UPC **epsc** Escola Politècnica Superior de Castelldefels

UNIVERSITAT POLITÈCNICA DE CATALUNYA

MASTER THESIS

TITLE: Study of admission and control system in a Centralized Cognitive Radio Network for Heterogeneous Wireless Frequency Devices

MASTER DEGREE: Master in Science in Telecommunication Engineering & Management

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DATE: May 25th 2011

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Data: 25 de Maig del 2011

Resum

Aquest projecte te com a punt de partida la tecnologia anomenada Cognitive Radio Network inicialment proposada per Joseph Mitola a finals dels 90.

Aquest concepte introdueix la idea de que els sistemes de telecomunicacions d'avui en dia son prou evolucionats per tal de poder conèixer millor les necessitats de recursos dels equips sens fils en base als recursos que necessiten. D'aquesta manera doncs aprofitant aquesta característica es pretén millorar l'eficiència de l'espectre freqüencial disponible compartint l'espectre de manera oportunista entre usuaris llicenciats i usuaris secundaris.

En base aquest concepte Nicolas Bolívar del grup de "Broadband Comunications and Distributed Systems" de la Universitat de Girona proposa un nou model centralitzat de xarxes amb control distribuït que empren la tecnologia de Cognitive Radio (CR).

L'objectiu d'aquest projecte és estudiar aquesta tecnologia per desenvolupar un simulador, utilitzant el programa Matlab, per veure les característiques i el comportament dels sistema d'admissió i control en el model de CR proposat.

Després d'haver llegit aquest projecte es tindrà una visió global del significat de la tecnologia CR, així com una eina de simulació que permetrà analitzar de manera fàcil el comportament del sistema de control del sistema.

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Overview

This project focuses on the Cognitive Radio Technology initially proposed by Joseph Mitola at the end of 90s. The concept of Cognitive Radio introduces the idea that nowadays telecommunications systems must be aware of the environment and the user needs to efficiently use the available resources. Considering this property the efficiency of the wireless frequency spectrum is intended to be optimized, sharing frequencies in an opportunistic manner with licensed (Primary Users) and unlicensed users (Cognitive Radio Users).

Nicolas Bolívar from the "Broadband Communications and Distributed Systems" group of the Universitat de Girona proposes a new centralized model with distributed control for a Cognitive Radio Network (CRN) in order to consider different wireless technologies in the same network. Expanding that work, the aim of this project is to study the Cognitive Radio technology to develop a simulator using Matlab to test the behavior and the performances of the admission and control in the proposed Cognitive Radio model.

After finishing this project, a global overview of the Cognitive Radio technology will have been presented, as well as a simulation tool to easily analyze and check the behavior of the control system of the centralized CRN with distributed control.

Dedicate to Adela.

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Introduction

Nowadays, the number of wireless devices is increasing, producing an important decrease of the wireless spectrum availability. A new technology called Cognitive Radio Network (CRN) is developing to increase the spectrum efficiency, sharing the available channels with the needs of the devices at any moment in opportunistic manner.

This project is based in the work of Nicolas Bolivar from the "Broadband Communications and Distributed Systems" group of the "Universitat de Girona" (UdG). They proposed a Centralized Cognitive Radio Network with distributed control model using the idea of a Cognitive Radio Network firstly proposed by Joseph Mitola on 1998.

The aim of this work is to study the Cognitive Radio technology to develop a simulator using Matlab to test the behavior and the performances of the admission and control in the proposed Cognitive Radio model.

This work is organized as follows: In chapter I, we explain the main characteristics of a Cognitive Radio Network to understand the technology. In chapter II, we focus into the proposed model studying the main parameters, the architecture and the modules, specifically on the admission and control system.

In chapter III, the algorithms used in [3] are explained in order to clarify the requirements of the algorithms for the simulation program in Matlab. In chapter IV, a description of the Matlab program is presented. In chapter V, simulations of the model using different parameters are shown. These results are analyzed and explained in order to validate the model.

Finally, in chapters VI and VII, some conclusions and the future work for this project are presented in order to enhance the important points of the model and to project future studies.

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Chapter I.   Cognitive Radio Network

In the next lines we explain the concept and the general characteristics of a Cognitive Radio Network (CRN).

I.1   Definition of Cognitive Radio Network

The Cognitive Radio (CR) term was initially presented by Joseph Mitola III in 1998 and later published on article in 1999 by him and Gerald Q. Maguire. They present the idea for wireless technologies that "the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context and to provide radio resources and wireless services most appropriate to those needs".[1]

The aim of the CR technology is to provide the maximum efficiency of the spectrum to improve its utilization by using dynamic spectrum access techniques. The key to enabling the maximum spectrum efficiency is to provide the capability to share the wireless channel with licensed users in an opportunistic manner. This goal might be achieved using dynamic and efficient spectrum management techniques.

In order to achieve this goal, the Cognitive Radio Users (CRU) in a Cognitive Radio Network must:

- Determine which portions of the spectrum are available (Spectrum Sensing)
- Select the best available channel (Spectrum Decision)
- Coordinate access to this channel with other users (Spectrum Sharing)
- Vacate the channel when a licensed user (Primary User) is detected (Spectrum Mobility)

The main characteristics that a CRN must comply are:

- Reconfigurability: In order to allocate the CRU into a large dynamic frequency range, the transceivers and receivers of the devices in the CRN must allow the reconfiguration of their parameters over a wide frequency range. Dynamic spectrum access is one of the major challenges in the design of a CRN.
- Cognitive Capability: This is the real-time interaction that allows the identification of the portions of the spectrum that are unused at specific time or location. This characteristic is not been used in this project since we only used the dynamic spectrum capabilities of CRN.

