Universitat de Girona

MEDIUM ACCESS CONTROL MESSAGING SCHEME FOR COGNITIVE RADIO NETWORKS

Nicolás BOLÍVAR DÍAZ

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DEPARTMENT OF COMPUTER ARCHITECTURE AND TECHNOLOGY

Ph.D. THESIS

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ADVISOR:

Dr. JOSÉ LUIS MARZO LÁZARO

DOCTORAL PROGRAMME IN TECHNOLOGY

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Submitted in fulfillment of the requirements of the: DOCTORAL PROGRAMME IN TECHNOLOGY

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2012

CERTIFICADO

El Dr. José Luis Marzo Lázaro, profesor catedrático de la Universidad de Girona, por medio de la presente

Certifica que

Con este trabajo, titulado “MEDIUM ACCESS CONTROL MESSAGING SCHEME FOR COGNITIVE RADIO NETWORKS,” que ha estado bajo su dirección, Nicolás Bolívar Díaz cumple con todos los requisitos necesarios para aspirar al título de Doctor en Tecnología.

A los once días del mes de junio de 2012, en la ciudad de Girona,

Dr. José Luis Marzo Lázaro

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ABSTRACT

Cognitive Radio (CR) is one possible option for mitigating the inefficient wireless spectrum distribution that occurs as a result of fixed spectrum allocation. The use of Dynamic Spectrum Access capabilities will potentially enable secondary users to utilize available and unoccupied frequency slots (channels) whenever the licensed users for those channels are absent.

In Cognitive Radio Networks (CRNs), whenever users access the spectrum in an opportunistic manner, control messaging is a crucial issue to ensure that secondary users, i.e. Cognitive Radio Users (CRUs), do not interfere with the licensed users, i.e. Primary Users. In CRNs, where not all CRUs share the same set of channels, i.e. CRUs with Heterogeneous Frequency Devices (HFD), a set of channels must be chosen with care to allow all CRUs in the network to be able to transmit and receive control information.

The thesis considers how Control Messaging Schemes (CMSs) can be used within CRNs and proposes a novel CMS for a CRN supporting HFDs. The thesis starts by classifying the CMSs; generating a new taxonomy and identifying the main characteristics for an efficient CRN with HFD. Then, different mathematical approaches for choosing the set of channels used for control information are presented. Next, a CMS for a CRN with HFDs model based upon the aforementioned characteristics and calculating the minimum number of channels for transmitting control information is proposed. Finally the thesis concludes with a number of CMS being presented and evaluated in terms of their impact upon transmission efficiency.

RESUMEN

Los sistemas de radio cognitivos son una solución a la deficiente distribución del espectro inalámbrico de frecuencias. Usando acceso dinámico al medio, los usuarios secundarios pueden comunicarse en canales de frecuencia disponibles, mientras los usuarios asignados no están usando dichos canales.

Un buen sistema de mensajería de control es necesario para que los usuarios secundarios no interfieran con los usuarios primarios en las redes de radio cognitivas. Para redes en donde los usuarios son heterogéneos en frecuencia, es decir, no poseen los mismos canales de frecuencia para comunicarse, el grupo de canales utilizado para transmitir información de control debe elegirse cuidadosamente.

Por esta razón, en esta tesis se estudian las ideas básicas de los esquemas de mensajería de control usados en las redes de radio cognitivas y se presenta un esquema adecuado para un control adecuado para usuarios heterogéneos en canales de frecuencia.

Para ello, primero se presenta una nueva taxonomía para clasificar las estrategias de mensajería de control, identificando las principales características que debe cumplir un esquema de control para sistemas heterogéneos en frecuencia. Luego, se revisan diversas técnicas matemáticas para escoger el mínimo número de canales por los cuales se transmite la información de control. Después, se introduce un modelo de un esquema de mensajería de control que use el mínimo número de canales y que utilice las características de los sistemas heterogéneos en frecuencia. Por último, se comparan diversos esquemas de mensajería de control en términos de la eficiencia de transmisión.

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To my friends and all the other people that, in one way or another, contributed to finish my thesis.

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GLOSSARY

(Frequency) Band: a continuous part of the wireless frequency spectrum used for communications.

Beacon: a radio signal for guidance.

Binary Integer Linear Program (B-ILP): a mathematical optimization problem in which all variables are binary, i.e. ‘0’ or ‘1’. The B-ILP is a NP-Hard problem.

Broadcast Signaling: a method for transmitting the same signals to all the users in a specific range.

Channel: a part of a wireless frequency band used for user communications.

Common Control Messaging (CCM): A method in which control messages are all sent through one common channel.

Control Channel Problem: the problem of finding the channel(s) needed to transmit control signals to all the users in a network.

Control Messaging (Scheme): a method for transmitting control messages to all users in a network.

Control Plane: the part of the architecture in which control functions of the network are included.

Cognitive Central Base Station (CCBS): the central entity in a Centralized Cognitive Radio Network.

Cognitive Pilot Channel (CPC): a channel that is used for transmitting pilot signals while using the same characteristics as a Cognitive Radio Network.

Cognitive Radio (CR): the evolution of Software Defined Radio (SDR), where devices are able to learn and adapt (Mitola III & Maguire, 1999).

Cognitive Radio Network (CRN): network where user devices are able to adapt to the environment (Mitola III & Maguire, 1999).

Cognitive Radio User (CRU): a user able to learn and adapt from the environment (Mitola III & Maguire, 1999).

Dedicated Control Messaging (DCM): a method in which control messages are sent through specialized channel(s), i.e. no data is sent through those channels.

Dynamic Spectrum Access (DSA): mode in which users enter the frequency spectrum in a dynamic manner.

Energy Reduction (ER): A method for reducing the power used in the network.

Fixed Control Messaging (FCM): a method in which control messages are always sent through the same set of channels.

Frequency Agile (Network): networks able to rapidly change their operation frequency.

Frequency Assignment Problem: the problem of assigning a part of the spectrum for communications to the biggest possible number of users.

Frequency (-Division) Approach: a method in which different signals are sent at the same moment through different frequency slots.

Frequency Slot: a predefined part of the wireless frequency spectrum.

Greedy Approach: a method for solving global optimization problems by finding local optimum solutions.

Heterogeneous Frequency Devices (HFD)/Heterogeneous CRU: CRU devices that use different sets frequency slots (channels) to communicate.

Hop: a change in the operating frequency slot/channel of a user.

Hopping Control Messaging (HCM): a method in which the channels where control messages are transmitted vary over time.

In-band Transmission: information transmitted in the same logical channels of the data transmission (Sallent, et al., 2009).

Medium Access: the method for a user to access the medium, e.g. the wireless spectrum.

Medium Access Control (MAC) Protocol: the control protocol used in a network for each user to access a part of the medium for communications.

Minimum Channels Problem: the problem of finding the minimum set of channels needed to transmit control signals for each user.

Multiple Control Messaging (MCM): a method in which control messages are sent through more than one channel.

Multiplex: simultaneous transmission of several messages through the same channel.

NP Problem: nondeterministic polynomial time problem, i.e. a solvable problem in polynomial time by a nondeterministic Turing machine.

NP-complete Problem: an NP-problem for which no polynomial-time algorithms are known to solve this problem.

NP-hard Problem: an NP problem which is at least as hard as the hardest problems in NP.

Out-band Transmission: information transmitted in different channels of the data transmission (Sallent, et al., 2009)

Overlay (Transmission): transmitting signals using a certain level of power that can interfere other transmissions if a set of rules is not properly defined.

Opportunistic Spectrum Access (OSA): accessing the spectrum in an opportunistic manner, e.g. when a channel is free to be used.

Primary User (PU): a user that has priority to use a band or channel. PUs are usually licensed users, i.e. users that have a license to use a bans or channel.

Satisfiability Problem (SAT): the problem of determining if a set of variables of a Boolean formula can be assigned to make the entire formula TRUE.

Secondary User (SU): a user that has partial, or no license to transmit through a channel, but can communicate through that channel when the channel is available.

Shared Control Messaging (SCM): a method in which control messages are sent through the same channels data is sent.

(Wireless Frequency) Spectrum: frequency representation of the wireless medium in which data can be possibly sent through.

Spectrum Access: 1. the process in which a user enters the spectrum for communication. 2. in this work, we consider the spectrum decision and spectrum sharing as parts of an entity called spectrum access, considering those two blocks responsible for the users' medium access.

Spectrum Decision: the process of deciding in which holes to allocate communications (Akyildiz, et al., 2008).

Spectrum Hole: a part of the spectrum that is not used at a specific moment.

Spectrum Mobility: the CRU ability to leave a frequency portion of the spectrum occupied when a PU starts using the same part of the spectrum and then, to find another suitable frequency hole for communication (Akyildiz, et al., 2008).

Spectrum Scarcity: the absence of available spectrum to communicate.

Spectrum Sensing: identification of the most likely white spaces or spectrum holes in a specific moment (Akyildiz, et al., 2008).

Spectrum Sharing: function consists on maximizing the Cognitive Radio Users (CRUs) performance without disturbing Primary Users (PUs) and other CRUs (Akyildiz, et al., 2008), (Wang, et al., 2008).

Time (-Division) Approach: a method in which different signals are transmitted in the same channel through different time slots.

Turing Machine: a device that manipulates symbols according to a table of rules.

Underlay (Transmission): the transmission of signals under a predetermined threshold.

Underlay Control Messaging (UCM): a method in which control messages are transmitted below a threshold to not interfere with data transmissions while possibly using the same channels.

Wireless Frequency Allocation Problem: the problem of allocating new resources into the wireless frequency spectrum.

White Space: (syn.) Frequency/Spectrum Hole.

Chapter 1. Introduction

1.1 Cognitive Radio Networks and the Wireless Frequency Allocation Problem

1.1.1 Wireless Frequency Allocation Problem

One of the main problems that was identified in the insertion of future wireless applications is that an apparent scarcity exists in the wireless frequency spectrum. However, studies have demonstrated that the spectrum is inefficiently distributed as opposed to scarce (Shukla, A. et al. QinetiQ Ltd., 2007). In Fig. 1, the difference between spectrum scarcity and spectrum misuse is shown. In the first scenario, a new application, represented by U6, wants to use the wireless spectrum but has no space to communicate. In the second scenario, the same application is not able to communicate due to an inefficient distribution.

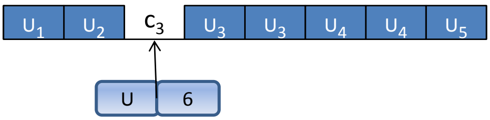


FIG. 1.1 Spectrum scarcity

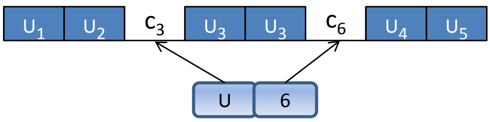


FIG. 1.2. Spectrum misuse

Fixed spectrum licensing has produced an apparent scarcity in the wireless frequency spectrum. In order to improve the use of the spectrum, Cognitive Radio (CR) has been suggested for efficient spectrum occupation. The CR systems have the ability to detect free frequency slots in the spectrum, i.e. "white spaces", and to allocate the CR communications in these white spaces by using Dynamic Spectrum Access (DSA) mechanisms (IEEE, 2006) (Akyildiz, et al., 2008) (Mitola III & Maguire, 1999) (Shukla, A. et al. QinetiQ Ltd., 2007). CR has already been considered as the main technology for the Institute of Electrical and Electronics Engineers (IEEE) standards, such as the IEEE 802.22 for Wireless Regional Area Network (WRAN), which identifies white spaces in the TV frequency spectrum. CR is also considered for standards related to DSA networks that are included in the IEEE SCC41 (IEEE, 2008).

1.1.2 Cognitive Radio Networks

CR Networks (CRNs) were defined as networks where user devices are able to adapt to the environment (Mitola III & Maguire, 1999). Among the adaptability characteristics, the CRN should use the spectrum in an opportunistic manner. In order to do so, CR devices should be able to recognize spectrum holes, and to use DSA capabilities through those frequency slots. Therefore, CRNs are excellent candidates for solving the apparent scarcity problem.

In general, a CRN should be able to perform 4 tasks efficiently: spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. Spectrum sensing refers to the identification of the most likely white spaces, or spectrum holes, in a specific moment. Spectrum decision refers to the process of deciding in which holes to allocate communications (Akyildiz, et al., 2008). The spectrum sharing function consists on maximizing the Cognitive Radio Users (CRUs) performance without disturbing Primary Users (PUs) and other CRUs (Akyildiz, et al., 2008) (Wang, et al., 2008). In this work, we consider the spectrum decision and the spectrum sharing tasks as parts of an entity called Spectrum Access. Spectrum mobility is the CRU ability to leave a frequency portion of the spectrum occupied when a PU starts using the same part of the spectrum and then, to find another suitable frequency hole for communication (Akyildiz, et al., 2008). These spectrum tasks are depicted in Fig. 2.

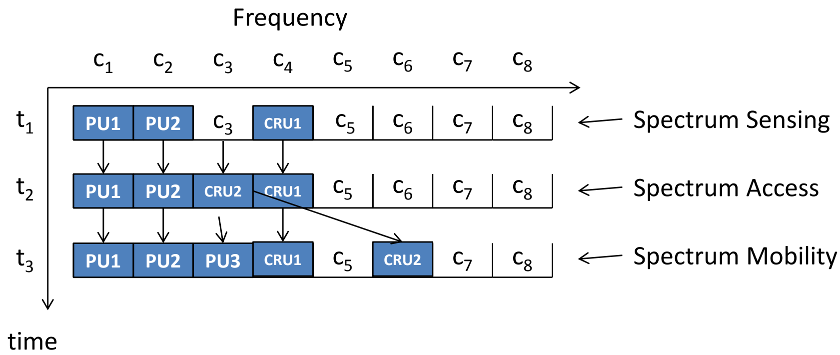


FIG. 2. Spectrum Tasks

CR devices should have, then, the ability to sense, recognize and adapt to specific characteristics of the environment. One of the CRN most important characteristics is the ability for the CRU to dynamically access the spectrum. However, CRUs might also be capable of recognizing patterns of occupancy, to reduce the energy used for sensing, signaling and transmission. For this reason, Cognitive Radio has been considered as an alternative to reduce energy consumption for wireless communications and has also been appointed as a solution to the apparent wireless spectrum scarcity problem (Akyildiz, et al., 2008) (Palicot, et al., 2010) (Mitola III & Maguire, 1999).

1.2 Cognitive Radio Networks Control Messaging: Background and Past Contributions

A cognitive pilot channel (CPC) is a solution proposed in the End-to-End Reconfigurability (E2R) project for enabling communication among heterogeneous wireless networks. The CPC consists of controlling frequency bands in single or multiple "pilot" channels (Bourse, et al., 2007) (E3, 2009) (Filo, et al., 2009) (Sallent, et al., 2009). In (Bolívar & Marzo, 2011), we have presented a basic model for a Centralized CRN that uses CPCs for signalization and control. The main idea is to introduce a control signal, basically periodical beacons, to announce channel availability, for spectrum access and the requirement of leaving a channel if a PU wants to access its licensed channel. The basic model of the CRN provides signaling through CPCs distributed in every available channel or frequency slot. The control is performed by using frequency-division and time-division multiplexing techniques. This control, as expected, allows the utilization of the CRN by heterogeneous CRU devices. In terms of energy, transmitting through every available channel would be inefficient as the entire wireless spectrum channels would all be occupied in a specific moment. Considering this problem, new alternatives should be explored to reduce the energy used for signaling CRUs channel availability. In order to reduce energy consumption, in (Bolívar & Marzo, 2010), we used the characteristics of the combined time/frequency approach for the Central Cognitive Base Station (CCBS) in order to send a signal with a new available channel only when a CRU that was not transmitting is requesting communication. We also considered the benefits of using a distributed control and a centralized database to reduce the amount of energy used to signal this availability in the CRN.

However, the CCBS still needs to broadcast signals to its users at specific moments. Signals that must be broadcast by the base station include periodical beacons and alarms, among others (Chiu, et al., 2004). Several broadcasting problems, such as the minimum broadcasting energy problem (Cagalj, et al., 2002) and the allocation for broadcasting heterogeneous data in multiple channels (Hsu, et al., 2005) (Tsai, et al., 2009), have been studied. The channel allocation/frequency assignment problem has been studied in static and dynamic environments. We have studied the articles of (Aardal, et al., 2007) and (Katzela & Naghshineh, 1996) for an overview of models and solutions to the frequency assignment problem in those environments, respectively. One of the main considerations for studies in frequency assignment problems is that a channel can generate interference in adjacent channels. In this work, since the broadcast signaling is transmitted identically for each channel and only in a couple of a large number of sub-channels (Bolivar, et al., 2010) (Bolívar & Marzo, 2010), by using adequate modulation/coding schemes, interference among adjacent channels can be assumed to be non-existent.

The broadcast frequency assignment problem for frequency agile networks was introduced by Steenstrup in (Steenstrup, 2005). The problem is analyzed for an ad-hoc network and a greedy approach was used to find the minimum number of channels that are needed for broadcasting control information. In (Kunar, et al., 2008), the authors define clusters for finding this minimum number of frequency channels under the same conditions as in (Steenstrup, 2005). In (Lazos, et al., 2009), the authors considered different base stations and use the clustering approach for finding the minimum number of channels needed for control in a CRN. A greedy approach is used to solve the corresponding clustering problem.

The problem of obtaining the minimum number of channels for a base station, e.g. the CCBS, to transmit to all its users is an optimization problem. The dynamic characteristics of the CRN include not only the entrance and departure of CRUs, but also external factors, e.g. the presence of PUs, must be considered. In (Bolívar & Marzo, 2011), the authors associated this problem to a satisfiability one, which is NP-complete. A greedy approach was used to find the minimum number of channels for the broadcasting transmission. We extend the results of (Bolívar & Marzo, 2011), by associating the broadcasting signaling problem for one base station with a set covering one which is known to be NP-hard. We compare the solutions given by a Binary Integer Linear Program with those obtained by using a greedy approach by considering the dynamics of the system and trying to find a compromise for choosing an acceptable number of channels for the broadcasting signaling problem.

Joint time and frequency control for assuring effective spectrum sharing are used to effectively control the CRN. For transmitting channel availabilities, network discovery and channel petitions, a frequency-based approach, using beacons in a CPC for communication between the CCBS and CRUs is proposed. The CCBS sends beacons via parallel communication in the first two sub-channels of the previously determined minimum number of channels (frequency slots). With this approach, the system is guaranteeing to be using all the available frequency bands for communications. The utilization of the CPCs instead of a dedicated control channel allows Heterogeneous Frequency Devices (HFD) i.e. devices that operate in different channels, to communicate in the CRN. When a CRU requests access to the CRN, the CRU already knows which channels are available by using these beacons. A complementary control is used and it is based on a time-division approach, in which the PU entrances are detected via time slots.

1.3 Objectives and Motivation

1.3.1 General Objective:

The main objective of this work is to design a CR Messaging Scheme using CPCs to control the CRN by using some of the available channels.

1.3.2 Particular Objectives:

The particular objectives for this work are

1. For Spectrum Access: To create a blueprint for communicating with HFDs by using a time/frequency approach combined with CPCs.
2. For Spectrum Mobility: To design a method for finding the minimum number of CPCs to reduce energy consumption meanwhile guaranteeing efficient communication among all CRUs.

1.3.3 Motivation:

The motivations behind this work can be related to the particular objectives as:

1. Avoiding the presence of a dedicated control channel so HFDs can be controlled in the same CRN.
2. Reducing the numbers of hops, so that hops only exist when a CR User (CRU) needs to leave a channel.

1.4 Outline of the thesis:

This thesis proposal is structured as follows. In Chapter 2, the state of the art for control messaging schemes (CMS) classification and a taxonomy for the CMS are presented. In Chapter 3, the minimum channel number problem is presented and analyzed using two mathematical approaches: greedy and binary integer linear programming (B-ILP). In Chapter 4, a CRN model suitable for users with Heterogeneous Frequency Devices is presented and a CMS energy reduction, by using the minimum channel problem for this model, is analyzed. In Chapter 5, a summary of the conclusions and some final remarks are presented.

1.4.1 General Contribution:

The general contribution related to the main objective is to propose a strategy to use the advantages of CR in networks formed by heterogeneous frequency CRUs.

1.4.2 Particular Contributions:

The particular contributions we present in this thesis are:

1. The creation of a classification of control mechanism schemes, presented in Chapter 2 and in (Bolívar & Marzo, 2012).
2. A mathematical method for finding the minimum number of channels needed to communicate with all CRU in a centralized CRN, shown in Chapter 3 and in (Bolívar & Marzo, 2011).
3. A CR model suitable for CRUs that use HFDs, i.e. operate in different channels, introduced in Chapter 4 and in (Bolivar, et al., 2010). Several publications have been developed from this model (Bolívar & Marzo, 2010) (Bolívar & Marzo, 2011).

