

Broadcast Signaling for a Centralized Cognitive Radio Network with Distributed Control

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

Index Terms— *Broadcasting; Cognitive Pilot Channel; Cognitive Radio Networks; Dynamic Spectrum Access*

I. 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. CRU with partial Access to use specific bands of the wireless spectrum, 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]. This means that have the ability of sensing, recognizing and adapting to specific characteristics of the environment. One of the CRNs most important characteristics is the ability for the Cognitive Radio Users (CRU) to dynamically access the spectrum. However, CRUs might be also capable of recognizing patterns of occupancy, to reduce the energy used for sensing, signaling and transmission. For this reason, Cognitive Radio technology has been also considered as an alternative to reduce energy consumption for wireless communications [4].

Several CR MAC protocols have been developed from Multi-channel MAC protocols. These MAC protocols can be

categorized in dedicated control channel, split phase, common hopping, and default hopping [5]. Some specific CR MAC protocols use a dedicated common control channel [6, 7]. However, heterogeneous CRU devices that do not share this control channel are not able to communicate in this CRN. Other than the aforementioned dedicated control channel approach, the other three approaches can be considered for efficient spectrum utilization because the CRN must operate in different frequency bands. On the other hand, 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 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 [8-11]. In [12], we have presented a basic model for a Centralized CRN that uses CPCs for signalization and control. 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. The basic model of the CRN provides signalling through CPCs distributed in every available channel or frequency slot. The control is performed by using frequency-division and time-division multiplexing techniques. This control, as expected, permits the utilization of the CRN by heterogeneous CRU devices.

In terms of energy, transmitting through every available channel would be inefficient. This is because the entire wireless spectrum channels would be occupied in a specific moment. Considering this problem, new alternatives should be explored to reduce the energy used for signaling CRUs channel availability. For reducing the energy, in [13], we used the characteristics of the time/frequency combined to approach for the CCBS to signal 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 CCBS, however, still needs to broadcast signals to its users in some specific moments. Signals that must be broadcasted by the base station include periodical beacons, alarms, among others [14]. Several broadcasting problems such as the minimum broadcasting energy problem [15] and the allocation for broadcasting heterogeneous data in multiple channels [16-17], among others have been studied. To the

best of the authors’ knowledge, none of the broadcasting studies deal with the problem of broadcasting availability through a minimum number communication channels, in general; not for CRNs, in particular. The channel allocation/frequency assignment problem, however, has been studied in static and dynamic environments. We refer to [18] and [19] for an overview of models and solutions of the frequency assignment problem in those environments, respectively. One of the main considerations for studies in frequency assignment problems is that a channel can generate interference in adjacent channels. In 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 [12-13], we can assume that using adequate modulation/coding schemes, interference among adjacent channels is non-existent [19].

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, the presence of PUs must be considered. However, several approaches that use algorithms to solve general optimization and broadcasting problems such as reduce the Greedy Algorithm, Satisfiability (SAT) theory [20], among others, might be adapted to solve this problem. In this paper, an adaptation of the greedy algorithm is proposed to solve the minimum number of channels problem, when this number of channels is low.

The rest of this paper is divided as follows: In Section II, the model of the CRN and the description of the solution are depicted. In Section III, basic considerations for the algorithm are shown. In Section IV, early results of the minimum channel algorithm obtained by using the strategies are presented. In Section V, the results and future work are discussed.

II. MODEL

The basic model of the CRN used in this work is shown in Fig. 1. A Central Cognitive Base Station (CCBS) controls CRU communication so that these CRU do not interfere each other or a Primary User (PU). For modeling the CCBS, in this paper, 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.

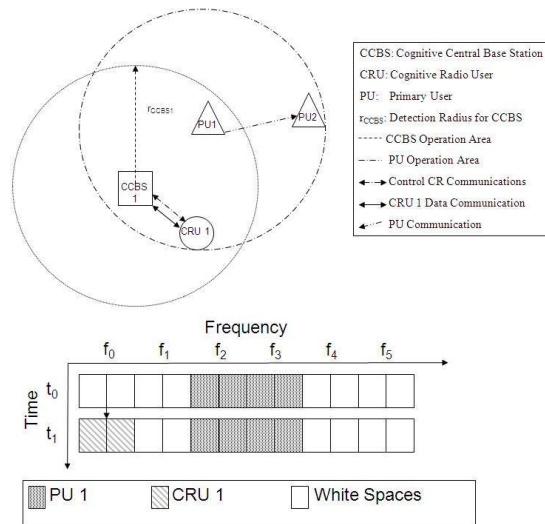


Fig. 1. CRN Model

In Fig. 1, CRU1 is communicating with its corresponding 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 used for PU1-PU2 communication. A frequency/time representation of the corresponding scenario is also shown. 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 CRUs’ terminals and therefore, keeping those terminals simple while using today’s available technologies. We also assume that the CCBS decides which channel to assign for each CRU, according to the available channels and characteristics of the CRU.