FigureI.1shows the different channels of wireless technology using dynamic spectrum access techniques. As we can see *white space or spectrum hole* can be found in time. The idea is to take this hole for the transmission of a CRU.
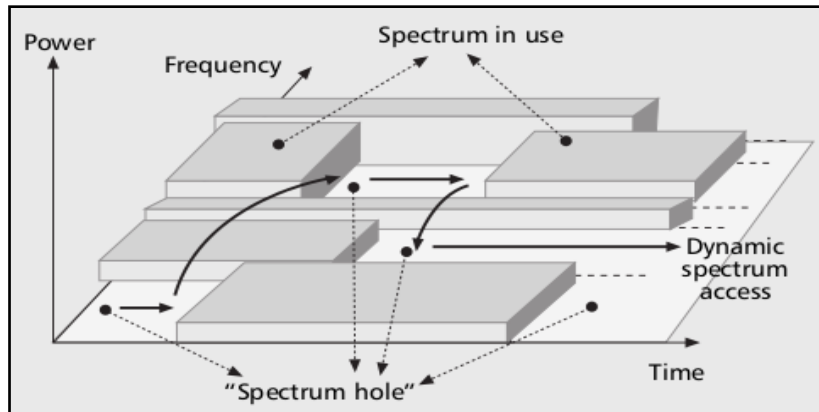

FigureI.1 The spectrum hole or white space concept [2]

I.1.1   Architecture

An example of the coexistence of a Cognitive Radio Network with other existing networks can be seen in the Figure I.2.
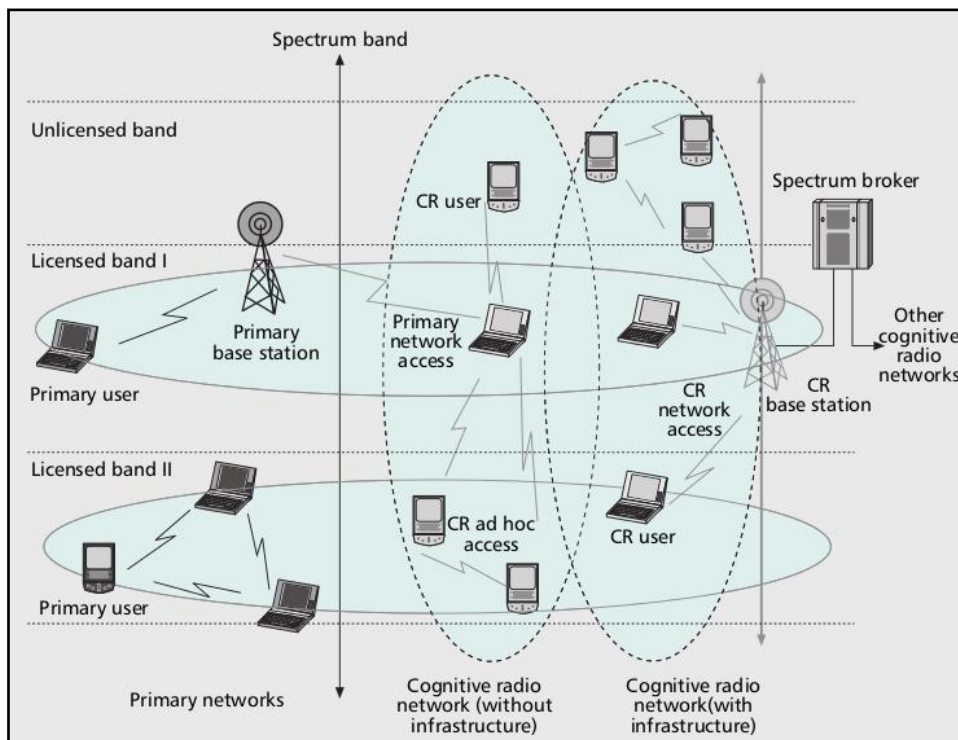

Figure I.2 Coexistence of a Cognitive Radio Network [2]

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In the project we focus in a CRN with infrastructure scheme, so we only describe this part in this work. In this scheme we are only considering: *Primary Networks* and one *CRN.*

A primary network (licensed network) is an existing network for Primary Users (PU). They have permission to communicate through licensed bands. The operations of PUs are controlled by their Primary Network. The primary users have high priority in their bands so they should not be interfered by CRUs. CRUs have their own Cognitive Radio Base Stations (CRBS) where the CRU access to their resources.

CRUs, then, must only communicate when PUs are not using their licensed bands. As we can see in the Figure I.2, they can also use unlicensed bands. This heterogeneous spectrum capability of CRU is an important characteristic that must be taken into account.

In general, a CRN should be able to perform efficiently the spectrum sensing, the spectrum decision, the spectrum sharing, and the spectrum mobility tasks. The spectrum sensing consists in monitoring the spectrum and to detect spectrum holes. In the spectrum decision task, CRUs are allocated in the different available frequencies. This function not only depends on frequency availability, but also depends on some internal or external policies.

Since various CRUs could try to access the same resources, we need to coordinate these accesses to prevent collisions between multiple CRUs. These actions are performed by the spectrum sharing function. Finally, if a PU would enter to a portion of spectrum that is occupied by a CRU, this CRU must be reallocated to a different frequency in order to not affect the PU communication. This is the spectrum mobility function. In this project, we are focusing into the spectrum decision and spectrum sharing in order to control the CRN.

Chapter II.   Centralized Cognitive Radio Network model

In this section we focus into the main characteristics of the Centralized Cognitive Radio Network model proposed and studied in [3].