Chapter 2. Control Plane Definitions and Previous Work

In order to efficiently distribute the CRUs in their corresponding channels without interfering with both previous CRU communications and PU in their licensed bands, coordination and control signals must be continuously sent in the CRN. The need of a control plane has been discussed in (Jing & Raychaudhuri, 2007). A literature review of some of the available control channel strategies can be found in (Lo, 2011). Similar strategies are presented in (Chowdury & Akyildiz, 2011) and in (Theis, et al., 2011) for the rendezvous problem, i.e. user discovery in a DSA environment. In this chapter, we provide a quick review about the control plane alternatives by combining the classifications defined in the abovementioned literature and expanding them to consider all the control plane alternatives.

2.1 Taxonomy

In (Lo, 2011), a classification for the control channel schemes is presented. Control channels can be classified into overlay and underlay. The overlay approach can be divided into in-band and out-band. The in-band control channels are divided then into sequence-based and group-based. At the same time, a different classification was being studied and was presented in (Bolívar & Marzo, 2012). In the latter taxonomy, which will be used for this work, the same underlay and overlay classification is used, but four different dichotomies were presented.

There have been different approaches for transmitting control signals for CRN. Since a dedicated common control channel might not be available at all times, several techniques have been discussed for the ‘control channel’ problem. However, control signals are basically transmitted through the following strategies.

According to the specialization of the channel, we can divide the control messaging strategies in dedicated and shared control messaging; according to the number of channels used for control messaging, in single (common) and multiple control messaging. According to the frequency-changing nature of the channels, in fixed and hopping control messaging. Finally, according to the lever of power, we can divide them in underlay and overlay control messaging.

The utilization of dedicated control messaging implies the presence of specialized control channels, while the shared control messaging indicates that the same channels are used for both control and communication messages. In single, or common, control messaging only one channel is used for transmitting control messages. On the other hand, multiple control messaging implies that at least two channels are used at the same time for control message transmission. Fixed control messaging indicates that the channel(s) for the transmission of control messages are the same for the whole period of time. Hopping control messaging is presented when the channels used for control messaging vary over time. Finally, underlay control messaging indicates that the control messages are sent below a power threshold, while overlay control messaging indicates that these messages are sent only through available channels. In this section, these classes of messaging are explained in detail.

2.1.1 Dedicated Control Messaging (DCM):

This approach is the equivalent of having Dedicated Control Channels (DCCs). In this case, the control messages are transmitted separately from the data messages, i.e. through different channels. In Fig. 3, an example of the dedicated DCM with one DCC is shown.

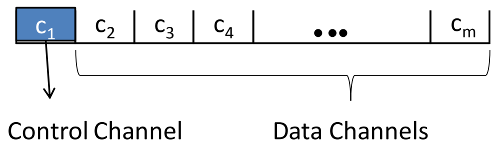


FIG. 3. Dedicated control messaging

The advantage of using DCM is that no additional processing is needed to differentiate the control messages from the data ones. The main disadvantage is that in the case that control messaging is not needed at every time slot, a waste of resources, which is a critical issue for CR as a solution of the wireless spectrum scarcity problem, is present.

2.1.2 Shared Control Messaging (SCM):

On the other hand, in the SCM the same channels are used for transmitting both control and data messages. Different strategies must be taken into account for separating both types of transmission. In Fig. 4, an example of a frequency-division for the control transmission in the same data channels is shown. Other strategies include time-division and code-division, among others.

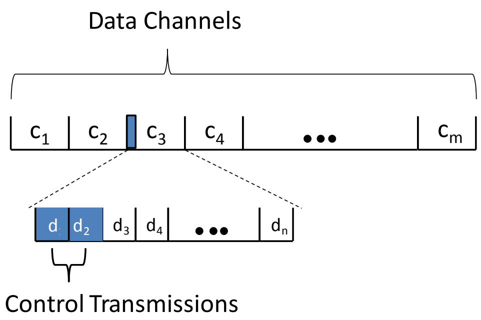


FIG. 4. Shared control messaging (Frequency-division)

In the case from Fig. 4, two sub-slots are used for transmitting control messages. In this scenario, the resources might be used more efficiently but more complex processing is needed, compared to DCM.

2.1.3 Single (Common) Control Messaging (CCM):

In this case, only one channel is used for transmitting control messages. To be a suitable alternative for transmitting control messages, CCM requires that all devices must have at least one available channel in common for being the Common Control Channel (CCC). In Fig. 5, c_3 is selected among all the data channels for transmitting the control messages as a CCC.

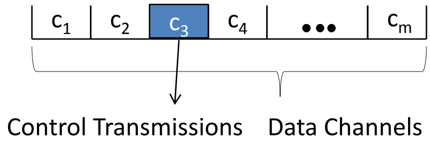


FIG. 5. Common control messaging

The main problems that might arise for this strategy in CRN are that the control channel could be also affected by the presence of PU. For heterogeneous devices, this approach might not be useful since the devices in the CRN could present different sets of channels.

2.1.4 Multiple Control Messaging (MCM):

In this case, multiple channels are used for transmitting control information. This approach is very useful when not all of the users share the same characteristics such as frequency bands and location. In Fig. 6, c_1 and c_3 are the channels selected for control transmissions.

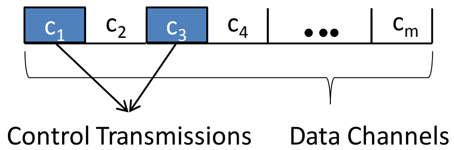


FIG. 6. Multiple control messaging

The main disadvantage of MCM is that the users must be able to receive control messages in different channels. A special case of the MCM is the clustered approach, in which users are divided into clusters according to a specified characteristic. In Fig. 7, an example of the clustered control messaging is shown.

2.1.4.1 Clustered Approach

Let us suppose a centralized CRN covering 8 CRUs: U1, U2, … , U8, each of them using different sets of frequency channels. A Central Cognitive Base Station, in this case, BS, should assign them the necessary channels to transmit control information.

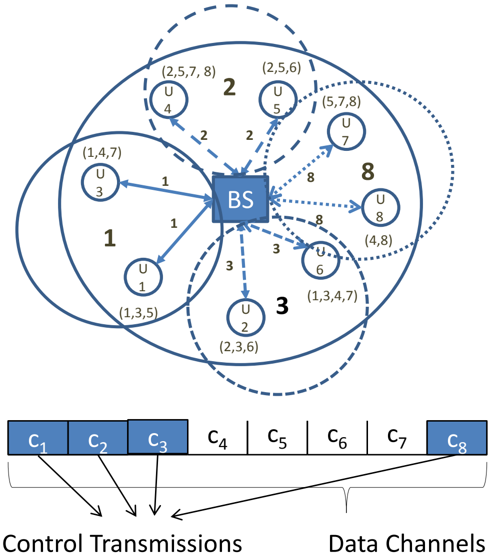


FIG. 7. Clustered Control Messaging

In the example shown in Fig. 7, four channels are selected for transmitting control information. Channel 1 is used for U1 and U3, channel 2, for U4 and U5. Channel 3, for U2 and U6, and channel 8, for U7 and U8.

2.1.5 Fixed Control Messaging (FCM):

In this scenario, the same sets of channels are used to transmit control messaging over time. The advantage of FCM is that the receivers are set in the same frequencies. In Fig. 8, c_3 is chosen to be the channel used for control transmissions.

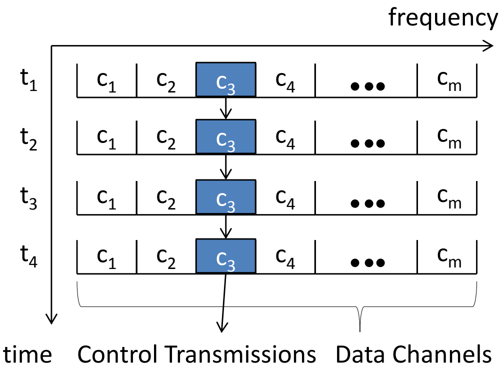


FIG. 8. Fixed control messaging

The main disadvantage of the FCM is that the channels used for control might be also affected by the presence of PU and could be unavailable for control transmission in critical moments.

2.1.6 Hopping Control Messaging (HCM)

In this scenario, the users change along time the channels they use to receive control messages. In Fig. 9, a sequence for choosing the channel used for control messaging is shown.

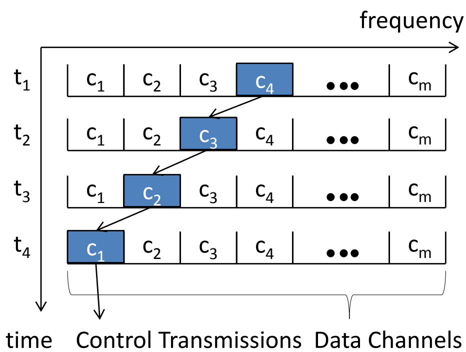


FIG. 9. Hopping control messaging

The main advantage of the HCM is that if a PU is present in a channel that was assigned for control transmissions, another channel might be selected for control messaging. The main disadvantages are that both extra information and a synchronization mechanism are needed.

2.1.6.1 Default Hopping (DH-HCM)

In this hopping mechanism, a pattern for the control channel is introduced. CRUs should be aware of the sequence beforehand. In Fig. 10, besides the frequency vs. time representation, the time vs. frequency representation is shown, to represent continuity in time.

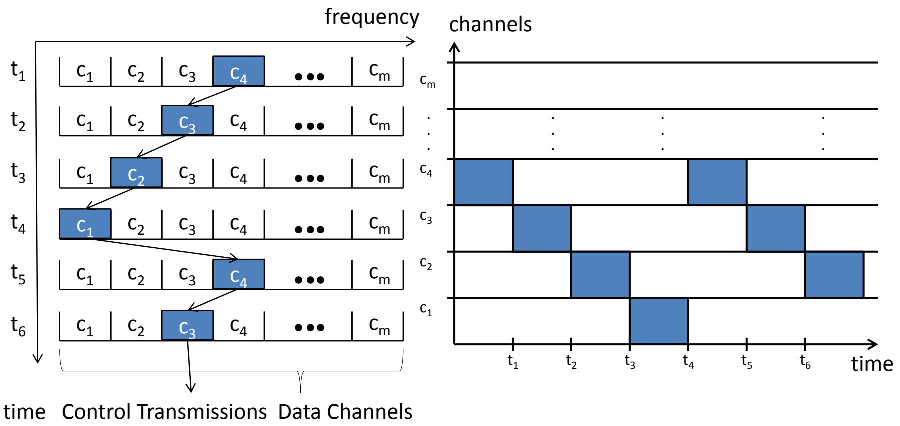


FIG. 10. Default Hopping

2.1.6.2 Common Hopping (CH-HCM)

In this hopping mechanism, two or more users, after negotiating, hop to the same channel in order to share control information. In this scenario, the next channel(s) used for control information is chosen from the set of available ones. In Fig. 11, both representations in frequency vs. time and vice versa are presented.

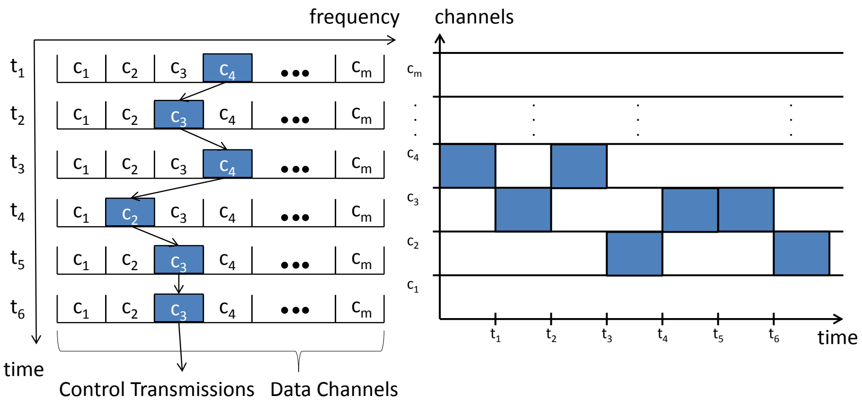


FIG. 11. Common Hopping

2.1.7 Underlay Control Messaging (UCM):

This approach is the equivalent of transmitting control signals below a power threshold among one or more channels. An example of the UCM is shown in Fig. 12.

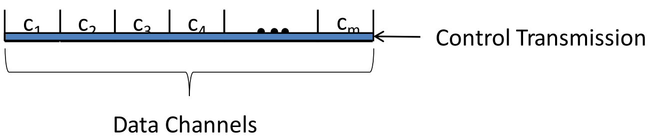


FIG. 12. Underlay control channel

In this case, if a PU requests to use its licensed channel, the control signals should not interfere with the PU transmission. The main advantage is that control transmissions should be performed at any time. The main disadvantage is that the power limit should be chosen carefully in order to guarantee that no licensed user is disturbed.

2.1.8 Overlay Control Messaging (OCM):

This approach is the equivalent of using Opportunistic Spectrum Access (OSA), i.e. a channel could be used for transmitting control information only if in that channel power indicates that the channel is unoccupied, or DCCs. An example of an OCM using OSA is shown in Fig. 13.

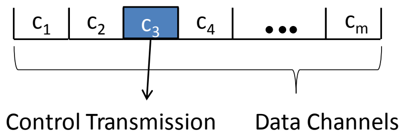


FIG. 13. Overlay control channel

The main problem that might arise for this strategy is that in the case of a DCC, resources might be wasted. On the other hand, in the OSA case, a power level might be misinterpreted in the sensing part and cause interference, and in presence of PU, a hopping mechanism might be needed to be activated to avoid the interference.

2.2 Control Messaging Schemes for Heterogeneous Frequency Devices

2.2.1 Parent Structures

The problem for controlling a network with HFDs is that not every CRU has the same available set of channels in order to communicate. According to the taxonomy in section 2.1, we can define a CMS using the parent structures, e.g. DCM, CCM, FCM, and OCM for representing the use of a dedicated and fixed overlay control channel, to construct a CMS for controlling the CRN. In Fig. 14, we show this representation by signaling in red the chosen parent structures for the CMS.

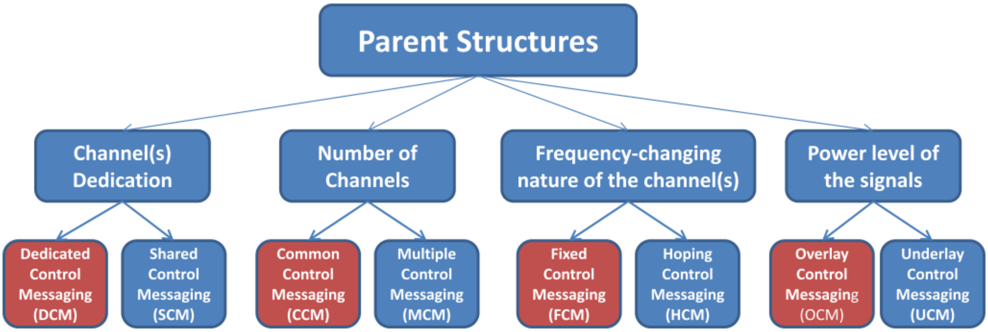


FIG. 14. Parent structures

2.2.2 Cognitive Radio Medium Access Control (MAC) Protocols

Several CR MAC protocols have been developed over the premise of the presence of a dedicated common control channel (Wang, et al., 2008) (Lien, et al., 2008). In this CR MAC approach, all CRU must be able to communicate in this common control channel. Thus, the CR capacity is under-utilized, since data communications cannot be sent or received on the common control channel. The CR MAC protocols that improve this performance are based on multi-channel MAC protocols. This approach can be considered for efficient spectrum utilization because the CRN must operate in different frequency bands. The main difference between multi-channel and CR MAC protocols is that in the CR MAC protocols, the presence of PUs is considered. Multi-channel MAC protocols can be categorized in dedicated control channel, split phase, common hopping, and default hopping (Wang, et al., 2008). Other than the aforementioned dedicated control channel approach, these multi-channel MAC protocols need some kind of user synchronization to determine the control channel beforehand. Furthermore, in multi-channel MAC protocols, all CRU must be able to use the same frequency channels, which is not always the case in heterogeneous systems.

2.2.3 Comparison

A comparison among the proposal, CPCDF-MAC, multi-channel MAC protocols from (Wang, et al., 2008), existing CR MAC protocols from (Yau, et al., 2008), (Lazos, et al., 2009) and CMSs parent strategies from the categories explained in section 2.1 is shown in Table I.

TABLE I. COMPARISON AMONG CMS FOR CRN WITH HFD

Protocol	Specialization of the Channel(s)	Number of Channels	Frequency -Changing Nature	Power Level	Time Sync Needed	Support for fully Heterogeneous Frequency Devices
Common Control Channels	Yes	n_1	No	Fixed	No	Yes
Common Hopping	No	n_2	Yes	Fixed	Yes	Yes
Default Hopping Sequence	No	n_3	Yes	Fixed	Yes/No	Yes
Underlay Control	No	n_4	No	Below Threshold	No	Yes
OSA-MAC	Yes	1	No	Fixed	Yes	No
HC-MAC/ OS-MAC	Yes	1	No	Fixed	No	No
SOC	No	n_5	Yes	Fixed	Yes/No	Yes
Proposal	No	n_6	Yes	Fixed	Yes	Yes

From Table I, we can see that the number of channels needed for transmitting control signals in schemes that support fully HFDs are variable. In order to reduce energy consumption, this number should be as low as possible. This minimum number can be obtained by using mathematical strategies that will be discussed in the next chapter.

2.3 Discussion

The control plane for Cognitive Radio Users is a very important part for the spectrum access and mobility in a CRN. Different authors propose their methods for controlling the CRN; however, a classification of the control messaging strategies for deciding which strategy is most suited to a specific CRN did not exist at the time.

In parallel, another classification was created by Lo, in (Lo, 2011). Comparing the classifications, the presented taxonomy considers different planes that are useful for controlling HFDs. One of the main differences in the presented classification is that the number of channels needed to transmit control messages is considered. This characteristic is very important for a CRN with fully heterogeneous wireless frequency devices, since the intersection of the available set of channels for the CRUs might be empty.

This is the reason why, in this chapter, a classification for the transmission of control messages as a blueprint in order to compare the advantages and disadvantages of these control strategies was proposed. Each control mechanism can be classified according to four basic characteristics: control messaging channel dedication, number of channels used for control messaging, changes on the location of these channels over time and level of power for transmitting the control messages.

In general, each strategy for control messaging is classified into four of the previous categories. For example, when only one channel is used for transmitting control information all the time, and in this channel no data is sent, this approach can be classified into Dedicated, Common, Fixed and Overlay Control Messaging (DCM, CCM, FCM and OCM or DCFOCM). Another example is transmitting control information below a threshold in a fixed set of channels that are also used in an overlay manner for CR. In that case, the control approach can be classified as Shared, Multiple, Fixed and Underlay (SCM, MCM, FCM and UCM or SMFUCM).

In the next section, a model proposed to transmit control information to heterogeneous users in a centralized CRN while using OSA is presented. This model uses SCM, MCM, HCM and OCM.

Several concepts such as the beacon strategy and CPCs are also introduced and a combined time/frequency approach is presented. We consider that the best way to control the centralized CRN with HFD is by using this SMHOCM approach. However, researchers are encouraged to suggest others, by using the classification previously provided.

Keep in mind that some of the strategies, while not always apparent, might solve problems that arise in different circumstances. For example, a common problem for cognitive radio ad-hoc networks (CRAHNs) is the discovery of the channel when HCM is selected due to PU presence. In the case, DH-HCM can be an excellent strategy considering that, although time synchronization among the CRUs is needed, the discovery of the channel where control messages are sent is solved because the CRUs are able to know where to 'listen' for control information at any specific moment. The difference between the Centralized CRN approach and the CRAHNs can be seen if Fig. 15.

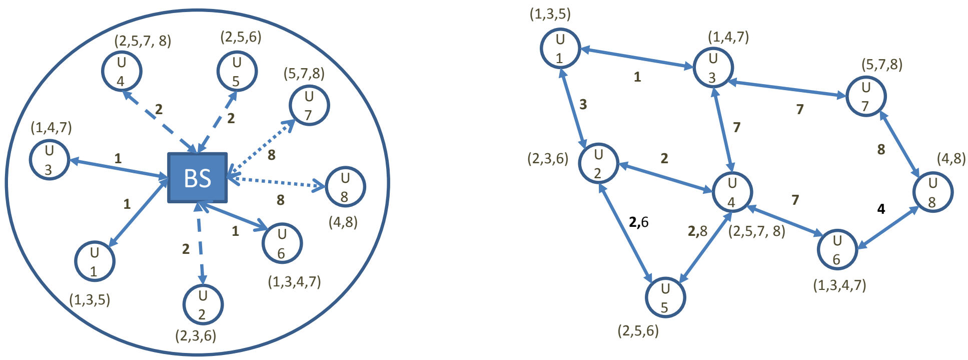


FIG. 15. Centralized and Ad-Hoc CRNs.

