Escola Politècnica Superior de Castelldefels
UNIVERSITAT POLITÈCNICA DE CATALUNYA

FINAL PROJECT

TITLE: Performance analysis of channel assignment schemes for coordinated cognitive WLAN networks

DEGREE: Technical Engineering in Telecommunications, speciality Systems of Telecommunication

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DATE: January, 26th 2008

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Fecha: 26 de Enero de 2008

Resumen

Hoy en día las redes locales inalámbricas son muy utilizadas por un gran número de personas y su uso sigue aumentando. Esto provoca un incremento de interferencia y como consecuencia, congestión en la banda sin licencia de 2.4GHz, causado por el aumento de usuarios en una zona y la limitación de canales que ofrece dicha banda.

Como solución a este problema, en este proyecto se estudia la posibilidad de utilizar canales adicionales pertenecientes a bandas con licencia de uso para otros servicios de radiocomunicaciones. La utilización de dichos canales en la red local (denominada en este contexto usuario secundario de ese espectro) se hace de manera oportunista, siempre y cuando, no provoque interferencia a los usuarios del servicio que tiene los derechos de uso de ese espectro (denominados usuarios primarios en este contexto), ya que estos últimos tienen prioridad de acceso a estas bandas del espectro.

Como primera aproximación a la solución del problema de asignación, se estudia el comportamiento de una asignación aleatoria de canales en un escenario con una cierta densidad de redes locales que pueden generarse interferencia entre ellas y donde la disponibilidad de canales primarios para uso oportunista no es homogénea.

Posteriormente, constatadas la posibilidad de mejorar el nivel de interferencia incluso con asignaciones aleatorias de canales, se proponen dos métodos de asignación de canales diseñados para tener en cuenta la disponibilidad de los canales primarios. Un método se plantea mediante la formulación de un problema de programación lineal entera (ILP) que permite encontrar una solución óptima a costa de un elevado tiempo de ejecución. El otro método es un método heurístico basado en la obtención del Minimum Spanning Tree (MST) en términos de interferencia que permite obtener soluciones casi óptimas con tiempos de ejecución mucho más reducidos. En el proyecto se realiza una comparación detallada de ambos métodos para contrastar las ventajas de cada uno. Finalmente se identifican algunos aspectos de implementación de dichos métodos en un escenario real.

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Overview

Nowadays local wireless networks are very used by an elevated number of people and its use continues rising. This provokes an increase of the interference and as consequence, congestion in the non-licensed band of 2.4GHz, caused by the increase of users in a given zone and thus, the limitation of channels offered by this band.

As a solution to this problem, in this project it is studied the possibility of using additional channels from licensed bands used for other radio-communications services. The use of these channels in the local network (named in this context as secondary user of this spectrum) is done in an opportunistic manner, when ever it does not provoke any interference to the users of the service which have the rights to use this spectrum (named primary users in this context), since these ones have priority to access these bands of the spectrum.

As a first approximation to the solution of the assignment problem, it is studied the behaviour of a random channel assignment in a scenario with a certain density of local networks that can generate interference between them and where the availability of the primary channel for opportunistic use is not homogeneous.

Later, stated the possibility of improving the level of interference even with a random channel assignment, there are proposed two channel assignment methods designed to have in concern the availability of primary channels. The first method is set out through the formulation of an Integer Linear Programming (ILP) problem, which allows obtaining an optimal solution but with an elevated execution time. The other method is an heuristic one based on obtaining a Minimum Spanning Tree (MST) on interference terms, which allows to obtain near-optimal solutions in less time of execution. In the project it is done a detailed comparison of these two methods to contrast the advantages of each one. Finally, there are identified some aspects of the implementation of these methods in a real scenario.

INDEX

INTRODUCTION

In the ongoing days, wireless local networks are found in a large amount of civil applications and its use increases considerably day after day. This is caused by its easy installation, commodity of use and advantages compared to the traditional cable networks.

The most commercialized systems in this type of networks are IEEE802.11b and IEEE802.11g. Both work on the unlicensed ISM band that goes from 2.4 GHz to 2.5 GHz. In this project the network is formed by stations and access points. The stations are the network controllers in portable computers and the access points are devices in charge of managing the transmissions between stations or with an exterior network, as well as selecting the operating channel.

This type of systems transmit with a bandwidth greater than the channel separation, so if two nearby access points use the same channel they suffer spectral overlap. Consequently, even if the users do not use the same channel, they will interfere with each other if they transmit over close spectral channels and are situated physically in each others interference range.

First of all, it analyzes the possibility of acceding other bands in an opportunistic manner, specifically, primary bands addressed to license holders. This technique is named dynamic spectrum access, a technique that uses cognitive radio technology. The reason why the use of these bands is proposed comes from the fact that, apart from the congested ISM band of 2.4GHz, there is a scarcity of non-licensed bands with enough spectrum size, not having in concern the ones located in high frequencies, not considered due to the elevated attenuation introduced when working in these bands.

The next step consists on proposing a channel allocation that delimits the interference. This project raises two methods, an optimal and a near-optimal one. The suggested optimal formulation is based on linear programming, an important field which deals with solving optimization problems. This solution will be applied by establishing a certain number of objectives and constrains using a tool from Matlab 7, the programming environment chosen in this project. For the near-optimal solution a heuristic algorithm based on an extension of the minimum spanning tree problem from graph theory is proposed. In particular the algorithm will be an extension of Prim's algorithm, adapting it to our context and needs.

Once presented the approach, the following lines will detail the structure of the report. To begin with, the first chapter presents the context by explaining the main concepts of WLAN and cognitive radio in order to clarify the scenario and understand the functionalities. The second one starts by stating the problem, explaining the detailed reasons to use cognitive radio. It continues by presenting the system model, which includes the interference characterization, in which APs are going to be further based on it to obtain the available channels. Being these channels those that can be achieved without interfering with primary users. The system model also contains the proposed metric to measure the interference between pairs of nodes, named interference penalty, a combination of the spatial and frequency overlap. Next, the steps to calculate this penalty are detailed into two separate processes for every pair of APs in order to combine them, and finally, obtain the penalty of every secondary user with the rest. Chapter three explains the proposed channel assignment schemes, where after and introduction the algorithms of the optimal and near-optimal solutions are explained and formulated. The fifth chapter presents the simulation as well as its results with the different assignment schemes.

To end this report the main conclusions of the overall project are extracted, followed by a series of future lines, which are the main ideas that could not be applied but are possible investigation lines.

CHAPTER 1. WLAN AND COGNITIVE RADIO

Nowadays the use of wireless communications, especially wireless LANs, has increased due to its advantages. The proliferation of its use is making these networks less efficient because of the interference caused by its limited frequency band.

Therefore, this chapter will present the WLAN's main concepts, so as to further understand its main problem. It is also explained a possible solution to its congestion, cognitive radio.

1.1 WLAN

WLAN (Wireless Local Area Network) is a local network that follows the same characteristics as the local wired network (Ethernet), but including communications via radio. The most used is the standard IEEE 802.11 and its variants. It is mostly known by its commercial name, Wi-Fi (wireless fidelity), it was named this way because it gives the same fidelity as the cable network.

In wireless local networks the stations can transmit between each other or through an access point that coordinates the communication. At the offices it is often used as an adjunct to Ethernet network. At residential homes, it commonly used as only network to connect laptops or wireless printers as to get access to the internet through the DSL line.

In figure 1.1 can be appreciated one hybrid network formed by different devices, ones connected through wireless to both Access Points (AP) using a infrastructure mode, which is explained later on in the architecture section, and a desktop connected through a cabled LAN.

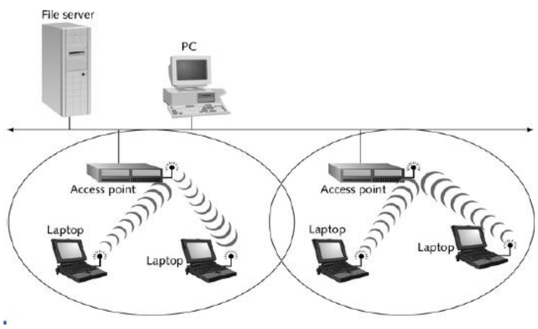

Fig 1.1 Hybrid network (cabled and wireless in a infrastructure mode)

1.1.1 Applications

The main objective of this kind of networks is to provide service to the users located inside the AP's transmission range, but without using cables, offering the advantages of mobility and flexibility with an easy and low cost installation. Among the most typical applications, it is used to compliment the LAN when the cable installation has a high cost or to provide service to mobile devices such as portable computers or mobile VoIP phones.

Originally WLAN was designed for corporate environments, but because of its advantages, nowadays we can find it in a big variety of places, both in the public and private sector such as residential homes, industrial zones, university campus, coffee shops, hotels, etc.

1.1.2 Architecture

The WLAN follows the generic standards applied to cable LANs (i.e. IEEE 802.3 or equivalent) but it adds the use of radio-electric resources. These specific rules define the physical and medium access control (MAC) layers which control the radio connection.

The WLAN, following [1] is mainly composed by, first of all, Client Stations (STAs), usually portable computers with a Network Interface Controller (NIC) which include a radio transceiver and an antenna, or multiple antennas, depending on the technology employed; Access Points (APs), as before mentioned, are those devices in charge of sending the information from the cable network (Ethernet or DSL line) to the STAs NIC; and, finally, it can be found the AP Controllers for deployments in which various APs are required so as to increase coverage or to improve traffic.

As the majority of local networks, WLAN commonly follows two types of topologies, Ad-Hoc network and infrastructure mode, both are now briefly explained.

An Ad-Hoc network consists on a group of devices that communicate directly with each other through radio signals without using an access point. The devices that want to communicate with each other must use the same radio channel.

Whereas, in the infrastructure mode devices communicate with each other through an access point (AP). This configuration is much more feasible than the Ad-Hoc network because the AP coordinates and administers the communication assuring that the information reaches to its destiny.

Also, as WLAN does not require licence and its low cost installation, it is also used for point-to-point links. These connections can have coverage ranges of a few kilometres with direct visibility.

1.1.3 Technology and standards

The most common way in which WLAN is usually transmitted is using spread-spectrum or OFDM modulation technology over non-licensed bands depending

on the standard it follows. This section explains the variety of standards and its pertinent technologies.
The first standard was created by the IEEE (Institute of Electrical and Electronics Engineers), and published in 1997. It is transmitted over the ISM band of 2.4GHz and uses basically two types of modulations, the DS-SS (Direct Sequence Spread Spectrum) and it is also employed the FH-SS (Frequency Hopped Spread Spectrum”). The maximum speed reached by this communication is of 1 or 2 Mb/s depending on the manufacturer. Nowadays, this standard is practically in disuse due to the appearance of new variants which improve certain features of the first exemplar, for example the transference speed, coverage, special functions of security as well as the integration with cable networks.

However, the standard which has given WLAN the popularity it has nowadays has is the IEEE 802.11b. This evolution of 802.11 exclusively uses a DS-SS modulation with the CCK (Complementary Code Keying) codification system allowing a maximum transference speed of 11Mb/s. Another characteristic introduced by the standard is the DRS (Dynamic Rate Shifting), a technique that allows the wireless adapters to reduce the speed to compensate possible reception problems, commonly generated by the long distances between devices as well as the objects the radio wave must cross, that introduces diffraction and attenuation to the received signal.

Moreover, another evolution ratified in 1999 is the 802.11a. This standard is also known by the name of Wi-fi 5 and its fundamental difference among the previous ones is that transmits over the band of 5GHz using the radio modulation technique OFDM (Ortogonal Frequency Division Multiplexing). This technique allows dividing a high speed carrier in 52 low speed sub-carriers transmitted in parallel.

In 2003 the standard 802.11g was approved, and as this norm is based on the previous mentioned 802.11b it is completely compatible. It works in the same frequency band situated in 2.4Ghz and its capable to use two modulation methods, DS-SS and OFDM. Thus, this standard is able to increase the transmission speed, reaching 54 Mbps already offered by 802.11a, but maintaining the characteristics referred to distance, consume levels and work frequency of 802.11b.

Apart from these evolutions there are also other standards that work over the 5GHz band but did not had industrial acceptance. These are HiperLAN 1 and HiperLAN 2, proposed by the ETSI (European Telecommunications Standards Institute). However, in the present project it is not detailed because it centres in the standards of 802.11, but the main characteristics are presented on Table 1.1 from [2], in which the mentioned standard features are summarized.

Finally, it can be mentioned the Home RF, very similar to 802.11 but able to support voice calls.

System	Supporter	Capacity	Spectrum	Comments
802.11	IEEE	1Mb/s	2.4GHz	Frequency Hopping(79 frequencies)
802.11	IEEE	2Mb/s	2.4GHz	DS-SS (similar to CDMA, it sends in all frequencies)
802.11b	IEEE	11Mb/s	2.4GHz	DS-SS , also known as Wi-Fi
802.11a	IEEE	54Mb/s	5GHz	OFDM, also known as Wi-Fi 5
802.11g	IEEE	54Mb/s	2.4GHz	OFDM
HiperLAN1	ETSI	23.5Mb/sec	5GHz	OSM-based radio access, rarely used
HiperLAN2	ETSI	54Mb/sec	5GHz	Similar to 802.11a but incompatible
HomeRF	IEEE	10Mb/s	2.4GHz	802.11 FH-SS but with support for voice calls. Also known as SWAP-Shared Wireless Access Protocol

Table 1.1 WLAN standards

1.1.4 Available Spectrum: Non-licensed bands

As mentioned previously, a WLAN works over non-licensed bands, specifically over the ISM band of 2.4 GHz and 5GHz.