II.1 Model Description

The main goal of this model is to concentrate most of the decisions in a centralized base station in order to keep CRUs as simple as possible. The general scenario of the centralized cognitive radio network model is shown in Figure II.1.
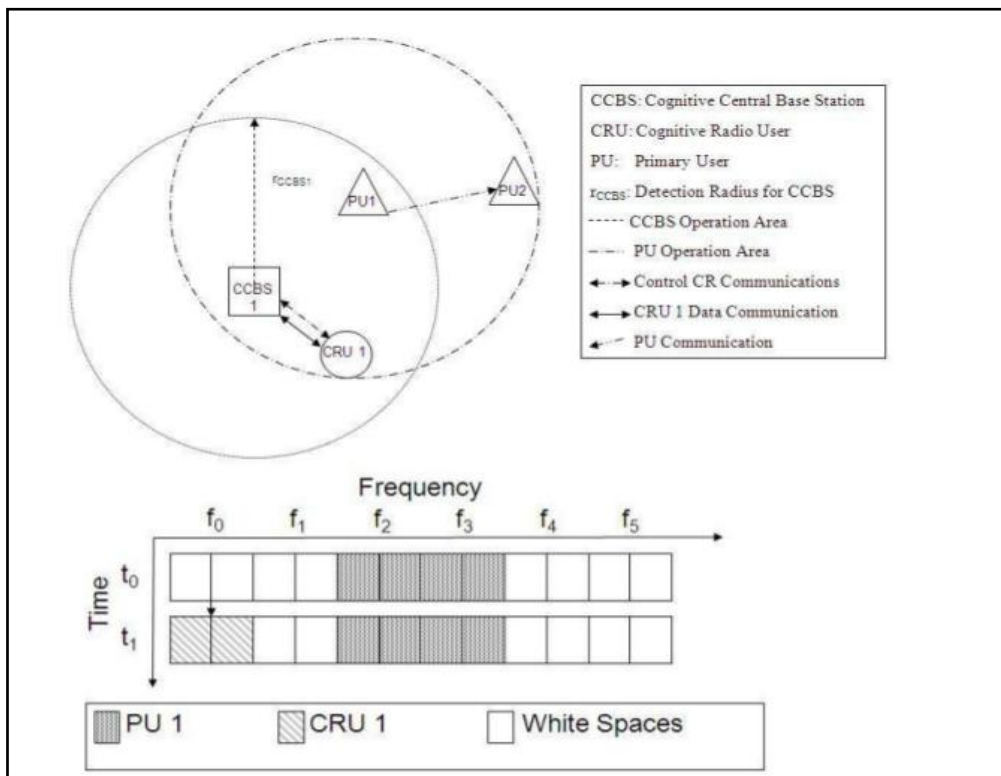

Figure II.1 Representation of Centralized Cognitive Radio Network [3]

The scenario is formed by a Centralized Cognitive Base Station (CCBS) that has a defined coverage area (c_{rabs}). In the first time slot of observation, PU1 is using some frequency slots that the CRN is also able to use. When a CRU enters this area, this user can use some white spaces to transmit.

If a new PU user enters to coverage area and wants to transmit through frequencies occupied by CRU, the CRU 1 must leave for the PU transmission.

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The communication between the CCBS and the CRUs is divided into different frequency slots. These slots can be used by both PUs and CRUs. Each slot has sub-frequency slots used to exchange information between them for communication. This frequency distribution is shown in Figure II.2.
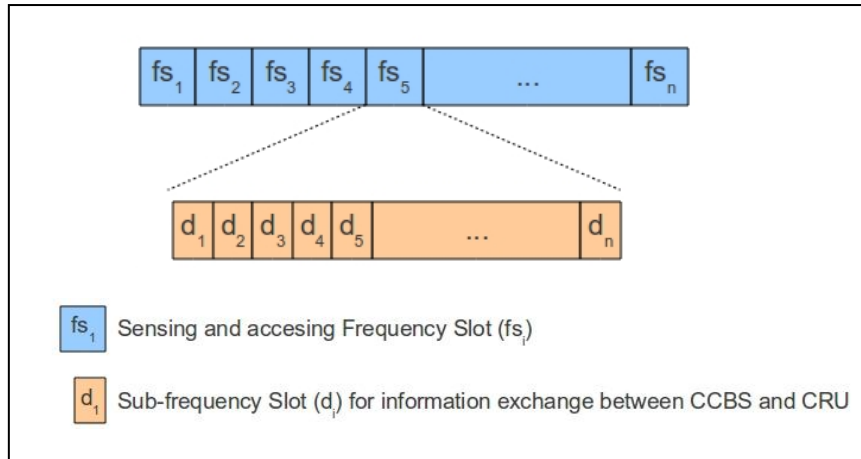
Figure II.2 Frequency slots and sub frequency slots of Centralized Radio Network

As we can see in Figure II.2, each frequency slot is divided into different sub-frequency slots. The information goes through these sub-frequency slots, reserving various sub slots at specific moments of time for the control mechanism, and the others for the data information of the CCBS or the CRUs.