Chapter 3. Minimum Channel Problem

The basic model of the CRN provides signaling through CPCs distributed in every available channel or frequency slot. The control is performed by using frequency-division and time-division multiplexing techniques. This control, as expected, permits the utilization of the CRN by heterogeneous CRU devices. However, in terms of energy, this control can be very inefficient due to the fact that at specific periods of time, the network might be completely in use. In this section, a mathematical approach was used to reduce the number of channels to transmit control information in the control messaging schemes.

3.1 Background: Broadcast Signaling

For signaling and controlling a centralized CRN with users operating in different sets of channels, a dedicated common control channel is not a useful approach. Different strategies have been studied for this CRN control, some of them using time division mechanisms. This is because employing a channel per each CRU to simultaneously control them is not efficient. However, for signaling specific events to all CRUs in a CRN, the base station needs to communicate to all the operating devices in the CRN domain. Reducing the number of broadcast signaling channels is then a must for good performance and energy efficiency of the CRN. In this chapter, for the solution of this broadcasting signaling problem, each CRU is represented by an array considering its channel usability. Using this array, a static evaluation of the problem is initially performed. Then, the dynamic characteristics of CRNs are included to find an acceptable number of channels to communicate to every user in a specific CRN.

3.2 CRN Model

The proposed model of the CRN is an infrastructure-based architecture for effective spectrum access, sharing and management. The main reason for using a centralized model is to concentrate wideband spectrum sensing and spectrum decision in the central station and as a consequence, to reduce operations and the hardware required in the CRU devices. A basic representation of the centralized CRN model can be seen in Fig. 16. The elements of the CRN are the cognitive central base stations (CCBS) and the CRUs, which operate and coexist with the PUs.

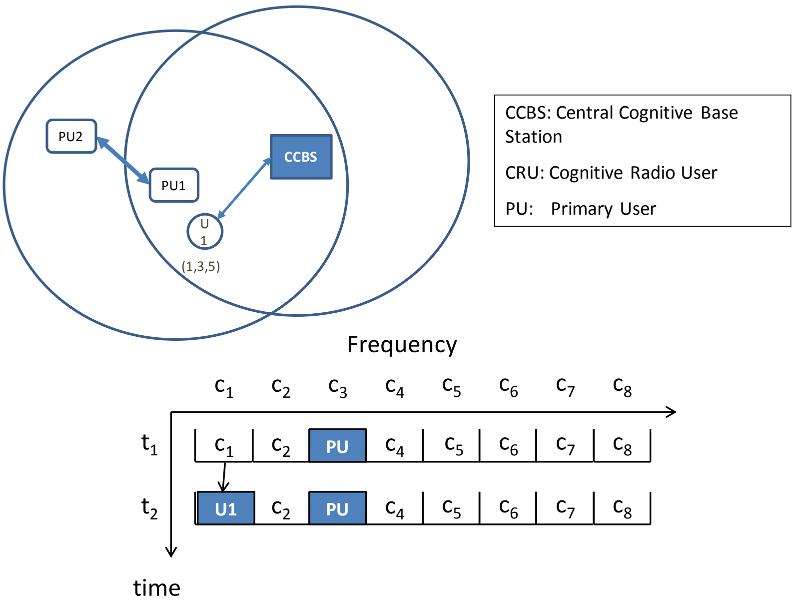


FIG. 16. CRN Model

In Fig. 16, CRU1 is communicating with the CCBS (CCBS1), while PU1 is communicating with PU2. PU1 transmission is within the range of the CCBS1 and CRU1. This means that the communication between CRU1 and CCBS1 must be performed in a different frequency slot than the ones that the PUs are using. Hence a CR radio spectrum model that uses fixed frequency slots for both CR frequency sensing and CR medium access is proposed in order to ease CR operation. A frequency/time representation of the corresponding scenario is also shown in Fig. 16.

The basic model of the CRN used in this work is shown in Fig. 16. A CCBS controls CRU communication so that these CRU do not interfere each other or a PU. For modeling the CCBS, in this work, the spectrum is considered to be continuously and perfectly sensed. For each frequency band, a threshold is decided to determine if a user is already using that channel. A logical “1” is then assigned if a communication exists in a frequency slot; otherwise, a logical “0” is assigned. This information is stored as a vector in a database, which also stores information from the channel control and data communications.

3.3 Mathematical Description and Considerations

Having m users, $u_1, u_2, \ldots, u_m$, each of them able to use several of the n channels that a CRN presents, $c_1, c_2, \ldots, c_n$, the idea is to find an array in which a base station CCBS is able to transmit to each user (u_i) utilizing the minimum number of channels.

The matrix that relates channel usability for each CRU U(m x n). U(i, :) is always different than 0. So, not considering primary occupation, the problem can be defined as finding a vector v(1 x n) such that sum(or (v .* U) 1:n)1:m = m. This problem can be easily related to a satisfiability problem (SAT) which is known to be NP.

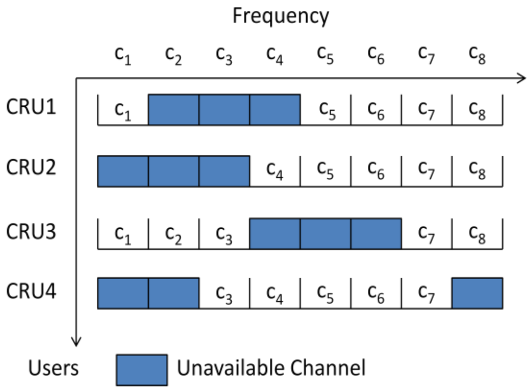
As shown in Fig. 2, CRUs enter and leave the CRN dynamically. Furthermore, a channel is inoperative when used by a PU. The presence of PUs can be described by using the mask vector *p* containing the PU occupancy stored in the CCBS database. Considering that u_i is the usability vector for CRU i, the vector $u'_i = u_i * p$ represents the availability vector for transmitting broadcast signals by the CCBS.

When primary occupation is considered, a new matrix must be constructed. Defining A(1xn) as the availability vector in t = t_x (1 means channel free to use, 0 means primary occupation, thus unavailability to transmit), the utilization matrix in t = t_x is given by B(1:m) = A. Then, the utilization matrix in t = tx, W can be defined as W(m x n) = U .* B. This means that in some specific moments a CRU i defined as u(i) = U(i,:) might be unavailable for communication.

Assuming that for an array consisting on m users and n channels, the minimum number k of broadcasting channels for the array has been found. If a new CRU enters the network, the minimum number of channels for needed to broadcast signals to each of the CRU devices is at most k+1, and at least k. Similarly, if a CRU leaves the CRN, the minimum number for the broadcast signaling channels is at least k-1, and at most k.

3.4 Mathematical Representation as a Set Covering Problem

For finding the minimum number of the broadcast transmission channels needed in a specific moment, the usability matrix was defined. An example of a usability matrix, i.e. the relation among the frequency slots (channels) and CRUs, is shown in Fig. 17.



Usability Matrix

Frequency

Users	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
CRU1	1	0	0	0	1	1	1	1
CRU2	0	0	0	1	1	1	1	1
CRU3	1	1	1	0	0	0	1	1
CRU4	0	0	1	1	1	1	1	0

FIG. 17. Frequency Slot Utilization by CRUs

In Fig. 17, the matrix that relates channel usability for each CRU is represented as Usability Matrix (U_{mxn}). In (Bolívar & Marzo, 2011), the authors show that this problem is NP-complete by relating it to the satisfiability problem. In this work, a stronger stance is made by relating it to a set covering problem, which is known to be NP-hard.

The minimum channel problem can be defined as finding a vector X_{1xn}, which is a subset of the n possible channels in a CRN, that covers m users, U1, U2, …, Um, each of them able to use different sets of the abovementioned n channels that a CRN presents, c_1, c_2, …, c_n, in which a base station CCBS is able to transmit to each user (u_i) utilizing the minimum number of channels.

If a cost for transmitting in a channel I is defined as q_i, the problem can be represented then as:

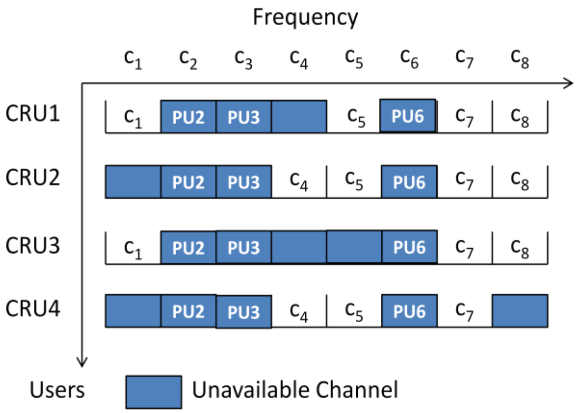
$$\text{Minimize } \sum q_i x_i, \qquad \text{s.t.} \tag{1}$$

$$Ux \geq 1_{mx1} \tag{2}$$

$$x \in [0,1] \tag{3}$$

This means that every user is at least covered by a channel, which is the definition of the set covering problem.

Considering that CRUs enter and leave the CRN dynamically, the algorithm for finding the minimum solutions vectors must consider the dynamics of the network. A mask vector o can be defined, considering user presence or not of a CRU at a specific moment. However, a channel is inoperative when used by a PU. The presence of PUs can be described by using the mask vector p containing the PU occupancy stored in the CCBS database. Considering that U(i,j) is the usability of channel j by CRU i, the element A(i,,j) = U(i,j)*o(i,1)*p(1,j) represents the availability for the CCBS to transmitting broadcast signals to user i using channel j. When primary occupation is considered, in some specific moments a CRU i defined by A(i,:) might be unavailable for communication. The dynamics of the network are then considered by analyzing the availability matrix, i.e. usability matrix considering primary occupation and CRU entrances, at each time slot. The relation among the frequency slots (channels) and CRUs in a specific time is shown in Fig. 18.



Availability Matrix

Frequency

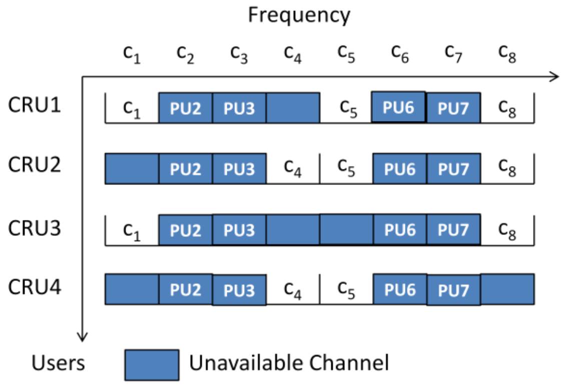
Users	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
CRU1	1	0	0	0	1	0	1	1
CRU2	0	0	0	1	1	0	1	1
CRU3	1	0	0	0	0	0	1	1
CRU4	0	0	0	1	1	0	1	0

FIG. 18. Frequency Slot Utilization by both PUs And CRUs (In Time)

In Fig. 18, the availability matrix per CRU (A) in a specific time is presented. A channel is unavailable to a CRU due to two reasons: a PU is using an available channel for the CRU or the CRU cannot communicate through that channel. Using this information, each CRU is represented by a row and each channel, by a column. Each element represents then the availability of a channel to a CRU in a specific moment. A logical '1' is assigned in this case if the channel is available to the user and a '0' if the channel is unavailable.

In the availability matrix represented in Fig. 18, the seventh column, corresponding to c_7, is a unitary column. This means that using that channel (c_7), the CCBS can broadcast communication to all the users in its CRN during that period of time.

The relation among the frequency slots (channels) and CRUs in a specific time slot was shown in Fig. 17. In Fig. 18, PU2, PU3 and PU6 were using their respective licensed channels but c_7 was free to be used for control. In Fig. 19, a case where more than one channel is needed for the CCBS to broadcast is shown. Considering again that the CCBS has knowledge of the channels that each of the CRUs is able to use, for finding this minimum number of the broadcast transmission channels needed in a specific moment, the proposed availability matrix is used.



Frequency

Users		c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
	CRU1	1	0	0	0	1	0	0	1
	CRU2	0	0	0	1	1	0	0	1
	CRU3	1	0	0	0	0	0	0	1
	CRU4	0	0	0	1	1	0	0	0

FIG. 19. Frequency Slot Utilization by both PUs And CRUs

In Fig. 19, the availability matrix per CRU (A) in a specific time is presented. A channel is unavailable to a CRU due to two reasons: a PU is using an available channel for the CRU or the CRU cannot communicate through that channel. Using this information, each CRU is represented by a row and each channel, by a column. Each element represents then the availability of a channel to a CRU in a specific moment. A logical ‘1’ is assigned in this case if the channel is available to the user and a ‘0’ if the channel is unavailable.

In the case presented in Fig. 19, the availability matrix shows that the CCBS needs more than one channel to communicate with all the CRUs in the network. The matrix composed with all the vectors that use the minimum channels for the CCBS to communicate is represented as Minimum Solutions. In general, the problem of finding this minimum solution vectors is the same as finding the vectors with the least numbers of ‘1’s such that the intersection of them with each of the row vectors that compose the availability matrix is not empty.

FIG. 20. Frequency slot utilization by both PUs and CRUs (in time)

In Fig. 20, the availability matrix shows that at least the CCBS needs two channels to communicate with all the CRUs in the network, e.g. c_1 and c_4. The matrix composed with all the vectors that use the minimum channels for the CCBS to communicate is represented as Minimum Solutions. In general, the problem of finding this minimum solution vectors is the same as finding the vectors with the least numbers of ‘1’s such that the intersection of them with each of the row vectors that compose the availability matrix is not empty.

The set covering problem for this case can be written as

$$\text{Minimize } \sum q_{ti}x_i, \qquad \text{s.t.} \tag{4}$$

$$Ax \geq 1_{mx1} \tag{5}$$

$$x \in [0,1] \tag{6}$$

3.5 Greedy Approach

The Greedy algorithm is one of the straightforward methods to solve optimization problems. The main idea is to find the solution that fits the most a local problem and then to extend this solution to the global problem.

For a matrix A that is filled with 1's and 0's and in which the idea is to find a vector *v*(1 x n) such that sum(or (v .* U) 1:n)1:m = m, the approach is presented as follows. First, the column with the most ones is found and then, it is assumed that the frequency band represented by that column will be used for transmitting broadcast signaling. After that, the next column with most ones is found, and that channel is also assumed to be used for communication. The process is repeated until all CRUs are covered using those channels. The vector v is then formed using ones in each of the frequency bands found with the algorithm and zeros in the others.

The problem with this approach is that since CRUs are using more than one frequency band for communicating, this approach might generate redundant information and unnecessary resources could be utilized. A simple modification for this Greedy approach consists on removing all the CRUs that can be accessed through the channel with most ones for the next step in the algorithm. When the new column with most ones is calculated, this assures that the broadcast is sent to the CRUs through one and only channel per each of them. Since this approach generates a sub-optimal response to the NP problem, vector *v* might not be the one with the less number of channels for the CCBS to communicate with the CRUs. However, taking into account that the speed of the algorithm is good and that the accuracy is not that far from the optimal solution, this approach has to be considered in this study.

3.6 Case Study

In this section, early results obtained when using low numbers of channels and CRUs in the network are presented. The number of channels was defined to be low in order to compare the results of the algorithm for obtaining the minimum number of channels to communicate with all the CRUs with the real minimum number.

For the first simulation, the number of channels n was defined as 8. The number of CRUs, *m*, was also defined as 8, due to the fact that the maximum number of users that can communicate in a specific moment is the number of channels available in the network. The number of time slots, *t*, is defined to be 10. CRU and PU presence in the CRN are defined as random, with probabilities 0.2 and 0.5, respectively. In Table II, the channel usability of all the possible CRUs in the CRN is shown.

TABLE II. CHANNEL USABILITY (CRU NUMBER = 8)

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
CRU 1	1	0	0	0	0	0	1	0
CRU 2	1	1	0	0	0	0	1	1
CRU 3	1	0	0	1	0	0	1	0
CRU 4	1	0	1	1	0	1	0	0
CRU 5	0	0	0	0	1	0	0	1
CRU 6	0	1	0	0	1	0	0	0
CRU 7	1	0	0	1	0	0	0	0
CRU 8	1	0	0	1	0	0	1	1

As shown in Table II, the minimum number of channels needed to transmit to all CRUs in the network is 2, using c_1 and c_5.

An advantage of the broadcasting solution is that the base station, e.g. the CCBS, in theory is able to communicate with as many CRUs in the CRN as desired. This means that even idle CRUs can receive information from the CCBS. As a proof, a simulation of this situation is presented where the number of CRUs is doubled. Results are shown in Table III.

TABLE III. CHANNEL USABILITY (CRU NUMBER = 16)

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
CRU 1	1	0	0	0	0	0	1	0
CRU 2	1	1	0	0	0	0	1	1
CRU 3	1	0	0	1	0	0	1	0
CRU 4	1	0	1	1	0	1	0	0
CRU 5	0	0	0	0	1	0	0	1
CRU 6	0	1	0	0	1	0	0	0
CRU 7	1	0	0	1	0	0	0	0
CRU 8	1	0	0	1	0	0	1	1
CRU 9	0	1	0	0	1	0	0	0
CRU 10	0	0	0	0	0	0	0	1
CRU 11	0	0	0	0	1	0	0	0
CRU 12	0	1	0	0	1	0	0	0

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
CRU 13	0	0	0	0	1	0	0	1
CRU 14	1	0	0	0	0	0	0	0
CRU 15	0	0	0	0	1	1	0	0
CRU 16	0	0	1	0	0	0	0	0

Notice that the number of minimum channels for communicating with all CRUs is similar. In this case, this number is four, two more than in the previous situation. Besides, this is because CRU 10 and CRU 16 only have c_8 and c_3, respectively as their usable channels. A possible minimum solutions vector is then v = [1 0 1 0 1 0 0 1]. The similarity on the number is because the CRUs, while heterogeneous in frequency, are defined with similar characteristics.

The algorithm considered for solving the minimum number of channels is an adaptation of the Greedy Algorithm. The basic idea is that the channel that might be used the most by the CRUs is the first to be considered as a possible solution to communicate to all the CRUs. The next channel to be considered as a solution to the problem is the second that might be used the most by the CRUs. The vector is constructed by defining as '1' all these channels until all the possible channels are considered. An obvious improvement for this algorithm is to discard the CRUs that are covered with the channel in the previous step, and repeat the process until every CRU is able to receive communication from the CCBS. For reducing the calculations for the following time slots, the property that the difference between the minimum numbers of channels needed for broadcasting in consecutive time slots is at most one. Considering the patterns of entrance and departure of the CRUs, shown in Table IV, the numbers of channels, defined by *mod(v)*, needed to broadcast to all active CRUs are presented in Table V.

TABLE IV. AVAILABILITY OF THE CRU ACCORDING TO THE TIME

	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}
CRU 1	0	0	0	0	0	1	0	0	1	0
CRU 2	0	0	0	0	0	0	0	0	0	0
CRU 3	0	0	0	0	1	1	1	0	0	0
CRU 4	0	0	0	0	0	0	0	0	0	0
CRU 5	0	0	0	0	0	0	0	0	0	0
CRU 6	0	0	0	1	1	0	0	0	0	0
CRU 7	0	0	1	1	1	0	0	0	0	0
CRU 8	0	1	0	0	0	0	0	0	0	0

TABLE V. MINIMUM SOLUTION VECTOR (WITHOUT PUS)

	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}
mod(v)	0	1	1	2	2	1	1	0	1	0

Next, the presence of PUs is considered and shown in Table VI. Results for a minimum solutions vector are shown in

Table VII. The considerations were the same as for the case when PUs were not included, m = 8, n = 8, t = 10.

TABLE VI. PRIMARY USER OCCUPATION (IN TIME)

	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}
c_1	0	0	0	0	1	1	0	0	0	0
c_2	1	1	1	1	1	0	0	0	0	1
c_3	0	0	0	0	0	0	1	1	1	1
c_4	0	0	0	0	0	1	1	0	0	0
c_5	0	0	0	0	0	0	0	0	0	0
c_6	1	1	1	1	1	1	0	0	1	1
c_7	1	1	1	1	0	1	0	0	0	0
c_8	0	0	0	1	1	1	1	0	0	0

TABLE VII. MINIMUM SOLUTION VECTOR (WITH PUS)

	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}
mod(v)	0	1	1	2	2	0*	1	0	1	0

As expected, CRUs might not receive information from the CCBS because the channels are occupied by the PUs. This can be seen when $t = t_6$. CRU1 and CRU3 are in the CRN but the CCBS cannot transmit information to any of them because their available channels are already in use by PUs. Another situation that might arise because of PUs' presence is the necessity for the CCBS to transmit through more channels to reach the same CRUs.

