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Memòria justificativa de recerca de les beques predoctorals per a la formació de personal investigador (FI)

La memòria justificativa consta de les dues parts que venen a continuació:
1.- Dades bàsiques i resums
2.- Memòria del treball (informe científic)

Tots els camps són obligatoris

1.- Dades bàsiques i resums

Títol del projecte ha de sintetitzar la temàtica científica del vostre document.
MEDIUM ACCESS CONTROL MESSAGING SCHEME FOR COGNITIVE RADIO NETWORKS

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Paraules clau: cal que esmenteu cinc conceptes que defineixin el contingut de la vostra memòria.
Cognitive Radio Networks; Control Messaging Schemes; Dynamic Spectrum Access; Heterogeneous Frequency Devices; Minimum Channel Problem

Data de presentació de la justificació
27/06/2012

Nom i cognoms, i signatura del beneficiari/ària

Vist i plau del/de la director/a del projecte

Resum en la llengua del projecte (màxim 300 paraules)
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.

Resum en anglès(màxim 300 paraules)
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.

2.- Memòria del treball (informe científic sense limitació de paraules). Pot incloure altres fitxers de qualsevol mena, no més grans de 10 MB cadascun d'ells.

Introduction

Cognitive Radio Networks (CRNs) have been appointed as a solution to the apparent wireless spectrum scarcity problem [1-3]. This is because Cognitive Radio (CR) systems are able to detect free frequency spaces (bands) in the spectrum and to allocate communications in those spaces by using Dynamic Spectrum Access (DSA) mechanisms. CRN allow secondary users, i.e. non-licensed devices, to use free frequency bands while the Primary Users (PU), i.e. licensed users of specific bands, are absent. In general, a CRN should be able to perform 4 tasks efficiently: spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility [2].

One of the CRN most important characteristics is the ability for the Cognitive Radio Users (CRU) to dynamically access the spectrum. A cognitive pilot channel (CPC) is a solution proposed in the E2R project for enabling communication among heterogeneous wireless networks. The CPC consists on controlling frequency bands in a single or multiple "pilot" channels [3-6]. In [7], 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 necessity 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 interference, transmitting through every available channel would be a problem; when a PU accesses its licensed spectrum, the control transmission could interfere for a short period of time the PU transmission. Considering this problem, new alternatives should be explored to reduce the number of channels used for signaling CRUs channel availability. For reducing the number of channels used for control transmissions, in [8], we used the characteristics of the combined time/frequency approach for the Central Cognitive Base Station (CCBS) in order to beacon 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 for reducing the amount of energy used to signal this availability in the CRN.

The problem of obtaining the minimum number of channels for a base station, e.g. the CCBS, to transmit to all the users in its network is an optimization problem. For solving this problem, the dynamic characteristics of the CRN that include not only the entrance and departure of CRUs, but also external factors, e.g. the presence of PUs, must be considered. In [9], 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. This broadcasting signaling problem for one base station can be associated to a set covering problem which is known to be NP-hard. In [10], the authors presented a Control Messaging Schemes (CMSs) Classification technique, in which all control messaging strategies can be catalogued into.

Objectives and Motivation

A.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.

A.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.

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.

Outline of this work:

In this work, we will use the aforementioned classification to compare different CMSs that are suitable for CRN that are able to support Heterogeneous Frequency Devices (HFD). The rest of the work is structured as follows: in section II, the CMS classification is summarized. In section III, the minimum channel problem is presented. In section IV, a case where the minimum channel problem is solved by different mathematical methods is shown. In section V, the CRN with HFD model is presented. In section VI, we compare our CMS with other CMSs suitable for the model displayed in section V by using a mathematical technique from section III. Finally, in section VII, a brief discussion is presented.

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.

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 [10].
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 [9].
3. A CR model suitable for CRUs that use HFDs, i.e. operate in different channels, introduced in Chapter 4 and in [7]. Several publications have been developed from this model [8-9].

Control Messaging Schemes (CMSs) Classification

In order to efficiently distribute the CRUs in their corresponding channels without interfering 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 good control plane has been discussed in [11] and the coexistence of HFD in the same CRN was introduced in [12] However, to the authors' best knowledge, there is not a review in the literature about the alternatives for transmitting control messages for HFDs. The closest ones are presented in [13] and [14] for the rendezvous problem, i.e. user discovery in a DSA environment, and the presented by Lo, in [15]. In this chapter, we provide a quick review about the control plane alternatives combining the classifications defined by [13-15] and expanding them to consider all the control plane alternatives.

Classification

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 control messaging. On the other hand, multiple control messaging implies that at least two channels are used at the same time for control messages transmission. Fixed control messaging indicates that the channel(s) for the transmission of the 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

Fig. 1, our CMS classification is depicted.