The acronym ISM stands for Industrial, Scientific and Medical because this radio bands were originally reserved internationally for the use of RF electromagnetic fields for these purposes other than communications. In general, communications equipment transmitting in the ISM band must be able to accept any interference generated by devices transmitting in the same band.

These bands are defined by the ITU-R in 5.138, 5.150, and 5.280 of the Radio Regulations. Nevertheless, these recommendations should be adapted since every country has different national radio regulations.

Since communication devices using the ISM bands must tolerate any interference from other ISM equipment, these bands are typically given over to uses intended for unlicensed operations, a type of communication that needs to be interference tolerant from other devices anyway. An example for this would be the Bluetooth technology as it uses frequency hopping rarely interferes with 802.11 networks and vice versa; even if they work over the same band due to the compatibility of their transmission techniques.

The ISM bands defined by the ITU-R are specified in the following table:

Frequency range [Hz]	Centre frequency [Hz]	Availability
6.765–6.795 MHz	6.780 MHz	Subject to local acceptance
13.553–13.567 MHz	13.560 MHz	
26.957–27.283 MHz	27.120 MHz	
40.66–40.70 MHz	40.68 MHz	
433.05–434.79 MHz	433.92 MHz	Region 1 only (Europe, Africa, the Middle East west of the Persian Gulf including Iraq, the former Soviet Union and Mongolia.)
902–928 MHz	915 MHz	Region 2 only (The Americas, Greenland and some of the eastern Pacific Islands.)
2.400–2.500 GHz	2.450 GHz	
5.725–5.875 GHz	5.800 GHz	
24–24.25 GHz	24.125 GHz	
61–61.5 GHz	61.25 GHz	Subject to local acceptance
122–123 GHz	122.5 GHz	Subject to local acceptance
244–246 GHz	245 GHz	Subject to local acceptance

Table 1.2.Non-licensed frequency availability

For many people, the most commonly encountered ISM device is the home microwave oven operating at 2.45 GHz. However, in recent years these bands have also been shared with license-free error-tolerant communications applications such as wireless LANs and cordless phones in the 915 MHz, 2450 MHz, and 5800 MHz bands. Because unlicensed devices already are required to be tolerant of ISM emissions in these bands, unlicensed low power communications are generally able to operate in these bands without causing problems for ISM users. Note that the 915 MHz band, as is indicated in the above table, should not be used in countries outside Region 2, except those that specifically allow it, such as Australia and Israel, especially those that use the GSM-900 band for cell phones. The ISM band is also widely used for Radio-frequency identification (RFID) applications with the most commonly used band being the 13.56 MHz band used by several systems, including those used by biometric passports and contact less smart cards.

This project is based on WLAN operating over the 2.4 GHz ISM band which supports the most popular protocols, such as 802.11b and 802.11g. This band is segmented into 14 channels but every country has different channel availability defined by the regulatory authorities of every region. The regulatory authorities in North America are the FCC (Federal Communication Commission) and the IC (Industry Canada) and in Europe the ETSI (European Telecommunications Standards Institute). In the following table from [3] the different channel allocation are listed.

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Channel	Frequency (GHz)	North America	Europe	Israel	China	Japan
1	2.412	X	X	—	X	X
2	2.417	X	X	—	X	X
3	2.422	X	X	X	X	X
4	2.427	X	X	X	X	X
5	2.432	X	X	X	X	X
6	2.437	X	X	X	X	X
7	2.442	X	X	X	X	X
8	2.447	X	X	X	X	X
9	2.452	X	X	X	X	X
10	2.457	X	X	—	X	X
11	2.462	X	X	—	X	X
12	2.467	—	X	—	—	X
13	2.472	—	X	—	—	X
14	2.484	—	—	—	—	X

Table 1.3.Regional channel allocation in the 2.4GHz ISM band for 802.11b/g

1.2 Cognitive radio

The current wireless networks use a static spectrum allocation policy, where governmental agencies assign the radio spectrum to license holders on a long term basis for large geographical regions, among them, as an example, it can be included the analogue television, mobile phone networks and most of the telecommunication systems. In consequence of the increase of the spectrum demand, this policy faces a scarcity of available spectrum bands. In contrast, studies confirm a large portion of the assigned licensed spectrum is used sporadically, so a significant amount of the spectrum is underutilized, as denoted in [4]. For example, cellular network bands are overloaded in most parts of the world, but amateur radio and paging frequencies are not. Independent studies performed in some countries confirmed this observation, and concluded that spectrum utilization depends strongly on time and place. Hence, dynamic spectrum access (DSA) techniques were recently proposed to solve these inefficiency problems. The DSA has different approaches as shown in figure 1.2 from [5]. This project is centred in a Hierarchical Access Model, specifically in an Opportunistic Spectrum Access (OSA). DSA is certainly an important application of cognitive radio (CR), defined in the next section, but CR represents a much broader paradigm where many aspects of communication systems can be improved via cognition. As in this project applies cognitive radio for OSA, sometimes it will not distinguish them even if there are not the same.

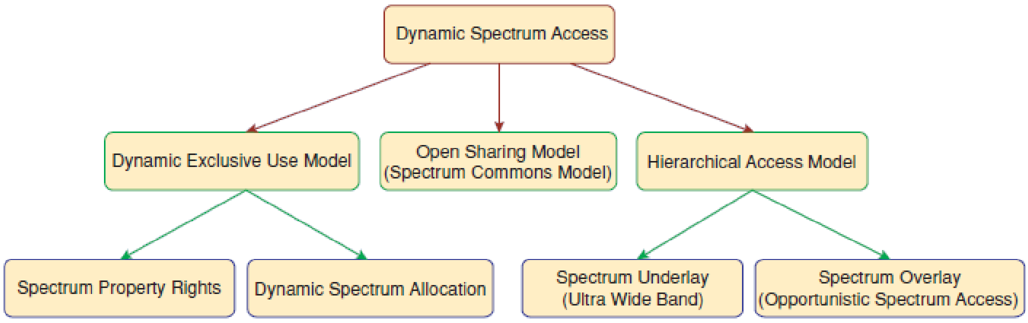


Figure 1.2.Taxonomy of dynamic spectrum access

1.2.1 Definition

Cognitive radio is built on a software radio platform. It is a context-aware intelligent radio potentially capable of autonomous reconfiguration by learning from and adapting to the communication environment [6]. In this project the key enabling technology of dynamic spectrum access techniques is cognitive radio (CR) technology, which provides the capability to share the wireless channel with licensed users in an opportunistic manner. So, with this technology the devices can intelligently detect which communication channels are in use and which are not, and instantly move into vacant channels while avoiding occupied ones. This way optimizes the use of available radio frequency (RF) spectrum and minimizes the interference to other users.

Initially the idea of CR was presented officially in an article by Joseph Mitola III and Ferald Q. Maguire, Jr in 1999 [7] proposing wireless devices are computationally sufficient about radio resources and node to node communications to detect the needs as a function of the context of use, to provide the most appropriate radio resources and wireless services to those needs.

So, cognitive radio extends to the software with a radio domain model based reasoning about a set of RF bands, air interfaces, protocols, and spatial and temporal patterns that moderates the use of the radio spectrum.

This way, cognitive radio enhances the flexibility of personal services through the knowledge of the features above mentioned plus devices, software modules, propagation, networks, user needs and application scenarios in a way that supports automated reasoning about the needs of the user. So, software radios will negotiate among peers the use of the spectrum depending on the space, time and user context.

1.2.2 Characteristics

From this definition, two main characteristics of cognitive radio can be defined, cognitive capability and reconfigurability [8].

To begin with, cognitive capability identifies the portions of the spectrum that are unused at a specific time or location through real-time interaction with the radio environment. As shown in Fig. 1.3a, CR enables the usage of temporally unused spectrum, referred to as spectrum hole or white space. Consequently, the best spectrum can be selected, shared with other users, and exploited without interference with the licensed user.

The other characteristic is that a CR can be programmed to transmit and receive on a variety of frequencies, and use different access technologies supported by its hardware design allowing reconfigurability.

Through this capability, the best spectrum band and the most appropriate operating parameters can be selected and reconfigured. In order to provide these capabilities, CR requires a novel RF transceiver architecture. The main components of a CR transceiver are the radio front-end and the baseband processing unit that were originally proposed for software-defined radio (SDR), as shown in Fig. 1.3b. In the RF front-end the received signal is amplified, mixed, and analogue to digital (A/D) converted. In the baseband processing unit, the signal is modulated/demodulated. Each component can be reconfigured via a control bus to adapt to the time-varying RF environment. The novel characteristic of the CR transceiver is the wideband RF front-end that is capable of simultaneous sensing over a wide frequency range. This functionality is related mainly to the RF hardware technologies, such as wideband antenna, power amplifier, and adaptive filter. RF hardware for the CR should be capable of being tuned to any part of a large range of spectrum. However, because the CR transceiver receives signals from various transmitters operating at different power levels, bandwidths, and locations; the RF front-end should have the capability to detect a weak signal in a large dynamic range, which is a major challenge in CR transceiver design.

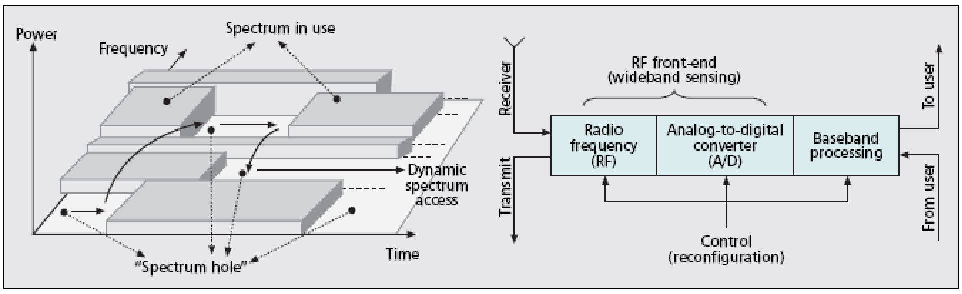


Figure 1.3.Overview of cognitive radio: a) the spectrum hole concept; b) cognitive radio transceiver architecture.

1.2.3 Architecture

Cognitive radio works in heterogeneous networks formed by different devices using different access techniques. This components can be classified in two groups, primary and secondary networks.

The primary network (or licensed network) is referred to an existing network, where the primary users have a license to operate in a certain spectrum band. If primary networks have an infrastructure, primary user activities are controlled through primary base stations. Due to their priority in spectrum access, the operations of primary users should not be affected by unlicensed users. The same example as before can be used, due to networks such as mobile telephony and television broadcasting pay to have a licence to transmit over specific reserved radio frequency bands.

On the other hand, CR network, also referred to it as dynamic spectrum access network, secondary network or unlicensed network does not have a license to operate in a desired band. Hence, secondary users require additional functionalities to share the licensed band due to they cannot interfere with license holders.

So, secondary users are capable of accessing licensed portion of the spectrum used by primary users and the unlicensed bands through wideband access technology mentioned in the WLAN section. Consequently, the operation types for CR networks can be classified as licensed band operations and unlicensed band operations.

The licensed band is primarily used by the primary network. Hence, CR networks are focused mainly on the detection of primary users in this case, so the channel capacity depends on the interference at nearby primary users. Furthermore, if primary users appear in the spectrum band occupied by CR users, CR users should vacate that spectrum band and move to available spectrum immediately to let that band free. In the case of the unlicensed band, CR users have the same right to access the spectrum primary users when ever it is not used by primary users.

As the scenario is a heterogeneous network formed by primary and secondary users, as shown in figure 1.4, CR users can communicate with each other through three different access types: CR network access, CR ad hoc access and primary network access.

To begin with, CR users can access their own CR base station on the licensed and unlicensed bands because all interactions occur inside the CR network. In the same way, they can also communicate with other CR users through and ad hoc connection on both bands. But, if secondary users access the primary band through the licensed band, unlike for other access types, they require an adaptive medium access control (MAC) protocol, which enables roaming over multiple primary networks with different access technologies.

As mentioned above, CR networks impose unique challenges due to their coexistence with primary networks as well as QoS requirements. Thus, new spectrum management functions are required for CR networks with critical design challenges as avoid interference with primary networks, support a QoS aware communication to decide an appropriate spectrum band considering the dynamic and heterogeneous spectrum environment, and to provide a seamless communication regardless of the appearance of primary users.

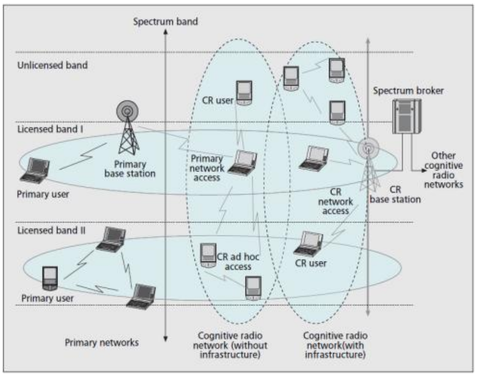


Figure 1.4.Cognitive radio network architecture.