3.7 Branch and Bound Algorithm

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 $0 \leq x \leq 1$.

The algorithm creates a search tree by repeatedly adding constraints to the problem, i.e. branching. 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.

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 (Mathworks, 2012).

3.8 Results

The main objective of this chapter is to find the minimum number of channels to use for broadcasting signaling. The plan is to consider channel distribution of each CRU and, channel entrance distributions of PUs, to find an efficient algorithm that manages to provide an acceptable broadcasting vector for the CRN at any moment.

A greedy approach and a branch and bound integer linear programming (ILP) approach are considered. All the simulations were performed in MATLAB. For the linear programming, the results are obtained using a binary linear programming function with the branch and bound algorithm, since all the values for the output variables are 0 or 1.

The input variables used for simulation purposes are number of users, *m*, as 16, number of channels, *n*, as 8, and time slots for the simulation, *ts*, as 60. CRU and PU presence in the CRN are defined as random, with probability 0.2. The channel usability for a CRU is also random, with probability 0.4 and the cost of using a channel is also random and a integer between 1 and 10. The greedy approach and the binary integer linear programming (B-ILP) are compared in three aspects: number of channels of the solution, elapsed time and number of non-covered users the solution present for the time frame evaluated in the simulation. Three different solutions are also compared: the channel array found in $t = t_1$, the channel array found that uses the maximum number of channels (k_{max}) and a varying channel array found on each time slot. The results obtained from this simulation are compiled in Table VIII.

TABLE VIII. SIMULATION RESULTS

	Number of Channels (k_{max})	Elapsed Time (t_f)	Number of non-covered users (e)
Greedy Approach Solution in $t = t_1$	3	1.45s	181
Greedy Approach Solution with k_{max}	5	1.72s	70
Greedy Approach Dynamic Solution	5	1.82s	25
B-ILP Approach Solution in $t = t_1$	3	2.9s	81
B-ILP Approach Solution with k_{max}	4	3.32s	69
B-ILP Approach Dynamic Solution	4	3.5s	25

As shown in Table VIII, in this scenario the B-ILP Approach uses approximately the double of the time as the greedy approach, but when using same number of channels, the number of non-covered users is less. Another conclusion from Table VIII is that the greedy approach might use more channels than needed for covering all the users. This situation can be seen when k_{max} = 5 for the greedy approach while for the B-ILP, k_{max} = 4. However, the results when using the vector that uses the most number of channels to cover the availability matrix at a specific time of the whole time frame are very similar for both approaches. Finally, the B-ILP and the Greedy approach gave 25 'errors' when using a dynamic solution. This result was expected because during the entire time frame, 25 users could not be covered due to the fact that PUs were using all their available channels.

3.9 Discussion

The transmission of broadcasting signals is essential in a centralized network. In this manner, the base station can reach all its users, in this case CCBS and CRUs, respectively. This is in order for the CCBS to signal alarms and availability, among others. When broadcasting availability as a periodical beacon to heterogeneous frequency systems, reducing the number of broadcasting channels is a must for energy reasons.

The sole idea of analyzing a simple network to find a vector composed of the minimum number of channels a cognitive radio base station needs to broadcast signals to all its users is a NP-complete problem. Different solutions might be found by using diverse techniques. For easing the algorithm, several characteristics of the proposed CRN model are used.

When considering primary occupation, some of those characteristics are not useful. This is the reason why a greedy approach was considered at first. The fact that both the number of CRUs and channels were considered to be low helped to make the decision to choose the greedy approach, which is known to be useful in those cases.

For future works, different techniques when expanding the number of channels and users, such as tree-based and genetic approaches, as well as satisfiability techniques will be considered. For deciding which technique to base the new minimum solution algorithm, three characteristics will be evaluated: complexity of the algorithm, time of execution and closeness to the optimal solution. In the area of energy reduction, further strategies to reduce energy transmission, such as database use for PUs and low-energy transmission mechanisms, will be explored.

The minimum number of channels for broadcasting problem was found to be NP-hard. Taking into account the typical number of users and channels for a CRN, two strategies were considered: a greedy and an ILP approach. The results indicated that, because covering all the possible users in the CCBS range is the main requisite for the network, a sensing of the environment have to be performed before each time slot the CCBS want to communicate for control.

The ILP approach, which was a binary linear programming approach considering that all the possible values were either 0 or 1, obtained vectors where the number of channels were lower or equal to the ones from the greedy approach. On the other hand, computing time was lower in the greedy approach than in the ILP. However, when considering static solutions, the results obtained with the ILP were significantly better, although not as good as the ones obtained when solving the set covering problem in each time slot.

For future work, we plan to consider more static solutions in order to compare the minimum number of channels not covered with a static solution. If possible, the idea is to expand the findings to a channel assignment/broadcasting joint system. An extension of this work is also planned for an ad-hoc network, where users not only need to consider their available channels, but also to which users they are able to communicate using those channels.

Chapter 4. Model

In this chapter, the model used for the description of the CRN is presented. In this model, the control of the CRN is distributed among the frequency spectrum considered for transmission using cognitive pilot channels (CPCs). This control is performed by using frequency-division and time-division multiplexing techniques. Frequency-division is used to divide the spectrum into predetermined frequency slots in which cognitive radio users (CRUs) communicate. Then, the frequency slots are divided into sub-frequency slots, some of which are defined as CPC and used by the CRUs to communicate with a central cognitive base station (CCBS) and to determine availability in a frequency slot. Time-division is used to determine if a primary user (PU) has accessed the channel used by CRUs. Using this time-division approach, the presence of PUs is detected. A CRN able to work with today's available technologies and CRU devices that use different frequency bands of operation have been designed.

4.1 Introduction

There have been different approaches for transmitting control and coordination signals for spectrum access and mobility in CRN. Given that a dedicated common control channel might not be available at all times, several techniques for the control channel problem have been discussed. For a CRN, the relationship beten the spectrum functions might be represented as in Fig. 21.

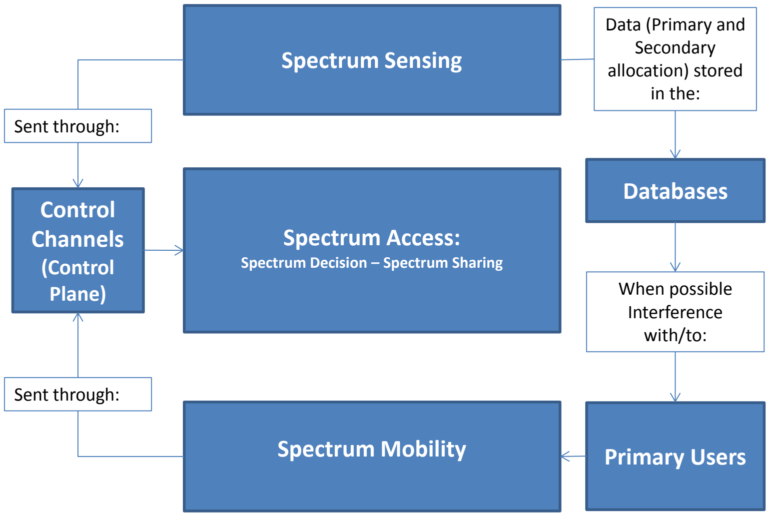


FIG. 21. Spectrum Functions and Control Plane

The utilization of beacons to control the medium access of the network devices into the frequency bands was suggested as a solution for spectrum access (Hulbert, 2005). Architectures with more than one beacon have been proposed to improve performance (Mangold, et al., 2006). In these proposals, the beacons are sent by the PU through a cooperative control channel or a beacon channel, with the latter being considered a better option in (Ghasemi & Sousa, 2008). This approach has two main disadvantages for implementation in a CRN with today's available technologies; the first is that a new set of primary users must exist or new hardware must be developed given that the PUs would have to inform the nearby CRU about their presence, and the second disadvantage is that a new channel must be reserved for the beacon signals.

A Cognitive Pilot Channel (CPC) is a solution proposed in the E2R project to enable communication among heterogeneous wireless networks (Bourse, et al., 2007). The CPC consists on controlling frequency bands in a single or various "pilot" channels, which is analogue to the beacon proposal. In both the CPC and beacon proposal, there are "in-band" transmissions, i.e. control information transmitted in the same logical channels of the data transmission, and "out-band" transmissions, i.e. control information transmitted in channels different of the used for data transmission (Filo, et al., 2009). Studies have been conducted to define the quantity of information that should be transmitted in the CPC, the bandwidth for each CPC, the “out-band” and the “in-band” transmissions, and solutions that use a combination of both (Filo, et al., 2009) (Pérez-Romero, et al., 2007) (Sallent, et al., 2009). In Fig. 22, the difference of the in-band and out-band control transmission is shown.

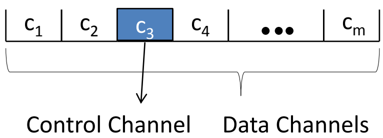


FIG. 22.1.In-band Control Channel

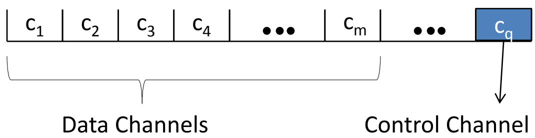


FIG. 22.2.Out-band Control Channel

Most control signals should be sent via broadcast to the users in the CRN. Several broadcasting problems, such as the minimum broadcasting energy problem (Cagalj, et al., 2002) and the allocation for broadcasting heterogeneous data in multiple channels (Hsu, et al., 2005) (Tsai, et al., 2009), among others, have been studied in the literature. The channel allocation/frequency assignment problem has been studied in static and dynamic environments. An overview of models and solutions of the frequency assignment problem in those environments can be found in respectively in (Aardal, et al., 2007) (Katzela & Naghshineh, 1996).

The broadcast frequency assignment problem for frequency agile networks, i.e. networks in which users can shift their operating frequency, was introduced by Steenstrup (Steenstrup, 2005). The problem is analyzed for an ad-hoc network and a greedy approach was used to find the minimum number of channels that are needed for broadcasting information.

For CRN, in general, and for heterogeneous frequency CRN, specifically, a fixed CCC might not be available. Some of the reasons could be different PU presence according to the location, for homogeneous frequency CRN, and also different sets of channels for the heterogeneous case. In order to solve this problem, and to use the minimum amount of energy as possible, a minimum number of clusters (channels), must be found. In Fig. 23, the minimum number of channels for the example used in Fig. 7 is found.

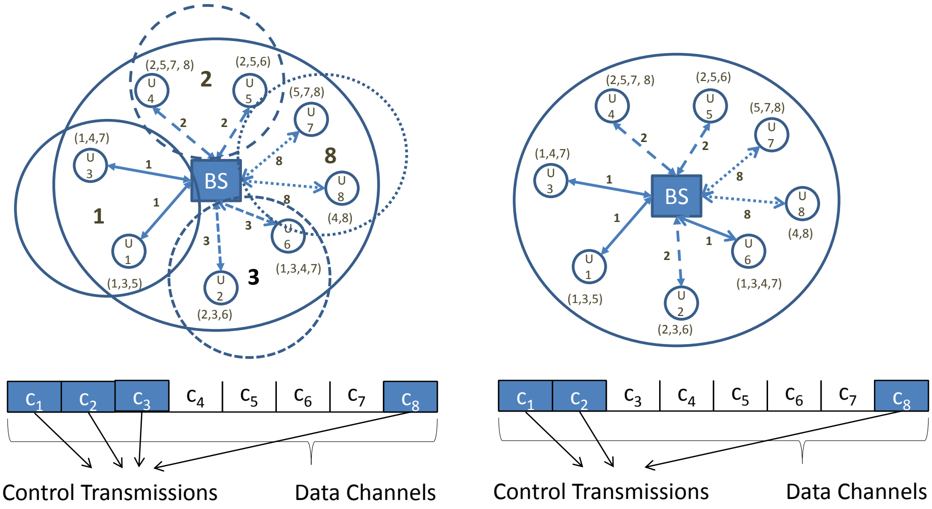


FIG. 23. Minimum number of channels for a clustered MCM

In (Kunar, et al., 2008), the authors define the clusters for finding this minimum number of frequency channels under the same conditions as used in (Steenstrup, 2005). In (Lazos, et al., 2009), the authors considered the control plane and used the clustering approach to find the minimum number of channels needed for control in a CRN. A greedy approach is used to solve the corresponding clustering problem. For future work, several techniques to solve the minimum number of channels problem in both centralized and ad-hoc networks are planned to be used, as shown in Fig. 24.

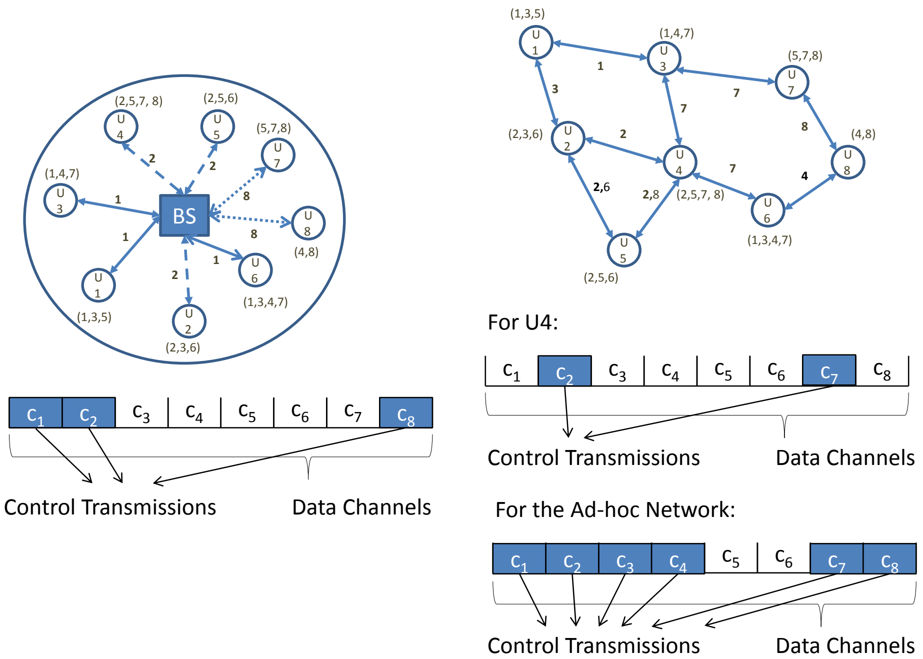


FIG. 24. Minimum Channel Problem for Centralized and Ad-hoc CRN

In the following lines, the bases for solving for this channel allocation/frequency assignment problem are presented by implementing a combined spectrum access/mobility strategy in the control plane.

4.2 CCBS Control Architecture

In the proposed architecture, the management of the network is assumed to be performed in the CCBS, which permits to reduce the amount of processes from the CRU terminals and therefore, keeping those terminals simple while using today's available technologies. We address the spectrum sharing problem, since we assume that the CCBS decides which channel to assign for each CRU, according to the available channels and characteristics of the CRU. Using the structure from Fig. 16, the CCBS model is shown in Fig. 25.

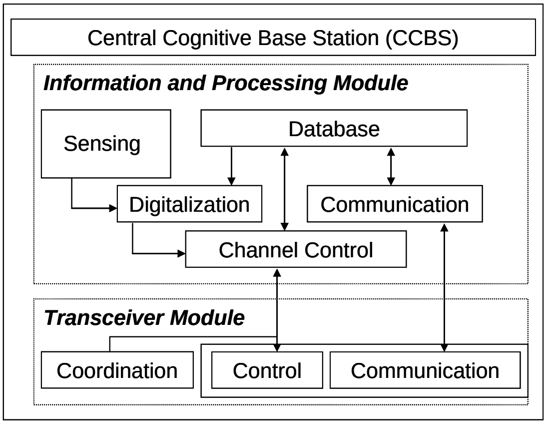


FIG. 25. CCBS Control Architecture

The utilization of two major modules, information and processing module and transceiver module is proposed. The information and processing module is divided in five sub-modules: sensing, database, digitalization, channel control and communications. The sensing sub-module senses the analog radio frequency spectrum, which is assumed to be perfectly and continuously sensed. In the digitalization sub-module, the analog signal is digitalized within predefined frequency slots. An Analog/Digital (A/D) converter is used considering the thresholds determined for each channel according to the location. A logical “1” is then assigned if a communication exists in a frequency slot; otherwise a logical “0” is assigned. This information is stored as a vector in the database sub-module, which also provides the specifications of the location that are loaded into the digitalization sub-module. The database sub-module also stores information from channel control and communications sub-modules. The channel control sub-module uses a frequency subdivision of the frequency slots (sub-frequency slots). In those sub-frequency slots, CCBSs and CRUs exchange both control and data information. The channel control sub-module is responsible of controlling which CRUs are communicating and the frequency slots used. In this sub-module, for CRUs are assigned free frequency slots to communicate. This information is sent in a vector to the control of the transceiver module, while it is also kept in the database. Fig. 26 shows the division in frequency and sub-frequency slots. Finally, the communications sub-module is responsible of data communication, which uses the frequency slot that has been defined in the previous sub-module.

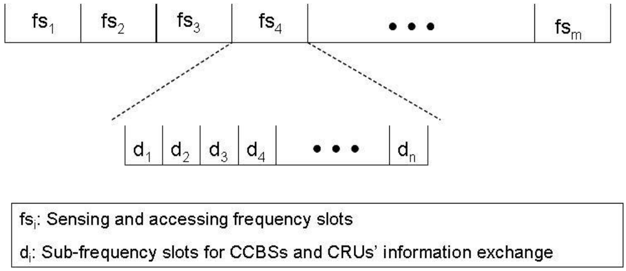


FIG. 26. Frequency slot and sub-frequency slot division of the spectrum

The Transceiver Module is divided into 3 sub-modules, control, communication and coordination. These sub-modules are responsible for communicating with the control module of the CRUs, the communications module of the CRUs, and with other CCBSs for cooperation, respectively. This architecture allows cooperation among the base stations of adjacent CRNs by using in each sub-channel a logical OR with the data from other CCBS. However, in this work, the possible coordination among CRN is not considered.

For this work, only the CRN control is studied; the control algorithm for the CCBS is represented in Fig. 27. In this figure, the frequency spectrum sensing and A/D conversion block represent the equivalent processes that are shown in the CCBS Algorithm. On the other hand, the channel control block from Fig. 25 is divided into CCBS Control Broadcast Transmission, CCBS-CRU Control Communication and the time synchronization needed. It is worth to mention that both database storage and information and control transmission/reception are considered for the algorithm as part of the CCBS Control Broadcast Transmission and CCBS-CRU Control Communication processes.

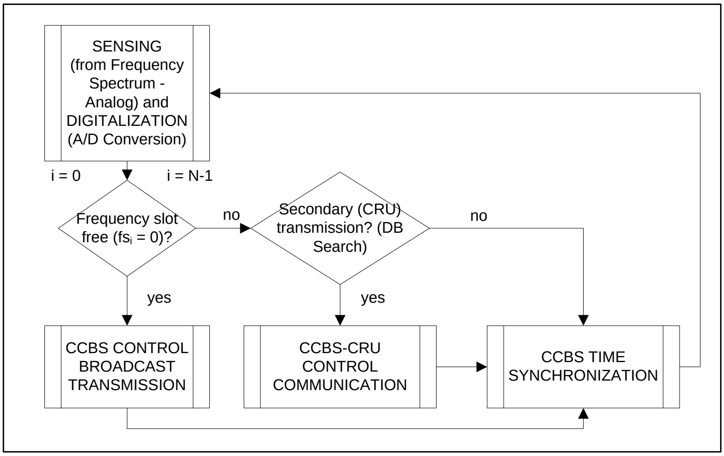


FIG. 27. CCBS Algorithm per each frequency slot i (fsi)

In the following subsection, the control of the system is explained, considering the control processes of the CCBS Algorithm. The algorithm is also related to each of the required dynamic functionalities for CRN, Dynamic Spectrum Access (DSA), Dynamic Spectrum Sharing (DSS) and Dynamic Spectrum Management (DSM).