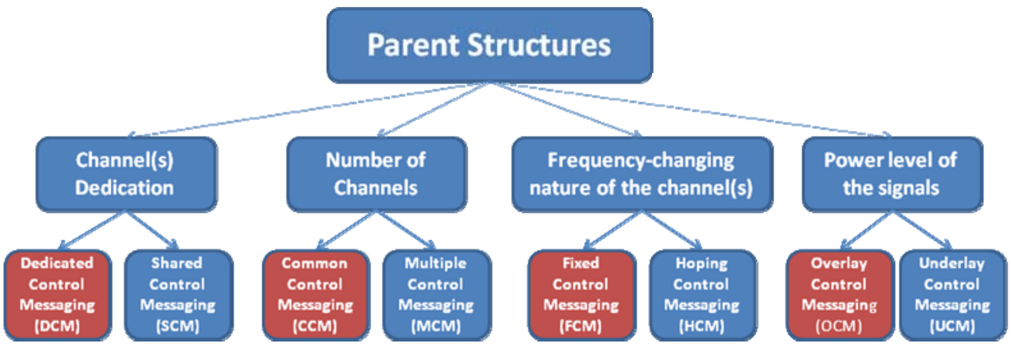

Fig. 1. Control Messaging Schemes Classification

Comparison

A comparison among our proposal, CPCDF-MAC, multi-channel MAC protocols from [16], existing CR MAC protocols from [17], [18] and CMSs parent strategies from the categories explained in section 2.1 is shown in Table I.

TABLE I. CMS COMPARISON

Protocol	Specialization of the Channels	Number of Channels	Frequency Changing Nature	Power Level	Time Synchronization 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, as stated in [19]. This minimum channel problem can be solved by using mathematical strategies, e.g. Binary Integer Linear Programming (B-ILP).

Minimum Channel Problem

The main reasons for using the minimum number of channels for broadcasting and control are reducing energy transmissions and to optimize spectrum usage. In [8], we showed that 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). Results indicated 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, considering that 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. Then, the idea is to find the minimum number of broadcasting channels for the CCBS needed broadcasting transmission and control.
Considering again that the CCBS knows the channels that each CRU is able to use, for finding this minimum number of the broadcast transmission channels needed in a specific moment, a matrix called usability matrix is defined. The relation among the frequency slots (channels) and CRUs is shown in Fig. 2.

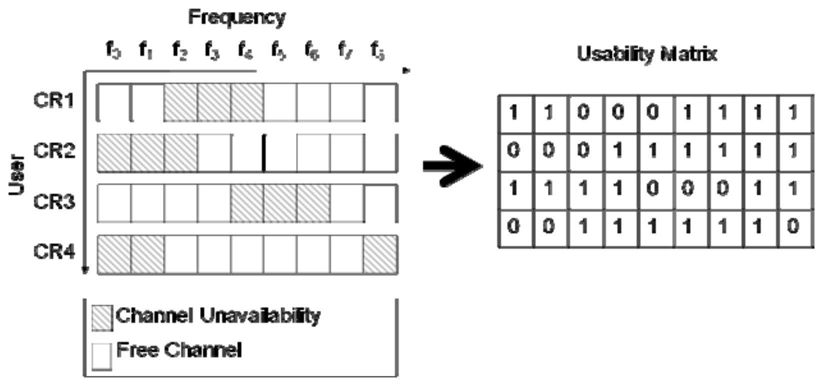

Fig. 2. Frequency slot utilization by CRUs

In Fig. 2, the matrix that relates channel usability for each CRU is represented as Usability Matrix (Umxn). In [9], the authors show that this problem is NP-complete by relating it to the satisfiability problem. In this work, we make a stronger stance 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 X1xn, 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, b1, b2, …, bn, in which a base station CCBS is able to transmit to each user (ui) utilizing the minimum number of channels.

If we define a cost for transmitting in a channel i as qi, The problem can be represented then as

$$\text{Minimize } \sum qi*xi, \qquad \text{s.t.} \qquad (1)$$
$$Ux \geq 1mx1 \qquad (2)$$
$$x \in [0,1] \qquad (3)$$

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.

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. The relation among the frequency slots (channels) and CRUs in a specific time slot is shown in Fig. 3.

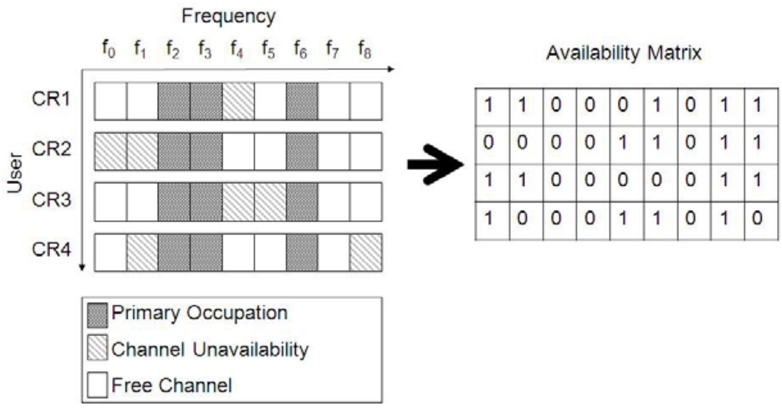

Fig. 3. Frequency slot utilization by both PU and CRUs

In Fig. 3, 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. 3, the eighth column, corresponding to f7, is a unitary column. This means that using that channel (f7), the CCBS can broadcast communication to all the users in its CRN during that period of time. In Fig. 4, a case where more than one channel is needed for the CCBS to broadcast is shown.

