i,j}$ using the Hungarian algorithm. Compared with the optimal algorithm, the main benefit of this suboptimal is that there is no need of the optimal power allocation calculations and consequently, no need to calculate or update the dual variables while its drawback is the high complexity of the Hungarian method especially for high number of subcarriers.

4.5.3 Fixed Pairing Suboptimal (Suboptimal + Fixed)

The subcarrier matching, in this algorithm, is prefixed instead of obtaining the optimal subcarrier pairing. Without loss of generality, the subcarrier pairing is denoted by

$$j(i) = i, \quad \forall i, \tag{4.34}$$

This indicates that the signals from transceivers T_1 and T_2 transmitted over one subcarrier in the MA phase is retransmitted over the same subcarrier in the BC phase. Once the pairing is done, we proceed to the relay assignment as detailed in subsection 4.4.1. This algorithm is of very much low complexity than the optimal but on expense of performance, where it is poor compared to the other algorithms.

4.6 Complexity Computations

The optimal solution for the nonlinear primal problem is sometimes difficult to be obtained due to its high computational complexity, especially, when the number of N is significantly large. In each iteration, $(M+4)$ dual variables have to be updated. Therefore, in order to solve the problem efficiently low complexity suboptimal algorithms are proposed to find a suboptimal solution of the primal problem, which will be compared to the optimal one at the last section of this chapter through a simulation process.

The primal problem is decomposed into $N(NM+1)$ sub-problems where each sub-problem requires $O(NL^{N-1})$ complexity to obtain its corresponding power allocation. Afterwards, the relay assignment is determined by performing M functions evaluations for $N!$ Subcarrier matching possibilities. Finally, the Hungarian algorithm is performed with a complexity $O(N^3)$. Accordingly, the optimal solution has a complexity of $O(T(N^3(ML^{N-1}+1)+N^2L^{L-1}+MN!))$ where T is the number of iterations required to converge which is usually high.

In the proposed scheme, suboptimal algorithm 3, every subcarrier in the MA requires no more than $2(NM + 1)$ function evaluations to be paired and assigned to the best relay. Therefore, the complexity of the proposed algorithm is $O(2N^2M + 2N^2)$.

The computational complexity comparison between the optimal and suboptimal algorithms is summarized in table 4.3.

Table 4.3 Computational complexity comparison

Algorithm	Complexity
Optimal	$O(T(N^3(ML^{N-1} + 1) + N^2L^{L-1} + MN!))$
Proposed Suboptimal	$O(2N^2M + 2N^2)$
Suboptimal + Hungarian	$O(MN^2 + 2N + N^3)$
Suboptimal + Fixed	$O(MN^2)$

4.7 Simulation Results

In this section a simulations process is performed under the scenario given in Fig. 4.1 to reveal the performance of the introduced and proposed algorithms. An OFDM system of $N = 16$ subcarriers, which is sufficient to have a zero duality gap [3] and $M = 6$ relays are assumed. The noise variance is assumed to be $\sigma = 5 \times 10^{-6}$ and the channel gains are outcomes of independent Rayleigh distributed random variables with unity mean.

The simulation is held in two phases. First, we fix the value of the interference threshold level $I_{th} = -10\ dBm$ and calculate the rate of the optimal and suboptimal algorithms over node power constraint values of -10 to 15 dBm while in the second phase of simulation, we fix the power on a middle value, $-2.5\ dBm$ and sweep I_{th} over $-10\ to\ 2\ dBm$. The resulting figures of the two phases simulations are shown in Fig. 4.2 and Fig. 4.3, respectively.

Fig. 4.2 depicts the achieved capacity of the optimal and suboptimal schemes versus the transceivers and relays power constraints when the interference threshold is fixed to -10 dBm. It can be noted that the capacity of all schemes increases with the power constraint. This increase in the capacity continues until it becomes constant at a certain value of the power constraints regardless of the power constraint increase. This is because the induced interference results from transmitting with the available power reaches the prescribed threshold and the system cannot use more power. Additionally, the dual decomposition based solution has the highest performance with the best data rate that outperforms the other algorithms as it is an optimal solution and it works as an upper bound of the rest of the suboptimal schemes. The closest performance to the optimal solution is achieved by the *Suboptimal+ Hungarian* algorithm.

