Distributed Control and Signaling using Cognitive Pilot Channels in a Centralized Cognitive Radio Network

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***Abstract*—In this paper, a cognitive radio network (CRN) model 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, presence of PUs is detected. We have designed a CRN able to work with today's available technologies and CRU devices that use different frequency bands of operation. Since in terms of energy, this control can be very inefficient because at specific periods of time the network might be completely used, a method for energy reduction in a centralized cognitive radio network (CRN) is presented. Results of the performance of the network will be presented in terms of the number of CRU and the time these CRUs use the CPCs for control.**

Index Terms— Cognitive Pilot Channel; Cognitive Radio Networks; Dynamic Spectrum Access; Medium Access Control

I. INTRODUCTION

A basic model for controlling and signaling a Cognitive Radio Network (CRN) was presented in [1]. Considering that fixed spectrum licensing has produced apparent scarcity in the wireless frequency spectrum [2-3], strategies such as Cognitive Radio (CR) have 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 [4-6]. CR has already been considered as the main technology for IEEE standards, such as IEEE 802.22, which is the standard for Wireless Regional Area Network (WRAN) using white spaces in the TV frequency spectrum and for standards related to DSA networks that are comprised in the IEEE SCC41 [2-3, 6].

In general, a CRN should be able to perform 4 tasks efficiently, spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility [5]. Spectrum sensing refers to the identification of the most likely white spaces in a specific time. Spectrum decision refers to the process of deciding in which white spaces to allocate communications [5]. The spectrum sharing function consists on maximizing the cognitive radio users (CRUs) performance without disturbing Primary Users (PUs) and other CRUs; this is one of the main challenges for opportunistic spectrum access (OSA) in CRN [5, 7]. Spectrum mobility is the CRU ability to leave the frequency portion of the spectrum occupied when a PU starts using the same frequency portion and then, to find another suitable frequency slot for communication [5]. Spectrum sensing and spectrum mobility must be guaranteed in order to implement an efficient CR Medium Access Control (MAC).

Several CR MAC protocols have been developed over the premise of the presence of a dedicated common control channel [8, 9]. 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 [10]. 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. A comparison among our proposal, CPCDF-MAC, multi-channel MAC protocols from [10] and existing CR MAC protocols from [8] is shown in Table I.

TABLE I. COMPARISON AMONG CR MAC PROTOCOLS

Protocol	Specific Control Channel	Time Synchronization Needed	Multiple Transceivers	Support for Heterogeneous Frequency Devices
Common Control Channel	Yes	No	No	No
Common Hoping/ Default Hoping Sequence	No	Yes	No	Partial
OSA-MAC	Yes	Yes	No	No
HC-MAC/ OS-MAC	Yes	No	No	No
CPCDF-MAC (Proposal)	No	Yes	Yes	Yes

The utilization of beacons was suggested as a solution for spectrum sharing in [11], using these beacons to control the devices medium access into the frequency bands. Architectures with more than one beacon have been proposed to improve performance [12]. Decisions based on channel occupancy are performed by combining the information obtained in these beacons using data fusion techniques. The most common data fusion techniques to decide whether a particular frequency band is occupied are voting rules and logical operations [13]. 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 [14]. 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.

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 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. Studies have been conducted in [15-18] 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. The IEEE P1900.4 group, part of the IEEE SCC41, has accepted CPC as part of the architecture for the CR Access [16].

In the E2R project, for achieving communication between heterogeneous nodes and networks, and also scalability, a large band is divided into several sub-bands with one local CPC (LCPC). This LCPC is used for accessing a network, and informing the devices about the operator, frequencies and radio access technologies in this network [15-16]. In [17], CPC is considered for radio environment discovery, reconfiguration support and terminal radio environment information and context awareness. We expand the use of CPC in order to control the CRN. The objective is to build a CRN using today's available technologies that are able to support heterogeneous frequency CRU devices, i.e. CRU that use different operation frequencies, while using the spectrum as effectively as possible.

To control the CRN, joint time and frequency control for assuring effective spectrum sharing are used. For transmitting channel availabilities, network discovery and channel petitions, a frequency-based approach using beacons in a CPC is proposed. The utilization of the CPCs instead of a dedicated control channel allows heterogeneous systems to communicate in our CRN. In a first approach, a central cognitive base station (CCBS) sends beacons via parallel communication in sub-channels of all available frequency slots. With this approach, the use of all available frequency bands for communications was guaranteed. When a CRU requested access in the CRN, the CRU already knew which channels were available because of these beacons. 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 are explored to reduce the energy used for signaling cognitive radio users (CRU) channel availability.

