

Control Plane for Spectrum Access and Mobility in Cognitive Radio Networks with Heterogeneous Frequency Devices

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1. Introduction

One of the main problems that were identified for the insertion of future wireless applications is that an apparent scarcity exists in the wireless frequency spectrum. However, studies demonstrated that the spectrum is inefficiently distributed as opposed as scarce (Shukla et al, 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.

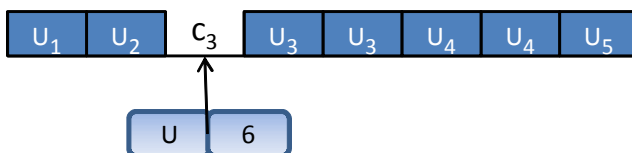


Fig. 1. a) Spectrum Scarcity

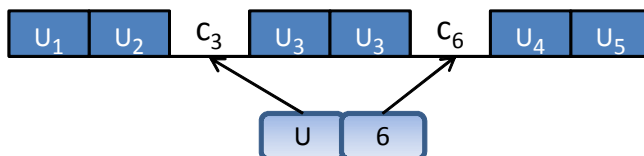


Fig. 1. b) Spectrum misuse

Cognitive Radio Networks (CRN) were defined as networks where user devices are able to adapt to the environment (Mitola & Maguire, 1999). Among the adaptability characteristics, CRN should use the spectrum in an opportunistic manner. In order to do so, Cognitive Radio (CR) devices should be able to recognize spectrum holes, and to use Dynamic Spectrum Access (DSA) capabilities through those frequency slots. Therefore, the use of CRN is an excellent candidate 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 our work, we consider the spectrum decision and spectrum sharing 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).

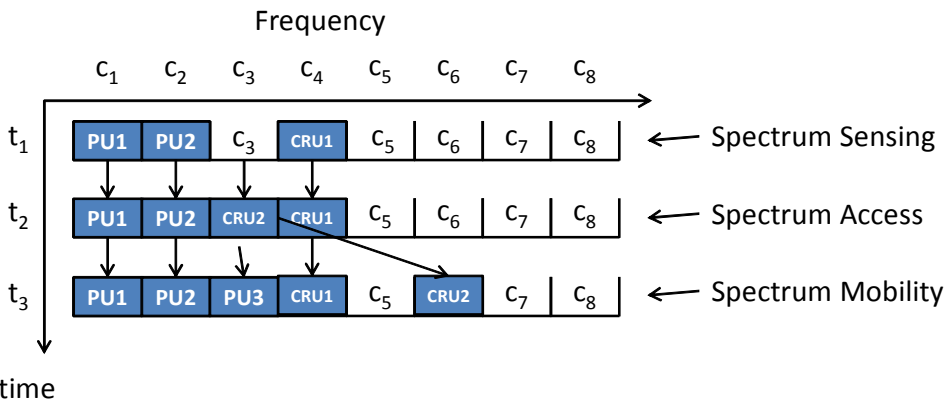


Fig. 2. Spectrum Functions

2. Control plane

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 control plane has been discussed in (Jing & Raychaudhuri, 2007). However, to the authors’ best knowledge, there is not a review in the literature about the alternatives for transmitting control messages. The closest ones 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 combining the classifications defined by (Chowdury & Akyildiz, 2011; Theis et al, 2011) and expanding them to consider all the control plane alternatives.

2.1 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 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. Hoping 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.

2.2 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.

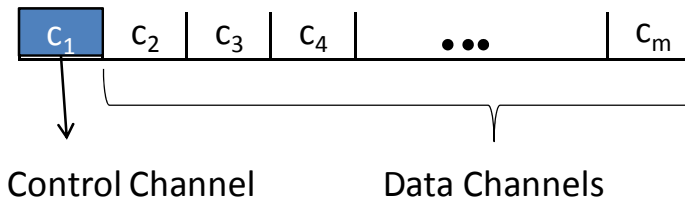


Fig. 3. Dedicated control messaging

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.

2.3 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.