CHAPTER 2. PROBLEM STATEMENT AND SYSTEM MODEL

Hinged upon the main theoretical points explained on the first chapter, this chapter presents the congestion in wireless LANs as the problem to solve.

This congestion is result of the interference caused by the increasing use of the limited 2.4 GHz ISM band, previously mentioned. The solution proposed is to allocate channels from licensed bands to the APs (when applying CR definitions are also named as secondary users) whenever it does not interfere with primary users (license holders).

2.1 Congestion in 802.11. First proposal: Cognitive radio

The installation requirements and the option of mobility are some of the advantages of the wireless network which have made it become common use for the internet services. Hence, the increment of the number of APs in a certain region produces a decrease of the QoS due to the interference caused by the limited number of channels.

When devices send traffic on the same channel, they have the potential to interfere with one another, a type of interference known as co-channel interference.

Unfortunately, the problem does not end there. Each of these channels has a substantial bandwidth in comparison to the channel separation and they have significant spectral overlaps with each other. This means that the signal from a given device on channel 1 could bleed over and interfere with another device transmitting on channel 2 or 3. As a result, there are only three non-overlapped channels in the 802.11b/g band, channels 1, 6, and 11 (Figure 2.1).

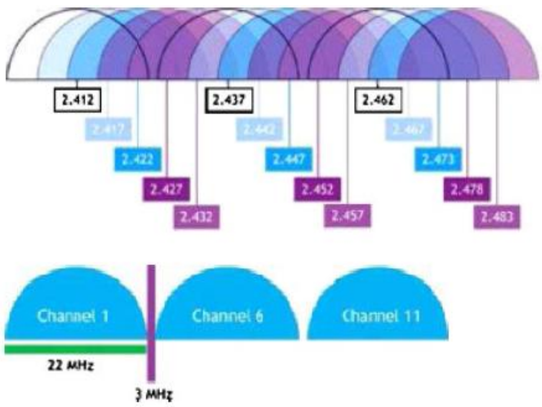


Figure 2.1.Adjacent overlapping channels
and non-overlapping channels 1, 6, and 11.

Usually, the network performance depends, partly, on the assignment of radio channels to APs. This assignment is often done using a manual process in which the designer attempts to assign channels in a way that minimizes co-channel overlapping. The coverage areas, and therefore the channel assignments, are dependent on, among other things, the radio propagation environment. But, as the radio propagation environment changes constantly, it is impossible to be sure whether channel assignment, valid at the time the network was designed will continue being further valid.

This project proposes cognitive radio to opportunistically use available channels from primary bands to increase the number of usable channels and as consequence reduce the interference in a scenario with a high density of APs, also refereed to them as secondary users (SU). The primary band considered [9] goes from 712MHz to 747 MHz and it is assumed that it has the same characteristics as the 2.4GHz band so the APs will dispose of 8 new channels of 5MHz.

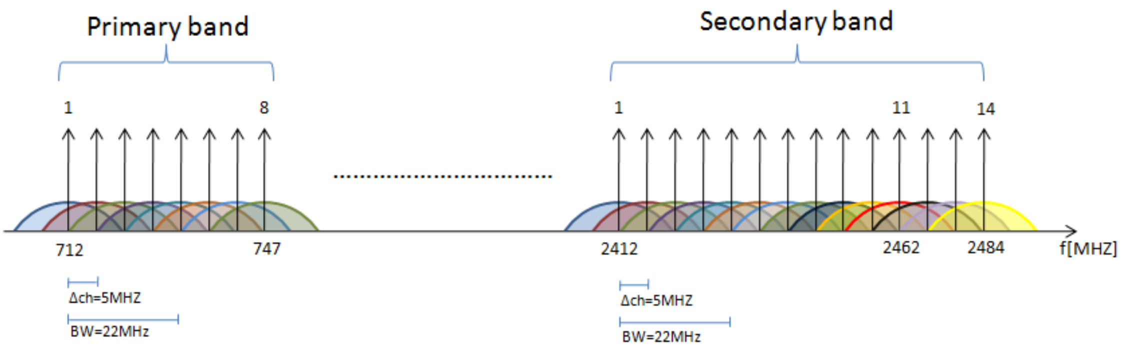


Figure 2.2.Primary and secondary band

Including this band, following the North American channel availability, the system disposes of a total of 19 channels, 11 of them belonging to the ISM band which, if chosen, will not interfere with nodes which transmit on channels from the new licensed band, as they are placed on a spectrum band far away from each other. Therefore, assuming both bands have equal characteristics, they will follow the same co-channel overlapping norms.With this configuration APs working on different bands, primary or secondary, will never interfere each other, but if the work on the same band they will interfere in the same manner as shown in figure 2.2.

This 8 primary channels are only available in a certain location, and are accessible whenever they are not being used by a primary user (PU). Secondary users cannot interfere with license holders as the last are paying to use this band, but at the same time if a PU causes interferences to a SU the option of using primary channels will no satisfy our needs. This interference level will be characterized in the second part of this chapter.

2.2 System model

The system model presented in this project is based on spectrum heterogeneity, where there will be dissimilar spectrum availability depending on the location.

In order to decide what primary channels are available, every access point has to have certain information of its environment. In this project it is assumed every AP disposes of it as this field will not be studied. Anyway, there are studies that propose different methods to share this information. For example, [10] proposes to share the information between APs using a distributed coordination framework. With this framework, users self-organize into local coordination groups, based on the similarity of locally available channels to pass the information from different coordination groups using bridge nodes. As mentioned, this project assumes that every AP disposes of this information, so it will leave the method to obtain it for further study.

However, in cognitive radio networks the channel assignment depends on the interference caused by PUs to SUs, SUs to PUs or SUs to other SUs. Conditions to determine spectrum reusability can be formulated in terms of the interference levels allowed in both the PU and SU receivers. Hence, as shown in figure 2.3, denoting as I_{SP} the interference level from a SU transmitter in a PU receiver, S_P the primary receiver sensitivity and M the required interference protection margin, the SU receiver condition usage is given by $I_{sp} \le S_p - M_p$. Analogously, the SU receiver condition usage turns into $I_{ps} \le S_s - M_s$.

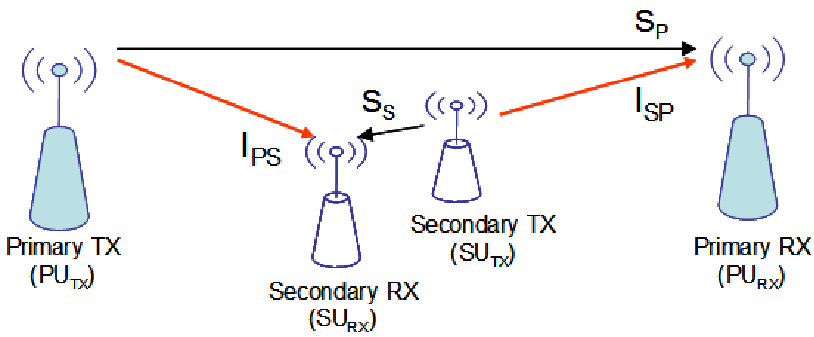


Fig. 2.3.Interference characterization for spectrum reuse.

This system model can lead to the definition of areas, as shown in figure 2.4, where the radius of each area derives from to the corresponding power levels. In spatial terms the interference radius (D_I) will be determined by the usage coverage radius (D_u) of the transmitters, the protection margin (M) and the sensitivity (S) of the interfered devices in each case. Hence, the usage distance is calculated from to the transmission power (P_{tx}), the environment and the users' characteristics as shown in equation 1. Denoting coverage usage radius as the maximum usage distance from the transmitter to the receiver.

(1) $P_{tx} = S + L_o + 10 \cdot \alpha \cdot \log(Du)$; (in logarithmic)

In this scenario there will be two types of devices for each network: base stations and user equipments in primary networks and, access points and client stations in secondary networks.

Primary base stations (BS) can transmit and receive or only transmit. An example for a BS that only transmits could be a television station. And for a BS that transmits and receives a cell phone base station. Primary user's equipments (UE) can transmit and receive or only receive. Following the same example, a television would only receive and a cell phone would transmit and receive. In this case, the interference radio will depend on the type of UE.

If the UE only receives information, the interference distance will only depend on the interference caused by the transmission power of the BS, but if the UE transmits and receives, and considering UE are placed along the limit of the usage coverage, the total interference distance will be the usage radio (Du_p) plus the interference radio (Dx_p) caused by the UEs, this is studied in the primary to secondary interference section of this chapter.

In the case of secondary users, following WLAN nomenclature, base stations are called Access Points (AP) and secondary user equipments are called stations (STA). In this case, all devices are transceivers because both transmit and receive information. Considering STAs are placed along the limit of the usage coverage, the maximum interference radio will be the usage radio (Du_s) of the AP plus the interference distance (Dx_s) caused by the STA. In this case the mentioned interference radio will be the only one considered because it is bigger than the one caused only by the AP.

Once presented the system model and the components in the scenario, the spatial definition can be appreciated in the following figure.

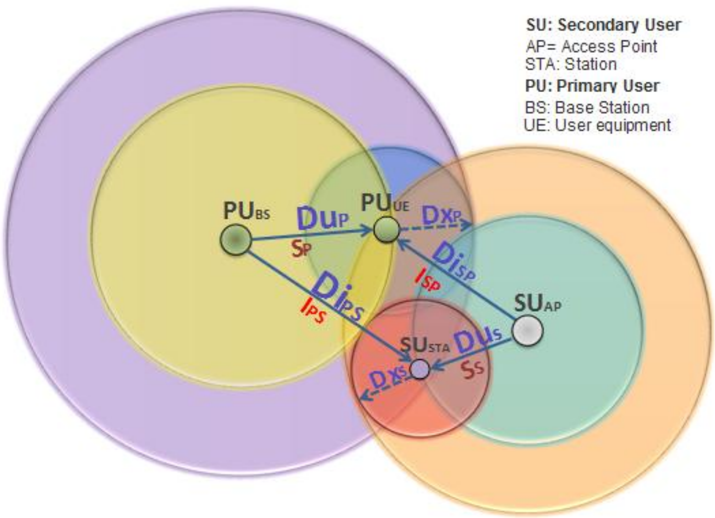


Fig. 2.4.Spatial characterization of the interference.

2.2.1 Interference characterization

As mentioned above, secondary users (SUs) can only access primary bands if they do not interfere with primary users (Pus) because they do not have license. Once they access, the objective is to guarantee that every user will be able to decode correctly the signal independently if it is a SU or a PU.

In area terms the interference level will be reflected in the surface overlap. This overlap will be accepted if the interference is below a threshold fixed by the users' receiving characteristics.

2.2.1.1 Secondary to Primary users' interference characterization

The interference caused by a SU to a PU has to be smaller than the sensitivity minus a certain protection margin (M) of a PU. The sensitivity is the minimum power a receiver can detect from the transmitter due to path losses. Hence, path losses will depend on the environment and the distance between the transmitter and the receiver.

(2) $I_{SP} < S_P - M_P$; (in logarithmic)

(3) $Lp = Lo + 10 \cdot \alpha \cdot \log(D)$;(in logarithmic), α : propagation model constant

As mentioned before, the maximum interference distance will be the usage distance of the AP plus the interference distance caused by the STA:

(4) $Di_{SP} = Du_S + Dx_S$;

(5) $I_{SP} = Ptx_S - Lo - 10\alpha \cdot \log(Dx_S)$; (in logarithmic)

Applying this equations, the relation between the interference radius and the usage radius results: $Di_{SP} = Du_S \cdot \left(1 + 10^{-\frac{\Delta S_{PS} - M_P}{10 \cdot \alpha}}\right)$, where ΔS_{PS} is the difference between S_P and S_S in dB ($\Delta S_{PS} = S_P - S_S$).

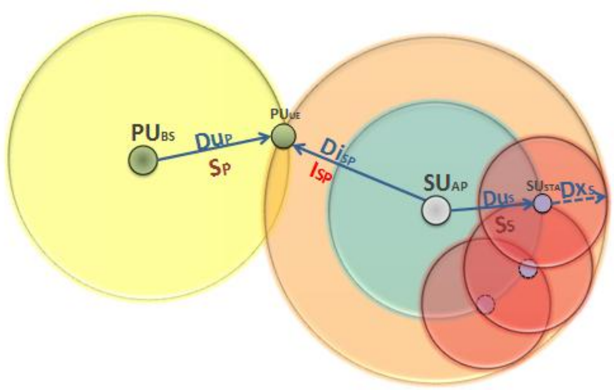


Fig.2.5.Spatial characterization of the secondary to primary interference.

2.2.1.2 Primary to Secondary users' interference characterization

The interference caused by a PU to a SU it is determined by the SU's sensitivity having in concern a protection margin (M_S). In this case, as it was above presented, there are two possibilities depending on the type of device the UE is, receiver or transceiver.