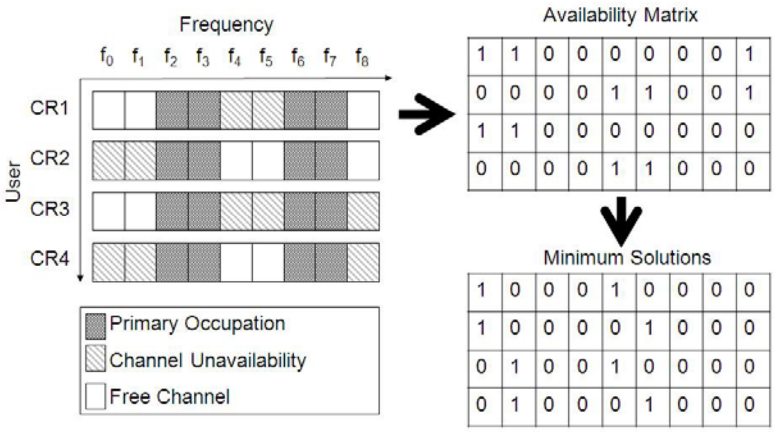

Fig. 4. Frequency slot utilization by both PU and CRUs (in time)

In the case presented in Fig. 4, the availability matrix shows that at least the CCBS needs two channels to communicate with all the CRUs in the network, for instance f0 and f1 in the example. 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

$$\text{Minimize } \sum qti*xi, \qquad \text{s.t.} \tag{4}$$
$$Ax \geq 1mx1 \tag{5}$$
$$x \text{ € } [0,1] \tag{6}$$

In the case when PUs are not considered, let's assume that for an array consisting on m users and n channels, the minimum number k of broadcasting channels for the array has been found. As shown in Fig. 4, CRUs enter and leave the CRN dynamically. This means that the algorithm for finding the minimum solutions vectors must consider the dynamics of the network. For reducing the complexity of the algorithm, the property that this CRN has that only a new CRU can enter/leave at a specific time is used. If a new CRU enters the network, the minimum number of channels 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 signalling channels is at least k-1, and at most k.
However, as shown in Fig. 4, 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 A(i,:) = U(i,:)*p represents the availability vector for transmitting broadcast signals by the CCBS. When primary occupation is considered, in some specific moments a CRU i defined by A(i,:) might be unavailable for communication.

Case Study

In this section, 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)

	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_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 f1 and f5, f4, f7, f3 and f5.
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, we simulate this situation by doubling the number of CRUs. Results are shown in Table III.

TABLE III. CHANNEL USABILITY (CRU NUMBER = 16)

	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_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
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 f8 and f3, 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}
f_1	0	0	0	0	1	1	0	0	0	0
f_2	1	1	1	1	1	0	0	0	0	1
f_3	0	0	0	0	0	0	1	1	1	1
f_4	0	0	0	0	0	1	1	0	0	0
f_5	0	0	0	0	0	0	0	0	0	0
f_6	1	1	1	1	1	1	0	0	1	1
f_7	1	1	1	1	0	1	0	0	0	0
f_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 = t6. 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.

The main objective of this section is to find the minimum number of channels to use for control messaging. 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 = t1, the channel array found that uses the maximum number of channels (kmax) 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 (kmax)	Elapsed Time (tf)	Number of non-covered users (e)
Greedy Approach Solution in t = t1	3	1.45s	181
Greedy Approach Solution with kmax	5	1.72s	70
Greedy Approach Dynamic Solution	5	1.82s	25
B-ILP Approach Solution in t = t1	3	2.9s	81
B-ILP Approach Solution with kmax	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 kmax = 5 for the greedy approach while for the B-ILP, kmax = 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.

CRN Model

The proposed model of the CRN is a centralized architecture for effective spectrum access. 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. 5. The elements of our CRN are the CCBSs and the CRUs, which operate and coexist with the PUs.

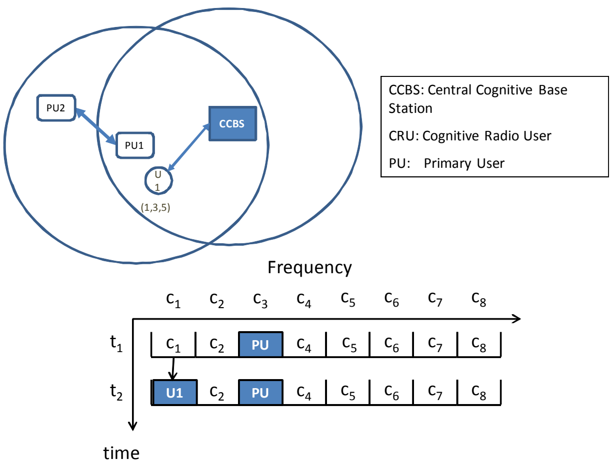

Fig. 5. CRN Model

In Fig. 5, 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. 5.