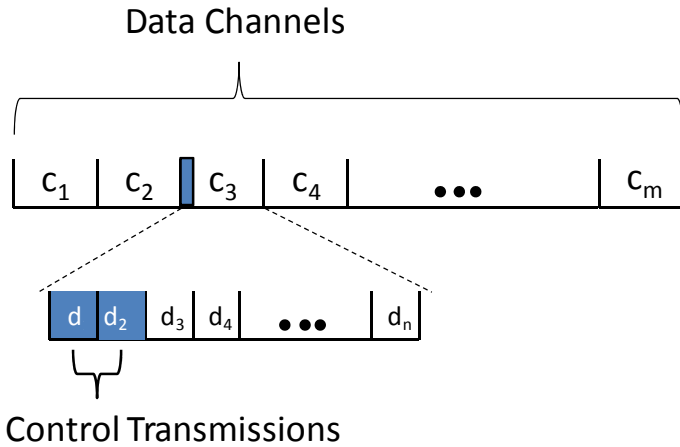


Fig. 4. Shared control messaging (Frequency-division)

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.

2.4 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.

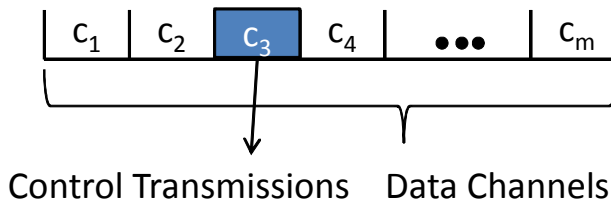


Fig. 5. Common control messaging

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.

2.5 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.

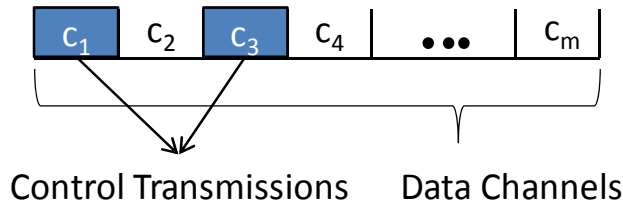


Fig. 6. Multiple control messaging

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.

2.5.1 Clustered approach

Let us suppose a centralized CRN covering 8 CRUs: U_1, U_2, \dots, U_8 , each of them using different sets of frequency channels. A Central Cognitive Base Station (CCBS), in this case, BS, should assign them the necessary channels to transmit control information.

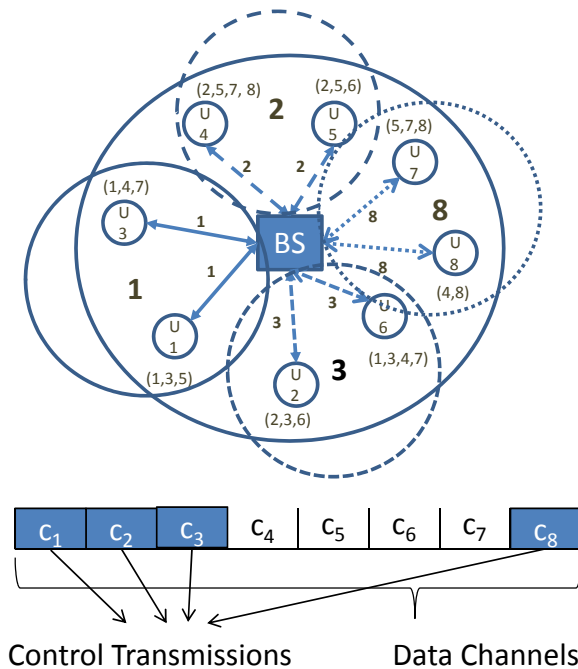


Fig. 7. Clustered control messaging

In the example shown in Fig. 7, four channels are selected for transmitting control information. Channel 1 is used for U_1 and U_3 , channel 2, for U_4 and U_5 . Channel 3, for U_2 and U_6 , and channel 8, for U_7 and U_8 .

2.6 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.