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. Considering that 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 technology has also been considered as an alternative to reduce energy consumption for wireless communications [19]. In [20], we explained the use of a distributed control and a centralized database for reducing the amount of energy used to signal this availability in the CRN. A complementary control based on a time-division approach, in which the PU entrances are detected via time slots, is also used. Finally, in this paper we present the performance of the network using this energy reduction method in our CRN with distributed control.

The remainder of this paper is organized as follows: Section II introduces the model of the network. Section III presents the expected results of our proposal and Section IV provides a discussion of our work.

II. PROPOSED MODEL

A. *CCBS Control Architecture*

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. 1. The elements of our CRN are the CCBS and the CRUs, which operate and coexist with the PUs.

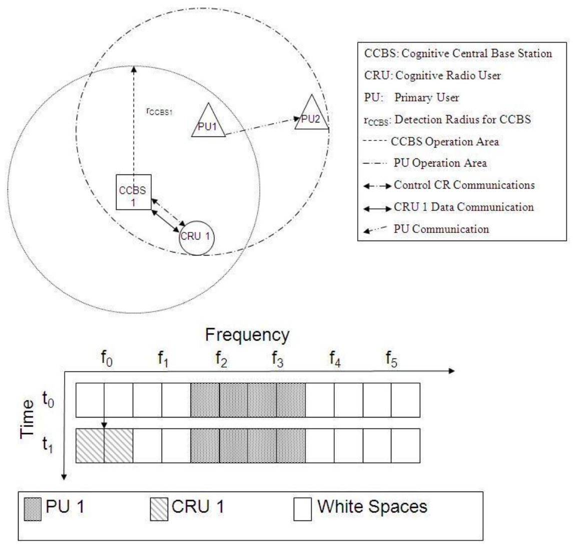

Fig. 1. CRN Model

In Fig. 1, 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 one that the PUs is using. Hence, in order to ease CR operation, a CR radio spectrum model that uses fixed frequency slots for both CR frequency sensing and CR medium access is proposed. A frequency/time representation of the corresponding scenario is also shown in Fig. 1.

In the proposed architecture, we assume that the management of the network is performed in the CCBS, which permits to reduce the amount of processes from the CR users (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 the characteristics of the CRU. The architecture of a CCBS is shown in Fig. 2.

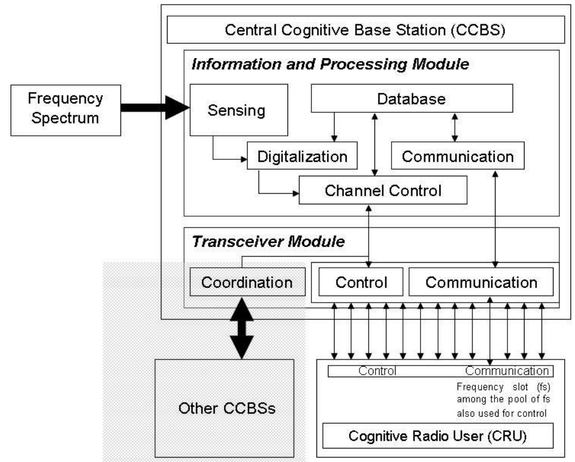

Fig. 2. CCBS Control Architecture

The CCBS is composed 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. In the sensing sub-module, the CCBS scans the analog radio frequency spectrum, which is assumed to be perfectly and continuously sensed. In the digitalization sub-module, the analog sensed 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. In addition, the database sub-module stores information related to the CRU frequency assignments from the channel control and the communication 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 for controlling which CRUs are communicating and the frequency slots used. In this sub-module, 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. 3 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.

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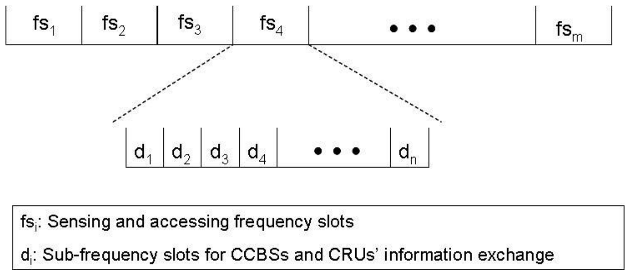

Fig. 3. Frequency slot and sub-frequency slot division of the spectrum

The Transceiver Module is divided into 3 sub-modules, control, communication and coordination. These sub-modules are responsible for communicating the information coming from the information and processing module with the control module of the CRUs, the communication 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 paper we are not considering the possible coordination among CRN.