In the basic model, a CCBS controls CRU communication so that these CRU do not interfere each other or a PU. For modeling the CCBS, in this work, we consider that the spectrum is continuously and perfectly sensed. We also consider that 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.

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 presented a basic model, shown in Fig. 5, for a Centralized CRN that uses CPCs for signalization and control [7]. In Fig. 6, we show a set of users that need more than one channel to be used for control messaging.

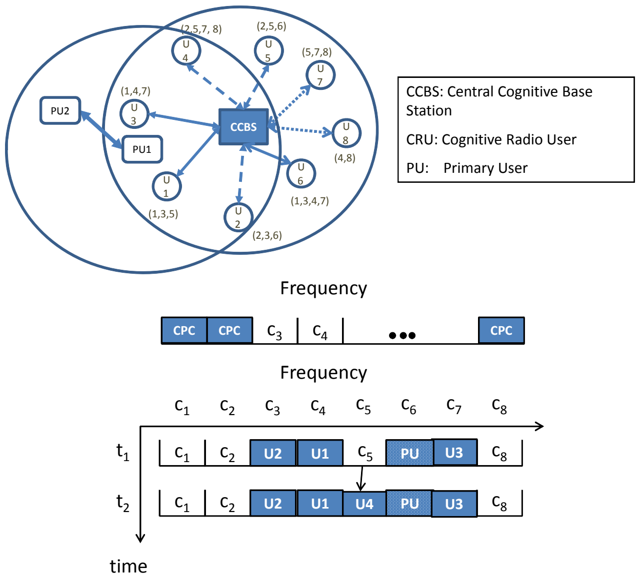

Fig. 6. Multiple Control Messaging in a CRN Model

In Fig. 6, we can see that c1, c2 and c8 are used as CPCs. 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 our scenario, since the broadcast signaling is transmitted the same for each channel and only in a couple of a large number of sub-channels [8], we can assume that using adequate modulation/coding schemes, interference among adjacent channels is non-existent. In Fig. 7 and Fig. 8, a division in channels and sub-channels is presented in order to use some of the sub-channels for beacon transmission.

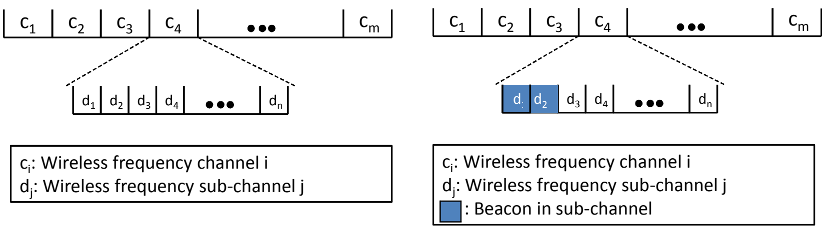

Fig. 7. Channel/Sub-Channel Division

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, transmitting control messages through dedicated channels would be inefficient. We decided then to transmit control and data through the same channels by using a frequency division approach.

We also considered 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. Using the example from Fig. 5, Fig. 6 and Fig. 7, the SCM and MCM of this model is shown in Fig. 8.

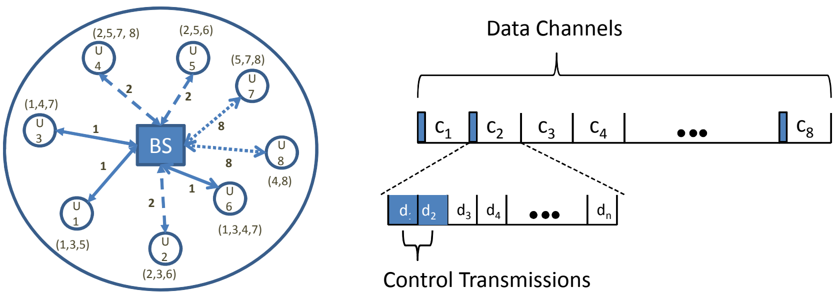

Fig. 8. Shared Control Messaging in the CRN Model

In order to reduce the energy consumption, the authors used the characteristics of the time/frequency combined approach for the Central Cognitive Base Station (CCBS) to only signal a new available channel when a CRU that was not transmitting is requesting communication [8].

Hopping Control Messaging

In Fig. 9, an example of the time/frequency approach is shown. According to the example in Fig. 6, U4 has four channels for communications (c2, c5, c7 and c8) and “senses” its environment.