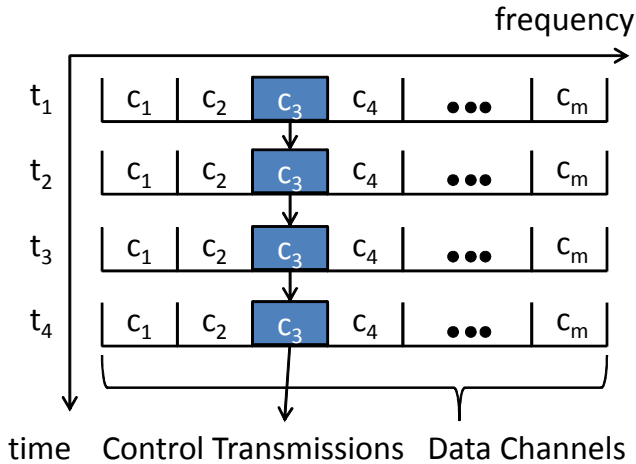


Fig. 8. Fixed control messaging

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.

2.7 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.

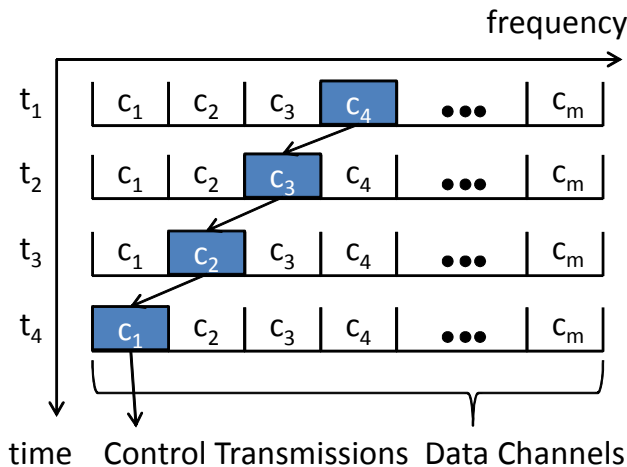


Fig. 9. Hopping control messaging

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.

2.7.1 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.

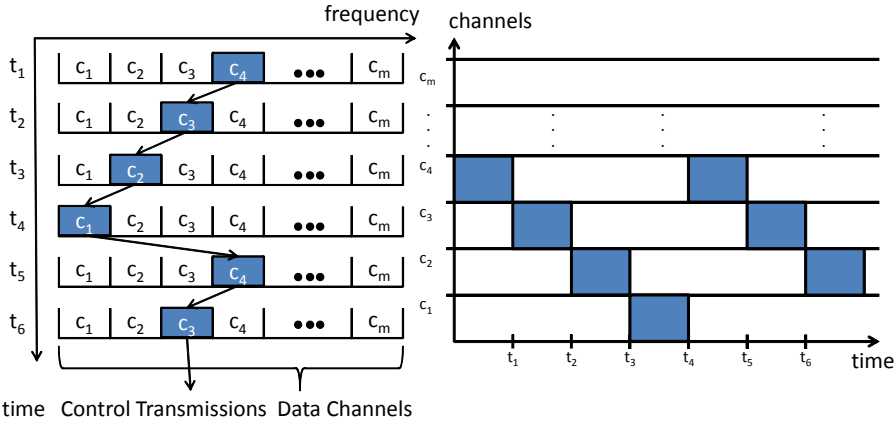


Fig. 10. Default Hopping

2.7.2 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.

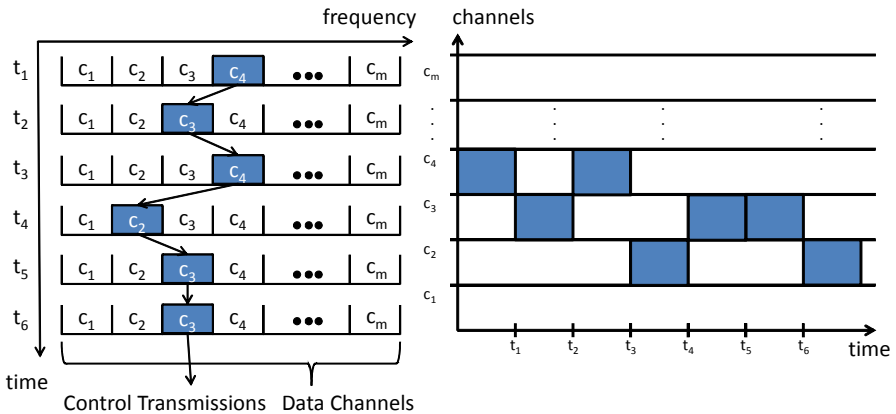


Fig. 11. Common Hopping

2.8 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.