II.2 Model Architecture

The architecture of the proposed Centralized Cognitive Radio Network is shown in Figure II..
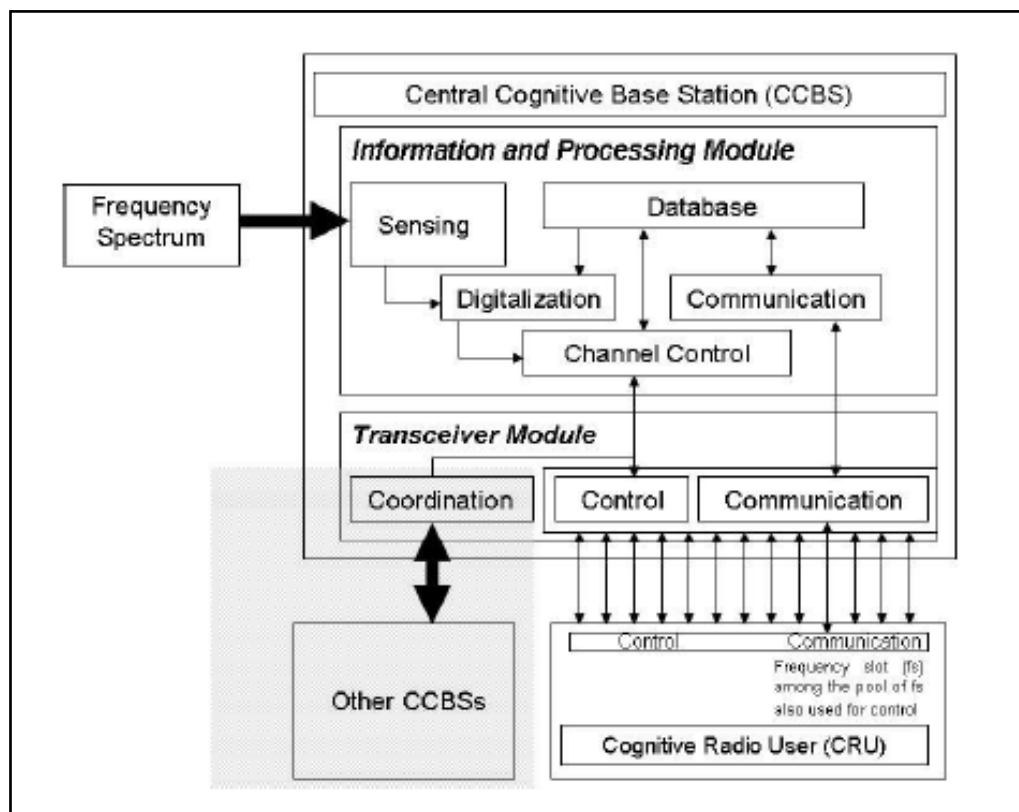

Figure II.3 Architecture of the Centralized Cognitive Radio Network [3]

The model is divided in two major modules, the information and processing module and the transceiver module.

The information and processing module is divided in five sub modules: sensing, database, digitalization, channel control and communication. This module is the core of the CCBS and implements the main algorithms to properly share the spectrum in an opportunistic manner (II.3.1Information and Processing module).

The transceiver module is responsible of communicating the decisions of the core module (Channel Control and Communication sub-module) to a CRU (Control and Communication sub-module module of the CRU) and with other CCBS for the properly cooperation. In this work the coordination and cooperation between CCBS is not analyzed.

In this project we focus into the simulation, design and functionality requirements for the Database module and Channel Control module.

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II.3 Modules and main functionalities

In this section the modules and main functions of the Cognitive Central Base Station (CCBS) are explained. We focus on the Information and Processing module, specifically on the Database and Control Channel sub modules.

II.3.1 Information and Processing module

In this module the main functionalities that a CCBS perform are explained. The aims of the information and processing module are to:

- Sense the frequency spectrum through the sensing module. For this work, this sensing is perfectly and continuously done.
- Digitalize the analog signal from the sensing module into predefined frequency slots.
- Store an array of frequency slots and sub-frequency slots into the database. Also, to store information from the channel control and communication modules.
- Process the information stored to decide channel allocation and to communicate the decisions to the aforementioned transceiver module.

We considered for the project the study of the processes after the digitalization of the analog sensing signal is performed, assuming that both sensing and digitalization of the spectrum are perfect.

II.3.1.1 Database module

This sub-module is responsible of storing all the information used for the control and communication algorithm. In the next lines, we present the main tables that we used.

The first table is the sensing table. This table stores the data from the digitalization of the analog signal from the sensing module. Predefined slots are used depending on the wireless technology that is sensed. This predefined slot is also communicated to the digitalization module and to A/D converter.

Another important table stored is the sub-frequency slot table that is used by the CRU and CCBS to exchange information about their transmission. The database module could also store other tables used by functions not belonging to the control function.

II.3.1.2 Channel Control Module

The channel control is the most important sub module in this study. This sub module is responsible of controlling the CCBS and CRU communication. There are different algorithms that can be used to control this behavior (See on Chapter III).

The proposed model use both frequency division and time division multiplexing techniques for controlling the CRN. The frequency division technique uses Cognitive Pilot Channels (CPC) for controlling the transmitting channel availabilities, network discovery and channel petitions.

In the Centralized CRN, the CCBS sends control signals in the first two sub slots of some available frequencies. This allows that when a CRU request access to the network, the CCBS already knows the available frequencies to communicate with CRUs in the network.

A time slot predefinition is also used in the Control Module. This approach consists into predefining a time slot with CRU for the control mechanism. With this technique CRUs are also able to detect PU transmission.

Chapter III.   CCBS-CRU Control

In the next lines the control process for the CCBS and the CRUs in the model are explained. Control algorithms are explained from both CCBS and CRU perspectives.