The basic model of the CRN provides signaling through cognitive pilot channels (CPCs) distributed in every available channel or frequency slot. The control is performed by using frequency-division and time-division multiplexing techniques. This control, as expected, permits the utilization of the CRN by heterogeneous cognitive radio user (CRU) devices. Frequency sub-slots are used by the CCBSs and CRUs to exchange both control and data information. The CCBS is responsible of controlling which CRUs are communicating and the frequency slots used, by assigning CRUs free frequency slots to communicate. This information is sent in a vector to the CRUs, while kept in the CCBS database. Fig. 2 shows the division in frequency and sub-frequency slots.

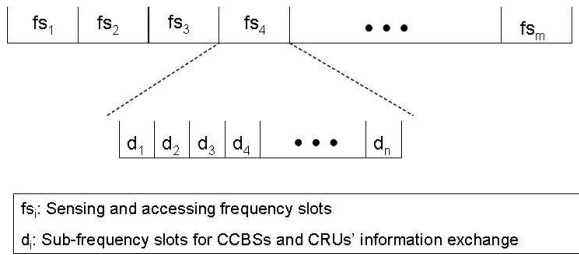


Fig. 2. Frequency and sub-frequency slot division of the spectrum

The basic algorithm for each frequency slot was defined by Fig. 3. The database was mainly used for keeping into memory the location of CRUs and PUs in the frequency bands. The main energy reduction is accomplished by reducing signalization transmissions.

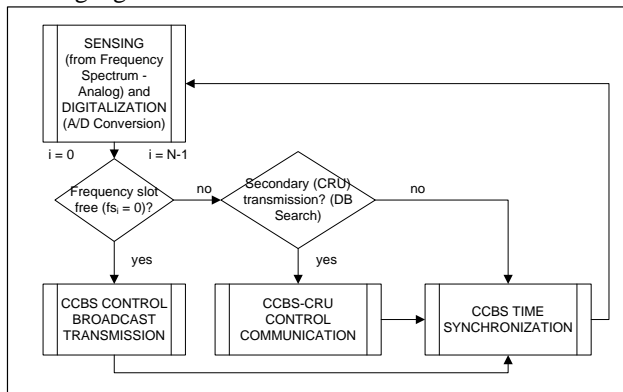


Fig. 3. CCBS Algorithm per each frequency slot i (fs_i)

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. The time slot division used for the CRN MAC presented in [12], as shown in Fig. 4, will be also used to reduce the signalization.

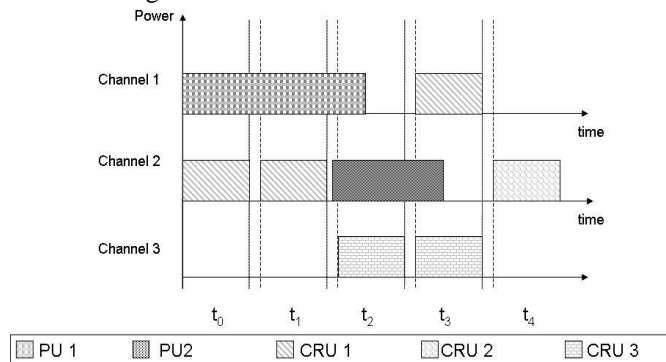


Fig. 4. Frequency slot utilization by both PU and CRUs (in time)

In Fig. 4, an example of the CRU admission in the CRN is shown. 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 t_2 .

In [13], two additional characteristics are added to the CRN model of [12] 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, and the number of periodical broadcast beacon transmission will be also reduced.

In [13], we also 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. 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. Then, the idea is to find the minimum number of broadcasting channels for the CCBS needed broadcasting transmission.

Considering again that the CCBS has knowledge of the channels each of the CRUs is able to use, for finding this minimum number of the broadcast transmission channels needed in a specific moment, a matrix called availability matrix is included. The relation among the frequency slots (channels) and CRUs in a specific time is shown in Fig. 5.