In this paper, only the CRN control is studied; the control algorithm for the CCBS is represented in Fig. 4. 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. 2 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.

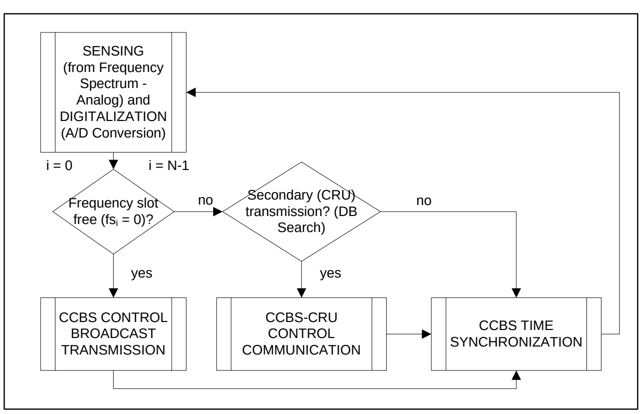

Fig. 4. CCBS Algorithm per each frequency slot i (fs_i)

In the following section, 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) [7].

B. 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 one or more of all the available frequency slots in which CRUs are able to communicate. This is the CCBS Control Broadcast Transmission process in Fig. 4. 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. 3 of all the available channels. The set of values corresponding to control are detailed in Table II.

TABLE II. 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 determining 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

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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. 5. 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.

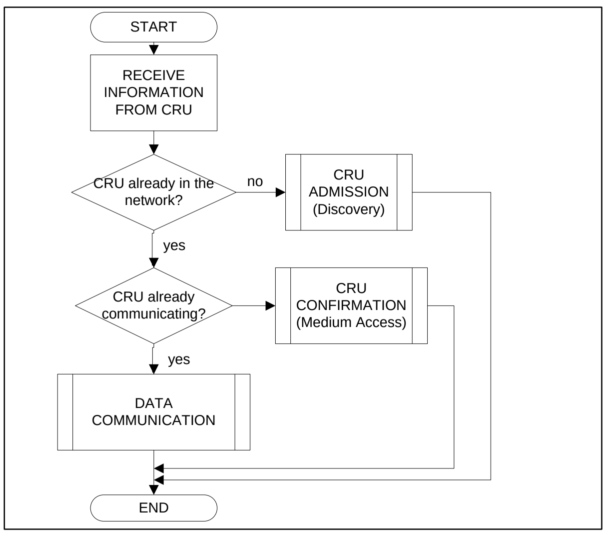

Fig. 5. CRU Admission in the CRN from the CCBS perspective

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, we assume that a PU is 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, we also propose a multi-channel approach, since several cognitive users might communicate in different channels. For the analysis of the system, we consider each communication channel 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. 6, which shows the utilization in time of a frequency slot by both PU and CRUs.

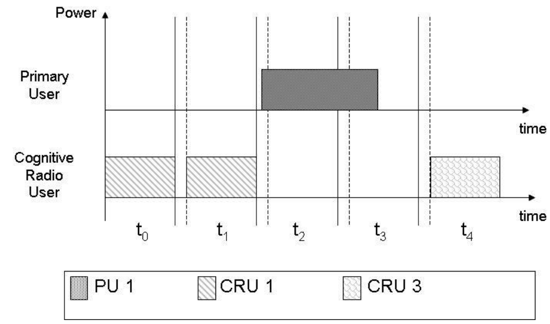

Fig. 6. Frequency slot utilization by both PU and CRUs (in time)

In [20], two additional characteristics are added to the CRN model of [1] to reduce broadcast transmissions. The first one is that CRU synchronization will be 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.

Using these alternatives, the flux diagram from Fig. 5 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 situation, only PUs could be using the channels; this means that the CRU is not able to 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 no 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, 7, an example of the CRU admission in the CRN is shown by using the same example as in Fig. 5. CRU 3, which has three channels for communications, "senses" its environment. Channel 1 is being used by a PU, so this channel is unavailable to CRU transmission. Channel 2 is occupied by CRU1. This makes the channel unavailable for CRU 3 use, but CRU 3 can detect the time slot position using CRU 1 transmission. Using that information, CRU 3 can access Channel 3 in time t2.