A) If the UE only receives, the interference will be only caused by the BS transmission power, so the interference radius will be determined by:

(6) $I_{PS} \leq S_S - M_S$ (in logarithmic)

(7) $I_{PS} = Ptx_P - Lo - 10 \cdot \alpha \cdot \log(Di_P)$; (in logarithmic)

Applying this equation, the relation between the interference radius of a PU to a SU results: $Di_{PS}(A) = Du_P \cdot 10^{-\frac{\Delta_{SP} - M_S}{10 \cdot \alpha}}$, where ΔS_{SP} is the difference between S_S and S_P in dB ($\Delta S_{SP}=S_S - S_P$).

B) If the UE receives and transmits the interference ratio will be the usage radius of the BS (Du_P) plus the interference distance, Dx_P, caused by the UE's transmissions, considering all UE are placed along the limit of usage coverage.

(8) $Di_{PS} = Du_P + Dx_P$;

(9) $I_{PS} = Ptx_P - Lo - 10\alpha \cdot \log(Dx_P)$; (in logarithmic)

Applying this equations and the equations above, the relation between the interference radius of a PU to a SU results: $Di_{PS}(B) = Du_P \cdot \left(1 + 10^{-\frac{\Delta S_{SP} - M_S}{10 \cdot \alpha}}\right)$.

From now on it will be considered that PU's UE only receive, so the primary to secondary interference distance will be the shortest, $Di_{PS}(A)$, interference caused only by the BS.

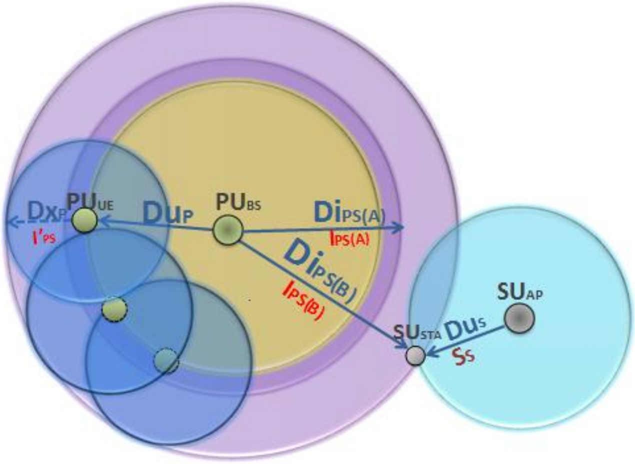


Fig.2. 6.Spatial characterization of the primary to secondary interference.

2.2.1.3 Secondary to Secondary users' interference characterization

The interference caused by a SU to another SU depends on the sensitivity and M of both SUs. As all the SUs are the same, the interference will be defined by its characteristics.

(10) $I_{SS} \leq S_S - M_S$; (in logarithmic)

(11) $I_{SS} = Ptx_S - Lo - 10 \cdot \alpha \cdot \log(Dx_P)$; (in logarithmic)

(12) $Di_{SS} = Du_S + Dx_S$;

In this case the sensibilities are the same so interference will not depend on the difference of sensibilities because it is zero. Consequently it will only depend on the transmission power of the secondary AP and the M_S of the STAs.

Applying this equations, the relation between the usage coverage and the interference radius is: $Di_{SS} = Du_S \cdot \left(1 + 10^{\frac{M_S}{10 \cdot \alpha}}\right)$.

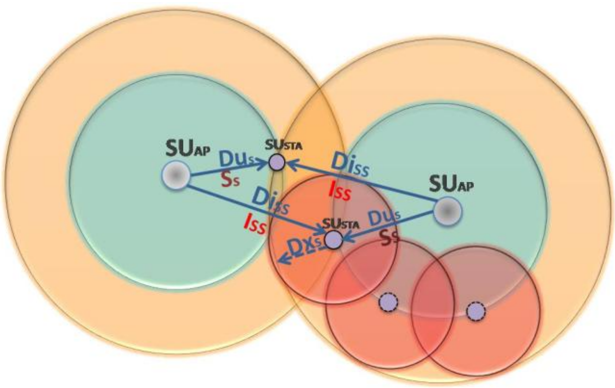


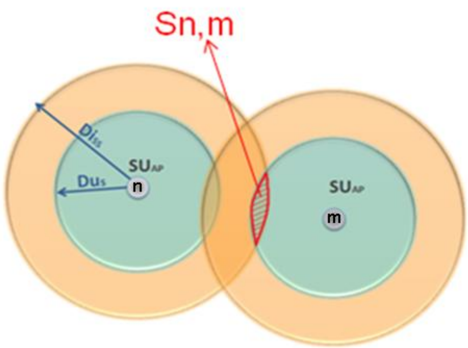
Fig. 2.7.Spatial characterization of the secondary to secondary interference.

2.2.2 Interference Penalty

The Interference Penalty (IP) is a metric to measure the interference level between each pair of APs. As shown in equation 13 this IP is determined by the overlapping surface $S_{n,m}$ and ρ. Hence, $S_{n,m}$ is the overlapping area between APs when a given margin is not satisfied for co-channel conditions mentioned in above and ρ is the overlapping channel factor, defined in [11] for the 802.11. In order to obtain an interference percentage it is normalized the interference surface by dividing $S_{m,n}$ between the usage surface of the AP calculated as $S_{AP} = \pi \cdot Du_s^2$.

(13) $$IP_{m,n}(f_m,f_n) = \frac{S_{m,n}}{S_{AP}} \cdot \rho(f_m,f_n);$$

(14) $$\rho(f_m,f_n) = \max\left(1 - 0.2 \cdot |f_m - f_n|, 0\right);$$



2.8. Interference surface

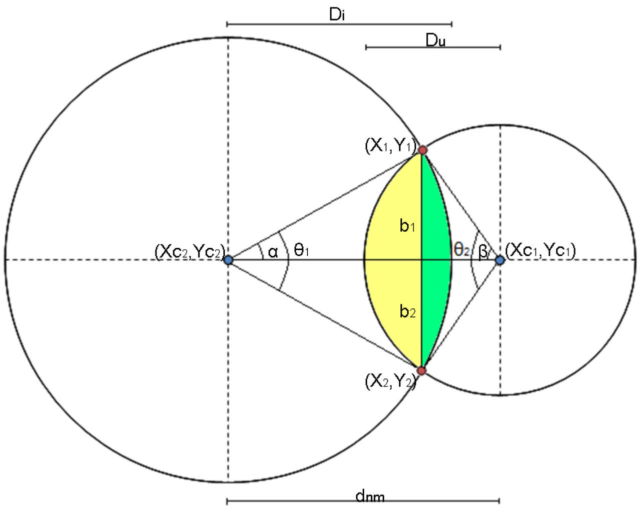
2.2.2.1 Spatial overlap

This overlapping surface is calculated using geometrical equations. To obtain this area, first it is looked for the circle portions coloured in yellow and green in figure 2.9. To be able to find these areas it is used equation 15 to calculate them independently and further on, sum them to obtain the total surface.

This equation is the result of integrating the formula of the circle's area using polar coordinates in order to obtain the area of "the cup" of a circle, being this portion the result of cutting the circle with a straight line. As shown in this equation this area can be found with the radius R of the circle and the angle θ, which is formed from by joining the centre of the circle to the two points where the circle intersects with the straight line.

(15) $$Area_{circle\_portion} = \frac{1}{2} \cdot R^2 \cdot (\theta - \sin\theta)$$; R: circle radius

Following figure 2.9 as an example, it is possible to define two different portions following equation 15, the first in which R corresponds to the radius of the interference circle Di, and the second one in which R is the usage distance, Du. The variables to calculate this portions are the same, so the order to calculate them is irrelevant. The procedure followed to calculate this areas is described in the Annex A.



2.9. Snm. Geometrical study

2.2.2.2 Channel overlapping function

As it is shown in equation 14, the channel overlap function ρ(fi,fj) depends on the difference between the selected channels. Hence, it measures the relative percentage gain in interference between the pair of APs. The multiplier 0.2 is the channel overlapping factor which is 1/5 for 802.11b and 802.11g.

This equation indicates that the value of the overlapping channel function is the maximum between $1 - |f - g| \times 0.2$ and 0, so it never achieves negative values. As mentioned in the first part of chapter two, this comes from the fact that users transmit in a bigger bandwidth than the size of the channel. So, as the bandwidth of the information is of 22MHz and the channels are of 5MHz, there is not co-channel overlap if the pair of APs are assigned channels 5 channels distant from each other. If this is the case and there is no frequency overlap, those nodes are not penalised regardless of the spatial overlap. As an example, if there are three nodes in the graph, in order to not be penalized they are assigned channels 1, 6 and 11. But, if the pair of APs n and m use frequencies that are less than five channels apart, then there is interference between them and thus, are penalized.

By combining this metric with the superficial overlap we establish a metric able to measure the interference between nodes, named interference penalty.

2.2.3 Interference Level

In order to obtain results and to be able to follow and evaluate the progress of the interference using the different channel allocation proposals, it is suggested an interference level to measure these values. If the IP_{mn} is the interference penalty between an AP m and an AP n, metric which measures the degree of coupling between every pair of APs. The mean value IP_m will provide the amount of interference an AP m is receiving from the rest of APs n (m≠n). So, if it is summed the mean values of all the nodes it is then obtained the interference level in each scenario, all this following equation 16.

$$(16)\quad Interference\_level = \sum_{m=0}^{Ns} IP_m = \sum_{m=0}^{Ns}\sum_{n=0}^{Ns} \frac{IP_{m,n}}{Ns} \;;$$

m \ n	1	2	…	Ns
1	0	$IP_{1,2}$	…	$IP_{1,Ns}$
2	$IP_{2,1}$	0	…	$IP_{2,Ns}$
…	…	…	…	…
Ns	$IP_{Ns,1}$	$IP_{Ns,2}$	…	0

$$P_m = \sum_{n=0}^{Ns} \frac{IP_{m,n}}{Ns}$$

m	IPm
1	IP_1
2	IP_2
…	…
Ns	IP_{Ns}

Table 2.1.Interference penalty between users ($IP_{m,n}$) and users's average penalty (IP_m)

CHAPTER 3. CHANNEL ASSIGNMENT SCHEMES

Once presented the problem, this chapter will propose different channel allocation solutions to reduce the interference in wireless networks applying cognitive radio. The first one will be the optimal solution using integer linear programming, and the second one will be a near optimal solution using minimum spanning tree techniques.

3.1 Channel assignment introduction

Wireless communications, as [12] explains, are used in many different situations such as mobile telephony, radio and TV broadcasting, satellite communication, wireless LANs, and military operations. In each of these situations a frequency assignment problem arises with application specific characteristics. Researchers have developed different models for each of the features of the problem, such as the handling of interference among radio signals, the availability of frequencies, and the optimization criterion.

The literature on frequency assignment problems, also called channel assignment problems, has grown quickly over the past years. This is mainly due to the fast implementation of wireless telephone networks, satellite communication, TV broadcasting and military communication. All these applications lead to many different models and within the models to many different types of instances. Nevertheless, all of them share two common features.

The first feature is that a set of wireless communication connections must be assigned frequencies such that data transmission between the two endpoints of each connection (the transceivers) is possible. The frequencies should be selected from a given set that may differ among connections.

The second one, is that the frequencies assigned to two connections may induce interference to one another, resulting in quality loss of the signal. Two conditions must bet fulfilled in order to have interference of two signals. To begin with, the two frequencies must be close on the Electromagnetic band. Harmonics may also interfere due to the Doppler Effect, but the parts of the Electromagnetic band that are generally selected prevent this type of interference. Also, connections must be geographically close to each other, so that interfering signals are powerful enough to disturb the quality of a signal.

Frequency assignment problems (FAPs) first appeared in the 1960s (Metzger 1970). The development of new wireless services such as the first cellular phone networks led to scarcity of usable frequencies in the radio spectrum. Frequencies were licensed by the government who charged operators for the usage of each single frequency separately. This introduced the need for operators to develop frequency plans that not only avoided high interference levels, but also minimized the licensing costs. It turned out that it was far from obvious to find such a plan. At this point, operations research techniques and graph theory were introduced. Metzger (1970) usually receives the credits for pointing out the opportunities of using mathematical optimization, especially graph colouring techniques, for this purpose.

Until the early 1980s, most contributions on frequency assignment used heuristics based on the related graph colouring problem. First lower bounds were derived by Gamst and Rave (1982) for the most common problem of that time. The development of the digital cellular phone standard GSM (General System for Mobile Communication) in the late 1980s and 1990s led to a rapidly increasing interest for frequency.

But also projects on other applications such as military wireless communication, radio-TV broadcasting, and most recently wireless LANs contributed to the literature on frequency assignment in recent years.

3.2 Optimal solution. ILP (Integer Linear Programming)

Once presented the solution proposed (channel assignment using cognitive radio techniques) in a theoretical manner, this part of the project puts in practice this proposal with an optimal channel assignment solution.

As in [11], the suggested optimal formulation is based on linear programming (LP), an important field in operations research which deals with solving optimization problems. The linear programming problems consist of a linear cost function also called objective function with a certain number of variables which is to be maximized or minimized subject to a certain number of constrains. This constrains are linear inequalities of the variables in the objective function.