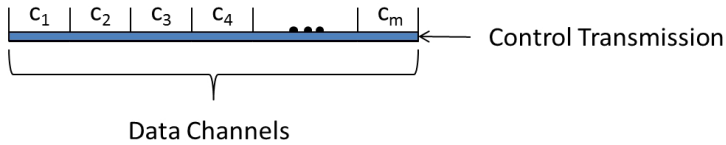


Fig. 12. Underlay control channel

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.

2.9 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.

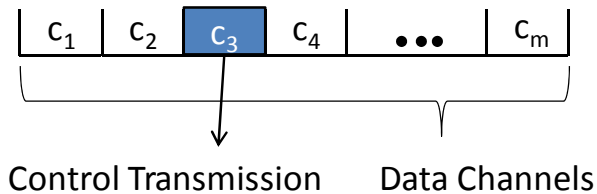


Fig. 13. Overlay control channel

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.

2.10 Discussion

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 DCM, CCM, FCM and OCM.

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 SCM, MCM, FCM and UCM.

Keep in mind that some of the strategies, while not 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 could 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. 14.

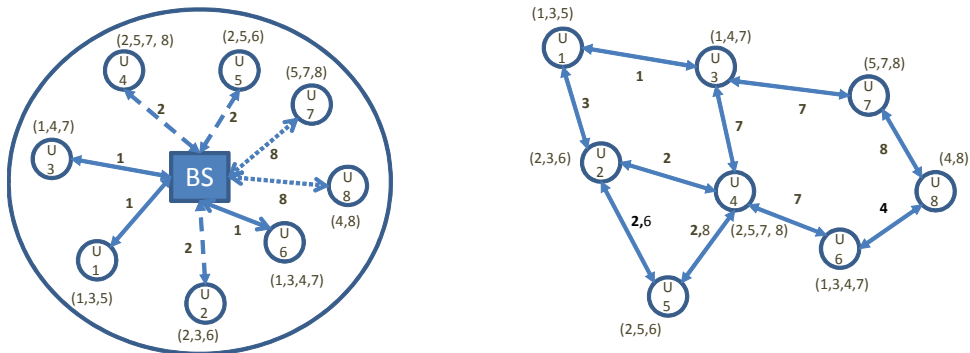


Fig. 14. Centralized and Ad-Hoc CRNs.

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.

3. Model

3.1 Antecedents

There have been different approaches for transmitting control and coordination signals for spectrum access and mobility in CRN. Since a dedicated common control channel might not be available at all times, several techniques have been discussed for the *control channel* problem. For a CRN, the relationship between the spectrum functions might be represented as in Fig. 15.

The utilization of beacons was suggested as a solution for spectrum access by using these beacons to control the medium access of the network devices into the frequency bands (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 since the PUs should inform the nearby CRU about their presence, and the second disadvantage is that a new channel must be reserved for the beacon signals. In Fig. 16, a division in channels and sub-channels is presented in order to use some of the sub-channels for beacon transmission.

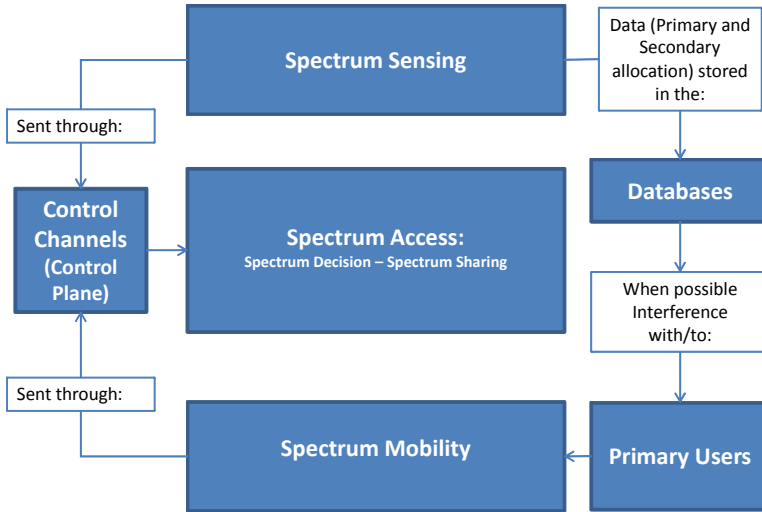
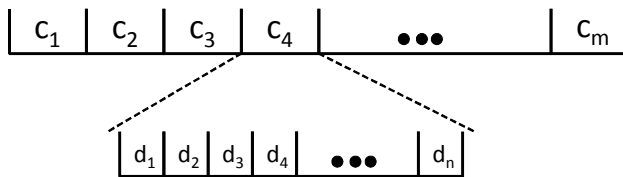
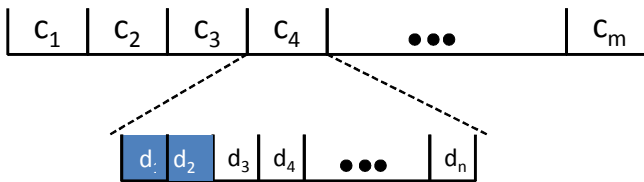