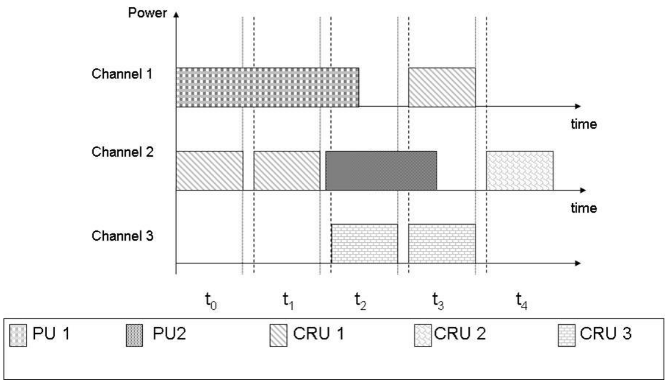

Fig. 7. Frequency slot utilization by both PU and CRUs (in time)

III. Results

In this section, the difference in expected transmission generated by both CRU interference to PU, and CRUs not having a frequency slot (channel) to transmit, which will be called transmission errors, will be analyzed. Due to the fact that none of the CR-MAC protocols shown in Table I present support for heterogeneous devices, no comparison is performed in this section. Results will be presented in terms of the number of CRU users and the relation of time dedicated for the Cognitive Control Algorithm.

In [20], a simulation is then performed in MATLAB to show the obtained results. The values used are the following: number of channels (n) = 128, number of sub-channels (m) = 256, control time/ (control + data) time = 1/10, and time duration (td) = 500 units of time. In Fig. 8, channel occupancy and power used when the CCBS sends broadcast signaling to announce availability is shown.

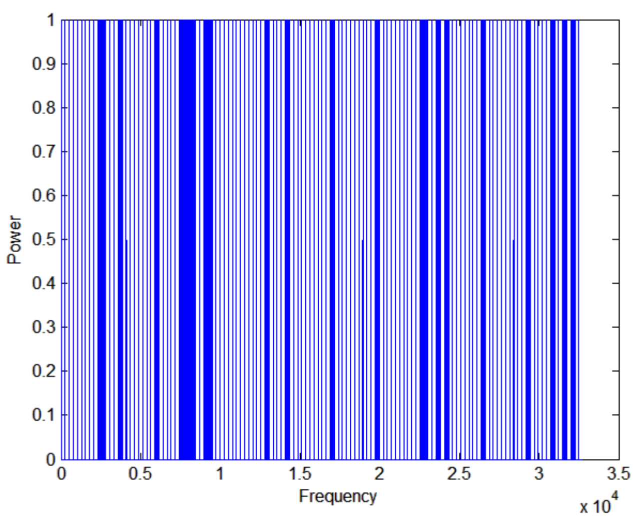

Fig. 8. Power used in the model presented in [3] in t = 481, when CCBS sends broadcast transmission.

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. 9, the power used and channel occupancy in the proposal is shown.

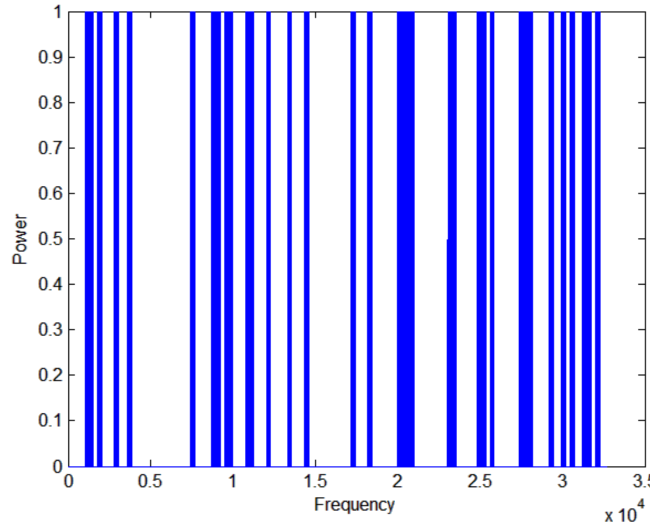

Fig. 9. Power used in the new model in t = 481, when CCBS in [3] would send broadcast transmission.

In Fig. 9, power used with the new model when CCBS in [1] 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 [1], unless the information is asked to be submitted again by the CCBS

The results show that in [20], 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.