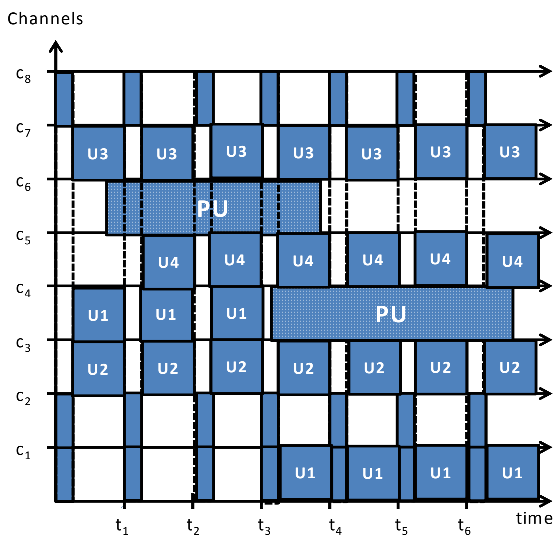

Fig. 9. Hopping Control Messaging in the CRN Model

Channel c7 is already used by U3, so this channel is unavailable. Among the other channels, U4 decides to use c5. Channel c3 is occupied by U2, c4 is occupied by U1 and c6, by a PU. Suppose that a PU wants to use c4 in a moment t, t3 < t < t4. 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 c1.

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. 3, let’s suppose that a PU that uses c8 appears in ti, with t3 < ti < t4, and a PU that uses c2 appears in tj, with t5 < tj < t6. We can see an approximate situation in Fig. 10.

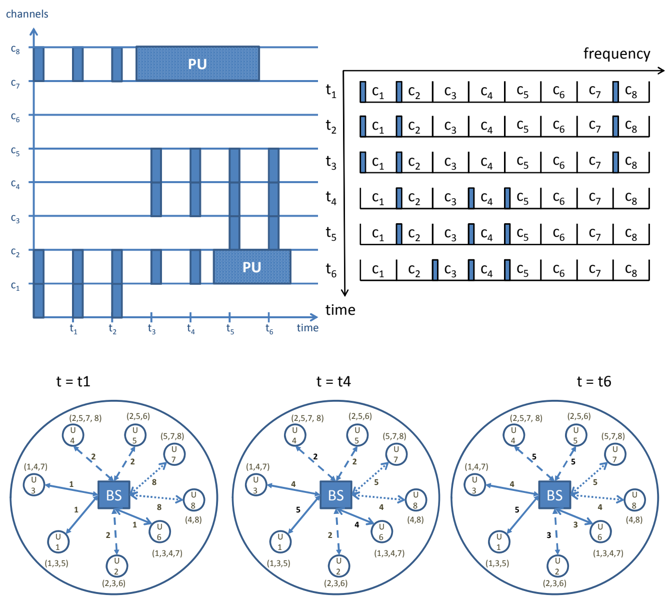

Fig. 10. Complete Hopping Messaging in the CRN Model

The control messaging must hop in t = t4 from c8 to another channel. However, in this process, in order to maintain the same number of channels, the control messaging from c1 also hops. All users are covered by c2, c4 and c5. In t = t6, c2 is unavailable, so its control transmissions are split into c3 and c5.

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, we want to guarantee that when a PU is communicating, no other signal is in its same channel for security reasons. This approach is clearly seen in Fig. 9 and Fig. 10.

Results

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.

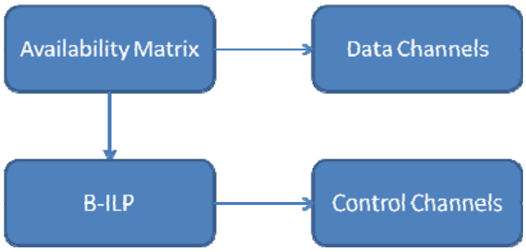

Fig. 11. Control messaging and data channel selection for the SMHOCM strategy (Proposal)