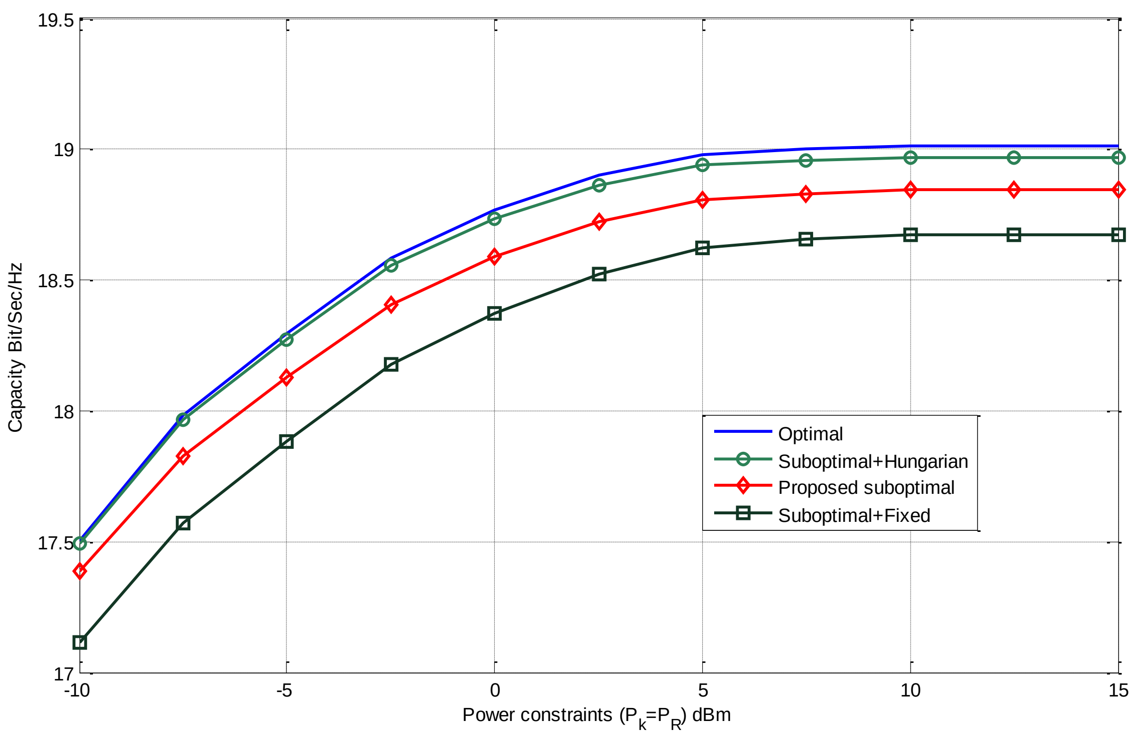

Figure 4.2 Achieved capacity vs power constraint

With a significant reduction in the computational complexity of the optimal scheme, the proposed efficient suboptimal algorithm achieves a good performance with much less complexity compared with the optimal and less than the *Suboptimal + Hungarian.* The complexity of the *Suboptimal + Hungarian* algorithm grows large as the number of subcarriers is significantly large which reveals the benefit of the proposed suboptimal for high number of subcarriers. The *Suboptimal + Fixed* algorithm has the lowest performance.

Fig. 4.3 shows the achieved capacity of the optimal and suboptimal schemes versus the interference constraint when the power constraints are fixed to 2.5 dBm. It can be noted that the capacity of all schemes are increased with the interference constraint. This can be justified by increasing the ability of the transceivers and different relays to transmit with higher power levels.

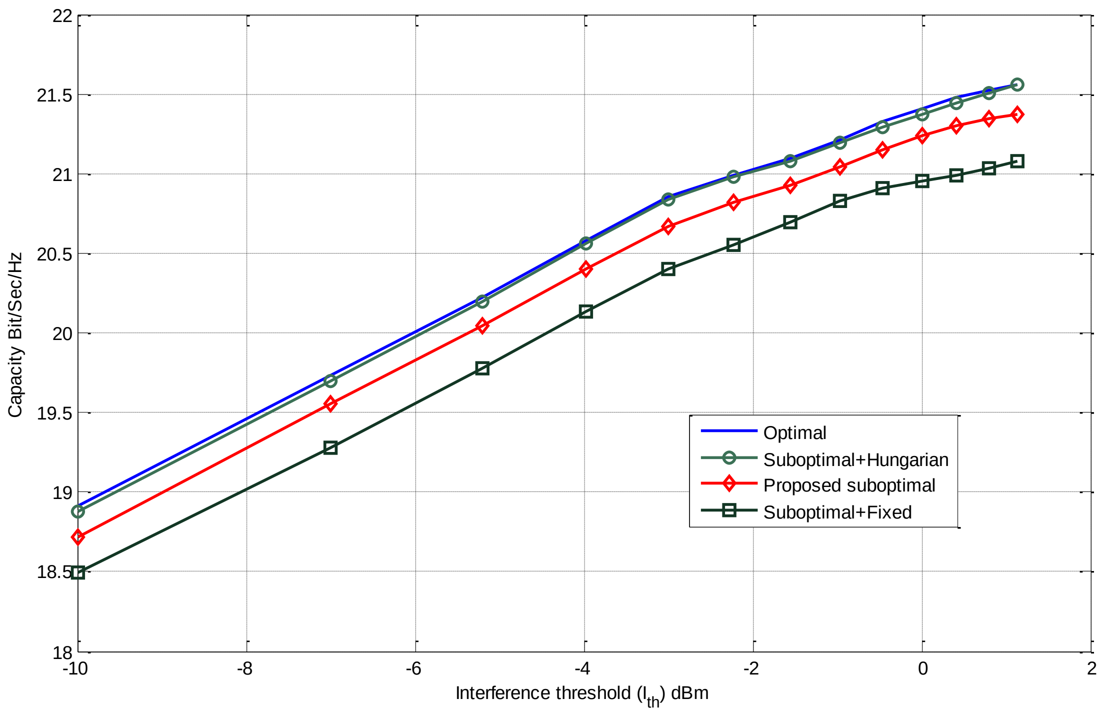

Figure 4.3 Achieved capacity vs interference threshold

Normally, this increase in the capacity with the increase of the interference constraint continues until the value of the interference becomes high with respect to the power constraints as the induced interference results from transmitting with the maximum power levels is below the prescribed threshold. The performance comparison between the different simulated algorithms follows the same behavior described for Fig. 4.2 where the complexity and performance has a tradeoff relationship.

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CHAPTER FIVE
CONCLUSION AND FUTURE WORK

5.1 Conclusion

Chapter 2

In this chapter, an overview of the CR technique was presented. A description of the cognitive networks characteristics was introduced; include the cognitive capability and reconfigurability. Moreover, the network architecture and cognitive cycle were also discussed, where the main cycle stages, spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility, are viewed in details. Finally, some of the current CR applications were exhibited.