Fig. 15. Spectrum Functions and Control Plane



c_i : Wireless frequency channel i
 d_j : Wireless frequency sub-channel j

Fig. 16. a) Wireless Frequency Channel-Sub channel Division



c_i : Wireless frequency channel i
 d_j : Wireless frequency sub-channel j
 : Beacon in sub-channel

Fig. 16. b) Beacons in Wireless frequency sub-channels

A Cognitive Pilot Channel (CPC) is a solution proposed in the E2R project for enabling communication among heterogeneous wireless networks (Bourse, 2007). The CPC consists on controlling frequency bands in a single or various “pilot” channels, which is analogue to the beacon proposal. In both CPC and beacons proposal, there are “in-band” transmission, i.e. information transmitted in the same logical channels of the data transmission, and “out-band” transmission, i.e. information transmitted in different channels of the data transmission (Sallent 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, and the “out-band” and the “in-band” transmission or other solutions with a combination of both (Filo et al, 2009; Pérez-Romero et al, 2007; Sallent et al, 2009). In Fig. 17, we can see the difference of the in-band and out-band control transmission.

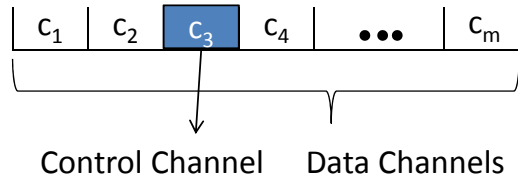


Fig. 17. a) In-band Control Channel

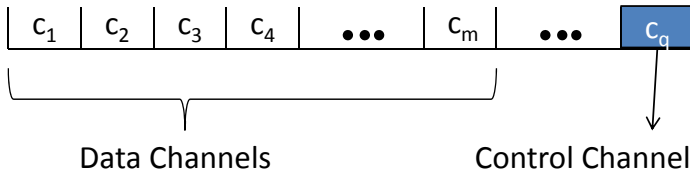


Fig. 17. b) Out-band Control Channel

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) and (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. For solving this problem, and in order to use as minimum energy as possible, a minimum number of clusters (channels), must be found. In Fig. 18, the minimum number of channels for the example used in Fig. 7 is found.