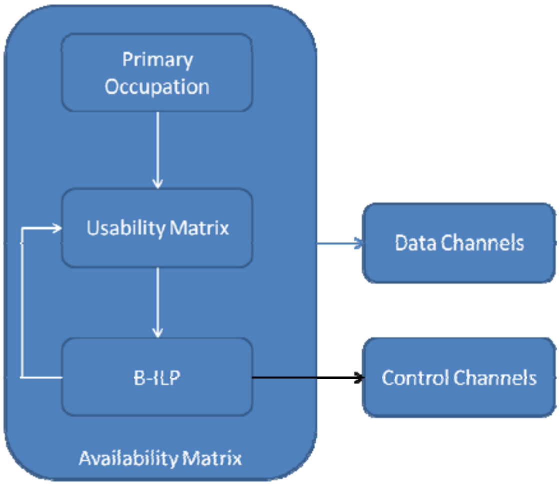

Fig. 12. Control messaging and data channel selection for the DMFOCM strategy

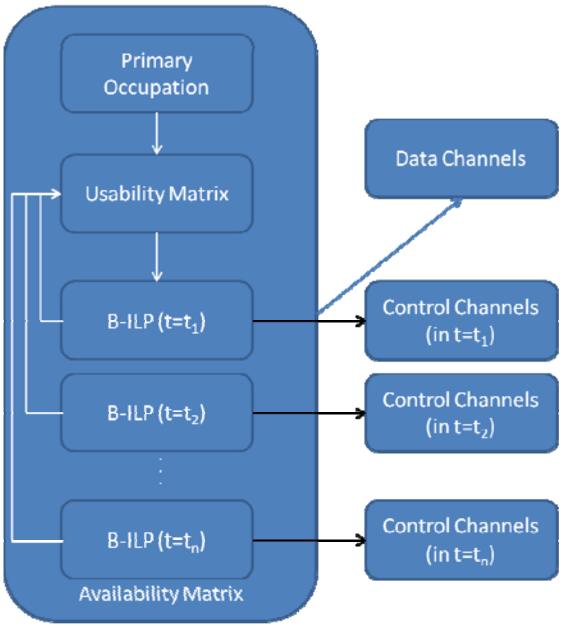

Fig. 13. Control messaging and data channel selection for the DMHOCM-DH strategy

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. 11, Fig. 12 and Fig. 13, the control messaging channels and data channels selection process is illustrated.

Parameter Definitions

Using the processes from Fig. 11, Fig. 12 and Fig. 13, 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 [7]. The time slot used for control in the SMHOCM is 0.2 of the total time slot as in [8]. This means that the effective SMHOCM data transmission is defined by:

$$\text{Eff. Trans} = [8/10] \times \{[(2 \times n) - 2)]/(2 \times n)\} \qquad (1)$$

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.

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. In all figures, when the number of CRU in the network is 8, the lines will be represented with blue; on the other hand, when the number of PU in the network is 16, the lines will be represented with red. Squares represent the DMFOCM strategy; circles, the DMHOCM-DH strategy, and crosses, the SMHOCM strategy.

For the first comparison, the SMHOCM is compared with the DMFOCM and DMHOCM-DH by changing the probability of CRU Channel Usability. In Fig. 14, both the availability errors and the normalized availability errors are shown.

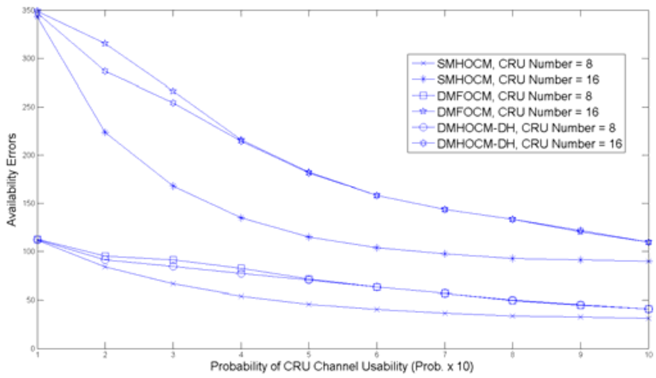

Fig. 14a. Absolute values for Availability Errors when CRU Channel Usability Probability changes

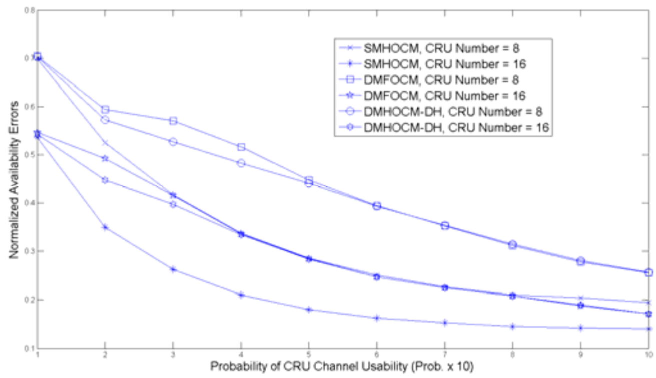

Fig. 14b. Normalized values for Availability Errors when CRU Channel Usability Probability changes

In Fig. 14, we can see that 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.
The other important measure for a CRN is how much interference is caused to the PUs from the control messaging. In Fig. 15, the information lost due to interference is shown. With these values, a comparison of the different strategies is performed.

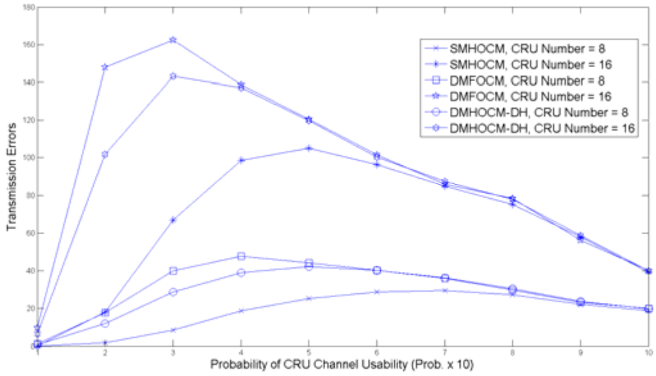

Fig. 15a. Absolute values for Transmission Errors when CRU Channel Usability Probability changes