4.3 Sensing/Digitalization and Identification

4.3.1 Antecedents

Different sensing methods have been discussed in the literature for determining if a primary user is utilizing a specific part of the wireless spectrum. One of the most common ones is the geospatial approach (IEEE, 2006) (Muck, 2007). Several problems arise, since for each channel, diverse methods are used for transmitting signals. If signals waves were known, communication in some bands might be detected by using strategies such as matched filters. That way, signals might be decoded to infer if a primary communication was being transmitted through that channel. However, even knowing the exact communication wave PUs use, obstacles might present a bigger challenge for CRN implementation. This is because some PUs might be hidden to the sensing devices, and thus, the hidden terminal problem appears. This problem is especially challenging to CRNs considering that one of the premises of the primary/secondary communication scheme is that secondary communication must not interfere any primary communication. The hidden terminal problem for CRNs is still under research and several proposals have been presented (Akyildiz, et al., 2008) (IEEE, 2006) (Mitola III & Maguire, 1999). In this work, sensing is assumed to be perfectly performed in the CCBSs for presenting the model; however, considering that in the real world no perfect sensing can be performed, an interference reduction mechanism is presented.

4.3.2 Interference Reduction (IR)

To reduce the interference generated by the CRUs to the PUs, and at the same time, maintaining CRU terminals as small as possible, the following scheme is proposed. In this work is assumed that highly powerful sensors are implemented in the CCBSs, so that sensing processes are simple in the CRUs. CRU devices must only have one transceiver. Using this transceiver, CCBSs and CRUs should be able to synchronize themselves to transmit information through different frequency bands (channels). To reduce the interference with PUs using the same transceiver, a time/frequency approach is introduced. CRUs can identify primary transmission on the beginning of each time slot if an unexpected communication is received in the coordination time. These signals are decoded by using a power/frequency sensing device with thresholds defined for each frequency band. However, an ‘expected’ signal might be obtained in this coordination process. In order to avoid interference as much as possible, a similar signal is sent to the CCBS which might help to detect whether incoming communication is from a CRU or both a CRU and PU and thus, disconnect secondary communication. In case a CRU communication might cause interference to a PU, the power and the amplitude of the CRU signals must be adjusted to requisites according to each frequency band. To assure that this interference will not last long, the CCBS might finish the connection with a specific CRU in any moment.

Regarding the digitalization process after sensing the environment, this must be simple in order to keep terminals small. In this case, a logical '1' is assigned to a frequency band if the power obtained in that particular band is above the threshold; otherwise, a logical '0' is assigned.

4.3.3 Database

In this work, there are three variables that must be taken into account for the analysis of the CRN performance. The first one is the frequency bands, the second one is the number of secondary users (CRUs) in the network and the last one is the time. For creating the database, these three characteristics must be considered to keep record if a CRU is utilizing a channel in a specific period of time, and if so, which user is communicating through that frequency band to assign it the preference to keep communication.

During the identification process, after the CCBS have given permission to a CRU to transmit, this CRU should send its specifications, i.e. CRU ID, available bands. The database in the CCBS keeps records of each CRU's characteristics and also, keeps into memory the present and the periods of time. This is in order to determine if a CRU asking for communicating into one band was already present and also to verify PU transmission.

The information stored in the database is forwarded to the channel control block from Fig. 25, which determines then, which channels should be signaled as available, as well as the channels to assign to each CRU in the network.

4.4 CCBS – CRU Control

The CCBS-CRU Control Communication is performed under three different scenarios, CRU network discovery, CRU medium access and while CRU data communication is being transmitted. DSA is present for the first two scenarios, DSS for the last two, while DSM only occurs for the last one. For the CR network discovery and from the CRU perspective, the process is as follows. When a new

CRU enters into a CCBS range, this CRU scans in its possible transmission channels, and sends in an available channel an identification frame that consists on: petition to enter, ID of the device, and type of device. This frame is sent in a frequency-based approach, since a CRU can enter for the first time to the network at any moment. When the CCBS receives this request, acknowledges the CRU type of device, keeps this information into memory, and sends a confirmation message. The CRU then waits for confirmation of the corresponding CCBS, and synchronizes itself with the CCBS.

From the CCBS perspective, a broadcast signal is first sent in available frequency slots in which CRUs are able to communicate. This is the CCBS Control Broadcast Transmission process in Fig. 27. Since a CRU can enter to the CRN at any moment, time synchronization does not exist yet, and a frequency beacon mechanism is proposed. This consists in a two bit signal sent in the first two sub-frequency slots shown in Fig. 26 of all the available channels. The set of values corresponding to control are detailed in Table IX.

TABLE IX. DISTRIBUTION OF CONTROL BITS FOR THE PROPOSED ARCHITECTURE

Bit 1/Bit 2	Process
00	CCBS and CRU coordination for using a channel
01	CRU request to use a channel
10	CCBS announcing availability
11	Frequency Slot occupied, CRU must leave immediately

When a CRU is trying to use the CRN, a message containing the identification frame is received from the CRU, and the process in the CCBS consists on determine if the information received is valid, i.e. no errors in the reception, if the CRU can access the CRN, and if both conditions are fulfilled, the CRU is accepted and its presence in the network is stored in the database.

According to the channel and device characteristics, the CRU medium access might be performed in a time-based approach or a frequency-based approach. Since the analysis for the 2-bit message is the same for both frequency division and time division based approaches, the case for the frequency-based approach is explained, without losing generality. The process for the CRU Medium Access to the network is then similar to the previously shown process for network admission. The differences are that the CRU is already present in the network, so there is no need to communicate the identification frame again and that after being admitted in a channel, data communication is the process that continues in the next time slot. The CCBS-CRU Control Communication process can be described then as in Fig. 28. When the CCBS receives information from a CRU in a communication channel, the CCBS compares this information with its database. If the CCBS does not identify this information as coming from a known CRU, the CRU admission process is started. If the CRU is already registered in the CRN, but this CRU is not communicating, the CRU confirmation process is activated. In the case this CRU has been already assigned a frequency slot, the data communication process is performed.

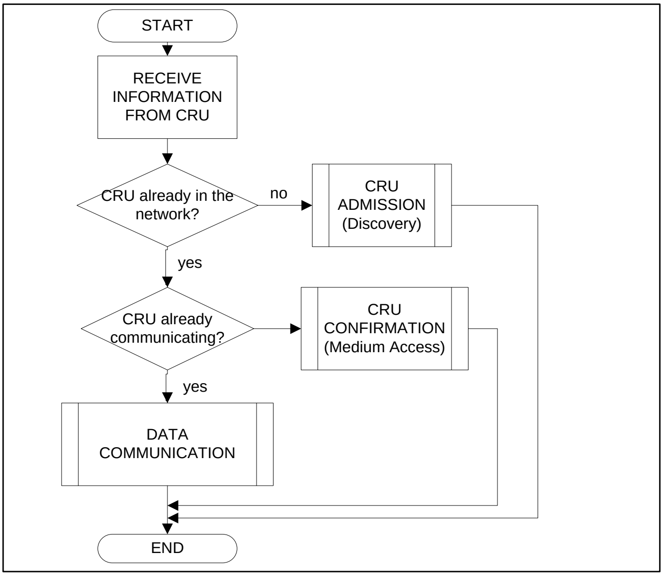


FIG. 28. CRU Admission in the CRN from the CCBS perspective

When a CRU data communication is already established, and since PU communication can enter at any moment, a time-based approach is implemented in order to discover PU presence. This frequency and time system allows the elimination of a dedicated control channel for spectrum sharing. Using the slotted predefinition, if a transmission is received in a moment no transmission should be performed, a PU is assumed to be communicating and, then, the channel is evacuated and the process of assigning a channel restarts, keeping into memory the last information that was going to be transmitted. For effective use of the wideband spectrum, a multi-channel approach is also proposed, since several cognitive users might communicate in different channels. For the analysis of the system, each communication channel is considered separately, since it is transparent for the CRU in which channel is transmitting. An example of the time-based approach for determining PU entrance in the operation range of a CRN is depicted in Fig. 29, which shows the utilization in time of a frequency slot by both PU and CRUs.

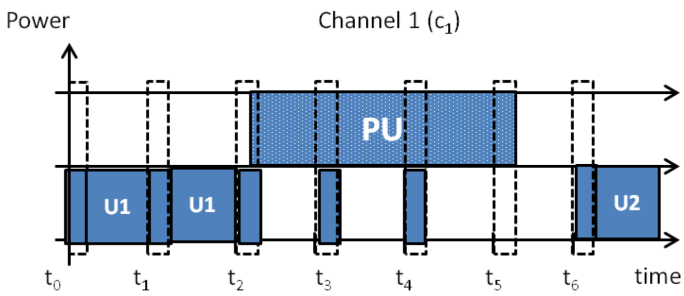


FIG. 29. Frequency slot utilization by both PUs and CRUs (in time)

4.4.1 Multiple Control Messaging

One of the main considerations for studies in frequency assignment problems is that a channel can generate interference in adjacent channels. The authors have presented a basic model, shown in Fig. 16, for a Centralized CRN that uses CPCs for signalization and control (Bolívar & Marzo, 2011).

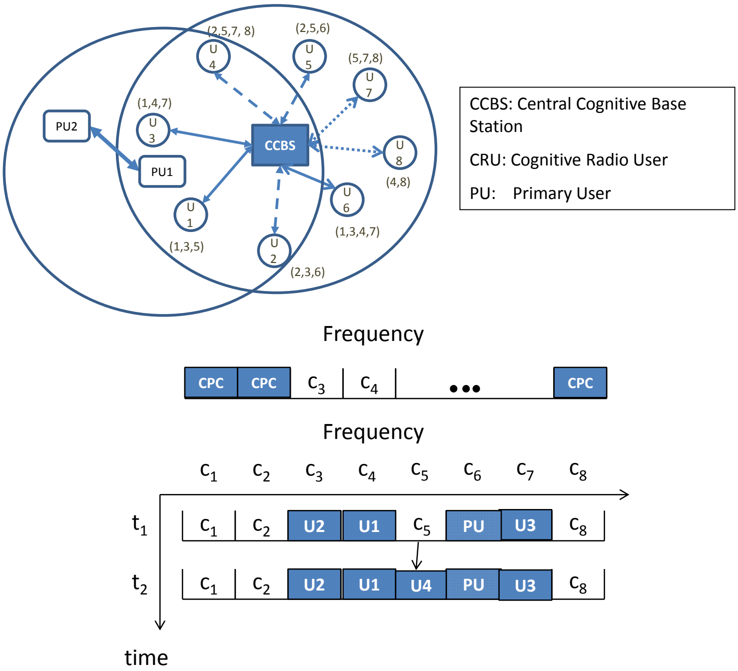
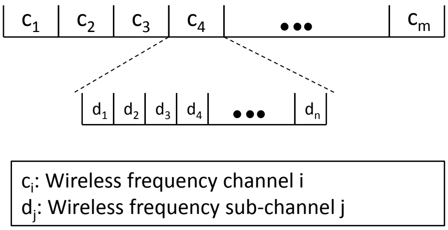


FIG. 30. Cognitive Radio Model

The main idea was to introduce a control signal, basically periodical beacons, to announce channel availability and the necessity of leaving a frequency slot if that one was occupied. In the presented scenario, since the broadcast signaling is transmitted the same for each channel and only in a couple of a large number of sub-channels (Bolivar, et al., 2010), by using adequate modulation/coding schemes, interference among adjacent channels can be assumed to be non-existent. In Fig. 30 and Fig. 31, a division in channels and sub-channels is presented in order to use some of the sub-channels for beacon transmission.



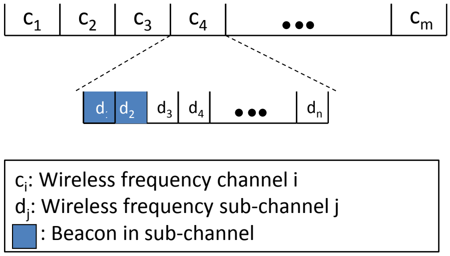


FIG. 31.1. Wireless Frequency Channel-Subchannel Division **FIG. 31.2.**Beacons in Wireless frequency sub-channels

4.4.2 Shared Control Messaging

The basic model of the CRN provides control signaling through CPCs distributed in several channels or frequency slots. The control is performed by using frequency-division and time-division multiplexing techniques, and allows the utilization of the CRN by heterogeneous CRU devices. However, as seen in Fig. 30, transmitting control messages through dedicated channels would be inefficient. Then, control and data were decided to be transmitted through the same channels by using a frequency division approach. The benefits of using a distributed control and a centralized database for reducing the amount of energy used to signal this availability in the CRN were also considered. Using the example from Fig. 4, Fig. 6 and Fig. 16, the SCM and MCM of this model is shown in Fig. 32.

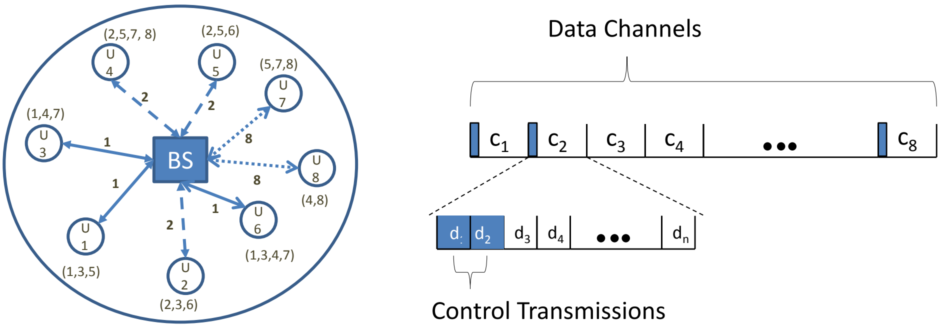


FIG. 32. Shared and multiple control messaging (Frequency-division)

4.4.3 Hopping Control Messaging

In Fig. 33, an example of the time/frequency approach is shown. According to the example in Fig. 32, U4 has four channels for communications (c_2, c_5, c_7 and c_8) and "senses" its environment.

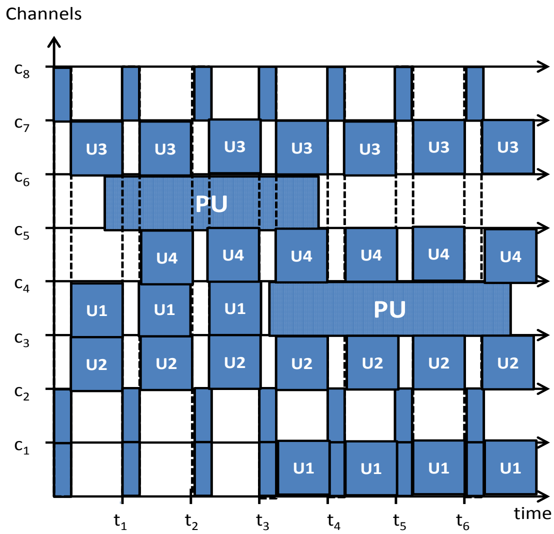


FIG. 33. Time slot utilization by both Primary Users (PU) and Cognitive Radio Users (U1, U2, U3, U4) in time

Channel c_7 is already used by U3, so this channel is unavailable. Among the other channels, U4 decides to use c_5. Channel c_3 is occupied by U2, c_4 is occupied by U1 and $c_{6,}$ by a PU. Suppose that a PU wants to use c_4 in a moment t, $t_3 < t < t_4$. Using the time slot division, U1 is able to know that the channel must be evacuated and U1 starts transmitting in the following time slot in c_1.

The CCBS, however, still needs to broadcast signals to its users, especially when unexpected PU communication appears in the CRN in some specific moments. This, as expected, is a part of the spectrum mobility issue. Using the same example from Fig. 32, let's suppose that a PU that uses c_8 appears in t_i, with $t_3 < t_i < t_4$, and a PU that uses c_2 appears in t_j, with $t_5 < t_j < t_6$. An approximate situation is shown in Fig. 34.

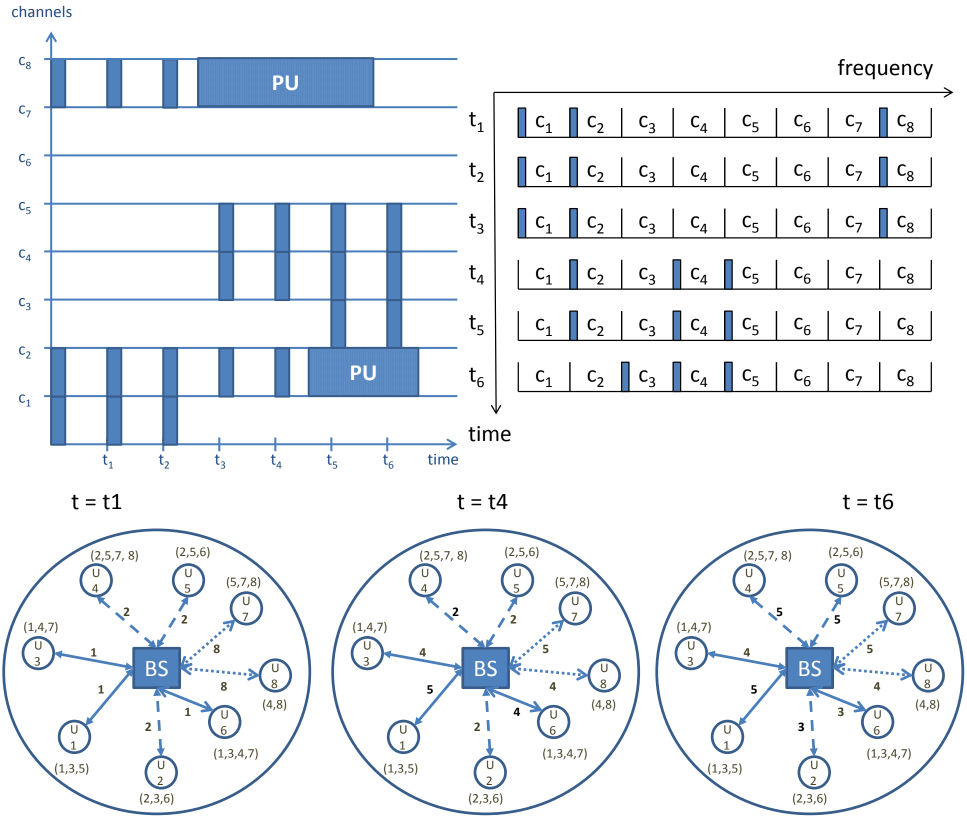


FIG. 34. Spectrum Mobility and HCM.

The control messages must hop in t = t_4 from c_8 to another channel. However, in this process, in order to maintain the same number of channels, the control messaging from c_1 also hops. All users are covered by c_2, c_4 and c_5. In t = t_6, c_2 is unavailable, so its control transmissions are split into c_3 and c_5.

4.4.4 Overlay Control Messaging

The main idea in this work is to use OSA to guarantee that no PU is interfered by a PU transmission by transmitting above a power threshold. Furthermore, when a PU is communicating, no other signal is in its same channel for security reasons. This approach is clearly seen in Fig. 13 and Fig. 33.

4.5 Energy Reduction (ER)

One of the CRNs most important characteristics is the ability CRUs have to dynamically access the spectrum. However, CRUs might be also capable of recognizing patterns of occupancy, to reduce the energy used for sensing, signaling and transmission. For this reason, Cognitive Radio technology has been also considered as an alternative to reduce energy consumption for wireless communications (Palicot, et al., 2010).

A CPC is a solution proposed in the E2R project for enabling communication among heterogeneous wireless networks. The CPC, as explained before, consists on controlling frequency bands in a single or various "pilot" channels. In (Bolivar, et al., 2010), a basic model for a Centralized CRN that uses CPCs for signalization and control was presented. The main idea was to introduce a control signal to announce channel availability and the necessity of leaving a frequency band if that one was occupied. For doing so, a basic signaling procedure, in which a two-bit signal was sent into sub-frequency slots on each available channel, was implemented. However, in terms of energy, transmitting through every available channel would be inefficient. This is because the entire wireless spectrum channels would be occupied in a specific moment. Considering this problem, new alternatives should be explored to reduce the energy used for signaling cognitive radio users (CRU) channel availability.

The idea to transmit signals through every available channel permits heterogeneous wireless frequency devices to communicate in an easy manner in the same network. To the best of the authors knowledge, since signaling availability through every communication channel is not a common strategy because of energy consumption, no standard procedure exist to reduce power usage. Among the strategies that might be applied to decrease this amount of energy are: reducing the number of channels and/or amount of time/symbols used for signalization, and recognizing patterns of transmission. Since the network is centralized, collisions on entrance of CRUs are reduced. In this work, the use of a distributed control and a centralized database for reducing the amount of energy used to signal this availability in the CRN is explained.

4.5.1 ER Mechanism

The basic model of the CRN used in this work is the one shown in Fig. 16. A Central Cognitive Base Station (CCBS) controls CRU communication so that these CRU do not interfere each other or a Primary User (PU). The CCBS is depicted in Fig. 25. The basic algorithm for each frequency slot was defined by Fig. 27. The database is mainly used for keeping into memory if a CRU was communicating in a specific frequency band. However, as Mitola suggested in (Mitola III & Maguire, 1999), this database can be also used to keep track of the environment to determine whether a PU might want to use a channel. In this work, the database is considered to be used only for CRU specifications. The main energy reduction is accomplished by reducing signalization transmissions.