There are different types of linear programming depending on the variables of the objective function. In the case of this project these variables are integers, so the problem is called integer programming (IP) or ILP following the same nomenclature as before. If only a subset of the variables are integers, the problem is called a mixed integer programming problem. On the other hand, if rather than arbitrary integers they are restricted to 0 or 1, the problem is called binary integer programming or BIP. In opposition with LP, IP problems are in the worst case undecidable, and in many practical situations NP-hard.

3.2.1 Problem formulation

In order to set out the formulation, the scenario is presented as a graph G=(V,E), where the nodes (vertices) $V=\{v_0,v_1,\dots v_n\}$ are the APs and the edges $E=\{e_0,e_1,\dots e_m\}$ are the connection between those pairs that are within each others range, being n and m the number of vertices and number of edges respectively.

This project requires a simple path, this is a sequence of nodes in a graph, such every two consecutive vertices in the sequence have a direct edge connecting them and no nodes are repeated. If the simple path passes through a node more than once, a cycle is resulted. So, for every AP v, one and only frequency f ϵ F(v) is assigned to v, being f one of the available channels of v.

Following this graph model, the variables, constrains and objective of ILP are presented. To begin with, a straightforward choice for the variables is to use binary variables to represent the choice of a frequency f to an AP_v. So for every node v and available frequency f we define:

$$(17) \quad X_{vf} \begin{cases} 1, \text{ if frequency } f \in F(v) \text{ is assigned to } AP_v \\ 0, \text{ otherwise} \end{cases}$$

As mentioned, each AP should be assigned only one frequency, with this the first constrain is established:

$$(18) \quad \text{Constrain 1: } \sum_{f=1}^{F} x_{vf} = 1, \quad v=1,\ldots,Ns$$

In order to establish the second constrain, pairs of users with a channel assignment that causes a penalty different from zero must be lower than a threshold value IP_{max}, so, if it excides the assignment is forbidden. This value will be determined during the simulations due to the execution time, as it is an important factor and the lower the threshold is, the longer it takes to obtain a solution.

$$(19) \quad \text{Constrain 2: } x_{vf} + x_{wg} \leq 1, f \in F(v), g \in F(w), IP_{vw}(f,g) > IP_{\max}$$

So, by way of an example, if we consider two secondary nodes that overlap each other spatially as in Figure 2.8, one using channel 2 and the other one using channel 5, according to the penalty matrix obtained from Equation 13, their mutual penalty value is different from zero. If this value is grater that the fixed threshold IP_{max}, then one of the frequencies or both of them must be changed until an option is valid. If the penalty is lower than IP_{max}, then the assignment is correct and those frequencies should not be changed.

As this project introduces the use of primary channels and these are not always available because primary users must always be respected and the environment changes constantly. It proposes another objective in order to reduce also the channel switching caused by the changes in the surroundings and as a consequence, the constant channel scanning and beacon broadcast to detect these changes and pass each other this information, matter not tackled in this project. So, it is propose to minimize the use of primary channels, and only used them when there is no more option in order to satisfy the constrains.

The next equation expresses the intention to minimize this other objective:

$$(20)\quad \text{MIN} \sum_{n=1}^{Ns} \sum_{f_1 \in F_p(n)} x_{n,j}$$

To perform the ILP in the simulated scenario, following [13], this project will use the function bintprog provided by the mathematical programming environment Matlab 7.

The function BINTPROG [14] uses a linear programming (LP)-based branch-and-bound algorithm to solve binary integer programming problems. The algorithm searches for an optimal solution to the binary integer programming problem by solving a series of LP-relaxation problems, in which the binary integer requirement on the variables is replaced by the weaker constraint. So, the algorithm searches for a binary integer feasible solution, updates the best binary integer feasible point found so far as the search tree grows and verifies that no better integer feasible solution is possible by solving a series of linear programming problems.

In order to understand the branch-and-bound method it is explained in greater detail in the following lines.

The algorithm creates a search tree by repeatedly adding constraints to the problem, that is, "branching". At a branching step, the algorithm chooses a variable x_j whose current value is not an integer and adds the constraint $x_j = 0$ to form one branch and the constraint $x_j = 1$ to form the other branch. This process can be represented by a binary tree, in which the nodes represent the added constraints. The following figure illustrates a complete binary tree for a problem that has three variables, x_1, x_2, and x_3. Note that, in general, the order of the variables going down the levels in the tree is not the usual order of their subscripts.

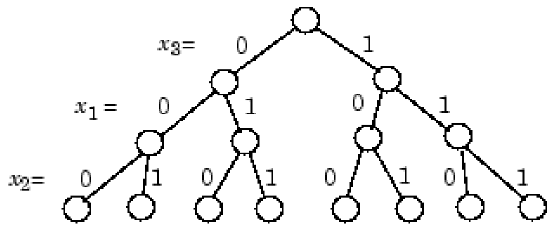


Figure 3.1.Binary tree for three variables, x_1,x_2 and x_3

At each node, the algorithm solves an LP-relaxation problem using the constraints at that node and decides whether to branch or to move to another node depending on the outcome. There are three possibilities. Firt of all, if the LP-relaxation problem at the current node is infeasible or its optimal value is greater than that of the best integer point, the algorithm removes the node from the tree, after which it does not search any branches below that node. The algorithm then moves to a new node. Second of all, if the algorithm finds a new feasible integer point with lower objective value than that of the best integer point, it updates the current best integer point and moves to the next node. Last of all, if the LP-relaxation problem is optimal but not integer and the optimal objective value of the LP relaxation problem is less than the best integer point, the algorithm will continue branching.

The solution to the LP-relaxation problem provides a lower bound for the binary integer programming problem. If the solution to the LP-relaxation problem is already a binary integer vector, it provides an upper bound for the binary integer programming problem.

As the search tree grows more nodes, the algorithm updates the lower and upper bounds on the objective function, using the bounds obtained in the bounding step. The bound on the objective value serves as the threshold to cut off unnecessary branches.

3.3 Near-optimal solution. MST (Minimum Spanning Tree)

Once presented the optimal solution we present an efficient heuristic algorithm based on the minimum spanning tree (MST) problem which is a well-studied problem in graph theory.

An acyclic graph (also known as a forest) is a graph with no cycles. A tree is a connected acyclic graph. Thus each component of a forest is tree, and any tree is a connected forest [15].

Theorem: The following are equivalent in a graph G with n vertices.

i. G is a tree formed by n nodes.
ii. There is a unique path between every pair of vertices in G.
iii. G is connected, and every edge in G is a bridge.
iv. G is connected, and it has (n - 1) edges.
v. G is acyclic, and it has (n - 1) edges.
vi. G is acyclic, and whenever any two arbitrary nonadjacent vertices in G are joined by and edge, the resulting enlarged graph G' has a unique cycle.
vii. G is connected, and whenever any two arbitrary nonadjacent vertices in G are joined by an edge, the resulting enlarged graph has a unique cycle.

Let G(V,E) be a connected graph. A spanning tree in G is a subgraph of G that includes all the vertices of G and is also a tree. The edges of the trees are called branches. There can be more than one spanning tree for every graph.

A minimum spanning tree is then a spanning tree with weight less than or equal to the weight of every other spanning tree. More generally, any undirected graph (not necessarily connected) has a minimum spanning forest, which is a union of minimum spanning trees for its connected components.

3.3.1 Problem formulation

In this project, the weight on the edge is considered to be the overlapped surface between the two nodes connecting the edge. So given a connected graph and a weight $w : E \rightarrow R+$, the algorithm will find a MST and while doing so it will assign to each node an appropriate frequency.

There are different types of algorithms to find the MST, the most common are Prim’s and Kruskal’s algorithms. This project will use Prim’s Algorithm’ to find the MST of a given graph. Prim’s Algorithm constructs the MST starting at an arbitrary node and at each stage it adds a new node to the tree already constructed. The algorithm stops when all the nodes have been reached. The nodes of the MST span at a rate of one node at a time during the execution of Prim’s Algorithm.

Having as an initial reference the NOFA-2 (Near-Optimal Frequency Assignment) of [11], but introducing the possibility of accessing those available channels from the primary band when ever the secondary channel election exceeds a fixed maximum penalty. In the following lines the proposed extension of Prim’s algorithm is detailed and for further study it also includes de pseudo-algorithm.

As mentioned, the algorithm will start on an arbitrary node assigning it the first channel from the primary band. From this point it will choose the node with minimum weight, in the case of this project the minimum weight is the maximum spatial overlap.

Secondary neighbours are defined as the nodes that already have assigned a secondary channel. As in the first round there is only a channel assigned, the actual node will only have a secondary neighbour. So, in this case the algorithm chooses the channel that is five apart from the neighbours’.

If the actual node has two neighbours, then it searches for a channel that is five channels apart from the channels of the neighbours. If there are multiple solutions it chooses the one that causes less penalty.

In the case of having three or more neighbours it only considers the three with higher spatial overlap. In this case it searches for a channel that is “d” channels apart from the channels of the three neighbours, being this d the distance between the desired channel of the actual node and its neighbours’. This d starts being five, but if it does not find any channel that satisfied this condition, it will reduce it in one unit until it finds one. If there are multiple solutions it chooses the one that causes the lowest penalty.

Once it explores the possibility of using the secondary band for the actual node, it calculates the penalty caused between the actual node and its neighbours. If all the penalties are below the fixed threshold, IP_{max}, it will keep the channel chosen from this band, but if it is not below, then it will evaluate the possibility of using primary channels for the actual node.

If any of the penalties exceeds the IP_{max} and the actual node has available primary channels, the algorithm will search for the primary neighbours, being this neighbours the ones with a primary channel assigned.

If it does not have any neighbours, the channel chosen will be any available primary channel the actual node has. In the case it has one, two or three neighbours, it will search for the primary channel that is “d_p” channels from its primary neighbours. Being this d_p the distance between the channels from the primary neighbours and the desired channel of the actual node. This d_p starts being five, but if it does not find any channel that satisfied this condition, it will reduce it in one unit until it finds one. In the case of using the primary band, as it is not always available, there is the possibility that the only solution is to choose the same channel as one of its neighbours. In this case and in the rest, it will choose the channel that causes less penalty with its neighbours.

So, as it did with the secondary band, it compares the penalty caused between the actual node and its primary neighbours with the IP_{max}. If the penalties pass this threshold, the assigned channel will be be one chosen from the secondary band. If the penalties are below the IP_{max}, it compares the penalties between the actual node and its primary neighbours and the penalties between the actual node and the secondary neighbours in order to assign the channel that produces lower penalties.

This process is repeated for every secondary node in order to assign a channel to each one.

In order to better understand this explanation the pseudo-algorithm proposed is detailed below.

Pseudo-Algorithm:

Data: A connected weighted graph with vertices V and edges E.
Result: Minimal spanning tree composed on Vnew and Enew where each $v \epsilon V$ vas a weight indicating its frequency (All eleven channels from the ISM band plus the available primary channels for every user are used).

```
begin
  Vnew={x}, where x is an arbitrary node (staring point) from V, Enew={}
  fx=1
  while  Vnew ≠V do
    Choose edge (u,v) from E with minimal weight (maximum spatial overlap) such that u is
    Vnew and V is not (if there are multiple edges with the same weigth, choose arbitrarily)
    if v has only one neighbour then
      fv=fu+5mod 11
    else if v has only two neighbours then
      let w be the second neighbour to v (u is the first neighbour)
      choose fv s.t. min(|fv-fu|, |fv-fw|)=5
    else
      let w and y be the second and third closest neighbours to v (u is the first neighbour)
      choose fv s.t. min(|fv-fu|, |fv-fw|, |fv-fy|)=d, where d=5
      if fv has multiple solutions then
        choose the channel that minimizes the penalty
      if d=5 does not produce an assignment for fv then
        try d=1,then d=3, then d=2, then d=1
    Calculate penalties of the neighbours with the channel assigned to v
    if (IPs(fv,fu)>IPmax) || (IPs(fv,fw)>IPmax) || (IPs(fv,fy)>IPmax)
      if Cp≠0 (it only assignes primary channel is there are available)
        if v has only one primary neighbour, then
          choose fv s.t. min(|fv-fk|)=dp, where dp=5
          if dp=5 does not produce an assignment for fv then
            try dp=1,then dp=3, then dp=2, then dp=1, then dp=0
          if dp=0
            choose the only possible channel
        else if v has only two neighbours then
          let z be the second primary neighbour to v (k is the first neighbour)
          choose fv s.t. min(|fv-fk|, |fv-fz|)=dp, where dp=5
          if dp=5 does not produce an assignment for fv then
            try dp=1,then dp=3, then dp=2, then dp=1, then dp=0
          if dp=0
            choose the channel of the neighbour that produces less spatial overlap
        else
          let z and t be the second and third closest primary neighbours to v (k is the first
          neighbour)
          choose fv s.t. min(|fv-fk|, |fv-fz|, |fv-ft|)=dp, where dp=5
           if fv has multiple solutions then
             choose the channel that minimizes the penalty
           if d=5 does not produce an assignment for fv then
             try dp=1,then dp=3, then dp=2, then dp=1, then dp=0
           if dp=0
             choose the channel of the neighbour that produces less spatial overlap
        Calculate penalties of the primary neighbours with the channel assigned to v
        if (IPp(fv,fk)>IPmax) || If (IPp(fv,fz)>IPmax) || If (IPp(fv,ft)>IPmax)
          Let IPtots be the sum of the secondary penalties and IPtotp be the sum of the
          primary penalties
          if IPtots<IPtotp
            the solution from the primary band is the assigned
          else
            the solution from the secondary band is the assigned
      else
        the solution from the primary band is the assigned
    else
      The solution from the secondary band is the assigned
   Add vs to Vnews or vp to Vnewp, add (u,v) to Enew
end
```

CHAPTER 4. SIMULATION RESULTS

Once contemplated the different channel assignment proposals, this chapter evaluates its results in the simulation. First it states the scenario and explains how to determine which primary channels are available. From there it does a random allocation in order to further on, appreciate the improvement in the interference level by the mere fact of using primary available channels. Once that is performed it will use it as a reference point to further on compare it with the result in the simulation of the channel assignment solutions proposed: ILP and MST.