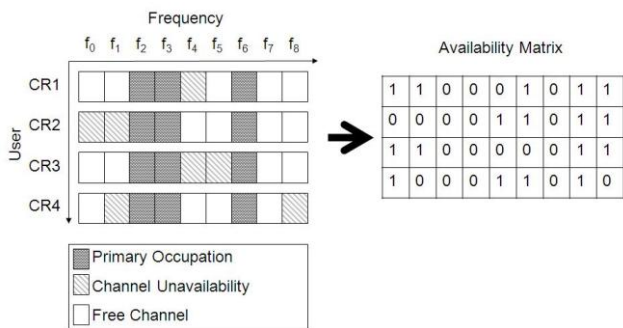


Fig. 5. Frequency slot utilization by both PU and CRUs (in time)

In Fig. 5, 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. 5, 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. 6, a case where more than one channel is needed for the CCBS to broadcast is shown.

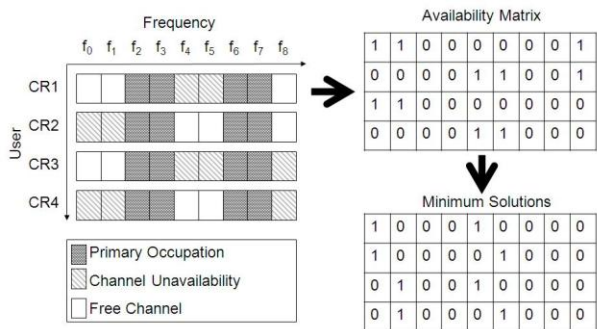


Fig. 6. Frequency slot utilization by both PU and CRUs (in time)

In the case presented in Fig. 6, the availability matrix shows that at least the CCBS needs two channels to communicate with all the CRUs in the network. The matrix composed with all the vectors that use the minimum channels for the CCBS to communicate is represented as Minimum Solutions. In general, the problem of finding this minimum solution vectors is the same as finding the vectors with the least numbers of ‘1’s such that the intersection of them with each of the row vectors that compose the availability matrix is not empty.

III. CONSIDERATIONS

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

The matrix that relates channel usability for each CRU is represented as $U_{m \times n}$. Each row vector defined by $U(i, :)$ is always different than 0, taking into account that each CRU must have at least one channel to communicate. So, not considering primary occupation, the problem can be defined as finding a vector $v \times n$ such that

$$\sum_1^n ((v \cdot *U(1,:)) \vee (v \cdot *U(2,:)) \dots \vee (v \cdot *U(m,:))) = n \quad (1)$$

in which the number of ‘1’s is minimum. This problem can be related to a satisfiability problem (SAT) which is known to be NP-complete [21]. This can be proved considering that

$$Z = \begin{bmatrix} (v \cdot *U(1,:)) \\ (v \cdot *U(2,:)) \\ \vdots \\ (v \cdot *U(m,:)) \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} & \dots & z_{1n} \\ z_{21} & & & \\ \vdots & & \ddots & \\ z_{m1} & & & z_{mn} \end{bmatrix}, \quad (2)$$

then

$$((v \cdot *U(1,:)) \vee \dots \vee (v \cdot *U(m,:))) \quad (3)$$

is equal to the vector

$$z' = \left[(z_{11} \vee \dots \vee z_{m1}) \quad \dots \quad (z_{1n} \vee \dots \vee z_{mn}) \right]. \quad (4)$$

Taking into account that

$$\sum z' = n \quad (5)$$

means that each

$$(z_{1i} \vee \dots \vee z_{mi}) \quad (6)$$

is ‘1’, so the problem is equal to find a vector v with minimum norm such that for every $j = 1:n$,

$$(z_{11} \vee \dots \vee z_{m1}) \quad (7)$$

is true, which is the definition of the n-satisfiability problem. This vector is defined in general for this paper as the vector of minimum solutions.

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.

IV. CASE STUDY

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

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

TABLE I. 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 I, the minimum number of channels needed to transmit to all CRUs in the network is 2, using f_1 and f_5, f_4, f_7, f_3 and f_5 .

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

TABLE II. 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 f_8 and

f_3 , respectively as their usable channels. A possible minimum solutions vector is then $v = [1\ 0\ 1\ 0\ 1\ 0\ 0\ 1]$. The similarity on the number is because the CRUs, while heterogeneous in frequency, are defined with similar characteristics.

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

TABLE III. 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 IV. 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 V. Results for a minimum solutions vector are shown in Table VI. The considerations were the same as for the case when PUs were not included, $m = 8, n = 8, t = 10$.

TABLE V. 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 VI. MINIMUM SOLUTION VECTOR (WITH PUS)

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

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

V. CONCLUSION AND FUTURE WORKS

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

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

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

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

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