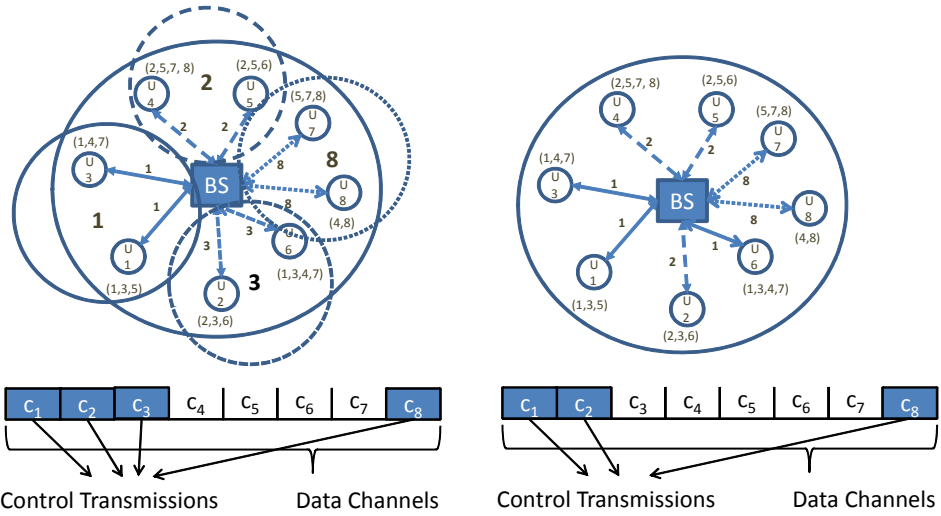


Fig. 18. Minimum number of channels for a clustered MCM

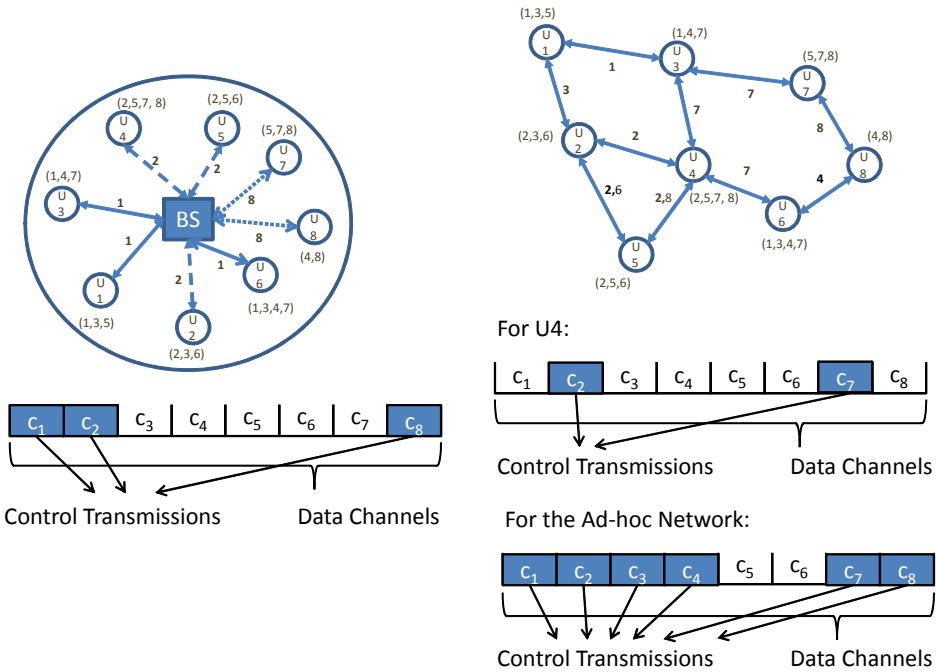


Fig. 19. Minimum Channel Problem for Centralized and Ad-hoc CRN

In (Kunar et al, 2008), the authors define the clusters for finding this minimum number of frequency channels under the same conditions used in (Steenstrup, 2005). In (Lazos et al, 2009), the authors considered the control plane and used 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. For future work, we plan to use several techniques for solving the *minimum number of channels problem* in both centralized and ad-hoc networks as shown in Fig. 19, using the example from Fig. 14.

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.

3.2 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. 20, for a Centralized CRN that uses CPCs for signalization and control (Bolívar et al, 2010).