4.1 Simulation settings

To have a starting point to compare it later on with the channel allocation solutions proposed, the first simulation will use a random channel allocation over cognitive radio networks, considering as available channels the ones from the ISM band and those channels from the primary band which do not interfere to other primary users, as specified in the interference characterization section of chapter 2. The simulator proposed can be done with any number of channels, but in the case of this project as in the reference studies, it follows the North American channel availability, so the ISM will be considered to have 11 channels.

The simulation is done over a one by one surface as shown in figure 4.1, placing on it primary and secondary nodes with random coordinates. The primary nodes will have a random channel allocation and from this point the SU will decide, depending on the interference with Pus, what channel they can or cannot use. Once every SU knows what primary channels are available, the channel selection will be made, in this case in a random way. Hence, in order to get a statistic to be able to appreciate the tendency of the interference, the simulator generates an elevated number (in the order of a thousand) of random static topologies.

The interference penalty will be function of the number of secondary nodes, the number of primary nodes and the number of primary channels available in the time and location the static scenario is suppose to reproduce. So, in order to obtain these first results the simulation will generate a thousand topologies for each set of parameters.

```
begin
  | for Ns=20:20:80 (20, 40, 60 and 80 SUs)
  |  | for Np=0:15:30 (0,15 and 30 PUs)
  |  |  | for Cp=0:2:6  (0, 2, 4, 6 Cp)
  |  |  |  | for top=1:1000 (1000 topologies)
  |  |  |  |  | 1.Gives random coordinates to the ns SUs and to the np PUs
  |  |  |  |  | 2.Assigns random channels from the Cp to the Pus
  |  |  |  |  | 3.Gives as available channels to de SUs those channels from Cp not used by PUs
  |  |  |  |  | (For every SU, it gives as available those used by PU that are at a distance to
  |  |  |  |  | the studied SU bigger than Dips+Dus and (Disp+Dup))
  |  |  |  |  |   …
end
```

In order to be able to obtain the results, the simulator creates these topologies with 20, 40, 60 and 80 SU, and for each case it evaluates 0, 15 and 30 PU that have available from 0 to 8 channels from the primary band with the intention of simulating all the possibilities.

Simulation configuration	
Number of secondary users(Ns)	20, 40, 60, and 80
Number of secondary channels(Cs)	11
Number of primary users (Np)	0, 15 and 30
Number of primary channels (Cp)	0, 2, 4, 6 and 8
Number of simulations	1000

Table 4.1.Simulation configuration

The usage distance of the secondary users, Du_s, following [10] is fixed to 0.15u and the interference distance of primary users to secondary users, Di_{ps}, is fixed to 0.3u. The u is a unitary unit due to the scenario is normalized to a one by one surface. In order to calculate the rest of desired distances the values from the table 4.2 are used as input values in the simulation, but these values can be changed for further studies.

Input values	
ΔS(ps and sp)	0dB
M_p	15dB
M_s	10dB
α	3.5
Di_p	0.3u
Du_s	0.15u

Table 4.2.Simulation input values to calculate the areas

It is assumed that the sensitivities, for primary users and secondary users are the same, so the difference between sensitivities is zero. The path loss exponent, α, is fixed to 3.5, being this number an intermediate value between the propagation model in free space and the propagation model having in concern the reflection from the earth surface. The protection margins are fixed to 15dBs and 10 dB, assuming primary users must have more protection than secondary user's.

This data permits the APs to calculate the different radius in order to distinguish those channels from the primary bands that are available by following the interference rules mentioned in the first part of this project and to obtain the superficial overlap in order to calculate the interference penalty IP. So, as the fixed distances are Du_s and Di_{ps}, the radius that must be calculated using the equations from the system model section are: Du_p , Di_{ss} and Di_{sp}.

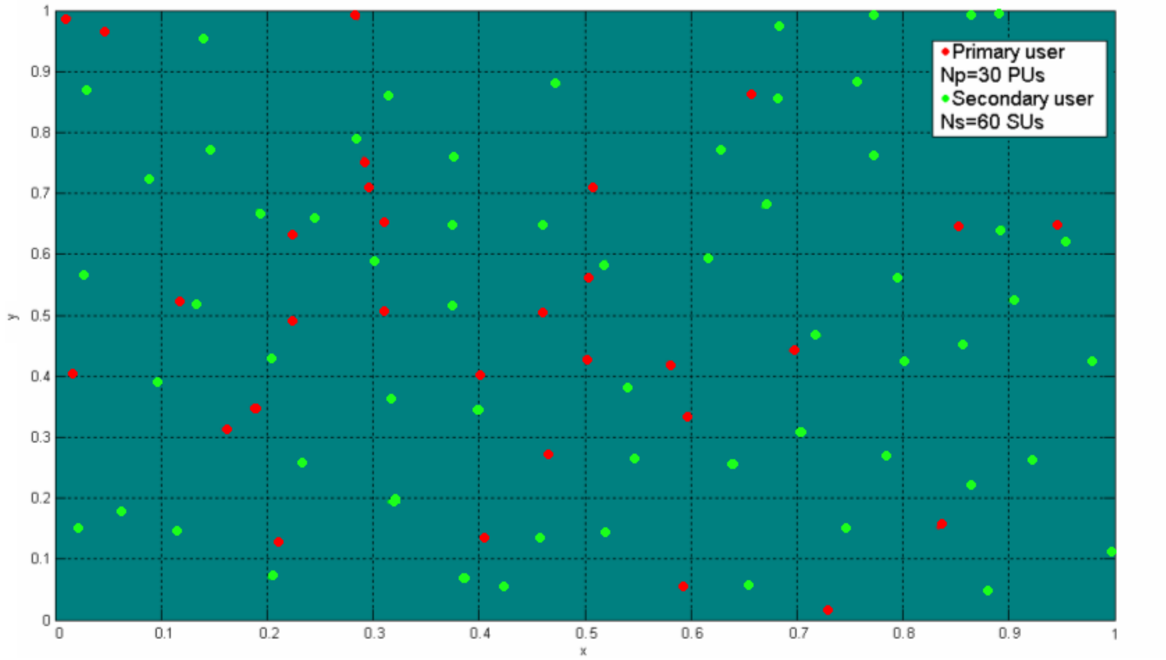


Figure 4.1.Simulation scenario. In this example: Np=30 Pus and Ns=60 SUs

With this information, results about the primary channel availability can be obtained throughout the simulation. As it can be proved in the following graphic, figure 4.2, in the absence of primary users, all secondary users can access the entire primary band. But, as the number of primary users in the scenarios increases, the average number of primary available channels reduces. So, on the first hand, with 4 primary channels and 15PUs there is, in average, nearly one available channel for every secondary user, this means some of the SU will be able to access at least one channel. On the other hand, with 8 channels there is, in average, more than an available channel even with 30PU and nearly three with 15PU in the surroundings.

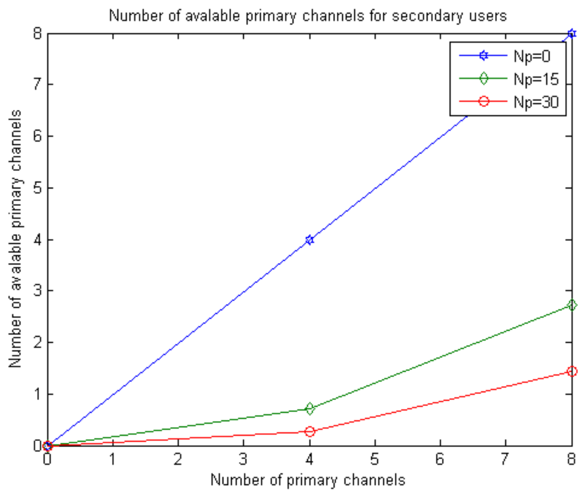


Figure 4.2.Number of available primary channels
(mean value of 1000 random topologies)

Hence, with these same variables, and knowing the coordinates of the rest of the secondary nodes, the APs can calculate the overlapped surface with the rest of secondary users by following the steps explained in appendix A.

4.2 First results. Random channel allocation

Moreover, to appreciate the reduction of the interference by the mere fact of being able to use channels from the primary band, the simulator will give randomly a channel to each secondary node from its available ones, being these channels all the ones from the ISM band and the available channels from the primary band. Using this data, every node calculates the channel overlapping function in order to obtain the interference penalty for each pair of secondary users. To finalize, following the steps indicated in the last part of chapter 2, the simulator obtains the interference level for each scenario.

The following graphic, figure 4.3, represents the mean value of the interference in each scenario.

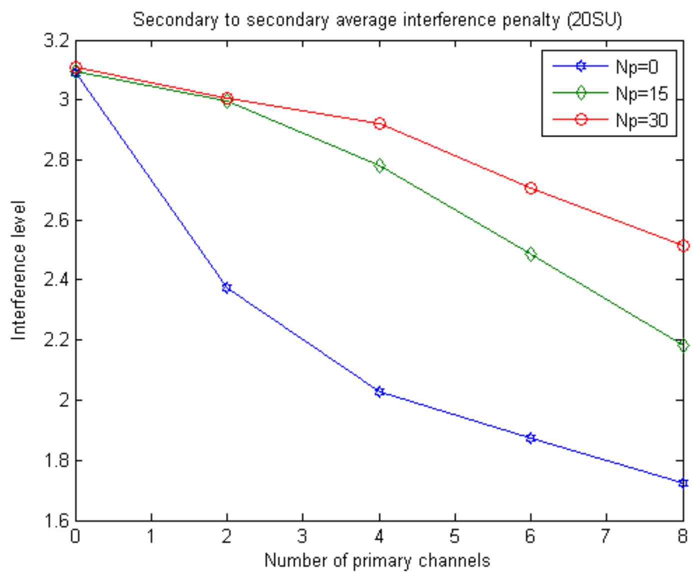


Figure 4.3.Interference level with a random channel assignment
(mean value of 1000 random topologies)

As it can be appreciated in this graphic, the interference level reduces significatively as the amount of primary channels in the surroundings increases. In order to appreciate the decrease of this interference it should be remembered the way to calculate this level, being it the sum of the main values of interference every SU receives in each scenario. So, as anticipated, the interference level reaches lower values if there is not any primary user in the surroundings because there are more available channels from the primary band, but as the number of primary users increases the reduction of the interference is less significant due to there are less usable channels.

An interesting detail found in this graphic is that even reaching lower levels of interference in the absence of PUs, the more channels there are the slower it reduces, while in the presence of PUs, the opposite happens, the interference reduces slower with a few channels but as the number of primary channels increases, the interference reduces faster manner.

So, with this graphic it has been proved that, with a random allocation, a valid way to obtain good statistics, the interference level reduces by allowing the access to primary channels, due to the increase of the useful band and to the fact that, as they are in spectral locations distant from each other, the nodes with secondary frequencies assigned will not interfere with each other.

Once reached this point and verified that the first approach of using primary channels gives good results, the next step it to perform different channel assignment methods in order to delimit the interference.

4.3 ILP versus MST

As mentioned, in order to simulate the ILP problem, it is used a function designed to handle binary integer programming. This function is BINTPROG, from the optimization toolbox proportioned by the programming environment Matlab 7.0 and its superior versions. Unfortunately, it is limited by the computer's architecture and cannot handle a large number of variables.

As already detected in [13], with a large number of variables the function BINTPROG takes a long time to find a solution and in some cases, it cannot find any. In order to solve this problem, found during simulation, the simulation configuration is redesign in order to reduce the number of variables. This reduced configuration is detailed in the table 4.1. Notice also that the number of simulations is reduced in order to shorten the total time of execution.

Simulation configuration	
Number of secondary users(Ns)	8
Number of secondary channels(Cs)	6
Number of primary users (Np)	0, 15 and 30
Number of primary channels (Cp)	0, 2 and 4
Number of simulations	100

Table 4.3.Reduced simulation configuration

So, from now on, whenever the ILP problem is compared with other assignment methods, this reduced configuration is employed in every simulation.

The channel assignment based on ILP always gives a solution with a penalty between pairs bellow the fixed IPmax, as consequence, it gives a much lower interference level than the MST when ever the threshold is very restrictive, defining very restrictive any value lower than 0.4 for IPmax. But as inconvenient its computational time increases too much. This information is verified in the following lines with the results obtained from the simulation.

As it can be appreciated in the following graphic, figure 4.4, the ILP algorithm always gives the optimal solution to its fixed constrains. As one of the constrains consists on limiting the IP to a maximum value IPmax, in a large amount of simulations, in order to obtain a statistic result, it can be appreciated that the interference penalty between pairs of nodes, IP, never exceeds the threshold IPmax.