When a CRU is trying to use the CRN, a message containing the identification frame is received from the CRU, and the process in the CCBS consists on determine if the information received is valid, i.e. no errors in the reception, if the CRU can access the CRN, and if both conditions are fulfilled, the CRU is accepted and its presence in the network is stored in the database. According to the channel and device characteristics, the CRU medium access might be performed in a time-based approach or a frequency-based approach. Since the analysis is the same for both frequency division and time division based approaches, the case for the time-based approach is explained, without losing generality. When a CRU data communication is already established, and since PU communication can enter at any moment, a time-based approach is implemented in order to discover PU presence.

This frequency and time system allows the elimination of a dedicated control channel for spectrum sharing. Using the slotted predefinition, if a transmission is received in a moment no transmission should be performed, a PU is assumed to be communicating and, then, the channel is evacuated and the process of assigning a channel restarts, keeping into memory the last information that was going to be transmitted. The time slot division used for the CRN MAC presented before, as shown in Fig. 26, will be also used to reduce the signalization.

In this section, two additional characteristics are added to the CRN model to reduce broadcast transmissions. The first one is that CRU synchronization will be performed as follows: Since the CRUs know the duration of the time slot, the CRU will search during a time slot in its channels for continuous transmission. If a CRU finds a PU-free channel, the device will send a signal for announcing that this CRU wants to access the network. A channel occupied by a CRU will be identified because of the time slots used for control, so this scheme will not introduce collisions among CRUs.

The second reduction consists on using the ability the CCBS has to identify the channels every CRU in the network is able to use. In this manner, the CCBS will only send a new broadcast transmission for each channel petition. This means that now, the entire wireless frequency spectrum considered for the CRN domain will not be used at several moments. In Fig. 28, the CRU Admission in the CRN Model is shown.

Using these alternatives, the flux diagram from Fig. 28 presents two cases: A CRU wants to access the CRN, and another CRU exists in one of the CRU devices' available channels. In this case, the new CRU senses the occupation, and when the device senses no transmission, it synchronizes with the CRN and could send its network admission petition or use a free channel to transmit, since the CRU device is already synchronized in time with the CRN.

The other case is that no CRU is communicating in the network within the available channels for the new CRU device. In this case, only PUs, or neither PUs nor CRUs, are using the channels, but the CRU cannot recognize the time slot that must be used for synchronization. The CRU then uses its time sensing capability to detect that a channel is being occupied for more time that the time-slot duration, so the CRU does not transmit through that channel. Next, the CRU device must find another channel to synchronize. If there is not an available channel for this CRU, this device cannot access the CRN. When an available channel is found, the

CRU then simply sends a petition to use the channel that the CCBS responds in the corresponding time slot, so the new CRU can be now synchronized to the network.

In FIG. 35, an example of the CRU admission in the CRN is shown by using the same example as in Fig. 29. U2, which has three channels for communications, “senses” its environment. Channel 1 (c_1) is being used by a PU, so this channel is unavailable to CRU transmission. Channel 2 (c_2) is occupied by U1. This makes the channel unavailable for U2 use, but U2 can detect the time slot position using U1 transmission. Using that information, U2 can access Channel 3 (c_3) in time t_2.

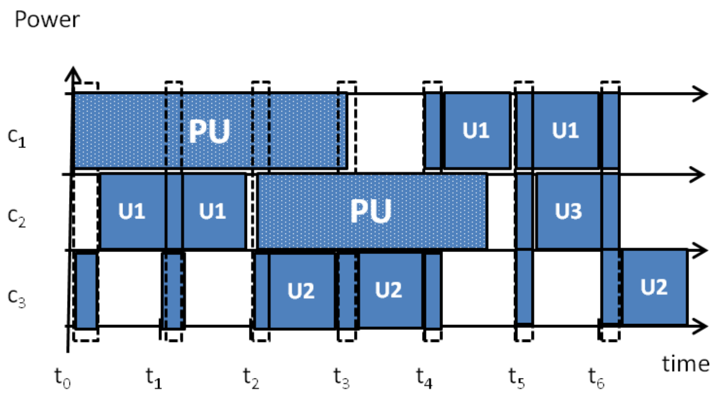


FIG. 35. Frequency Slot Utilization by both PU and CRUs (In Time)

4.5.2 ER Results

In this section, energy consumption due to signalization is analyzed in both the basic model presented in (Bolivar, et al., 2010) and in the model with the two modifications proposed in (Bolívar & Marzo, 2010).

In terms of energy reduction, the modifications provide the advantage of eliminating CCBS broadcasting transmission in all available channels, as explained in the previous section. This means a reduction per unit of time of (number of available channels) x (broadcasting transmission time) x (power used for beacon transmission).

The reduction might be also seen when CRUs are communicating or requesting communications. As some CRUs might be using or requesting channels, the energy decrease is not as straightforward as in the admission process. This reduction depends not only on the usage of the network, but on the numbers of requests at a specific moment.

A simulation is then performed in MATLAB to show the obtained results. The values used are the following: number of channels = 128, number of sub-channels = 256, control time/ (control + data) time = 1/10, and time duration = 500 units of time. In Fig. 36, channel occupancy and power used when CCBS sends broadcast signaling to announce availability is shown.

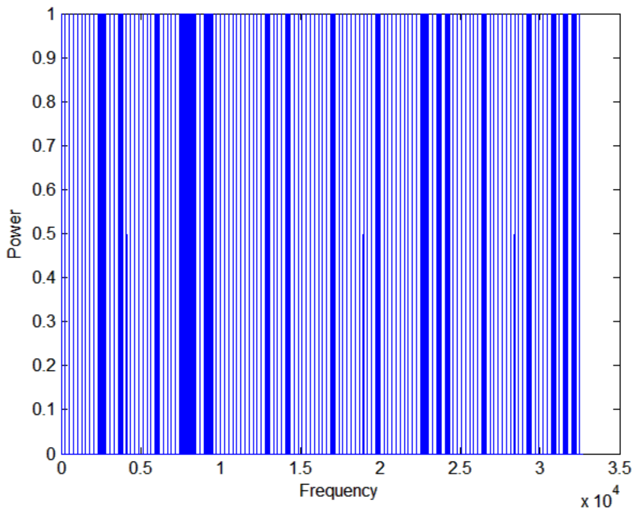


FIG. 36. Power used in the model presented in (BOLIVAR, ET AL., 2010) in t = 481, when CCBS sends broadcast transmission.

As expected, when CCBS sends broadcast transmission, every channel is occupied either by PUs (thick blue lines) or the CCBS broadcast transmission (thin lines). In Fig. 37, the power used and channel occupancy in the proposal is shown.

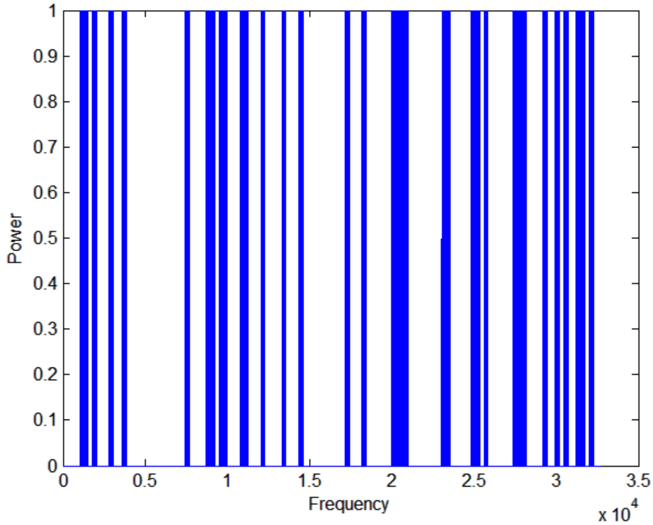


FIG. 37. Power used in the new model in t = 481, when CCBS in (BOLIVAR, ET AL., 2010) would send broadcast transmission.

In Fig. 37, power used with the new model when CCBS in (Bolivar, et al., 2010) would be sending broadcast transmission is shown. In this case, thick lines represent PU transmission, while thin lines represent CRU sending information to the CCBS. CRU lines in this case are thicker than in the previous model, since more information is sent in the first communication. This data is not sent later, as in (Bolivar, et al., 2010), unless the information is asked to be submitted again by the CCBS.

4.5.3 Minimum Channel Problem Reduction

In the last section, two additional characteristics are added to the CRN model of to reduce broadcast transmissions. The first one is that CRU synchronization is performed as follows: Since CRUs know the duration of the time slot, the CRU will search during a time slot in its channels for continuous transmission. If a CRU finds a PU-free channel, the device will send a signal for announcing that this CRU wants to access the network. A channel occupied by a CRU will be identified because of the time slots used for control, so this scheme will not introduce collisions among CRUs. The second reduction consists on using the ability the

CCBS has to identify the channels every CRU in the network is able to use. In this manner, the CCBS will only send a new broadcast transmission for each channel petition. This means that now, the entire wireless frequency spectrum considered for the CRN domain will not be used at several moments, and the number of periodical broadcast beacon transmission will be also reduced.

Eliminating CCBS broadcasting transmission channels means a reduction in terms of energy per unit of time of approximately (number of available channels) x (broadcasting transmission time) x (power used for beacon transmission). Then, the idea is to find the minimum number of broadcasting channels for the CCBS needed broadcasting transmission. For doing so, the method described in Chapter 3 will be used.

4.5.4 Results

4.5.4.1 Introduction

In this section, the CMS proposal, a combination of shared, multiple (clustered), hopping and overlay control messaging (SMHOCM) is compared to other CMS. The factors that are evaluated are basically two. The first one is the interference to PU caused by control messaging transmissions, which are called interference errors. The second one is CRUs not having a frequency slot (channel) to transmit, which are called availability errors. Results are presented in terms of the number of CRUs and the CRU load.

For analyzing the efficiency of the SMHOCM strategy for a CRN with HFD, this approach is compared with a dedicated, multiple, fixed and overlay control messaging (DMFOCM) approach and also with a dedicated, multiple, hopping and overlay control messaging – default hopping (DMHOCM – DH) approach.

In the SMHOCM proposal, since data and control share the same channels, the channels used for control messaging are obtained by using the B-ILP approach, and modified when PUs use one of the selected channels. Data channels are selected among all available channels, including the ones used for control messaging. In the DMFOCM, control channels are selected by using the B-ILP with the usability matrix and are fixed and dedicated in every time slot. Data channels should be then chosen from the available channels minus the previously selected control channels. Finally, in the DMHOCM-DH approach, control channels are also chosen from the usability matrix, but they are changed according to the time slot. The hopping channels are then decided by applying different stances of the B-ILP. In Fig. 38, Fig. 39 and Fig. 40, the control messaging channels and data channels selection process is illustrated.

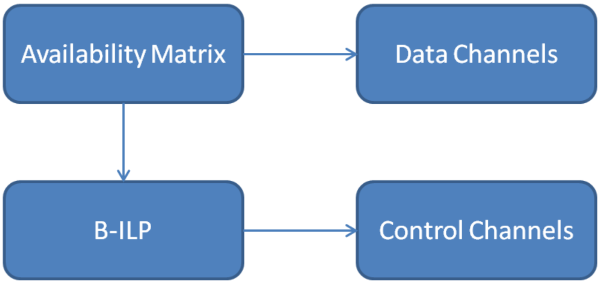


FIG. 38. Control messaging and data channel selection for the SMHOCM strategy (Proposal)

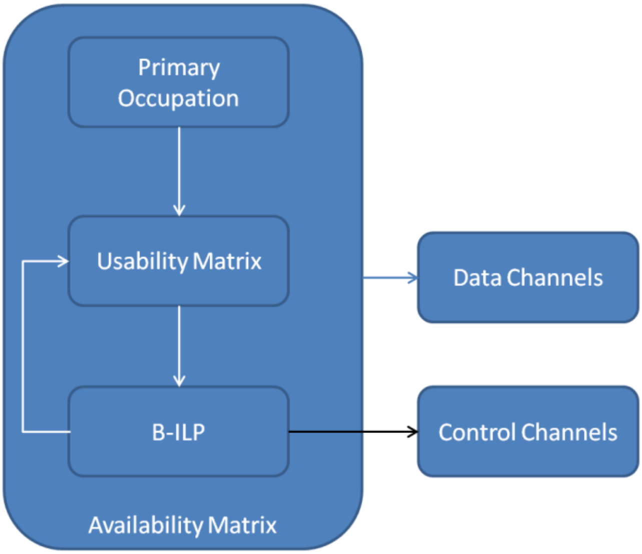


FIG. 39. Control messaging and data channel selection for the DMFOCM strategy

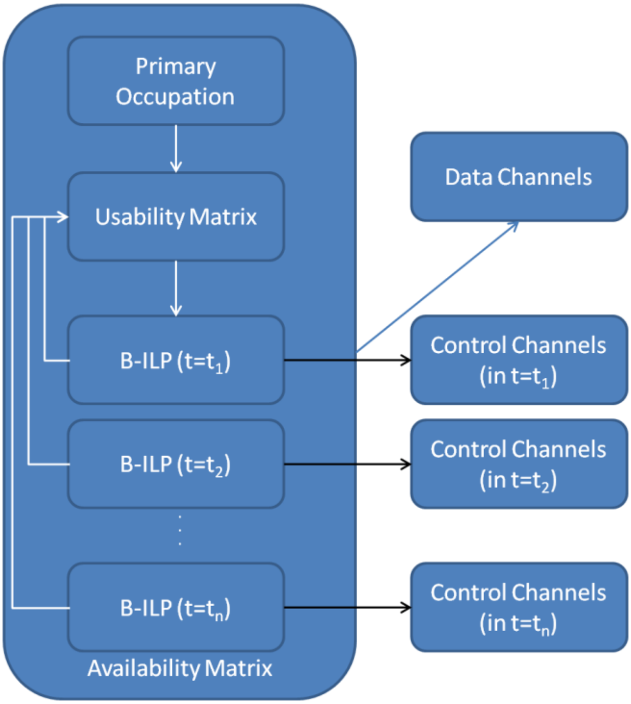


FIG. 40. Control messaging and data channel selection for the DMHOCM-DH strategy

4.5.4.2 Parameter Definitions

Using the processes from Fig. 38, Fig. 39 and Fig. 40, the simulations for each strategy are constructed. These simulations are performed in Matlab with the following parameters. The maximum number of CRUs in the network (*m*) is the same as the number of channels (*n*). Each channel has a PU with license to enter this channel at any moment. Two different scenarios are considered: *n = 8 and n = 16.* The number of sub-channels (*d*) is defined to be *2 x n.* The time slots considered for each simulation (*ts*) are equivalent to *5 x n*. The number of sub-channels used for control transmissions are 2, according to the definition in (Bolivar, et al., 2010). The time slot used for control in the SMHOCM is 0.2 of the total time slot as in (Bolívar & Marzo, 2011). This means that the effective SMHOCM data transmission is defined by:

$$\text{Eff. Trans} = [8/10] \times \{[(2 \times n) - 2)]/(2 \times n)\} \quad (7)$$

However, in this work, only the control messaging part is evaluated, in particular the effects the CMS have on channel availability and on interfering PUs.

The construction of the Usability matrix is performed as follows: using a random function, CRU usable channels are defined as rand(m,n) <= X, with X the proportion of expected usable channels. This means that if X is low, the CRUs are expected to have a low number of usable channels. As X is higher, the number of CRU usable channels is expected also to be higher. In the program in Appendix A, this variable can be modified.

The CRU load is also defined as rand(m,n) <= Y, with Y the proportion of expected CRUs that want to enter the channel. Finally, the PU load is also defined as rand(m,n) <= Z, with Z the proportion of expected PUs that use their licensed channels. Those two variables can be also modified in the program depicted in Appendix A.

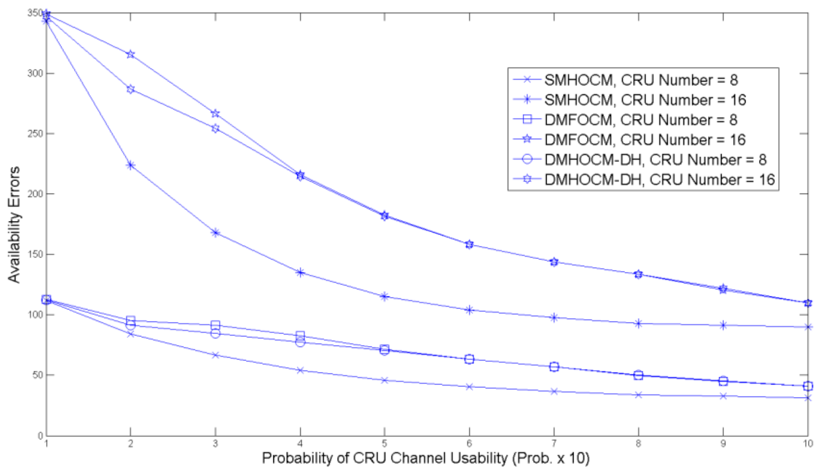
For testing the behavior of each of the CMSs, each of the three variables X, Y and Z are modified from 0.1 to 1, with intervals of 0.1 while setting the other two as

0.5. In this manner, all instances of PU and CRU load are considered, as well as the CRU usability possibilities. The procedure is repeated 512 times and the number of errors for each instance is calculated as the average of the 512 result each instance produces.

4.5.4.3 Analysis

For comparing the behaviors of the CMSs, the errors of the control transmissions are calculated as follows: if a CRU wants to transmit information and a channel is available, the user is entitled to transmit in that channel. If no channel is available, then, an availability error is detected. On the other hand, if while transmitting information, a PU appears, or a CRU attempts to use a channel occupied by a PU, a transmission error is detected. In all cases, the numbers of errors are presented in absolute and normalized values.

For the first comparison, the SMHOCM is compared with the DMFOCM and DMHOCM-DH by changing the probability of CRU Channel Usability. In Fig. 41, both the availability errors and the normalized availability errors are shown.



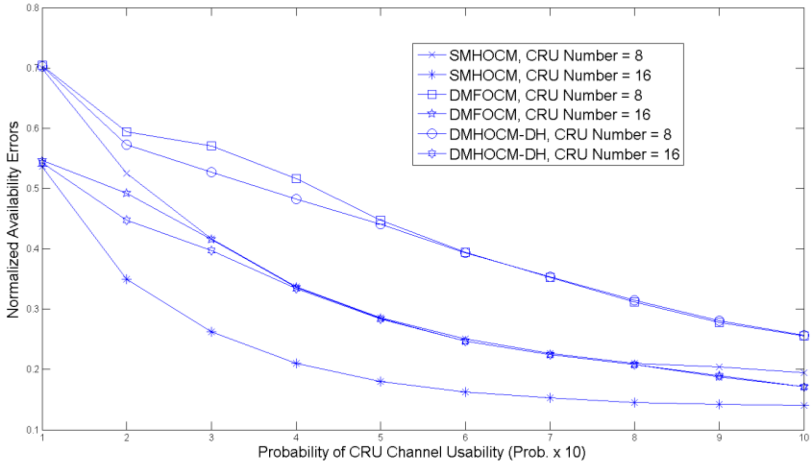


FIG. 41. Availability errors for the SMHOCM, DMFOCM and the DMHOCM-DH strategies

In Fig. 41, in both cases, the availability errors are lower in the SMHOCM case, considering that control and data information can be shared in the same channels. When the number of CRU increases, the difference in the availability errors, compared to the other strategies is more significant; however, the difference is actually more significant when the number of CRU is lower, in the normalized availability errors. The DMHOCM-DH works slightly better than the DMFOCM.

To validate that the obtained results for the Availability Errors, the average values of these errors (shown in Fig. 41) is presented in Table X with their respective confidence intervals for α = 0.05. The confidence intervals for the results obtained from this point are shown in Appendix C.