III.1 CCBS Control Algorithm

The CCBS Control algorithm is applied on each frequency slot. This is in order to know the frequency slot states in every time clock. The algorithm process is shown in Figure III.1.
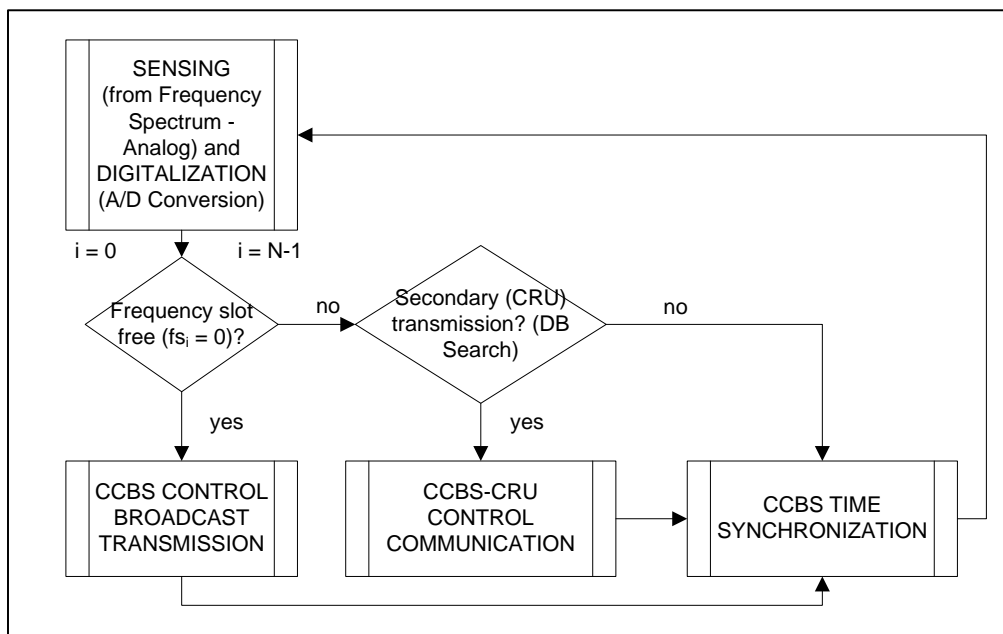

Figure III.1 CCBS Control algorithm [3]

The first block represents the sensing and digitalization method. This method is considered as a state array of the different available frequency slots. This block represents both the spectrum sensing and the analog signal conversion into a digital one through the A/D conversion of the digitalization module.

This frequency array from the sensing and digitalization block is processed. If the frequency that is evaluated is available for CRU transmission, then the *CCBS Control Broadcast Transmission* block is executed and the algorithm waits until the next clock time for *CCBS Time Synchronization.*

If the frequency is occupied then it is checked if the transmission in this frequency slot is due to a CRU transmission or not. If this transmission belongs to a CRU then a *CCBS-CRU Control Communication* is performed, and the algorithm waits for the time synchronization. Finally if the frequency slot is not used for CRU, that means a PU transmission, so the algorithm only waits for time synchronization.

In a CCBS Control Broadcast Transmission a frequency beacon mechanism is proposed. This consists on a two bit signal in the first two sub frequency slots of some available channels.

Table III.1 shows the different values that could be set.

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

Table III.1 Control bits used by CCBS Control Broadcast Transmission to announce the state process.

The first set of bits that the CCBS use is the "10" or "11" to announce the availability of the channel. If a CRU receives"10" it means that they could send the information to enter in the network through this frequency. Otherwise, this frequency is occupied by a PU, so the CRU is notable to communicate with the CCBS through this frequency.

The "01" combination is only used by a CRU to announce that it would use this channel to enter to the CRN. Finally, the "00" means that the CCBS and the CRU are coordinating some information to use a specific channel.

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III.2 CCBS – CRU Control Algorithm

This algorithm is related with the communication and control of the CCBS and a CRU. The process of the algorithm is depicted in Figure III..
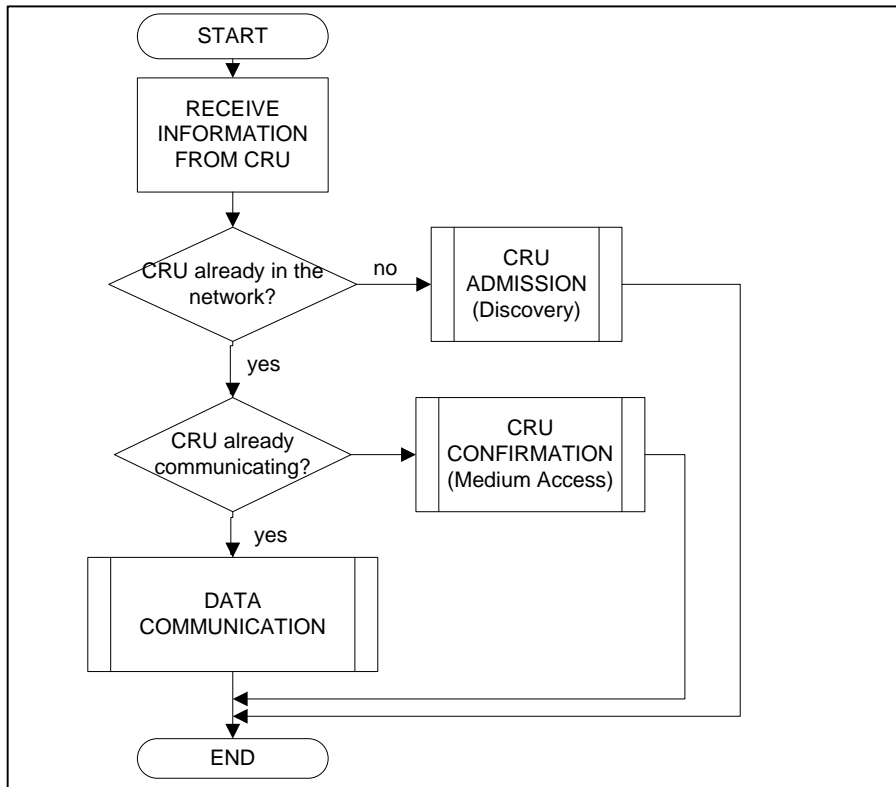

Figure III.2 CCBS-CRU Control algorithm [3]

The control algorithm is performed under three different scenarios, when a CRU would enter to the network (Network discovery), the CRU medium access and finally while a CRU is transmitting (Data Transmission).