Chapter 3

The OFDM technique features, advantages and drawbacks were showed in this chapter. Additionally, the important fields of OFDM applications were presented. Furthermore, we continued in the chapter by a brief entrance to the relaying networks showing its main transmission schemes, AF and DF. The common network types, one-way and two-way relaying networks where mathematically detailed. At the end of chapter 3, a recall of the main works in literature that is related to this dissertation approach was presented.

Chapter 4

In this chapter, the main contribution of this thesis was presented where a joint resource allocation problem in AF two-way multiple-relay OFDM CR system has been investigated where power allocation, subcarrier pairing and relay assignment were jointly optimized. The main optimization problem is formulated in order to maximize the total end-to-end throughput of the system subject to individual power and interference constraints. The dual decomposition approach is applied to solve the mixed integer programming problem and achieve an optimal solution. Due to the high computational complexity of the optimal scheme, calculated to be $O(T(N^3(ML^{N-1} + 1) + N^2L^{L-1} + MN!))$, suboptimal algorithms were proposed based on distributing the power uniformly over the total number of subcarriers, considering the interference constraints, to achieve acceptable performance with much less complexity than the optimal one. A greedy suboptimal algorithm was introduced where the subcarrier pairing was done by searching for the best second time slot subcarrier. The proposed greedy suboptimal was of complexity $O(2N^2M + 2N^2)$ which has much less than the optimal with efficient performance as demonstrated in the simulation results subsection.

5.2 Future Works

In this dissertation, a scenario that gathers CR, OFDM technique and two-way relaying has been considered. To the best of our knowledge, there is no significant work in such scenario. However, there are still many open issues to analyze. In the following, some important future research directions are listed

- The decode an forward (DF) scenario is considered as a possible and attractive future work extension where the rate expression has to be modified to suit this technique and the rest of the power allocation, relay assignment and subcarrier pairing can be optimized using similar approach.
- In this thesis, it is considered that the resource allocation is performed in a centralized way. The distributed allocation algorithms are of a considerable interest. According to the formulation of the problem. The distributed allocation algorithm might be derived from the centralized one [1]-[3]. The user, in this approach, reserves the channel by sending a flag packet to all other the users. Alternatively, game theoretic approaches can be used in the design of such algorithms [4–6].

- In fact, the assumption of perfect CSI and channel occupancy information knowledge is not realistic. There is always exists some uncertainty in this information due to the sensing errors or due to the unreliable feedback channel. As a result, the effect of this lack of perfect information should be taken into consideration and analyzed in order to determine the appropriate algorithms required. In [7], the imperfect CSI and sensing information is considered to find the optimal power allocation in OFDM based CR systems. The extensions of these results to consider the two way relay scheme are a good step forward. The CSI imperfection issues besides the way of exchanging the channels information between the PUs and the SUs are still open problems that need more search and investigation.
- In this study, the dual-hop DF scenario was considered. The multiple-hop network is a natural extension. More relaying protocols may have to be studied like the adaptive relaying. In the adaptive relying [8–10], the relay node decides the forwarding scheme based on the instantaneous channel quality and the decoding ability.

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Joint Resource Allocation in Multicarrier Based Cognitive Networks with Two-Way Relaying

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***Abstract*—In this paper, a joint resource allocation problem in amplify and forward (AF) OFDM based two-way multiple-relay cognitive radio network is considered, where two transceiver nodes exchange information via a relay node. The full transmission happens in two phases: Multiple Access (MA) phase and the Broadcast (BC) phase. Considering individual power and interference constraints, the power allocation, subcarrier pairing and relay selection are jointly optimized in order to maximize the sum-rate. The dual decomposition technique is applied to obtain the optimal solution. Additionally, an efficient suboptimal algorithm is proposed to reduce the computational complexity of the optimal solution with a small performance degradation. Finally, simulation results are shown to demonstrate the performance gain of the proposed algorithm.**

***Keywords*—Cognitive Radio, OFDM, Two-way relaying, resource allocation.**

I. Introduction

Cognitive radio (CR), nowadays, is considered as one of the most promising techniques which enables flexible usage of radio spectrum and improves the spectral efficiency by enabling unlicensed users to exploit the licensed spectrum in an opportunistic manner. In Cognitive radio (CR) networks, a secondary user (SU) coexists in the same geographical area with a primary user (PU) exploiting the spectrum holes in the licensed spectrum band. The SUs are allowed to communicate using these frequency slots as long as they do not cause harmful interference to the PUs. The CR principle can be applied in a relay network specially when there is no direct link between nodes that need to exchange information. Instead, intermediate nodes act as relays such that they guarantee better channel conditions and less transmission power, implies low level of interference caused to PUs than the direct transmission case.

Relay networks main contribution is the utilization of the spatial diversity gains inherited in multiuser systems without the need of multiple-antenna per node The relying schemes are divided, generally, into two main categories: one-way and two-way relay networks. In one-way relaying, the relay nodes receive a signal from a source node in the first time slot and retransmit it to a destination node in the second time slot, using the common cooperative schemes like decode and forward (DF) or amplify and forward (AF), which takes two time slots for one direction transmission. Consequently, in one-way relaying, four time slots are needed if two nodes want to establish full transmission since they cannot transmit at the same time. On the other hand, in the two-way relaying scheme the relay nodes receive signals from transceivers in the first time slot, also called multiple access phase (MA), and then in the second time slot -broadcast phase (BC)- they broadcast the received signals to the transceivers. This overcomes the one-way relay scheme and doubles the spectral efficiency since two time slots, only, are needed to full exchange of information between the two nodes. Employing the OFDM technique increases the spectral efficiency by transmitting information over multiple orthogonal narrowband subcarriers besides being very effective in mitigating inter-symbol interference (ISI) and combating frequency selective fading.