An important measure for a CRN is how much information in terms of bits is lost due to interference to PU and how much CRUs interferes PUs. Using the same parameters, n = 128, m = 256, td = 500, a simulation is performed. In Fig. 10, the information lost for the new model due to PU and CRU interference is shown.

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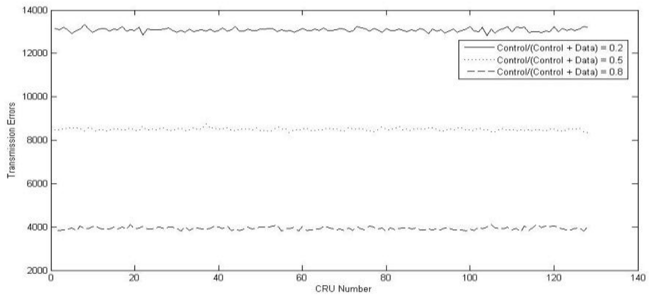

Fig. 10. Transmission Errors

The results show that transmission errors decrease when the portion of the time that is used for control increases; however, the data that could be transmitted in the same amount of time also decreases. Effective transmission errors, which we define as Eff. Trans. Errors = Transmission Errors/Data Transmitted, might provide then a better guidance for choosing a Control/(Control+Data) rate for the CRN. Fig. 11 shows the effective transmission errors per CRU number.

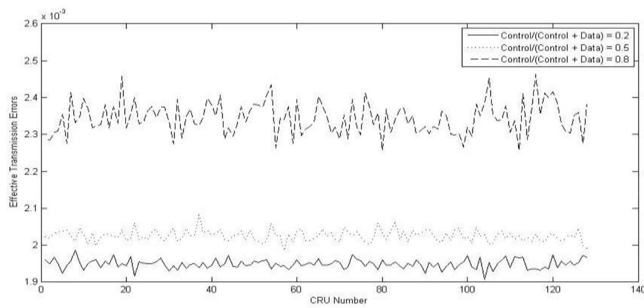

Fig. 11. Effective Transmission Errors

Results are very similar for different control time / control plus data time ratios. This is expected from the construction of the algorithm. Errors due to channel unavailability, defined as availability errors, in average, are shown in Fig. 12.

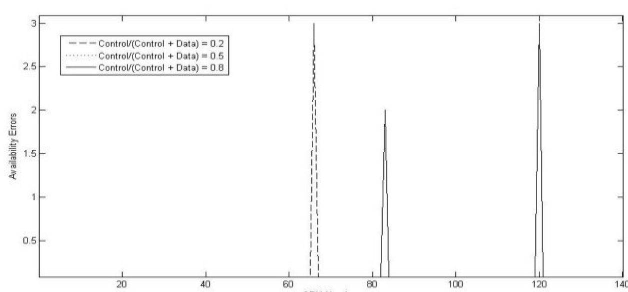

Fig. 12. Availability Errors

Results from Fig. 12 show that the availability errors are quite random; however, when the number of repetitions increases, we might conclude these errors are dependent on the CRU Number since more users might be trying to use the same number of channels. Combining these results with the ones from Fig. 11, and since the idea is to transmit as much data and less control information as possible, we conclude that it is possible to construct a CRN using a CPC with a low Control/(Control+Data) ratio.

IV. Discussion

The results indicate that a basic CR-MAC protocol can be implemented through CPC channels. Using this premise, a CRN composed by total heterogeneous wireless frequency devices could be developed. A comparison with a common control channel based CR-MAC, for future work, will permit to infer if better results could be obtained combining a common control channel approach with the CPC approach.

The expected results are that controlling a CRN using a CPC, while not significant, still affect the performance of the PU compared to a CRN controlled by a common control channel, while allowing the presence of heterogeneous frequency CRU. Lowering the transmission and availability errors is also a must in future proposals. The results will be compared with the obtained in other CPC proposals such as in [16] and [18].

The results also 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 are the ones that 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.

On the other hand, broadcasting signaling would still be needed in some cases. 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. Further works will be developed in this area to find the trade-offs for applying this combined approach while still guaranteeing effective heterogeneous communication.

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REFERENCES

[1] N. Bolívar, J. L. Marzo and E. Rodríguez-Colina, "Distributed Control using Cognitive Pilot Channels in a Centralized Cognitive Radio Network," in the Sixth Advanced International Conference in Telecommunications, pp. 30-34, May 2010, ISBN: 978-0-7695-4021-4.

[2] Overview of SCC41 and the 1900.x Working Groups. IEEE. http://grouper.ieee.org/groups/scc41/. Retrieved 2011-01-18.