TABLE X. COMPARISON OF CONFIDENCE INTERVALS FOR THE AVAILABILITY ERRORS WHEN MODIFYING CRU CHANNEL USABILITY

Availability Errors							
	CRU Number = 8				CRU Number = 16			
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	111,839844	110,420097	113,25959	0,1	342,972656	339,573897	346,371415
	0,2	84,0214844	82,7305449	85,3124238	0,2	223,5	220,981298	226,018702
	0,3	66,875	65,6478789	68,1021211	0,3	168,011719	165,99094	170,032497
	0,4	53,984375	53,0584276	54,9103224	0,4	134,830078	133,182448	136,477708
SMHOCM	0,5	45,6269531	44,828377	46,4255292	0,5	115,248047	113,839333	116,656761
	0,6	40,3339844	39,6388969	41,0290719	0,6	104,09375	102,78524	105,40226
	0,7	36,4277344	35,7304173	37,1250514	0,7	97,6757813	96,4299329	98,9216296
	0,8	33,671875	33,0326089	34,3111411	0,8	93,0097656	91,7025384	94,3169928
	0,9	32,8417969	32,1986002	33,4849935	0,9	91,3652344	90,0398934	92,6905753
	1	31,2050781	30,5787054	31,8314508	1	89,8847656	88,6396127	91,1299186
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	112,619141	111,171518	114,066763	0,1	349,095703	345,048844	353,142562
	0,2	95,0195313	93,2054516	96,8336109	0,2	315,203125	309,471222	320,935028
	0,3	91,5019531	89,6773893	93,326517	0,3	266,519531	263,343315	269,695747
	0,4	82,7148438	81,3544616	84,0752259	0,4	215,949219	213,548009	218,350429
DMFOCM	0,5	71,59375	70,524304	72,663196	0,5	182,410156	180,26654	184,553772
	0,6	63,359375	62,4102185	64,3085315	0,6	158,210938	156,267867	160,154008
	0,7	56,7578125	55,860419	57,655206	0,7	143,597656	141,994915	145,200398
	0,8	49,8027344	48,893628	50,7118408	0,8	133,349609	131,73396	134,965259
	0,9	44,671875	43,8463836	45,4973664	0,9	120,65625	118,866158	122,446342
	1	41,1074219	40,4161768	41,798667	1	109,728516	108,374045	111,082986
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	112,367188	110,95449	113,779885	0,1	346,972656	343,41058	350,534732
	0,2	91,5273438	90,0947859	92,9599016	0,2	286,542969	282,456049	290,629889
	0,3	84,46875	83,0523548	85,8851452	0,3	254,314453	251,528073	257,100833
	0,4	77,2773438	76,1823835	78,372304	0,4	214,679688	212,400874	216,958501
DMHOCM-DH	0,5	70,5019531	69,5520844	71,4518219	0,5	181,390625	179,402568	183,378682
	0,6	63,2734375	62,3753591	64,1715159	0,6	158,275391	156,548681	160,0021
	0,7	56,9492188	56,0810929	57,8173446	0,7	143,576172	142,029914	145,12243
	0,8	50,2285156	49,369404	51,0876273	0,8	133,353516	131,828753	134,878278
	0,9	45,1191406	44,3393557	45,8989256	0,9	121,994141	120,350603	123,637678
	1	41,1992188	40,5033101	41,8951274	1	109,791016	108,426666	111,155365

The other important measure for a CRN is how much interference is caused to the PUs from the control messaging. In Fig. 42, the information lost due is shown. With these values, a comparison of the different strategies is performed.

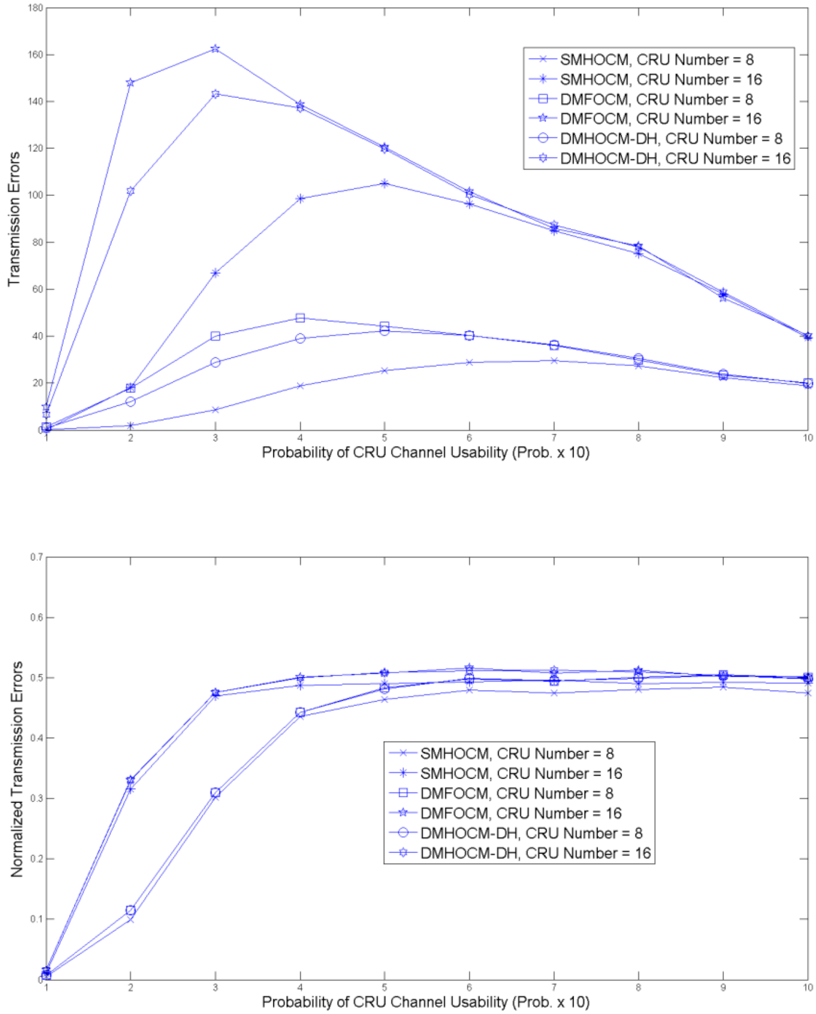


FIG. 42. Interference errors for the SMHOCM, DMFOCM and the DMHOCM-DH strategies

In Fig. 42, the interference errors created by the control transmissions are significantly lower in the SMHOCM strategy. This is as desired, considering that the proposed CMS interfere less the PU communication. On the other hand, the difference in the normalized transmission errors is not significant. This is because, the information sent in the SMHOCM in each time slot is less that in the other two cases. When the probability of channel usability is low, the DMHOCM-DH also improves the interference errors, compared to the DMFOCM.

For the second comparison, the SMHOCM is compared with the DMFOCM and DMHOCM-DH by changing the probability of CRU Channel Occupation. In Fig. 413, both the availability errors and the normalized availability errors are shown.

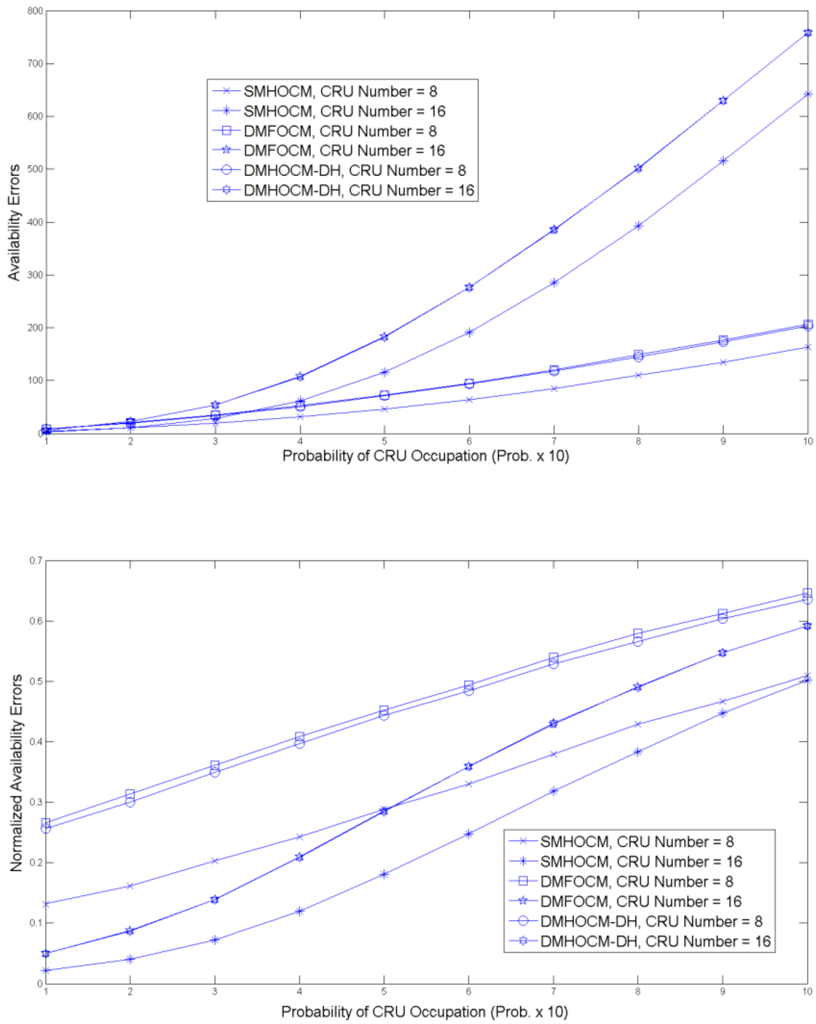


FIG. 43. Availability errors for the SMHOCM, DMFOCM and the DMHOCM-DH strategies

In Fig. 43, in both cases, the availability errors are lower in the SMHOCM case, considering that control and data information can be shared in the same channels. The DMHOCM-DH works as the DMFOCM. The availability errors increase exponentially when the CRU Channel Occupation increases.

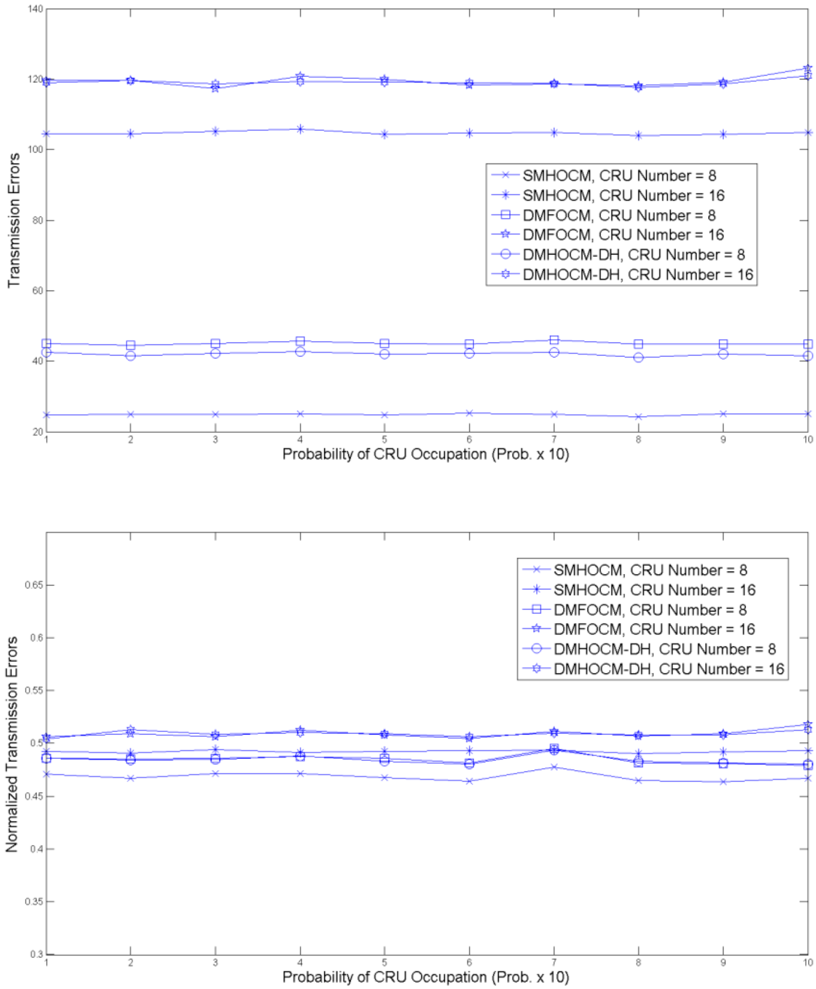


FIG. 44. Transmission errors for the SMHOCM, DMFOCM and the DMHOCM-DH strategies

The transmission errors for this case are shown in Fig. 44. At first, the reader might think that transmission errors would increase proportionally with the CRU occupation; however, since the control transmission depends on the PU occupation, the transmission errors were stable when the CRU Channel Occupation changed.

In Fig. 44, the normalized transmission errors confirm the abovementioned theory. Since the PU occupation probability was 0.5, the normalized transmission errors were close to 0.5. However, the SMHOCM strategy obtained the lowest results in both scenarios.

For the last comparison, the SMHOCM is compared with the DMFOCM and DMHOCM-DH by changing the probability of PU Occupation. In Fig. 415, both the availability errors and the normalized availability errors are shown.

In Fig. 45, when the PU occupation probability increases, the availability errors increase exponentially until no information could be transmitted (PU occupation = 1). This is expected, as when PU occupation = 1, means that there are no available channels for CRU transmission.

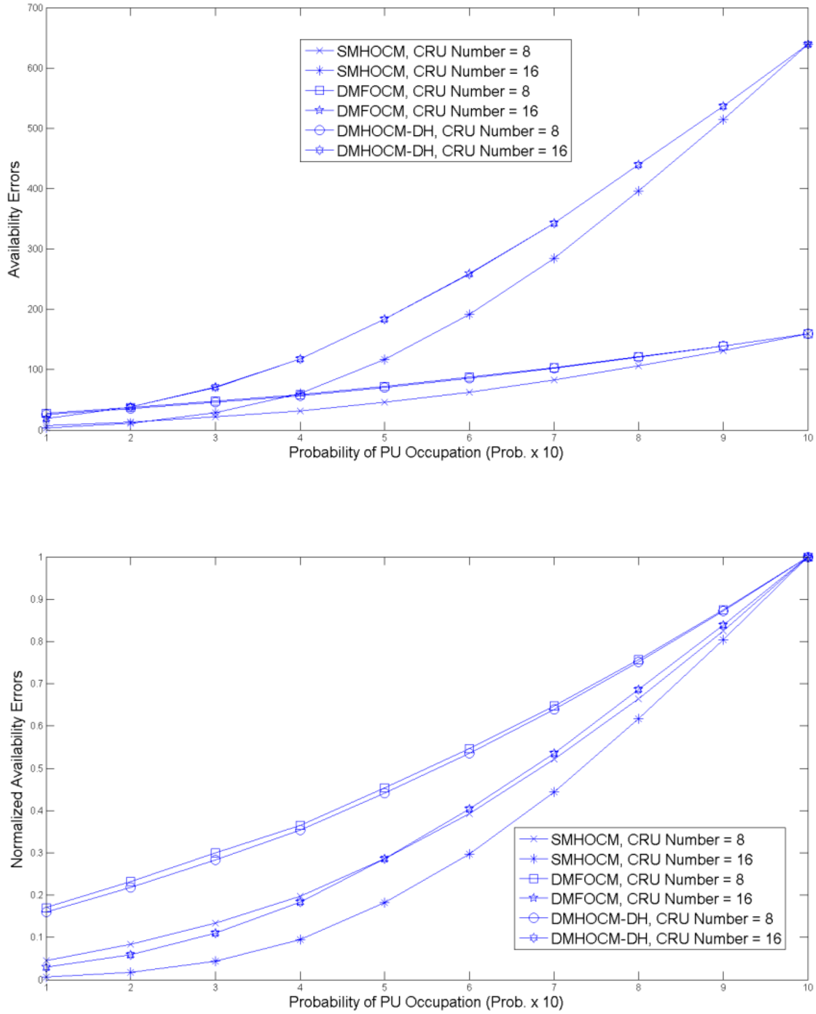


FIG. 45. Availability errors for the SMHOCM, DMFOCM and the DMHOCM-DH strategies

The transmission errors for this comparison are shown in Fig. 46. Since the SMHOCM was designed to lower PU interference, the results for this comparison are expected to be significantly better for the SMHOCM approach.

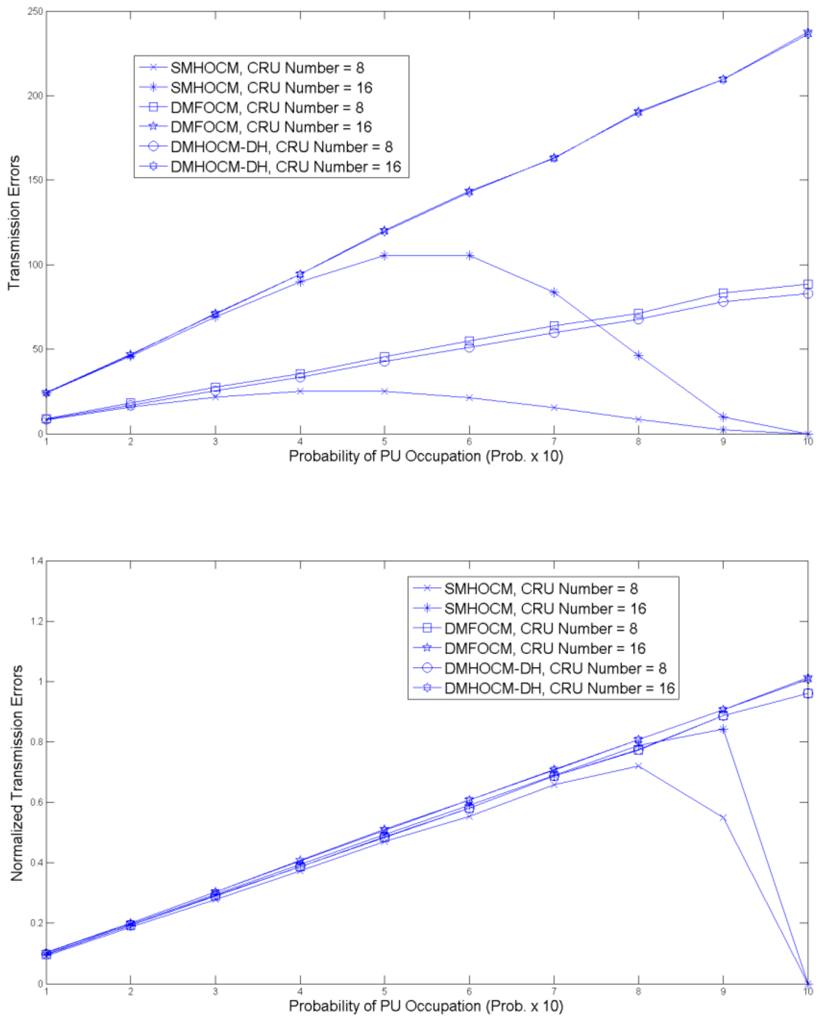


FIG. 46. Transmission errors for the SMHOCM, DMFOCM and the DMHOCM-DH strategies

As expected, when the PU occupation tends to be full, the transmission errors in the SMHOCM tend to be 0, considering the changing nature of the system, as shown in Fig. 46. The DMFOCM and the DMHOCM-DH strategies, due to their predetermined nature of their channels, cannot solve the CRU to PU interference problem when the PUs tend to use all the available spectrum.

4.5.5 Discussion

The model introduced in (Bolívar & Marzo, 2010) was categorized by using the classification from Chapter 2 and the control plane for a centralized CRN with heterogeneous frequency devices (HFD) was studied. In order to fulfill the basic control characteristics for spectrum access and mobility, the control strategy is presented as a combination of shared, multiple (clustered), hopping and overlay control messaging (SMHOCM).

The results indicate that a reduction in energy transmission due to signalization can be achieved by using the basic CRU sensing properties. Since the CRU can only detect values above a specific threshold for a determined period of time, the CRU might detect PU transmission due to its continuity, and CRU transmission due to its periodicity. Using that property, broadcasting transmissions, which contribute to energy waste, are reduced. Another advantage of using this property is that the CCBS is already aware of the available channels of each CRU. This is because in the admission process, each CRU has already indicated its characteristics.

Considering that the CCBS has this knowledge, direct channel assignation can be performed, so broadcast transmission is also reduced. The number of channels used for control transmission can be reduced to the minimum by solving the minimum channel problem. The minimum number of channels to communicate with all CRUs in the CRN can be found according to the characteristics of the CRU, and the access control would be performed through those channels.

The results indicate that a basic CMS can be implemented through CPC channels. The results also show that controlling a CRN using a SMHOCM is possible while allowing the presence of heterogeneous frequency CRU. The number of availability errors is lower with the SMHOCM strategy, considering that channels that are used for control can also be used for data. The most significant result is that by using the SMHOCM strategy the number of interference errors is greatly diminished compared with the DMFOCM strategy and compared with the

DMHOCM-DH strategy. Using this premise, a CRN composed of total heterogeneous wireless devices could be developed.

A comparison with an FCM-based CR-MAC supposes that better results could be obtained when hopping among channels according to PU occupation. In addition, combining HCM with SCM by using CPCs allows for more data communication. Further work will be developed in this area to find the trade-offs for applying this combined approach while still guaranteeing effective heterogeneous communication.

For future work, researchers are encouraged to compare the existent control strategies in environments where all the strategies are suitable. Likewise, the control plane study presented in this chapter is recommended to be expanded to include CRAHNs. Furthermore, more strategies to reduce energy transmission, such as database use for PUs and low-energy transmission mechanisms should be explored, as well as, security issues for CRU-CCBS communications and detection of malicious CRUs, in order to assure fairness in the network.