In the first scenario, the CRU would enter to the network so they send for the available frequencies the petition to enter, the id of the CRU and the kind of the device. The CRU could try to enter the network at any moment. Then, the CCBS looks in the database if this user is already in the network. If the CRU is not in the network, the Discovery process begins.

The information of the CRU request is stored into the CCBS database. When the CCBS acknowledges the CRU sends a confirmation message to indicate that this CRU is registered in the network. Then, the CRU waits for the confirmation of registration to the network and synchronizes itself with the CCBS.

If the CRU is already registered in the CCBS, the medium access process begins. In this stage the CRU and CCBS exchange information about what channel the CRU will use for data communication and other characteristics. In this moment the CRU is prepared for the data communication.

A time-based approach is performed in the communication between the CCBS and the CRU to identify if a PU would use the frequency slot assigned by the CCBS. Figure III.3 shows this behavior.
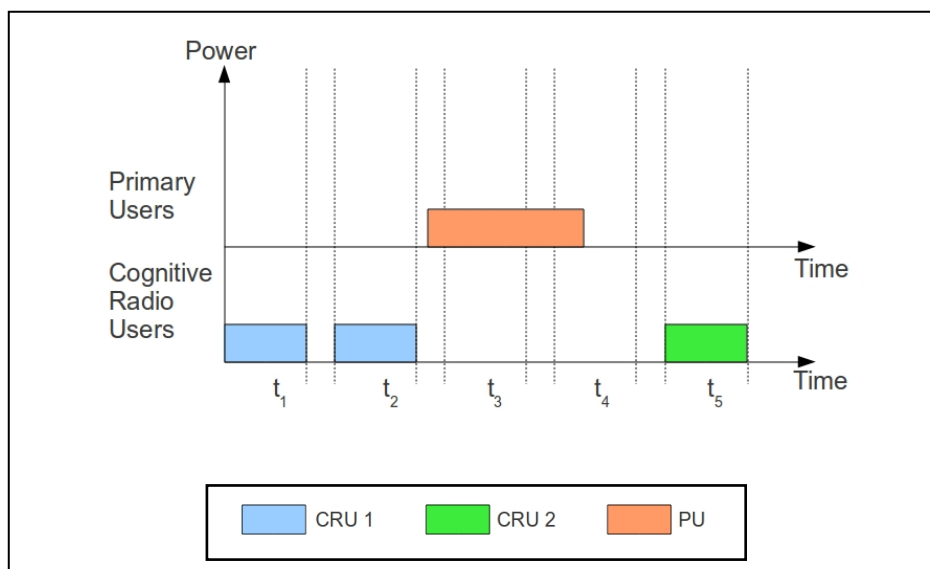

Figure III.3 PU and CRU transmission in time

When a transmission in an unexpected part of the time slot is performed the CCBS recognize this communication as PU presence, and if a CRU is using this frequency slot, the CCBS immediately alerts this CRU to leave the channel. In that case, the CCBS must search for another free frequency slot for this CRU to achieve the spectrum mobility characteristic of the CRN. When PU transmission is finished, the frequency slot can be occupied by another CRU.

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Chapter IV. Matlab model

In this chapter, the Matlab 0 simulation program is explained (See Annex I for simulator code).

IV.1 Core definition

The aim of the program is to study and to analyze the behavior of the CRN model and to find the maximum number of users and the maximal efficiency that the system could achieve for a defined number of CRU users, PU users, and frequency slots of the network during a specified period of time. The Matlab program works as a simulator that models the proposed control and communication algorithm. These algorithms are important to extract the main parameters for this study. This simulator is the main base of a program that will be complemented with the modules that are not studied in this project but explained in Chapter II.

In the first stage, the database module and control channel sub modules are programmed. The program simulates PUs and CRUs, with different traffic distributions considered for each of them (the traffic distributions can be seen on IV.1.3). This allows studying the results in a controlled environment knowing the input variables and also studying the behavior of the system with different traffic distributions.

When the input variables are correctly specified, the simulator introduces the traffic through the algorithm explained in Chapter III. The results show the percentage of traffic that CRUs were able to transmit correctly and graphically shows the behavior of the CRU in the system.

IV.1.1 Global Variables

In the next lines we present the global variables used in the program.

Number of frequency slots and maximum number of PU

The variable describes the number of frequency slots that the sensing system could have. This is also the maximal number of PUs that the system can support. The system can't support more PU than the maximal frequency slots available in the system. The worst condition will be that all frequencies are occupied by PUs. This variable is defined as 128 by default.

Number of CRU

This variable specifies the total number of CRU in the network. This number is the total number but do not specify that all CRUs transmit at the same time. In the next section we describe how these CRUs would transmit along time.

Time duration

This is the time interval duration of all the simulation. This is a dimensionless variable that only describes the number of time slots computed by the simulator. The variable takes effect in the distribution of the PUs and CRUs along the time.

IV.1.2 Traffic Generation

To study the simulation in a controlled environment we design traffic variables. They help us to study the behavior of the system.

These variables consist in two different tables, which act as an input to the program and can be modified applying different parameters. In Figure IV.1 we can see the characteristics of each traffic table.

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Figure IV.1 Traffic table characteristics

The first table is the *PU table* and describes the traffic behavior of the Primary Users. This table simulates the data that goes into the CCBS through the Sensing and Digitalization module. The table indicates if a frequency during a time is occupied by a PU or not. For primary occupation a logical "1" is assigned; otherwise, a logical "0" is.

The second table describes CRU transmission during the time duration. When a CRU would transmit we assign a logical "1"; if the CRU does not transmit, a logical "0" is assigned. The axes of the table are CRU id and time. The total time duration is specified by the global variable of time duration.