In contrast with the ILP solution, the MST is designed to find a good solution independently of the fixed IPmax. Due to the search mechanism of this algorithm explained in chapter 3, the fixed IPmax only affects in the decision of searching solutions in the primary band. So if this IPmax has elevated values, higher than the interference penalties produced by the nodes using only the secondary band, it will never explore the possibility of using primary bands as it does not find it necessary. As it can be appreciated in the same graphic, figure 4.4, the MST gives acceptable values, defining as acceptable the values below the fixed IPmax, when ever this IPmax is higher than 0.6, but as the IPmax becomes more restrictive, the percentage of times it exceed the threshold increases. This is because there is a point where the MST cannot obtain lower interference penalty values than the threshold, even if the channel assignment includes the possibility of using channels from the primary band. This will be verified further on with a graphic of the interference level.

As it can be verified in this figure, the random assignment is independent from the IPmax, so as this threshold becomes more restrictive, the amount of times the IP produced exceeds the IPmax, increases.

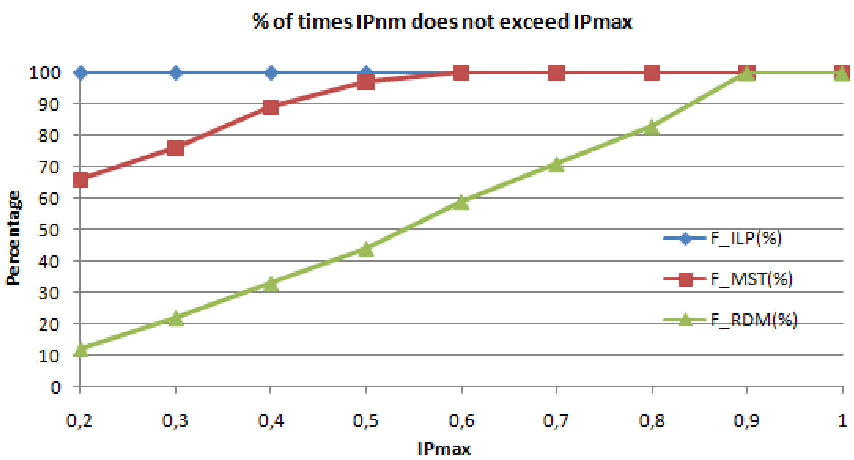


Figure 4.4.Percentage of times the IP does not exceed the IPmax .Np=0, Cp=4

In order to examine this feature in a more exhaustive manner, the figure 4.5 shows the interference level resulting from fixing different values of IPmax. Remember this interference level is the average value resulting from doing an elevated number of random topologies.

So, with this figure, it can be verified that the ILP algorithm, as it accepts any assignment that produces a penalty between pairs lower than the fixed threshold IPmax. With a low-restrictive threshold (greater than 0.4) it produces high levels of interference because it does not have the need to search for better values than the ones fixed by the IPmax. But as it always gives IP values lower than the IPmax, when ever this threshold becomes more restrictive, such as 0.3 or 0.2, the interference level produced by the assignment done by the ILP will give better results than the MST assignment.

The MST algorithm, in contrast with the results from the ILP assignment, even if the IPmax is one, it gives better results than the ILP for values of IPmax greater than 0.4. But as mentioned previously, with smaller values than 0.4 for the IPmax, the interference level seems to stabilize due to it cannot obtain better results.

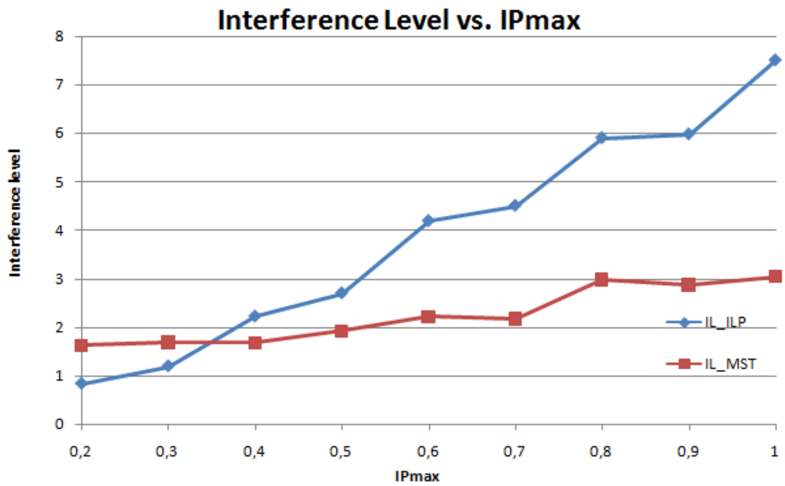


Figure 4.5.Interference level versus IPmax. Np=0, Cp=4

As mentioned previously, the ILP assignment, how more restrictive the IPmax is, the longer it takes to find a solution. This time increases in a way similar to an exponential growth as proved in simulation and shown in figure 4.6a. But the MST, as it always finds a solution independently of the value of IPmax, it takes practically the same in each case. The only difference, time-wise, is that the lower the value of IPmax is, the longer it takes the algorithm to execute because it has to explore the primary band in order to find a better solution than the one obtained by using only channels form the secondary band. But the extra time to execute this process is insignificant as it can be verified in figure 4.6b.

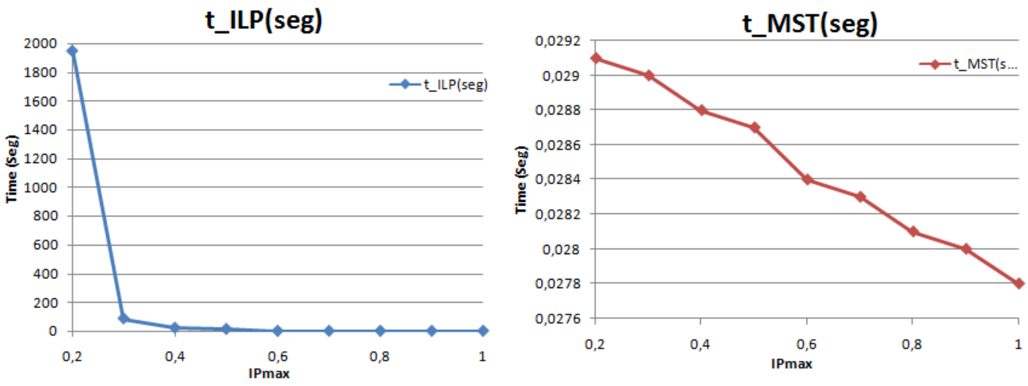


Figure 4.6.a) Assignment execution time for the ILP algorithm. Np=0, Cp=4
b) Assinment execution time for the MST algorithm. Np=0, Cp=4

This graphics do not proportion detailed data, specially the one of the execution time for the ILP algorithm. So in order to proportion the data so the growth of the execution time is appreciated, the following table, number 4.4, shows the detailed time, in seconds of the execution time.

IPmax	t_ILP(seg)	t_MST(seg)
1	0,0358	0,0278
0,9	0,0413	0,028
0,8	0,0423	0,0281
0,7	0,0725	0,0283
0,6	0,0789	0,0284
0,5	13,4043	0,0287
0,4	21,7633	0,0288
0,3	87,1818	0,029
0,2	1951,6034	0,0291

Table 4.4.Execution time of the algorithms versus time. Np=0, Cp=4

Once studied the interference decrease of every algorithm and the execution time versus different fixed thresholds. Even if ILP gives the optimal solution to the fixed constrains and the MST does not always satisfy them when the IPmax is lower than 0.6, it has been considered that the execution time of the ILP makes it an unviable solution for the studied context. So, in order to evaluate the decrease in the interference level for the first proposed scenario, where there is a high density of APs and the channels are the ones proposed in the first simulations, the following studies will evaluate only the results of the MST algorithm.

4.4 Interference level improvement. MST

To begin with, in order to do the following simulations, it is necessary to remember the simulation configuration from table 4.1.

As mentioned before, to appreciate the decrease of the interference level in the scenario by using the MST algorithm, the reference point of interference level to improve will be the one obtained in the first part of this chapter, using a random channel assignment. The following figures show the interference level obtained with a thousand simulations for the MST assignment and the random assignment for 20, 40, 60 and 80 secondary users.

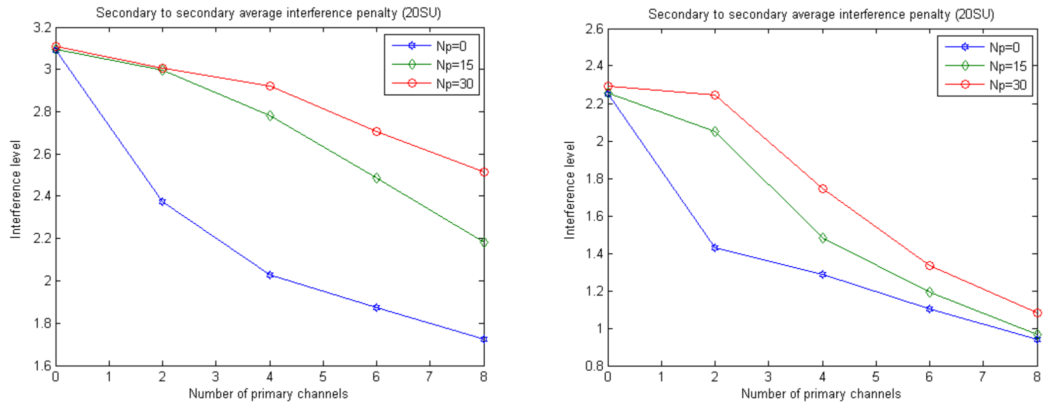


Figure 4.7.a) Random channel assignment for 20 SU b) MST channel assignment for 20SU

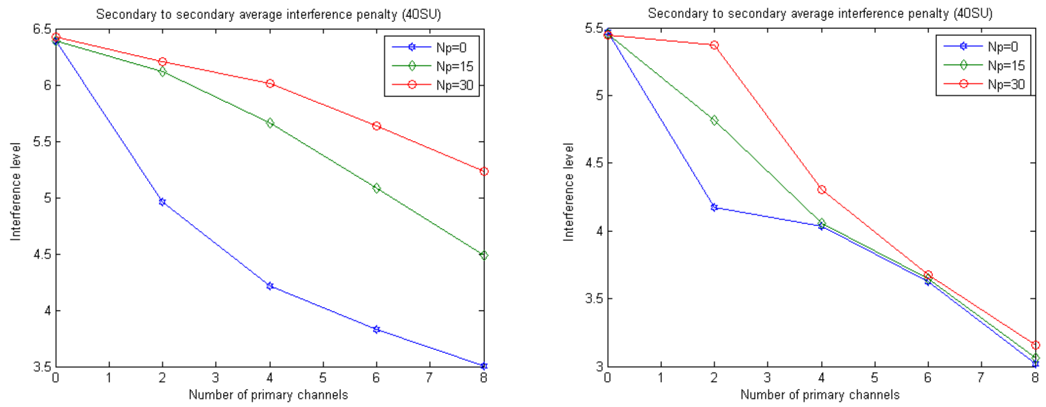


Figure 4.8.a) Random channel assignment for 40 SU b) MST channel assignment for 20SU

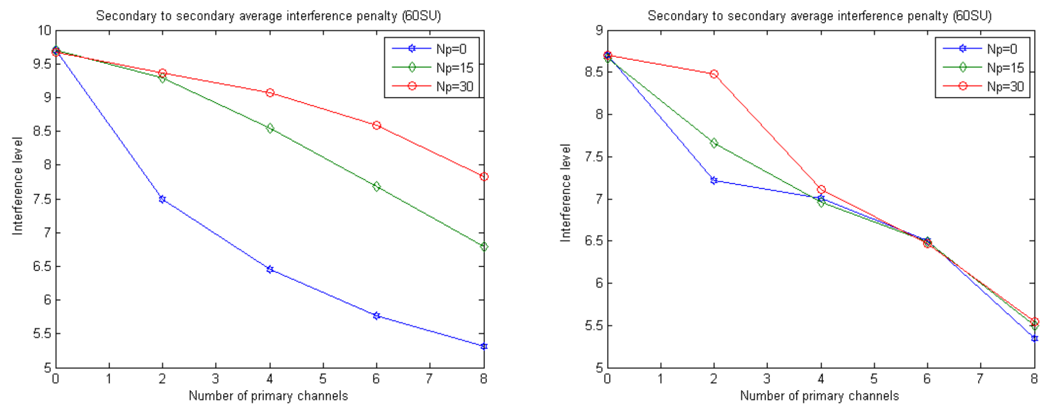


Figure 4.9.a) Random channel assignment for 60 SU b) MST channel assignment for 20SU

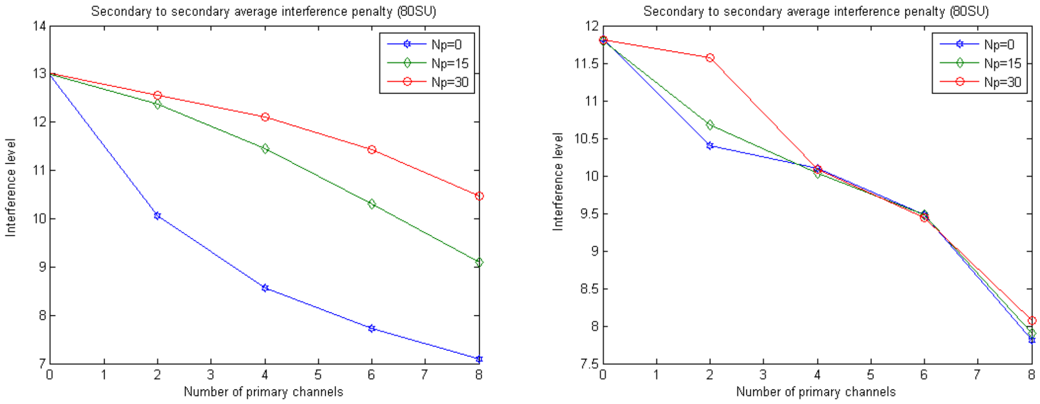


Figure 4.10.a)Random channel assignment for 80 SU b) MST channel assignment for 20SU

This graphics are made using an IPmax of 0.2 for the MST algorithm. As verified with simulation the MST does proportion lower values of interference level. A curious detail appreciated in this graphics is the fact that if there are more than 2 primary channels available, even if there are more primary users, the interference level is practically the same for 0, 15 and 30 primary users. This is because even if there are less available primary channels for the APs caused the presence of primary users, there are enough channels to obtain a lower value of interference level, having in concern that the MST follows the same pattern every time, so it will choose approximately the same amount of primary channels.