Resource allocation in relay communication networks has extensively discussed in literature. In [1], Shaat and Bader discussed the joint power and subcarrier allocation in OFDM based cognitive one-way relay network. Vu and Kong studied in [2] the optimal power allocation in non-cognitive two-way decode-and-forward OFDM relay network where three time slot transmission is considered. In [3] , a joint resource allocation was designed in AF OFDM based two-way non cognitive system where power allocation, subcarriers assignment and relay selection are jointly optimized. Jang et al. showed in [4] a two-step approach to power allocation for OFDM two-way AF network where a total power constraint scenario is proposed. In [5], Ubaidulla and Aissa proposed a joint relay selection and optimal power allocation among the SU nodes in a two-way relay CR network achieving maximum throughput under transmit power and PU interference constraints. Multiuser two-way AF relay methods for beamforming systems were discussed in [6] where multiple-input multiple outputs (MIMO) relay transceiver processing was proposed. Ho et al. in [7] considered an AF scheme for two-way relaying over OFDM, in which two nodes exchange information via a relay where they performed power allocation for the relay and transceiver nodes. The work in [2], [6], and in [7] discuss two-way relaying systems in non-cognitive environment which is not efficient in cognitive one due to the additional interference constraint. A two-way relay network in CR system was adopted in [8], where linear signal processing is done at the relay station to remove inter-pair interference for SUs and a power control algorithm is employed to maximize the sum rate of the secondary network while ensuring no harmful interference is introduced to PUs. The work in [5] and [8] is not valid for the multicarrier systems.

The main contribution of this paper is to jointly optimize the power, for transceivers and relay nodes, subcarrier pairing

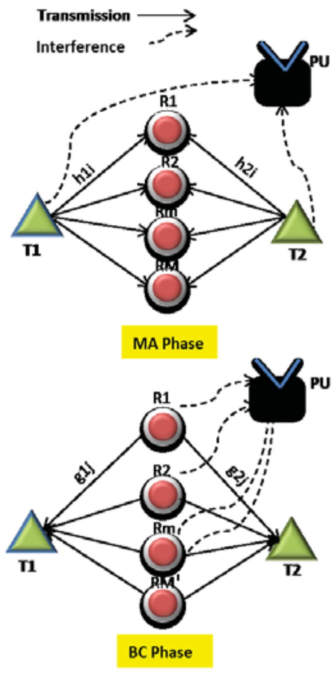

Fig. 1: System model of a two-way relaying OFDM cognitive radio network.

and the relay assignment that achieves the best capacity with minimal interference to PUs in OFDM-based cognitive two-way relay network. An optimal solution based on the dual method is proposed. An efficient suboptimal scheme is also presented to achieve a near optimal performance with a less computation complexity.

II. System Model and Problem Formulation

In this paper, an OFDM-based two-way relay CR network with multiple relays is investigated. As shown in Fig. 1, a CR relay system coexists with the primary system in the same geographical area. Due to the bad channel conditions, large distance and/or the existence of obstacles, there is no direct link between the two transceiver nodes T_1 and T_2. The transceivers try to exchange their information through M relay nodes. The network frequency spectrum is divided into N orthogonal subcarriers each having a Δf bandwidth. Perfect channel state information (CSI) of all links is available and the subcarriers and power can be feasibly allocated by a centralized scheduler or by one of the transceiver nodes. Moreover, all sub-channels are assumed to experience independent, frequency-selective fading. The CR system can use the temporarily unused PU bands guaranteeing that the total interference introduced to the PUs does not exceed the maximum interference threshold previously described by PU, I_{th}.

The relay nodes are assumed to be half-duplex, thus receiving and transmitting in two different time slots. To complete a full information exchange, two phases are considered, (MA) phase (BC) phase. In the MA phase, T_1 and T_2 transmit their data, simultaneously, to the selected m^{th} relay using the same subcarrier. In the BC phase, the selected relay amplifies the received signals, and broadcasts them to the two transceiver nodes. Once received, $T1$ and $T2$ can extract the required information by canceling self-interference.

The relay node, R_m, receives the combined signal on subcarrier i in the MA phase and then amplifies and broadcasts it on another subcarrier j in the BC phase. The subcarrier-pairing scheme between the two phases is deployed where subcarrier i in the first time slot and its corresponding subcarrier j in the second time slot form a subcarrier pair $\langle i, j\rangle$. Let h_{1i}^m and h_{2i}^m denote the channel coefficients over the i^{th} subcarrier from $T1$ and $T2$ to the relay m respectively. Similarly g_{1j}^m and g_{2j}^m denote the channel coefficients over the i^{th} subcarrier from the selected relay node to T_1 and T_2, respectively. In order to avoid the interference among the relays, each subcarrier pair is only allowed to be allocated to one relay node, but not vice versa. Accordingly, more than one pair of subcarriers may be assigned to a relay node.