All these tables could be modeled using different traffic models. In next section (IV.1.3), we describe the different traffic models that we implement for every table. The program is made to allow introducing new traffic models easily.

IV.1.3 Time Traffic Model

In order to model the PUs and CRUs and their traffic behavior in time, different traffic models are used. These traffic models are applied to both the PU table and CRU time table.

- ***Random Model***

This model is proposed as a first point of the study. All the traffic generated with this model is completely random. The random model have one parameter that specifies the relation between the number of "0" and "1", this parameter varies between zero and one. I.e. if the parameter takes the value 0.5, the number of zeros and ones are distributed with 50 % of zeros and 50% of one's distributed randomly.

- ***User Defined Model***

This model is proposed to allow the program user specify their own test tables. In the program the users can introduce their own tables to repeat the simulations within the same traffic characteristics. This allows the users to program the simulation of specific situations. When the users introduce the table, they must assure that the dimensions of the table are the same of the defined global variables. For example, if we select PU traffic as user defined and the global variables are: 10 frequency slots and the time duration equals to 10, the PU traffic table must consist of 10 rows and 10 columns.

- ***Distribution Model***

A high number of models have been studied and applied for modeling and characterizing the user and traffic behaviors on wireless devices. The next lines explain the distribution traffic applied to the simulator.

A classic characterization for the distribution selection is to mix the Poisson distribution for the arrival petitions and the negative exponential distribution for the duration of both PU and CRU transmission [5].

The Poisson distribution is chosen because petition arrivals are independent of each other and two or more events cannot occur at the same time. The parameter that defines this distribution is lambda, which means the average number of events per unit of time [4]. (See Annex II.A)

On the other hand, the negative exponential distribution is chosen for the transmission duration. This is because each transmission is considered as a call. In that case, transmission duration is considered to be between specific values and when this duration increases, the probability of occurrence is lower. The parameter that defines the behavior of the negative exponential time is the average time duration in our case [4] (See Annex II.B).

More traffic models exist and they could be introduced in the program as new traffic models, because each of them is programmed as an independent function.

IV.1.4 CRU frequency models

Some frequency table models are proposed to simulate the assigned frequencies to CRUs. These models are used in the definition of CRU frequency table. Figure IV.2 shows the CRU frequency table description.

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Figure IV.2 CRU frequency table

The y axis is the CRU id existing in the system. The x axis is the number of frequency slots available for the system; remember that this variable is specified by a global variable. In the next lines we describe the frequency models used in the simulation, which must be selected when before the simulation begins.

- *Random frequency model*

When random frequency model is selected, the simulator generates a random table that specifies the frequency slots available for each CRU to communicate with the CCBS. This random model also allows a parameter to change the distribution of zeros and ones in the frequency model table, as the traffic random model explained in IV.1.3.

- *User defined model*

This model allows specifying manually the frequencies that will be available for each CRU. The frequencies must be defined for every CRU and must be consistent with the defined global variables, e.g. if 10 CRU exists and 10 frequencies are available, then a table of 10 rows by 10 columns must be specified.

- *Band model*

As a simulation of the CCBS in heterogeneous wireless devices, a set of different devices can be found in the market that uses a different frequency bands. In order to distribute the available frequencies to each CRU we define different bands that can be used by CRUs. The simulation does not specify a defined technology or one of the available frequency standards, because the

simulation is for general purpose. When band type model is specified, the program randomly assigns bands to each CRU in the simulation. Figure IV.3 show an example of distribution bands along the frequency spectrum.
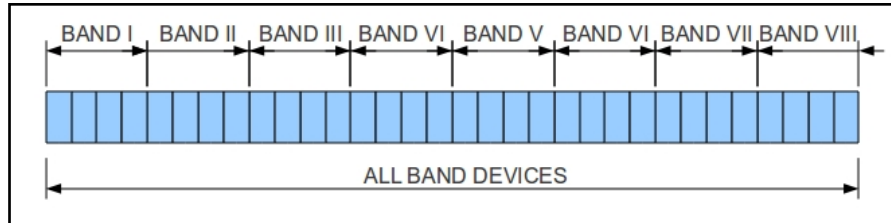

Figure IV.3 Band model for CRUs

Notice that for the available bands, since they are equally distributed, their length depends on the total number of frequency slots defined in the global variable and the number of defined bands for the simulation, i.e. If the total frequency slots are 128, the bands are considered as same length and the bands are uniformly distributed with 16 frequency slots per band. For the program, the total number of frequency slots must be multiple of the number of bands. An example of the strategy of assigning bands to the CRU is shown in Figure IV.4.

Figure IV.4 Band model strategy example

In the first table, the bands are randomly distributed for the CRUs in the system. In the example there are 3 bands, so the bands are distributed randomly to the CRUs. After that, the bands are transformed to the frequency slots for each band. In the example we have three frequencies for band, so we distribute the value of every band to the frequency slots that are included in the band.

This band model is programmed as an independent function to allow changes easily without modifying the entire program.

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IV.1.5 Control algorithm

The control algorithm has been programmed as an independent function of the main program. This is to allow the possibility to test and to modify this algorithm without affecting the main program.

The algorithm used for this project considers the PU table and CRU tables (CRU time table and CRU band model table) as inputs of the function, taking into account the main variables, i.e. as number of the frequency slots, the number of CRU, and the time relation.

The strategy for assigning the white spaces to the CRUs is to assign the first white space that is found to the first CRU in the table. This is like implementing a priority-based system. This strategy of assigning the white spaces to the CRU can be modified later to test different cognitive radio behaviors.

After running the algorithm, the output is a table that represents the wireless frequency occupation. An example of this result is showed in the Figure IV.5.