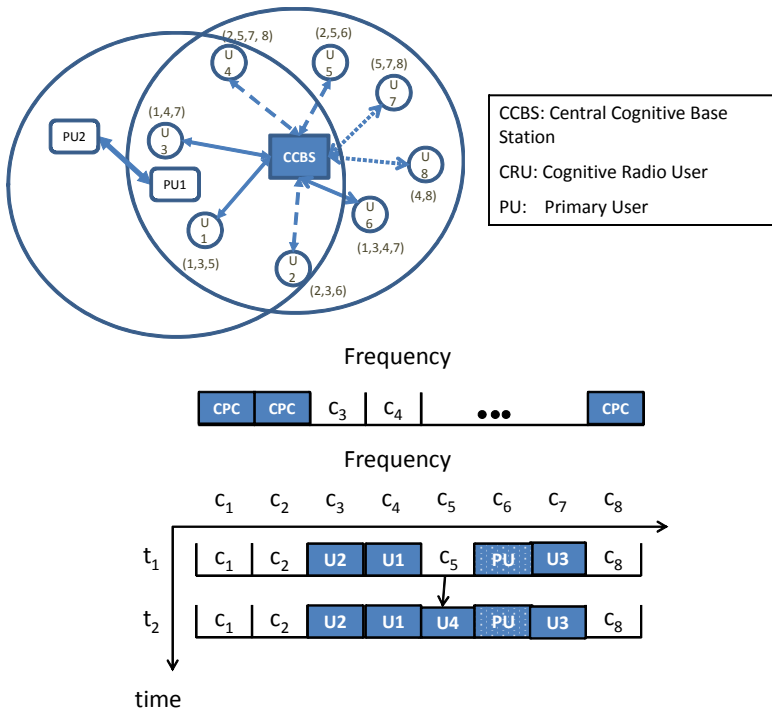


Fig. 20. Cognitive Radio Model

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 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 (Bolívar et al, 2010; Bolívar & Marzo, 2010), we can assume that using adequate modulation/coding schemes, interference among adjacent channels is non-existent.

3.3 Shared control messaging

The basic model of the CRN provided control signaling through CPCs distributed in every available channel or frequency slot. 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, in terms of energy, transmitting through every available channel would be inefficient. This is because the wireless spectrum channels would be occupied in a specific moment. Considering this problem, new alternatives should be explored to reduce the energy used for control signaling CRUs channel availability. 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 (Bolívar & Marzo, 2010). 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. 4, Fig.6 and Fig. 18, the SCM and MCM of this model is shown in Fig. 21.

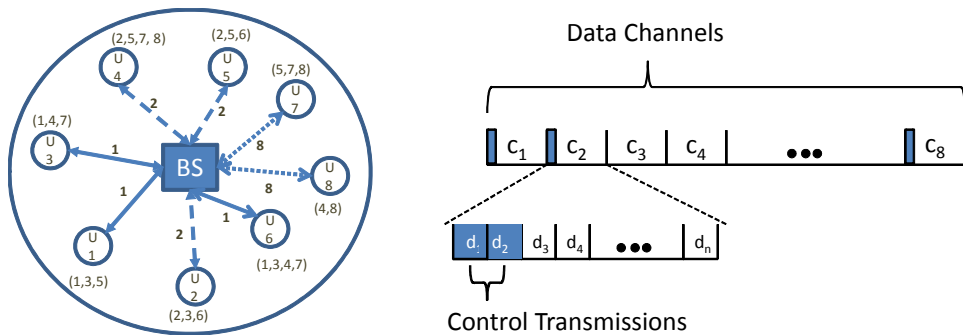


Fig. 21. Shared and multiple control messaging (Frequency-division)

3.4 Hopping control messaging

In Fig. 22, an example of the time/frequency approach is shown. According to the example in Fig. 20 and Fig. 21, U4 has four channels for communications (c_2 , c_5 , c_7 and c_8) and “senses” its environment.

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. 21, 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 $t_5 < t_j < t_6$. We can see an approximate situation in Fig. 23.

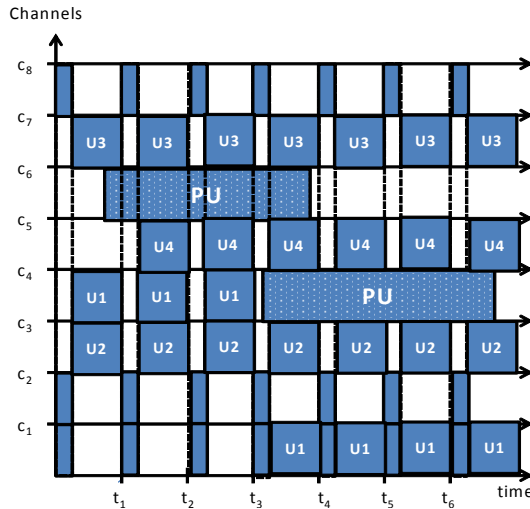


Fig. 22. Time slot utilization by both Primary Users (PU) and Cognitive Radio Users (U1, U2, U3, U4) in time