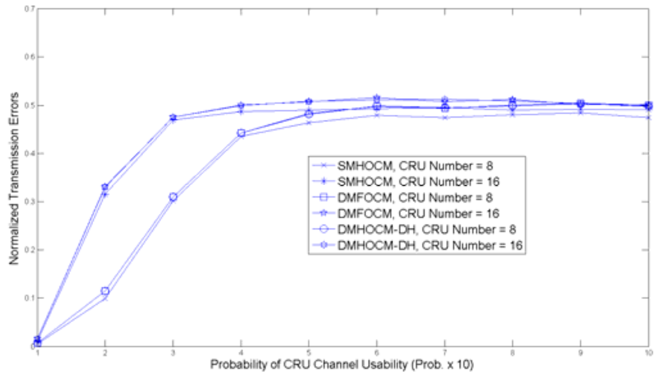

Fig. 15b. Normalized values for Transmission Errors when CRU Channel Usability Probability changes

In Fig. 15, we can see that 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. 16, both the availability errors and the normalized availability errors are shown.

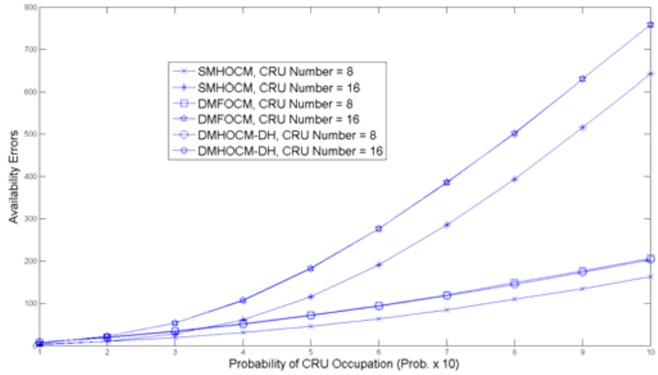

Fig. 16a. Absolute values for Availability Errors when CRU Channel Occupation Probability changes

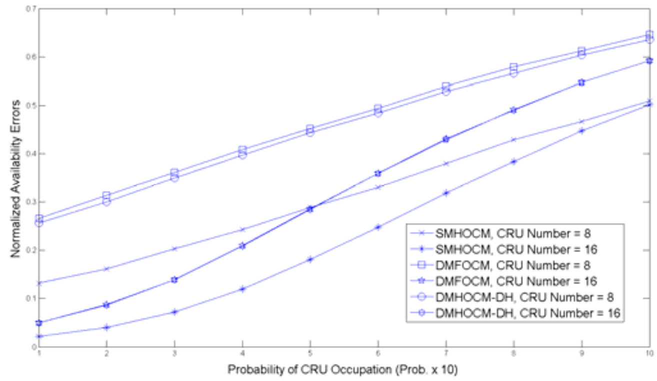

Fig. 16b. Normalized values for Availability Errors when CRU Channel Occupation Probability changes

In Fig. 16, we can see that 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.
The transmission errors for this case are shown in Fig. 17. At first, we 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.

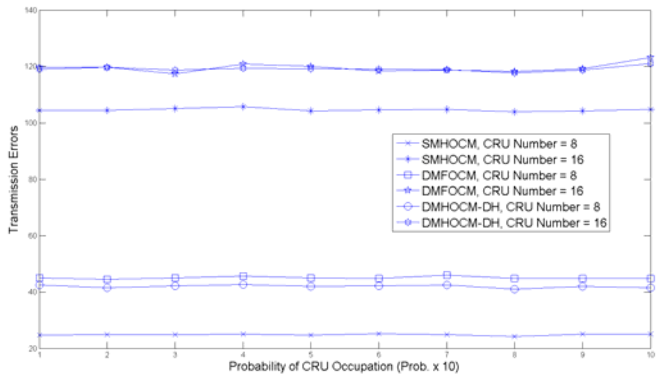

Fig. 17a. Absolute values for Transmission Errors when CRU Channel Occupation Probability changes

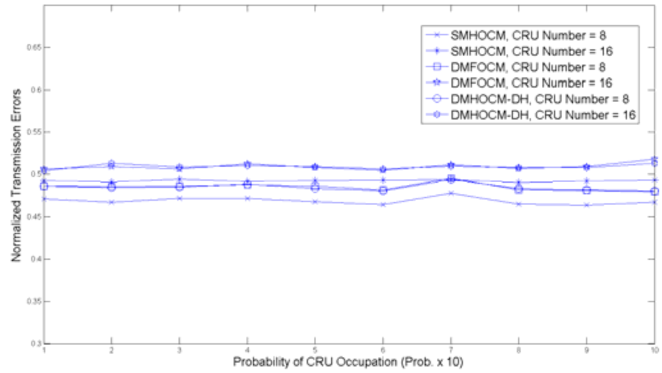

Fig. 17b. Normalized values for Transmission Errors when CRU Channel Occupation Probability changes

In Fig. 17, the normalized transmission errors confirm the abovementioned theory. Since both the PU occupation probability and the CRU channel usability were 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. 18, both the availability errors and the normalized availability errors are shown.