Chapter 5. Summary and Final Remarks

In this chapter, a summary of the conclusions obtained through this work and some final remarks are presented. For detailed conclusions, the reader is referred to the discussion section in each chapter.

On the use of CRNs as a solution for the wireless frequency allocation problem:

CRNs have been rapidly developing into a solution for the wireless frequency allocation problem, considering that studies have demonstrated that the main problem is because of spectrum misuse rather than spectrum scarcity. DSA and frequency agile characteristics of CRUs are used to transmit through unused portions of the spectrum.

Why it is so important to produce a good control plane definition:

Considering that these portions can be required by their licensed users, i.e. PUs, a good control CRN plane definition is a must for the CRUs in order not to interfere with the PUs and the other CRUs in the network. A good control plane definition is then a very important part of the spectrum access and the spectrum mobility mechanisms in a CRN. Different authors propose their methods for controlling the CRN, and only one classification was found in the literature. However, this classification was not suitable to control a CRN with HFDs.

The problem of a fully frequency heterogeneous CRN:

For constructing a fully heterogeneous CRN, control messaging has to be constructed in a specific manner. Several channels must be used for transmitting control information, considering that the CRUs communicate through different sets of channels. This means that MCM methods have to be applied. Different strategies for transmitting these control messages through the channels are compared and based on the results, for reducing energy consumption, the minimum number of channels for control messages should be used. The minimum channel problem was studied and was shown to be NP-hard.

Mathematical solution for the minimum channel problem:

The usual solutions for this problem in the literature were obtained by using a greedy approach. Other studies applied graph theory to find the required channels. Due to the fact that the problem is bounded to a centralized CRN and the possible states for a channel are available and unavailable for a user, B-ILP techniques can be used to find a solution to the NP-hard problem, by considering the users' availability matrix.

On model definitions and special characteristics:

Considering that opportunistic spectrum access was desired in order to use the same type of communications for both control and data transmissions, OCM and SCM were defined, and considering the changing nature of the availability matrix due to PU occupation, HCM was chosen. Then, in order to fulfill the basic control characteristics for spectrum access and mobility, the control strategy is presented as a combination of shared, multiple (clustered), hopping and overlay control messaging (SMHOCM).

Several concepts such as the beacon strategy and CPCs are also introduced and a combined time/frequency approach is presented for constructing the CMS for the centralized CRN. We show that the best way to control the centralized CRN with HFD is by using this SMHOCM approach.

Future work:

Researchers are encouraged to suggest other mechanisms and, if possible, to expand the presented taxonomy. As a continuation of this work, a comparison of CMSs is recommended to be performed in different environments, to decide which scheme is more suitable for each of the environments. Other mathematical approaches are suggested to be considered in order to solve the minimum channel problem. Finally, this study is recommended to be expanded for CRAHNs.

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APPENDIX A. RELEVANT PUBLICATIONS

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APPENDIX B. RELEVANT WORK

Internships/Workshops/Seminars

- Research Internship at RWTH Aachen. Project: Minimization of the number of Control Channels in Cognitive Radio Networks with Heterogeneous Frequency Devices. May 3rd – August 2nd 2011. Aachen, Germany.
- Session Chair at The First International Conference in Advances on Cognitive Radio (COCORA 2011). April 17 – 22, 2011. Budapest, Hungary.
- WGN8: VIII Workshop in G/MPLS networks. June 29, 2009. Girona, Spain.
- Hot-Tina, GRAAL/AEOLUS School on Hot Topics on Network Algorithms. May 4-8, 2008. Bertinoro, Italy.

Thesis Advisor

- Master Thesis Advisor. Study of admission and control system in a Centralized Cognitive Radio Network for Heterogeneous Wireless Frequency Devices. Albert Torró Vilert. May 25, 2011. Universitat Politècnica de Catalunya (UPC). Castelldefels, Spain.

Work

- Researcher at Universitat de Girona (Personal Investigador En Formació), Girona, Spain.

APPENDIX C. CONFIDENCE INTERVALS

Comparison of confidence intervals for the transmission errors when modifying CRU channel usability.

Transmission Errors								
	CRU Number = 8				**CRU Number = 16**			
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	0,04101563	0,00229006	0,07974119	0,1	0,12109375	0,03485766	0,20732984
	0,2	1,8828125	1,48895713	2,27666787	0,2	18,1621094	16,5838849	19,7403338
	0,3	8,66796875	7,91815369	9,41778381	0,3	66,8828125	64,6029569	69,1626681
	0,4	18,8945313	18,0477445	19,741318	0,4	98,609375	96,8702202	100,34853
SMHOCM	0,5	25,40625	24,7050675	26,1074325	0,5	105,007813	103,908387	106,107238
	0,6	28,9082031	28,3461593	29,4702469	0,6	96,2441406	95,2794822	97,2087991
	0,7	29,4726563	28,9425976	30,0027149	0,7	84,7792969	84,0038137	85,55478
	0,8	27,40625	26,8406799	27,9718201	0,8	75,1445313	74,2459822	76,0430803
	0,9	22,2910156	21,8571647	22,7248666	0,9	57,8457031	56,744884	58,9465223
	1	18,9042969	18,6342622	19,1743316	1	39,2558594	38,8691802	39,6425386
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	1,37890625	0,34060558	2,41720692	0,1	9,92382813	5,08131098	14,7663453
	0,2	17,8261719	14,8669726	20,7853712	0,2	147,923828	138,320881	157,526775
	0,3	39,9960938	37,0721729	42,9200146	0,3	162,470703	158,328716	166,61269
	0,4	47,8554688	46,0044074	49,7065301	0,4	138,808594	135,636672	141,980516
DMFOCM	0,5	44,2890625	43,0941113	45,4840137	0,5	120,556641	117,78578	123,327501
	0,6	40,2324219	39,3328111	41,1320327	0,6	101,574219	98,9310688	104,217369
	0,7	36,0273438	35,1150729	36,9396146	0,7	85,9453125	84,0487446	87,8418804
	0,8	29,8945313	28,9675345	30,821528	0,8	78,296875	76,4036297	80,1901203
	0,9	23,1992188	22,528778	23,8696595	0,9	56,2871094	54,5338248	58,040394
	1	20,015625	19,732386	20,298864	1	40,1425781	39,7312601	40,5538962
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	0,92773438	0,22629202	1,62917673	0,1	6,5546875	3,35126165	9,75811335
	0,2	12,1679688	10,1416626	14,1942749	0,2	101,875	95,1746317	108,575368
	0,3	28,7011719	26,6053803	30,7969635	0,3	143,347656	139,297552	147,397761
	0,4	38,9238281	37,3694397	40,4782166	0,4	137,226563	134,792192	139,660933
DMHOCM-DH	0,5	42,1445313	41,062733	43,2263295	0,5	119,828125	117,935399	121,720851
	0,6	40,2109375	39,4199591	41,0019159	0,6	100,462891	98,7399132	102,185868
	0,7	36,3496094	35,625527	37,0736918	0,7	87,3398438	85,8968734	88,7828141
	0,8	30,6367188	29,8987773	31,3746602	0,8	77,8945313	76,6571136	79,1319489
	0,9	23,9296875	23,3823775	24,4769975	0,9	58,8066406	57,4500873	60,1631939
	1	19,921875	19,644635	20,199115	1	39,8984375	39,49229	40,304585

Comparison of confidence intervals for the availability errors when modifying CRU channel occupation.

Availability Errors	CRU Number = 8				CRU Number = 16			
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	4,28710938	4,06556663	4,50865212	0,1	2,76367188	2,60018361	2,92716014
	0,2	10,4394531	10,052572	10,8263343	0,2	10,2207031	9,82530199	10,6161043
	0,3	19,5527344	18,9960204	20,1094484	0,3	27,9316406	27,2540013	28,6092799
	0,4	31,0976563	30,4254064	31,7699061	0,4	61,6796875	60,6223092	62,7370658
SMHOCM	0,5	46,4003906	45,5799658	47,2208155	0,5	116,150391	114,643332	117,657449
	0,6	63,5136719	62,632559	64,3947848	0,6	190,679688	188,926115	192,43326
	0,7	85,0664063	84,0574002	86,0754123	0,7	285,361328	283,499618	287,223039
	0,8	110,074219	109,077589	111,070849	0,8	392,8125	390,959755	394,665245
	0,9	134,505859	133,578042	135,433677	0,9	515,34375	513,62473	517,06277
	1	162,972656	162,068339	163,876974	1	641,650391	640,041608	643,259173
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	8,6015625	8,26019423	8,94293077	0,1	6,46875	6,17408744	6,76341256
	0,2	20,2089844	19,620474	20,7974947	0,2	22,4472656	21,7701252	23,1244061
	0,3	34,7695313	33,9702654	35,5687971	0,3	53,7441406	52,6210283	54,867253
	0,4	52,2675781	51,3100398	53,2251164	0,4	107,585938	106,019598	109,152277
DMFOCM	0,5	72,8632813	71,7528631	73,9736994	0,5	182,890625	180,862478	184,918772
	0,6	95,0703125	93,8933111	96,2473139	0,6	276,486328	274,135996	278,836661
	0,7	120,742188	119,37768	122,106695	0,7	384,898438	382,272963	387,523912
	0,8	148,570313	147,158892	149,981733	0,8	502,435547	499,845336	505,025757
	0,9	176,357422	174,985159	177,729685	0,9	630,013672	627,639364	632,38798
	1	206,800781	205,396786	208,204777	1	758,113281	755,565082	760,66148
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	8,31835938	8,00746123	8,62925752	0,1	6,43164063	6,14114058	6,72214067
	0,2	19,3339844	18,8279564	19,8400123	0,2	22,2441406	21,6057754	22,8825059
	0,3	33,5761719	32,8671025	34,2852413	0,3	53,7578125	52,686347	54,829278
	0,4	50,8085938	49,9430377	51,6741498	0,4	107,369141	105,910955	108,827326
DMHOCM-DH	0,5	71,3632813	70,3484084	72,3781541	0,5	182,259766	180,296664	184,222868
	0,6	93,1464844	92,0648578	94,228111	0,6	276,660156	274,525412	278,794901
	0,7	118,300781	117,098526	119,503036	0,7	386,351563	383,904322	388,798803
	0,8	145,099609	143,833701	146,365518	0,8	501,697266	499,46477	503,929761
	0,9	173,798828	172,539569	175,058087	0,9	630,039063	627,992081	632,086044
	1	203,267578	201,969484	204,565672	1	758,248047	756,122205	760,373889

Comparison of confidence intervals for the transmission errors when modifying CRU channel occupation.

Transmission Errors									
		CRU Number = 8					CRU Number = 16		
	Probability	Mean	Confidence Intervals			Probability	Mean	Confidence Intervals	
	0,1	24,7910156	24,0778209	25,5042104		0,1	104,523438	103,471375	105,5755
	0,2	24,8300781	24,1099424	25,5502138		0,2	104,484375	103,377789	105,590961
	0,3	24,8789063	24,14766	25,6101525		0,3	105,25	104,20314	106,29686
	0,4	25,1386719	24,4425789	25,8347648		0,4	105,777344	104,720263	106,834424
SMHOCM	0,5	24,8183594	24,100103	25,5366157		0,5	104,330078	103,251624	105,408532
	0,6	25,2304688	24,4871709	25,9737666		0,6	104,726563	103,611676	105,841449
	0,7	24,9042969	24,237935	25,5706588		0,7	104,8125	103,821923	105,803077
	0,8	24,2558594	23,4968394	25,0148794		0,8	104	102,992142	105,007858
	0,9	25,1035156	24,3595395	25,8474918		0,9	104,357422	103,303548	105,411296
	1	24,9941406	24,2509991	25,7372822		1	104,767578	103,739518	105,795639
	Probability	Mean	Confidence Intervals			Probability	Mean	Confidence Intervals	
	0,1	45,0253906	43,7907505	46,2600308		0,1	119,628906	117,250777	122,007035
	0,2	44,5820313	43,366194	45,7978685		0,2	119,722656	116,981609	122,463704
	0,3	45,0039063	43,7474269	46,2603856		0,3	117,330078	114,870525	119,789631
	0,4	45,7128906	44,5311874	46,8945939		0,4	120,826172	117,867116	123,785227
DMFOCM	0,5	44,96875	43,7324174	46,2050826		0,5	119,990234	117,621889	122,35858
	0,6	44,9277344	43,7016407	46,153828		0,6	118,269531	115,951256	120,587807
	0,7	46,0097656	44,8594411	47,1600901		0,7	118,591797	116,026243	121,15735
	0,8	44,7832031	43,4241353	46,142271		0,8	118,107422	115,367745	120,847099
	0,9	44,90625	43,6315937	46,1809063		0,9	119,078125	116,605475	121,550775
	1	44,8828125	43,6258017	46,1398233		1	123,113281	120,029078	126,197485
	Probability	Mean	Confidence Intervals			Probability	Mean	Confidence Intervals	
	0,1	42,4589844	41,3479799	43,5699888		0,1	118,951172	117,263832	120,638512
	0,2	41,5351563	40,4698931	42,6004194		0,2	119,578125	117,739609	121,416641
	0,3	42,1386719	41,0099672	43,2673766		0,3	118,697266	117,048193	120,346338
	0,4	42,7597656	41,6583288	43,8612024		0,4	119,365234	117,438557	121,291912
DMHOCM-DH	0,5	42,0683594	40,9473726	43,1893462		0,5	119,128906	117,446544	120,811269
	0,6	42,1542969	41,0151449	43,2934488		0,6	118,972656	117,209498	120,735815
	0,7	42,4921875	41,4531554	43,5312196		0,7	118,873047	117,222637	120,523457
	0,8	41,0527344	39,826298	42,2791708		0,8	117,650391	115,876577	119,424205
	0,9	42,0585938	40,9371772	43,1800103		0,9	118,619141	116,878354	120,359928
	1	41,4804688	40,3379899	42,6229476		1	121,011719	119,031039	122,992399

Comparison of confidence intervals for the availability errors when modifying PU channel occupation.

Availability Errors									
	CRU Number = 8					CRU Number = 16			
	Probability	Mean	Confidence Intervals			Probability	Mean	Confidence Intervals	
	0,1	7,359375	6,77079934	7,94795066		0,1	3,40625	3,01123079	3,80126921
	0,2	13,0449219	12,4323137	13,6575301		0,2	11,0292969	10,3590436	11,6995502
	0,3	20,796875	20,1081858	21,4855642		0,3	28,5	27,586102	29,413898
	0,4	31,8515625	31,0579757	32,6451493		0,4	60,7753906	59,6151643	61,935617
SMHOCM	0,5	46,0820313	45,2795045	46,884558		0,5	114,978516	113,575111	116,381921
	0,6	63,4921875	62,6526303	64,3317447		0,6	188,814453	187,110869	190,518037
	0,7	83,375	82,4852798	84,2647202		0,7	283,267578	281,538038	284,997118
	0,8	106,375	105,489697	107,260303		0,8	393,734375	391,930506	395,538244
	0,9	132,820313	131,948248	133,692377		0,9	515,132813	513,312829	516,952796
	1	159,957031	159,20003	160,714033		1	639,806641	638,15732	641,455961
	Probability	Mean	Confidence Intervals			Probability	Mean	Confidence Intervals	
	0,1	28,1875	27,0102707	29,3647293		0,1	18,0371094	16,9722947	19,101924
	0,2	36,4335938	35,2728703	37,5943172		0,2	38,3730469	37,0254096	39,7206842
	0,3	46,6621094	45,5469932	47,7772256		0,3	71,484375	69,7550411	73,2137089
	0,4	58,7402344	57,5810761	59,8993927		0,4	117,287109	115,33331	119,240909
DMFOCM	0,5	72,2207031	71,083943	73,3574632		0,5	181,265625	179,162781	183,368469
	0,6	87,5664063	86,5091788	88,6236337		0,6	255,966797	253,748889	258,184705
	0,7	103,654297	102,625248	104,683346		0,7	343,326172	341,312743	345,339601
	0,8	121,445313	120,51337	122,377255		0,8	436,695313	434,727235	438,66339
	0,9	141,007813	140,150157	141,865468		0,9	537,753906	535,959835	539,547978
	1	159,957031	159,20003	160,714033		1	639,806641	638,15732	641,455961
	Probability	Mean	Confidence Intervals			Probability	Mean	Confidence Intervals	
	0,1	25,9589844	25,0461784	26,8717903		0,1	17,9804688	17,007465	18,9534725
	0,2	34,6328125	33,6810215	35,5846035		0,2	38,0039063	36,7724256	39,2353869
	0,3	44,8847656	43,9349108	45,8346205		0,3	71,1054688	69,4964861	72,7144514
	0,4	56,8398438	55,8642851	57,8154024		0,4	117,726563	115,959577	119,493548
DMHOCM-DH	0,5	70,234375	69,2247134	71,2440366		0,5	180,566406	178,647629	182,485184
	0,6	85,7988281	84,8224615	86,7751947		0,6	255,244141	253,185054	257,303227
	0,7	102,328125	101,368071	103,288179		0,7	342,703125	340,826495	344,579755
	0,8	120,1875	119,289239	121,085761		0,8	436,898438	434,984207	438,812668
	0,9	140,519531	139,67209	141,366972		0,9	537,712891	535,911306	539,514475
	1	159,957031	159,20003	160,714033		1	639,806641	638,15732	641,455961

Comparison of confidence intervals for the transmission errors when modifying PU channel occupation.

Transmission Errors								
		CRU Number = 8				CRU Number = 16		
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	8,59765625	8,28642746	8,90888504	0,1	23,4589844	22,9503337	23,9676351
	0,2	16,0917969	15,6248409	16,5587528	0,2	46,2324219	45,4964238	46,9684199
	0,3	22,2128906	21,6987753	22,727006	0,3	69,1894531	68,2636901	70,1152161
	0,4	24,9765625	24,3227526	25,6303724	0,4	90,5273438	89,5066486	91,5480389
SMHOCM	0,5	24,9199219	24,2222639	25,6175799	0,5	105,861328	104,815527	106,907129
	0,6	21,4160156	20,6760678	22,1559635	0,6	106,041016	104,793695	107,288336
	0,7	15,3300781	14,7170476	15,9431086	0,7	84,6855469	83,2624664	86,1086274
	0,8	8,0546875	7,59288871	8,51648629	0,8	45,3046875	44,1778229	46,4315521
	0,9	2,36328125	2,1430135	2,583549	0,9	10,4003906	9,84109347	10,9596878
	1	0	0	0	1	0	0	0
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	9,28710938	8,94184764	9,63237111	0,1	23,6152344	23,028391	24,2020778
	0,2	18,0839844	17,5002241	18,6677446	0,2	46,84375	45,8403345	47,8471655
	0,3	27,3496094	26,6077785	28,0914402	0,3	70,0527344	68,4610864	71,6443824
	0,4	35,9707031	34,96892	36,9724862	0,4	94,65625	92,5524025	96,7600975
DMFOCM	0,5	44,3183594	43,1539143	45,4828045	0,5	119,083984	116,548708	121,619261
	0,6	54,2695313	52,7755681	55,7634944	0,6	144,410156	141,184224	147,636089
	0,7	64,1640625	62,5735097	65,7546153	0,7	167,914063	164,644238	171,183887
	0,8	71,859375	70,1059184	73,6128316	0,8	188,666016	184,759032	192,573
	0,9	81,2128906	79,2747739	83,1510073	0,9	215,34375	211,112307	219,575193
	1	91,171875	88,9557273	93,3880227	1	235,625	231,717693	239,532307
	Probability	Mean	Confidence Intervals		Probability	Mean	Confidence Intervals	
	0,1	8,56835938	8,24677108	8,88994767	0,1	23,7675781	23,2537549	24,2814013
	0,2	16,9628906	16,4215849	17,5041963	0,2	46,9199219	46,1054712	47,7343726
	0,3	25,9492188	25,2516138	26,6468237	0,3	70,9257813	69,812453	72,0391095
	0,4	33,3359375	32,4223752	34,2494998	0,4	94,59375	93,1547502	96,0327498
DMHOCM-DH	0,5	41,2617188	40,1895891	42,3338484	0,5	118,740234	116,992042	120,488427
	0,6	50,2773438	48,9645145	51,590173	0,6	141,878906	139,797416	143,960397
	0,7	60,0488281	58,5776082	61,520048	0,7	167,136719	164,920301	169,353137
	0,8	66,9589844	65,3792786	68,5386901	0,8	188,441406	185,816073	191,06674
	0,9	75,9726563	74,1987627	77,7465498	0,9	212,892578	210,089154	215,696002
	1	85,6621094	83,644419	87,6797998	1	237,990234	235,232199	240,74827