In the MA phase, the received signal $Y_{(m,i)}$ at the m^{th} relay over subcarrier i can be expressed as

$$Y_{mi} = h_{1i}^m \sqrt{p_{1i}^m} X_{1i} + h_{2i}^m \sqrt{p_{2i}^m} X_{2i} + Z_{im} \tag{1}$$

where $X_{ki}(k \in \{1, 2\})$ is the unit power transmitted symbol of the terminal node T_k over subcarrier i, p_{ki}^m is the average transmission power, and Z_{im} is the independent complex Gaussian noise with zero mean and variance σ_{im}^2.

The received signal by the m^{th} relay is multiplied by amplification factor $D = 1/\sqrt{p_{1i}^m h_{1i}^m + p_{2i}^m h_{2i}^m + \sigma^2}$ and broadcasted to the transceivers. Once received the signals, the transceiver nodes extracts the desired signals by canceling self-interference. The received signals at the terminal nodes T_1 and T_2 over subcarrier j in the BC phase are given by

$$Y_{1j} = D g_{1j}^m \sqrt{p_{Rj}^m} Y_{mi} + Z_{1j} \tag{2}$$

$$Y_{2j} = D g_{2j}^m \sqrt{p_{Rj}^m} Y_{mi} + Z_{2j} \tag{3}$$

Where X_{Rj} and p_{Rj}^m denote the unit-power transmitted symbol and the average transmission power of the relay node R_m over subcarrier j, respectively, and Z_{nj} is the independent complex Gaussian noise with zero mean and variance $\sigma_{nj}^2 (n \in \{1, 2\})$. Without loss of generality, the noise variance is assumed to be constant for all subcarriers, i.e. $\sigma_{im}^2 = \sigma_{nj}^2 = \sigma^2$.

The received end-to-end signal to noise ratio (SNR) at T_1 and T_2 through R_m over the subcarrier pair $\langle i, j\rangle$ can be expressed as [3]

$$SNR_1 = \frac{(p_{2i}^m p_{Rj}^m h_{2i}^2 g_{1j}^2)}{\sigma^2 (p_{Rj}^m g_{1j}^2 + p_{1i}^m h_{1i}^2 + p_{2j}^m h_{2i}^2 + \sigma^2)} \tag{4}$$

$$SNR_2 = \frac{(p_{1i}^m p_{Rj}^m h_{1i}^2 g_{2j}^2)}{\sigma^2 (p_{Rj}^m g_{2j}^2 + p_{1i}^m h_{1i}^2 + p_{2j}^m h_{2i}^2 + \sigma^2)} \tag{5}$$

The end-to-end AF data rate on a given subcarrier pair $\langle i, j\rangle$ that is allocated to the m^{th} relay, $R_{AF}^{m,i,j}$, is expressed as [5]

$$R_{AF}^{m,i,j} = \frac{1}{2} \log_2 (1 + SNR_1) + \frac{1}{2} \log_2 (1 + SNR_2) \tag{6}$$

The pre-log factor of $(1/2)$ in equation (6) above, is due to the fact that two time-slots are required for the complete transmission process.

Let $\mathbf{p} \triangleq (p_{1i}^m, p_{2i}^m, p_{Rj}^m)$ represents the transmission power of nodes T_1, T_2 and the selected relay R_m respectively. All channel gains for the network can be adopted by assuming classical channel estimation approaches and all the noise variances assumed to be equal σ^2. $\psi_{m,i,j} \in \{0,1\}$ is the relay selection indicator with $\psi_{m,i,j} = 1$ when the subcarrier pair $\langle i,j \rangle$ is allocated to the relay R_m. Moreover, $\theta_{i,j} \in \{0,1\}$ is the subcarrier-pairing indicator, that is, if subcarrier i in the first time slot is paired with subcarrier j in the second time slot, then $\theta_{i,j} = 1$ and otherwise $\theta_{i,j} = 0$.

Our objective is to jointly optimize the power, relay assignment and subcarrier pairing in order to maximize the throughput of the multi-relay two-way OFDM CR system and guarantee that the instantaneous interference introduced to the primary system is below the maximum tolerable threshold I_th. The optimization problem can be formulated as follows

$$
\begin{aligned}
&\max_{\psi_{m,i,j},\theta_{i,j},\mathbf{p}>0} \quad \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{m=1}^{M} \theta_{i,j}\psi_{m,i,j} R_{AF}^{m,i,j} \\
&s.t. \\
&\text{- (C1: Subcarrier pairing constraint):} \\
&\quad \sum_{i=1}^{N} \theta_{i,j} = 1, \forall j; \text{ and } \sum_{j=1}^{N} \theta_{i,j} = 1, \forall i \\
&\text{- (C2: Relay assignment constraint):} \\
&\quad \sum_{m=1}^{M} \psi_{m,i,j} = 1 \forall i,j \\
&\text{- (C3: Transceivers } T_1 \text{ and } T_2 \text{ power constraint):} \\
&\quad \sum_{i=1}^{N}\sum_{m=1}^{M} P_{ki}^m \le P_k, \quad k = \{1,2\} \\
&\text{- (C4: Relays individual power constraints):} \\
&\quad \sum_{j=1}^{N} P_{Rj}^m \le P_R, \quad \forall m \\
&\text{- (C5: Interference at the first time slot (MA)):} \\
&\quad \sum_{i=1}^{N}\sum_{m=1}^{M} (\Omega_{1i}^m p_{1i}^m + \Omega_{2i}^m p_{2i}^m) \le I_{th} \\
&\text{- (C6: Interference at the second time slot (BC)):} \\
&\quad \sum_{m=1}^{M}\sum_{j=1}^{N} \Omega_{Rj}^m p_{Rj}^m \le I_{th}
\end{aligned}
\tag{7}
$$

(C1) expresses the subcarrier allocation constrain. It implies that each subcarrier in the MA phase paired with one, and only one subcarrier in the BC phase. (C2) represents the relay selection constraint which indicates that each subcarrier pair can be assigned to one relay only. (C3) and (C4) express the individual power constraints in the transceivers and the different relays, respectively. I_{th} is the maximum tolerable interference to the primary users expressed by constraints (C5) and (C6) where $\Omega_{ki}^m, k = \{1,2\}$ and Ω_{Rj}^m are the subcarrier gains between the PU and the transceivers and relay nodes, respectively.