[3] M. Muck, S. Buljpre, P. Martigne, A. Kousaridas, E. Patouni, M. Stamatelatos, K. Tsagkaris. J.Yang, O. Holland, "IEEE P1900.B: Coexistence Support for Reconfigurable, Heterogeneous Air Interfaces," in IEEE Dyspan 2007, pp. 381-389, April 2007.

[4] J. Mitola III and G. Q Maguire, Jr., "Cognitive Radio: Making Software Radios More Personal," IEEE Personal Communications (Wireless Communications), vol.6, no. 4, pp. 13-18, August 1999.

[5] I. F. Akyildiz, W. Y. Lee, M. C. Buran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," IEEE Communications Magazine, vol. 46, no. 4, pp. 40-48, April 2008.

[6] IEEE 802 LAN/MAN Standards Committee 802.22 WG on WRANs (Wireless Regional Area Networks). IEEE. http://www.ieee802.org/22/. Retrieved 2011-01-18.

[7] F. Wang, M. Krunz, and S. Cui, "Spectrum Sharing in Cognitive Radio Networks," in IEEE 27th Conference on Computer Communications, INFOCOM 2008, pp. 36-40, April 2008.

[8] H. Wang, H. Qin, and L. Zhu, "A Survey on MAC Protocols for Opportunistic Spectrum Access in Cognitive Radio Networks," in IEEE International Conference on Computer Science and Software Engeneering 2008, pp. 214-218, December 2008.

[9] S. - Y. Lien, C. - C. Tseng, and K. - C. Chen, "Carrier Sensing based Multiple Access Protocols for Cognitive Radio Networks," in IEEE Conference on Communications 2008, ICC 2008, pp. 3208-3214, May 2008.

[10] A. Yau, P. Komisarczuk, and P. D. Teal, "On Multi-Channel MAC Protocols in Cognitive Radio Networks," in Australasian Telecommunication Networks and Applications Conference 2008, ATNAC 2008, pp. 300-305, December 2008.

[11] A. P. Hulbert, "Spectrum Sharing Through Beacons," in IEEE 16th International Symposium on Personal, Indoor and Mobile Radio Communications, pp. 989-993, September 2005.

[12] S. Mangold, A. Jarosch, and C. Monney, "Operator Assisted Cognitive Radio and Dynamic Spectrum Assignment with Dual Beacons – Detailed Evaluation," in First International Conference on Communication System Software and Middleware 2006, pp. 1-6, August 2006.

[13] Z. Quan, S. Cui, H. V. Poor, and A. H. Sayed, "Collaborative Wideband Sensing for Cognitive Radios," IEEE Signal Processing Magazine, vol. 25, no. 6, pp. 60-73, November 2008.

[14] A. Ghasemi, and E. S. Sousa, "Interference Aggregation in Spectrum-Sensing Cognitive Wireless Networks," IEEE Journal of Selected Topics in Signal Processing, vol 2, no. 1, pp. 41-56, February 2008.

[15] End to end efficiency. E3. https://ict-e3.eu/project/technical_highlights/5_enablers/enablers_2009_10.html. Retrieved 2011-01-18.

[16] M. Filo, A. Hossain, A. R. Biswas, R. Piesiewicz, "Cognitive Pilot Channel: Enabler for Radio Systems Coexistence," Second International Workshop on Cognitive Radio and Advanced Spectrum Management 2009, CogART 2009, pp. 17-23, May 2009.

[17] End to End Reconfigurability II (E^2R II) White Paper, "The E^2R II Flexible Spectrum Management (FSM) Framework and Cognitive Pilot Channel (CPC) Concept – Technical and Business Analysis and Recommendations," pp. 1-52, November 2007.

[18] O. Sallent, J. Pérez-Romero, R. Agustí, P. Cordier, "Cognitive Pilot Channel Enabling Spectrum Awareness," IEEE Conference on Communications Workshops 2009, ICC Workshops 2009, pp. 1-6, June 2009.

[19] J. Palicot, M. Katayama, A. Nafkna, G.Ravera, M.Massoth, J. Perez-Romero, "Challenges in Advanced Communications and Services," Panel AICT 2010, IARIA Panels, May 2010.

[20] N. Bolívar and J. L. Marzo, "Energy Reduction for Centralized Cognitive Radio Networks with Distributed Cognitive Pilot Channels," Accepted at 2010 Latincom, September 2010.