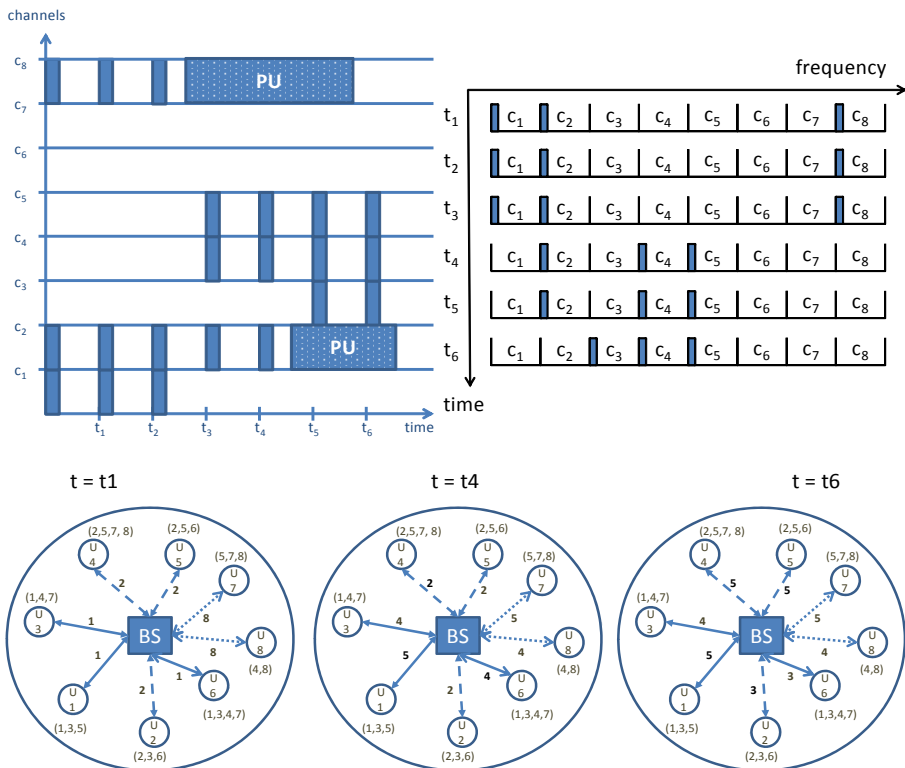


Fig. 23. Spectrum Mobility and HCM.

The control messaging 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 .

3.5 Overlay control messaging

As mentioned before, 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. 23.

4. Conclusion

The control plane for Cognitive Radio Users is a very important part for the spectrum access and mobility in a CRN. However, current studies for the control transmissions are not strongly correlated. Different authors propose their methods for controlling the CRN; however, since there was not a clear classification of the control strategies, to decide which strategy is most suited to a specific CRN could be a very difficult to perform.

This is the reason why in this chapter we wanted to propose a classification for the transmission of control messages as a blueprint in order to compare the advantages and disadvantages of these control strategies. 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.

Furthermore, we study a previous model introduced in (Bolívar & Marzo, 2010) by using this classification: the control plane for a centralized CRN with heterogeneous frequency devices (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).

Several concepts 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, we encourage researchers to suggest others, by using the classification previously provided.

For future works, 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.

5. Acknowledgement

Part of this work was supported by the Department of Universities, Research and Information Society (DURSI) of the Government of Catalonia, European Social Funds (SGR-1202), and by a FI Grant from the Government of Catalonia, in accordance with the Resolution IUE/2681/2008, and also by the Spanish Government (TRION MICINN TEC2009 - 10724).

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Advances in Cognitive Radio Systems

Edited by Dr. Cheng-Xiang Wang

ISBN 978-953-51-0666-1

Hard cover, 150 pages

Publisher InTech

Published online 05, July, 2012

Published in print edition July, 2012

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Nicolas Bolivar and Jose L. (2012). Control Plane for Spectrum Access and Mobility in Cognitive Radio Networks with Heterogeneous Frequency Devices, *Advances in Cognitive Radio Systems*, Dr. Cheng-Xiang Wang (Ed.), ISBN: 978-953-51-0666-1, InTech, Available from: <http://www.intechopen.com/books/advances-in-cognitive-radio-systems/control-plane-for-spectrum-access-and-mobility-in-cognitive-radio-networks-with-heterogeneous-freque>

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