III. Optimal Resource Allocation Based on Dual Decomposition

The optimization problem is satisfying the time sharing condition described in [9] and hence, the duality gap of the problem approaches zero as the number of subcarriers is sufficiently large regardless of the problem convexity. Thus, in this section the dual decomposition technique is used to find the optimal solution of the optimization problem. The dual problem is expressed as

$$\min_{\boldsymbol{\lambda}>0} D(\boldsymbol{\lambda}) \tag{8}$$

with $\boldsymbol{\lambda} = [\lambda_{T_1}, \lambda_{T_2}, \lambda_{R_1}, \cdots, \lambda_{R_M}, \lambda_{I_1}, \lambda_{I_2}]$, where $(\lambda_{T_1}, \lambda_{T_2})$ and $(\lambda_{R_1}, \cdots, \lambda_{R_M})$ are non-negative dual variables associated with individual power constraints (C3) and (C4). Moreover, the dual variables $(\lambda_{I_1}, \lambda_{I_2})$ are associated with the tolerated interference to the PU constraints (C5) and (C6). The dual function $D(\boldsymbol{\lambda})$ is defined as

$$
\begin{aligned}
D(\boldsymbol{\lambda}) \triangleq &\max_{\psi_{m,i,j},\theta_{i,j},p>0} \mathcal{L} \\
s.t. \quad & (\text{C1}), (\text{C2})
\end{aligned}
\tag{9}
$$

where the Lagrangian $\mathcal{L}$ is given by

$$
\begin{aligned}
\mathcal{L} = &-\sum_{m=1}^{M}\sum_{i=1}^{N}\sum_{j=1}^{N} \theta_{i,j}\psi_{m,i,j} R_{AF}^{m,i,j} + \sum_{k=1}^{2} \lambda_{T_k}\left(P_k - \sum_{i=1}^{N}\sum_{m=1}^{M} P_{ki}^m\right) \\
&+ \sum_{m=1}^{M} \lambda_{R_m}\left(P_R - \sum_{j=1}^{N} P_{Rj}^m\right) + \lambda_{I_2}\left(I_{th} - \left(\sum_{m=1}^{M}\sum_{j=1}^{N} \Omega_{Rj}^m p_{Rj}^m\right)\right) \\
&+ \lambda_{I_1}\left(I_{th} - \left(\sum_{i=1}^{N}\sum_{m=1}^{M} (\Omega_{1i}^m p_{1i}^m + \Omega_{2i}^m p_{2i}^m)\right)\right).
\end{aligned}
\tag{10}
$$

The dual function in (9) can be rewritten as follows

$$
\begin{aligned}
D(\boldsymbol{\lambda}) = \max_{\psi_{m,i,j},\theta_{i,j},p>0} \Bigg[&-\sum_{m=1}^{M}\sum_{i=1}^{N}\sum_{j=1}^{N} \theta_{i,j}\psi_{m,i,j}\mathcal{W}_{m,i,j} + \\
&\sum_{k=1}^{2} \lambda_{T_k} P_k + \sum_{m=1}^{M} \lambda_{R_m} P_R + I_{th}(\lambda_{I_1} + \lambda_{I_2}) \Bigg]
\end{aligned}
\tag{11}
$$

where

$$
\begin{aligned}
\mathcal{W}_{m,i,j} = &R_{AF}^{m,i,j} - \lambda_{T_k} P_{ki}^m - \lambda_{R_m} P_{Rj}^m - \lambda_{I_1}(\Omega_{1i}^m p_{1i}^m + \Omega_{2i}^m p_{2i}^m) \\
&- \lambda_{I_2}\Omega_{Rj}^m p_{Rj}^m
\end{aligned}
\tag{12}
$$

A two phase solution of the dual problem is adopted. First, the resources variables $\{\psi_{m,i,j}, \theta_{i,j}, \mathbf{p}\}$ are optimized for a given feasible dual variables vector $\boldsymbol{\lambda}$ and then a sub-gradient method is applied to optimize $\boldsymbol{\lambda}$ where each of $\{\psi_{m,i,j}, \theta_{i,j}, \mathbf{p}\}$ is refined at each iteration. Therefore, starting by assuming initial values for the dual variables and assuming that the subcarriers $\langle i,j \rangle$ are already matched and allocated to the m^{th} relay. Accordingly, the optimal power allocation can be determined by solving the following sub-problem for every (m,i,j) assignment

$$\max_{p_{1i}^m, p_{2i}^m, p_{Rj}^m} \mathcal{W}_{m,i,j} \qquad \text{s.t.} \qquad p_{1i}^m, p_{2i}^m, p_{Rj}^m \ge 0 \tag{13}$$

The power allocation problem does not have a trivial solution, since the multicast users, which share the same resources, are subject to different radio link conditions. For this reason there are several possibilities for performing the power allocation, e.g., according to the best or worst user within each subchannel, or taking into account the requirements of each individual user [10]. Based on that, the optimal power allocation can be obtained via searching over the power of T_1, T_2 and R_m taking into consideration that each takes discrete values over a number of power levels L and that the interference constraint does not violated.