The last figure shows the percentage of times the interference penalty between pairs exceeds IPmax. This graphic is done fixing IPmax to 0.2, the number of primary users to 30 and the number of primary channels to 6. As it is appreciated, in the case of the MST, the greater the density of secondary user is the higher this percentage becomes, so, the MST is less efficient for a large number of APs, even if it better than the random assignment. In the case of the random assignment, notice that is does not change much due to the penalty between pairs produced by the random assignment is not affected by the number of secondary users.

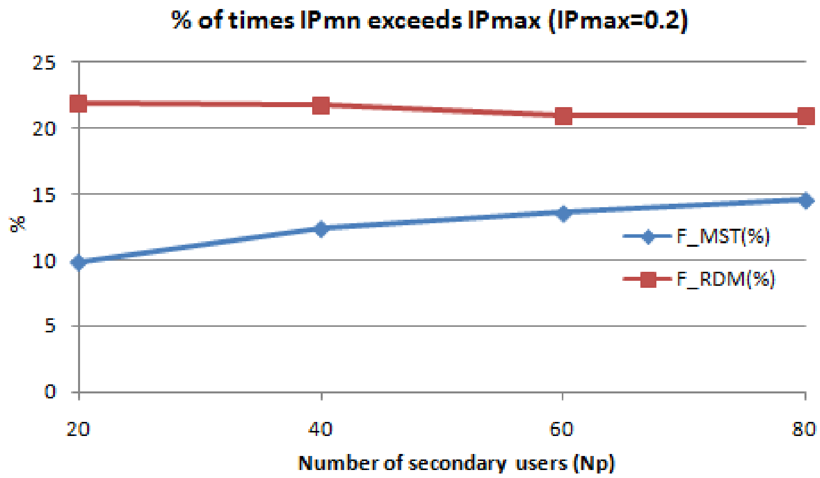


Figure 4.1.Percentage of times the interference between pairs of APs exceeds IPmax. IPmax=0.2, Np=30, Nc=6

CHAPTER 5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

In this study is has been proved that with the mere fact of using primary channels, the interference level reduces in a considerate manner even with a random channel allocation.

From the different channel assignment schemes proposed, the resulting conclusion from the simulation, on the one hand, is that the ILP algorithm obtains lower values of interference level because it always finds the optimal solution to the required constrains. But in a real scenario it would take too much time to execute it. So, the near-optimal solution, even if it does not always obtain an assignment that accomplishes the fixed constrains, its assignment provides interference penalty values close to the optimal.

On the other hand, as mentioned before, the execution time of the ILP to find a solution is unviable for a real local wireless network scenario due to there are two many variables to have in concern. Apart from this reason, it is also unviable because of the dynamic context of the cognitive radio network, where the APs have to adapt to the changes in their environment and the channel assignment must be done every time this context changes.

So as final conclusion, in a real WLAN scenario where it can access available licensed channels apart from the ones from the ISM band, the assignment scheme that adapts better to the context is the MST, because it gives a solution close to the optimal in an acceptable execution time.

5.2 Future work

The following lines present different ideas that could not be studied in this project but however are part of the line of this investigation. For further work different studies can be proposed.

To begin with, the MST assignment scheme can be done using different MSTs algorithms, for example Kruskal’s algorithm, and figure out if is possible to obtain better near-optimal results.

Other studies can be centred in aspects that this project had assumed, but however were not studied, as methods to pass information between APs. This could be done using a distributed coordination framework as proposed in [10], or a centralized coordination framework as the common telecommunication systems.

Finally, mention that in order to simulate a more real scenario the same study can be also applied considering indoor scenarios or adding the attenuations and reflections produced by and irregular environment.

ACRONYMS

LAN: Local Area Network
WLAN: Wireless Local Area Network
DSA: Dynamic Spectrum Access
OSA: Opportunistic Spectrum Access
CR: Cognitive Radio
PU: Primary User (license holders)
SU: Secondary User (cognitive radio users)
AP: Access Point
STA: Client Station
M: Protection margin
S: Sensitivity
BS: Base Station (for primary users)
UE: User Equipments (for primary users)
IP: Interference Penalty
IPmax: Maximum Interference Penalty
ILP: Integer Linear Programming
MST: Minimum Spanning Tree
Du: Usage Distance
Di: Interference Distance
Ptx: Transmission power
I: Interference Power
RF: Radio Frequency
FCC: Federal Communications Commission
IEEE: Institute of Electrical and Electronics Engineers
ETSI: European Telecommunications Standards Institute
IC: Industry Canada
DSSS: Direct-Sequence Spread Spectrum
OFDM: Orthogonal Frequency Division Multiplexing
CCK : Complementary Code Keying
DSL: Digital Subscriber Line
QoS: Quality of Service
MAC: Media Access Control
NIC: Network Interface Controller
VoIP: Voice over IP

REFERENCES

[1] Fidel Ramón García Pedraja /Vicente Quílez Sánchez *IEEE 802.11(Wi-Fi) El estándar de facto para WLAN*, Alcatel.

[2] Ramon Ferrús Ferré, *WLAN*, slides of the subject Comunicacions Mòbils from the EPSC.

[3] Appendix A - *Channels, Power Levels, and Antenna Gains from Cisco Aironet 1200 Series Access Point Software Configuration Guide for VxWorks*. http://www.cisco.com/en/US/docs/wireless/access_point/1200/vxworks/configuration/guide/bkscgaxa.html

[4] Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Vuran, and Shantidev Mohanty, *A Survey on Spectrum Management in Cognitive Radio Networks* Georgia Institute of Technology

[5] Qing Zhao and Brian M. Sadler, *A Survey of Dynamic Spectrum Access*, IEEE SIGNAL PROCESSING MAGAZINE MAY 2007.

[6] J. Mitola, *Cognitive Radio*. Licentiate proposal, KTH, Stockholm, Sweden.

[7] Mitola, J., III; Maguire, G.Q., Jr. *Cognitive radio: making software radios more personal*, Personal Communications, IEEE Volume 6, Issue 4, Aug 1999 Page(s):13 – 18 Digital Object Identifier 10.1109/98.788210

[8] Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Vuran, and Shantidev Mohanty, *A Survey on Spectrum Management in Cognitive Radio Networks*, Georgia Institute of Technology

[9] Kaushik R. Chowdhury, and Ian F. Akyildiz, *Cognitive Wireless Mesh Networks with Dynamic Spectrum Access* Student Member, IEEE, Fellow, IEEE.

[10] Jun Zhao, Haitao Zheng and Guang-Hua Yang *Spectrum sharing through distributed coordination in dynamic spectrum access networks* Microsoft Research Asia, Beijing, P.R. China, University of California, Santa Barbara, CA, U.S.A., Department of Electrical & Electronic Engineering, The University of Hong Kong, Hong Kong, P.R. China

[11] Wassim El-Hajj and Hamed Alazemi *Optimal frequency assignment for IEEE 802.11 wireless networks*, College of Information Technology, United Arab Emirates University, UAE, Computer Engineering Department, Kuwait University, Kuwait

[12] Karen I. Aardal_ Stan P.M. van Hoesely Arie M.C.A. Kosterz *Models and Solution Techniques for Frequency Assignment Problems* Carlo Manninox Antonio Sassanox,December 28, 2001

[13] Morgan Redfield, Ryan Timmons, *Mathematical Modeling of Common Scheduling*, April 9, 2007

[14] BINTPROG Matlab 7.0 help also found in:
http://www.mathworks.com/access/helpdesk/help/toolbox/optim/index.html?/access/helpdesk/help/toolbox/optim/ug/brnox9y.html&http://www.mathworks.com/access/helpdesk/help/toolbox/optim/ug/bintprog.html#f786287

[15] R.J. Wilson, *Introducción a la Teoría de Grafos*, Alianza Universidad, Alianza Editorial, Madrid, 1972.

ANNEX A. CALCULATION OF THE SUPERFICIAL OVERLAP

This overlapping surface is calculated using geometrical equations. To obtain this area, first it is looked for the circle portions coloured in yellow and green in figure A1. To be able to find these areas it is used equation 1 to calculate them independently and further on, sum them to obtain the total surface.

This equation is the result of integrating the formula of the circle's area using polar coordinates in order to obtain the area of "the cup" of a circle, being this portion the result of cutting the circle with a straight line. As shown in this equation this area can be found with the radius R of the circle and the angle θ, which is formed from by joining the centre of the circle to the two points where the circle intersects with the straight line.

(1) $Area_{circle\_portion} = \frac{1}{2} \cdot R^2 \cdot (\theta - \sin\theta)$; R: circle radius

Following figure Annex as an example, to be able to calculate this two areas let define θ_1 (θ_1=2α) and θ_2 (θ_2=2β). Now, it is possible to define two different portions following equation 13, the first in which R corresponds to the radius of the interference circle Di, and the second one in which R is the usage distance, Du. The variables to calculate this portions are the same, so the order to calculate them is irrelevant. Starting upon the yellow portion of the figure, to find α it is needed to know b, and to find b it must be known the intersection points where the two circles cross.

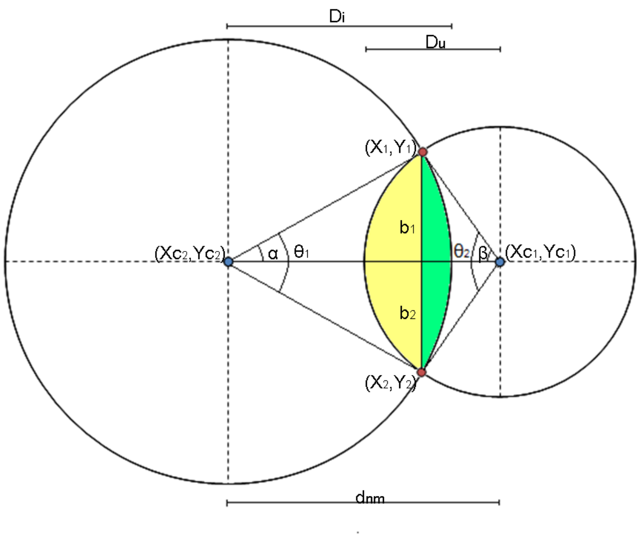


Figure A1. Snm. Geometrical study

To find these two intersection points we equal the equations of the two circles:

(2) Equation circle 1→ $D_u^2 = (X - Xc_1) + (Y - Yc_1)$

(3) Equation circle 2→ $D_i^2 = (X - Xc_2) + (Y - Yc_2)$

From the results of the equation system two values for X and two for Y are obtained. These values will be X_1, Y_1, X_2 and Y_2, the correspondent coordinates of the two points where the circles cross. Once known, let determine b as the straight line which joins these two points. Then, b_1 will be the same as b_2, the half of b.

The last step is to obtain θ_1, the double of α. Hence, α is determined by the following trigonometric rule in expression 4, where is shown the dependence among this parameter with b.

(4) a) $\alpha = \arcsin\left(\frac{b_1}{D_i}\right)$;

b) $\beta = \arcsin\left(\frac{b_1}{D_u}\right)$;

Once known the yellow portion, the green portion can be determined with θ_2, the double of β. In this case the method to find β, the angle needed to obtain the portion of the small circle, depends on how it is positioned in respect to the bigger circle.

If the distance between the centre of the two nodes is bigger than the interference distance, radius of the big circle, then β will be calculated with equation 4, θ_2 the double of β . But, if the distance between centres is smaller than D_i then θ_2' will be calculated as the conjugate angle of θ_2:

(5) $\theta_2' = 2 \cdot \pi - \theta_2 = 2 \cdot \pi - 2 \cdot \mathrm{asin}\left(\frac{b}{D_u}\right)$; in radians