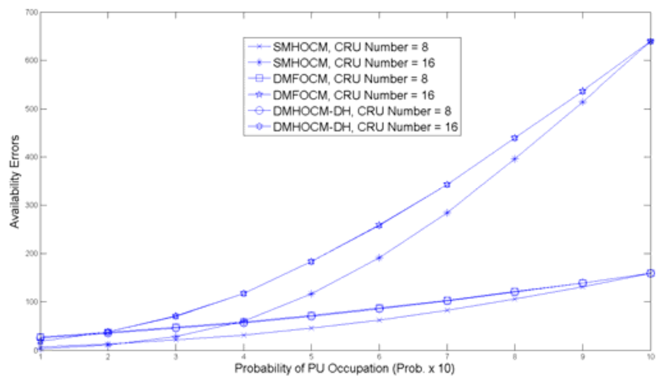

Fig. 18a. Absolute values for Availability Errors when PU Channel Occupation Probability changes

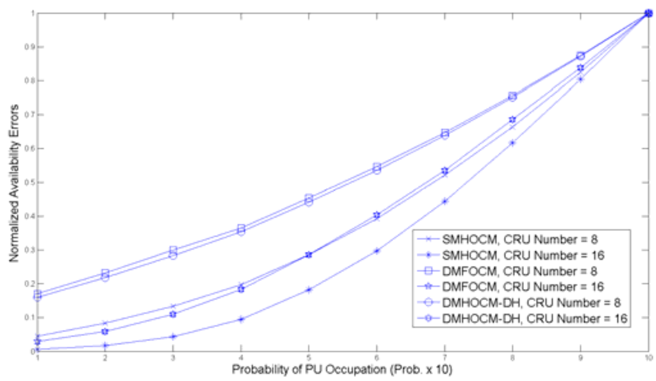

Fig. 18b. Normalized values for Availability Errors when PU Channel Occupation Probability changes

In Fig. 18, we can see that in this comparison, 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.

The transmission errors for this comparison are shown in Fig. 19. Since the SMHOCM was designed to lower PU interference, the results for this comparison are expected to be significantly better for the SMHOCM approach.

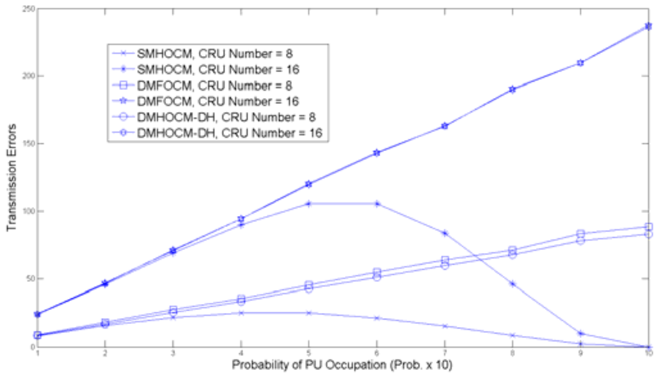

Fig. 19a. Absolute values for Transmission Errors when PU Channel Occupation Probability changes

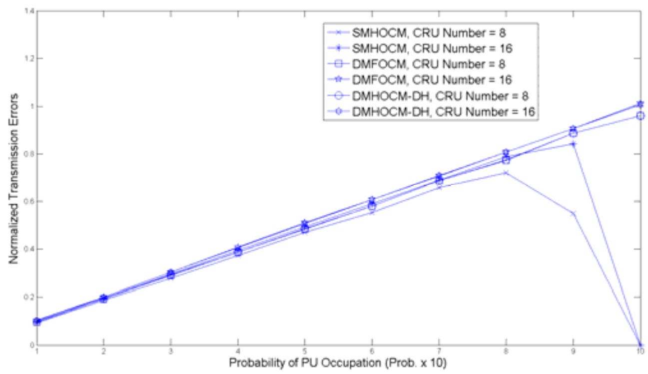

Fig. 19b. Normalized values for Transmission Errors when PU Channel Occupation Probability changes

As expected, we can see in Fig. 19 that when the PU occupation tends to be complete, the transmission errors in the SMHOCM tend to be 0, considering the changing nature of the system. 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.

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 [15]. 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, 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).

For a CRN with HFDs, more than one channel might be needed to control the network, as shown in Table I. We found out that the minimum number of channels for this problem is 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 since having all the users than can be covered in the CCBS range is the main requisite in our network, we have to perform a sensing of the environment 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.
We studied the model introduced in [7] by using the CMS classification: the control plane for a centralized CRN with HFD. 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 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 be also 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 by total heterogeneous wireless devices could be developed.
A comparison with a FCM-based CR-MAC permits to infer that better results could be obtained when hopping among channels according to PU occupation. Combining HCM with SCM by using CPCs permits 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, we would like to compare the existent control strategies in environments where all of them are suitable. Moreover, we would expand the study of the control plane for 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.

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