By substituting the solution of (13) into (12), the power variable can be evaluated and the best relay assignmnet can be determined for every $\langle i,j \rangle$ pair by solving the following optimization problem

$$\max_{\psi_{m,i,j}} \mathcal{W}_{m,i,j} \qquad \text{s.t.} \qquad (\text{C2}) \tag{14}$$

Therefore, the optimal allocation strategy is achieved by allocating each $\langle i,j\rangle$ pair to the relay which maximizes $W_{m,i,j}$. Accordingly, $\psi_{m,i,j} = 1$ if $m = \arg\max_{m} \mathcal{W}_{m,i,j}$ and zero otherwise.

Once the power levels as well as the best relay are determined for all the subcarrier pairs, the optimal subcarrier pairs is determined by solving the following problem

$$\max_{\theta_{i,j}} \mathcal{W}_{m,i,j} \qquad \text{s.t.} \qquad \text{(C1)} \tag{15}$$

The problem in (15) is a linear assignment problem which can be solved, efficiently, by the Hungarian algorithm with a complexity of $\mathcal{O}(N^3)$ [11].

The sub-gradient method can be used to solve the dual problem with guaranteed convergence [12] since a dual function is always convex. Based on initially selected dual variables vector, the different dual variables can be updated at the $(i+1)^{th}$ iteration by

$$\begin{aligned}
\lambda_{T_k}^{(i+1)} &= \lambda_{T_k}^{(i)} - \delta^{(i)} \left(P_k - \sum_{i=1}^{N} \sum_{m=1}^{M} P_{ki}^{*m} \right); \forall k \in \{1,2\} \\
\lambda_{R_m}^{(i+1)} &= \lambda_{R_m}^{(i)} - \delta^{(i)} \left(P_R - \sum_{j=1}^{N} P_{Rj}^{*m} \right); \forall m \\
\lambda_{I_1}^{(i+1)} &= \lambda_{I_1}^{(i)} - \delta^{(i)} \left(I_{th} - \left(\sum_{i=1}^{N} \sum_{m=1}^{M} (\Omega_{1i}^m p_{1i}^{*m} + \Omega_{2i}^m p_{2i}^{*m}) \right) \right) \\
\lambda_{I_2}^{(i+1)} &= \lambda_{I_2}^{(i)} - \delta^{(i)} \left(I_{th} - \left(\sum_{m=1}^{M} \sum_{j=1}^{N} \Omega_{Rj}^m p_{Rj}^{*m} \right) \right)
\end{aligned} \tag{16}$$

where $\delta^{(i)}$ is the step size that can be updated according to the nonsummable diminishing step size policy [12]. With the updated values of the dual variables, the different optimization variables are evaluated again. The iterations are repeated until convergence.

IV. Proposed Suboptimal Algorithm

The optimal solution derived previously has high computational complexity. $(M+4)$ dual variables are updated in every iteration. The primal problem is decomposed into $N(NM+1)$ sub-problems. Each sub-problem requires $\mathcal{O}(NL^{N-1})$ complexity to obtain its corresponding power allocation. Afterwards, the relay assignment is determined by performing M functions evaluation for the $N!$ subcarrier matching possibilities. Finally, the Hungarian algorithm is performed with a complexity of $\mathcal{O}(N^3)$. Accordingly, the optimal solution has a complexity of $\mathcal{O}\left(T\left(N^3(ML^{N-1}+1) + N^2L^{L-1} + MN!\right)\right)$ where T is the number of iterations required to converge which is usually high.

In order to solve the problem efficiently, a low complexity suboptimal algorithm is proposed. Significant weight of complexity is, essentially, required in the power allocation and in the Hungarian algorithm. Focusing on these two parts, the proposed algorithm tries to simplify the computational complexity and get an efficient algorithm. The proposed algorithm is started by distributing the power of the relays and transceivers uniformly over the subcarriers and also assuming that the interference introduced to the PU by every subcarrier is uniform. Therefore, the power allocation in the transceivers can be found using the following relation

$$p_{ki}^m = \min\left(\frac{P_k}{N}, \frac{I_{th}}{\Omega_k^i N}\right); k = 1,2 \tag{17}$$

while that of the relays can be found according to the following formula

$$p_{Rj}^m = \min\left(\frac{P_R}{N}, \frac{I_{th}}{\Omega_{R_m}^j N}\right) \tag{18}$$

Once the power levels are determined, the algorithm searches for the best second time slot subcarrier, i.e. j, and relay m that maximize the product of the SNR_1 and SNR_2, i.e. searching for j and m that maximizes $R_{AF}^{m,i,j}$. By defining $\mathcal{A}$ and $\mathcal{B}$ to include all the non-assigned subcarriers in the MA and BC phases,respectively, the assigning procedures of a particular subcarrier i are detailed in Algorithm 1.

Algorithm 1 *Proposed Sub-optimal Algorithm*

1) Evaluate the power allocated to the transceivers T_1 and T_2 using (17).
2) For every subcarrier j and relay m, evaluate the relays power using (18).
3) For every subcarrier $j \in \mathcal{B}$ and relay m, evaluate the product of the SNRs $\mathcal{Q} = SNR_1 * SNR_2$ where SNR_1 and SNR_2 are given by (4) and (5) respectively.
4) Determine $j^* \in \mathcal{B}$ and m^* satisfying $(J^*, m^*) = \arg\max_{j,m} \mathcal{Q}$.
5) Remove j^* from the set $\mathcal{B}$ and repeat the procedures until the set $\mathcal{A}$ is empty.

Every subcarrier in the MA phase requires no more than $2(NM+1)$ function evaluations to be paired and assigned to the best relay. Therefore, the complexity of the proposed sub-optimal scheme is $\mathcal{O}(2N^2M + 2N^2)$.

V. Simulation Results

The simulations are performed under the scenario given in Fig. 1. An OFDM system of $N = 16$ subcarriers, which is sufficient to have a zero duality gap [9] and $M = 6$ relays are assumed. The noise variance is assumed to be $\sigma^2 = 5 \times 10^{-6}$ and the channel gains are outcomes of independent Rayleigh distributed random variables with unity mean. All the results have been averaged over 1000 iterations. In the simulations, the following algorithms are considered

1) **Optimal**: apply the solution based on the dual decomposition technique presented in Sec. III.
2) **Suboptimal**: apply the proposed suboptimal algorithm described in Sec. IV.
3) **Suboptimal+Hungarian**: the power are allocated according to (17) and (18) while the relay assignment and subcarrier paring are performed by solving equations (14) and (15) respectively.
4) **Suboptimal+Fixed**: the power are allocated according to (17) and (18) while the relay assignment is found by solving (14). The subcarrier used for the transmission in MA phase is fixed and used again for the BC phase.

The computational complexity of the algorithms are summarized in Table. I.

Fig. 2 depicts the achieved capacity of the optimal and suboptimal schemes versus the transceivers and relays power constraints when the interference threshold is fixed to -10 dBm. It can be noted that the capacity of all schemes are increased with the power constraint. This increase in the

TABLE I: Computational complexity comparison

Algorithm	Complexity
Optimal	$\mathcal{O}\left(T\left(N^3(ML^{N-1}+1)+N^2L^{L-1}+MN!\right)\right)$
Proposed suboptimal	$\mathcal{O}(2N^2M+2N^2)$
Suboptimal+Hungarian	$\mathcal{O}(MN^2+2N+N^3)$
Suboptimal+Fixed	$\mathcal{O}(MN^2)$

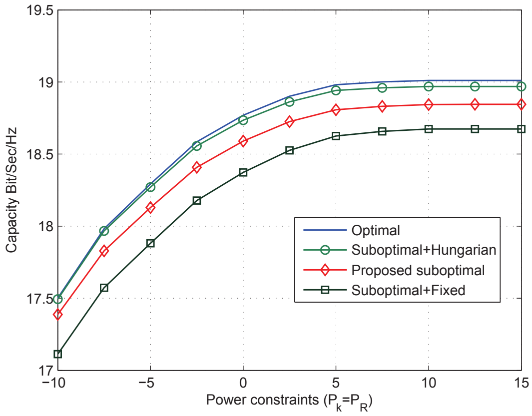

Fig. 2: Achieved capacity vs power constraint.

capacity continues until a certain value of the power constraints after which the capacity becomes constant with the power constraint. This is because the induced interference results from transmitting with the available power reaches the prescribed threshold and the system cannot use more power. Additionally, the dual decomposition based solution has the highest performance as its an asymptotically optimal solution and it works as an upper bound of the rest of the suboptimal schemes. The closest performance to the optimal solution is achieved by the *Suboptimal+Hungarian* algorithm. With a significant reduction in the computational complexity of the optimal scheme, the proposed efficient suboptimal algorithm achieves a good performance.

Fig. 3 shows the achieved capacity of the optimal and suboptimal schemes versus the interference constraint when the power constraints are fixed to 2 dBm. It can be noted that the capacity of all schemes are increased with the interference constraint. This can be justified by increasing the ability of the transceivers and different relays to transmit with higher power levels. Normally, this increase in the capacity with the increase of the interference constraint continues until the value of the interference becomes high with respect to the power constraints as the induced interference results from transmitting with the maximum power levels is below the prescribed threshold. The performance comparison between the different simulated algorithms follows the same behavior described for Fig. 2.

VI. Conclusion

In this paper, resource allocation problem in AF two-way multiple-relay OFDM CR system has been investigated where power allocation, subcarrier pairing and relay assignment are jointly optimized. The main optimization problem is formulated in order to maximize the total end-to-end throughput of the system subject to individual power and interference

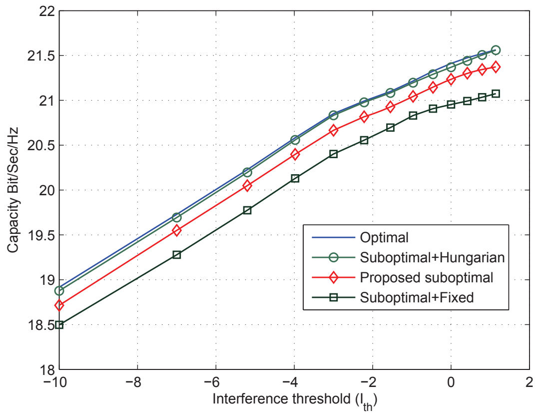

Fig. 3: Achieved capacity vs interference threshold.

constraints. The dual decomposition approach is applied to solve the mixed integer programming problem and achieve an asymptotically optimal solution. Due to the high computational complexity of the optimal scheme, suboptimal algorithms are proposed to achieve acceptable performance with much less complexity than the optimal one. We are currently working on the extension of this work to consider the decode-and- forward two-way relaying.

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