Figure IV.5 Result table after the control algorithm (White spaces, PUs and CRUs)

As seen in Figure IV.5, the axes of the table are frequency slots and time slots. PU transmissions are represented with '-1', white spaces with '0' and CRU transmissions with the ID that is assigned to each CRU.

IV.2 User Interface

In Figure IV.6the program user interface is presented. This interface is created for a user to easily modify and run the parameters that describe the cognitive radio system.
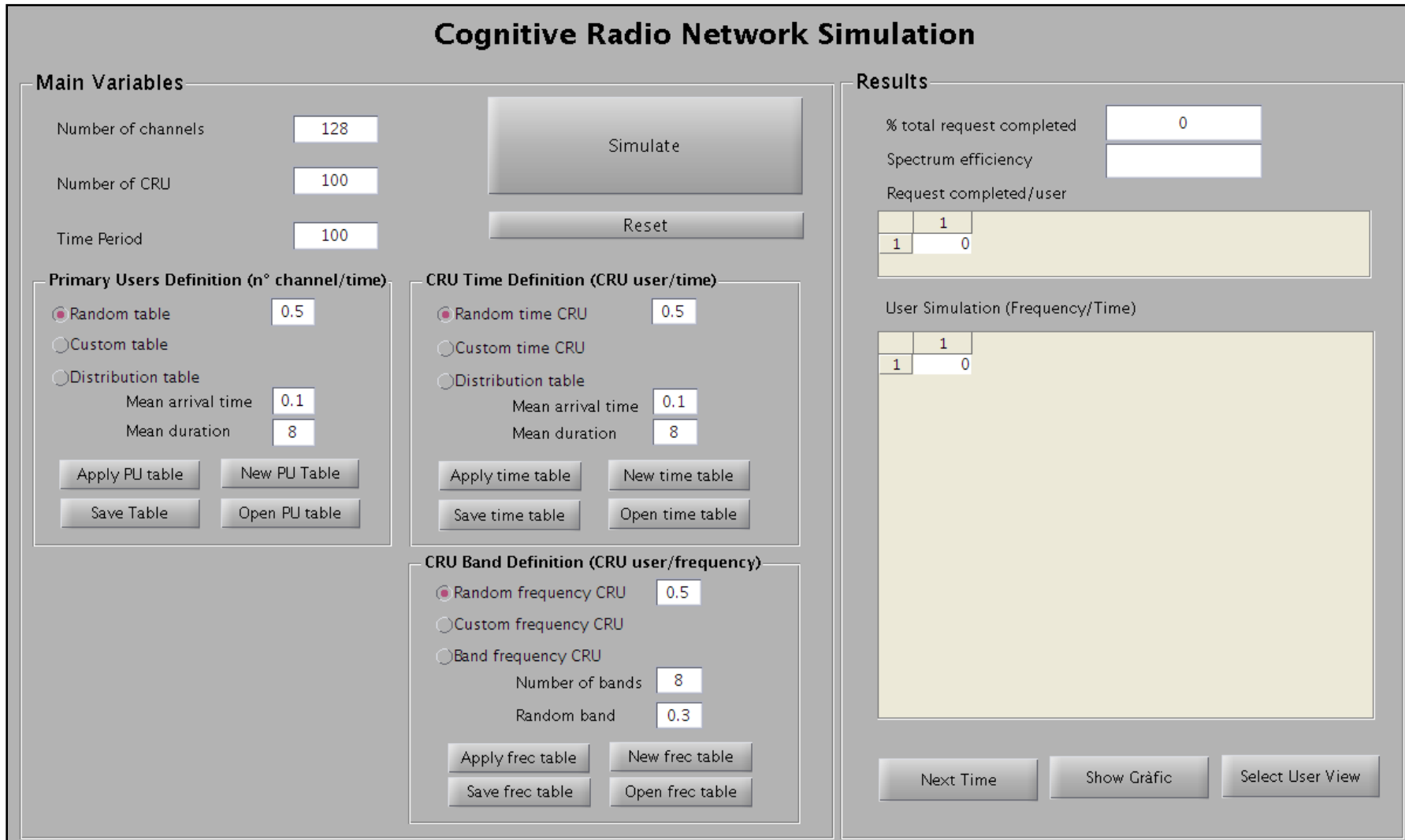
Figure IV.6 User interface of simulation program

We develop the program in Matlab®. A Centralized Cognitive Radio Network Simulation guided user interface (GUI) is created, as Figure IV.6 shows. The user interface has two main parts, the main variables and the results. At the beginning of the application, default values appear in the interface.

IV.2.1 Main variables panel

The main variables allow the user to specify the global variables of the system that are explained in section IV.1.1. When the global variables are specified, the next step is to define the PUs and CRUs characteristics.

For the definition of the PUs and CRUs behavior we have three panels (Primary User Definition, CRU Definition and CRU Band definition). The Primary User Definition panel allows the user to specify the PU table explained in section IV.1.2 with a specific time distribution (explained in sectionIV.1.3). The CRU Time Definition panel is defined in the same manner. The CRU band definition panel allows the user to specify the CRU frequency table explained in section IV.1.4.

We can see that all these panels have three radio buttons for the users to choose among three different characteristics: random, custom and distribution for the traffic models in time and random, custom and bands for the CRU frequency distribution. When one of these radio buttons is selected, the others remain unselected. These panels also have four pushbuttons: apply table, save table, new table and open table. When the radio button choice is random or default (distribution for traffics and bands for frequency), we need to press the apply table pushbutton to load the table into the simulator. If the custom radio button is chosen that means that the user would define the table, and the user must press open table or new table push button to specify the custom user table. After pressing open table or new table, a pop-up window will appear to select the table or to define the new table, respectively. When the user defines the table, it is loaded to the simulator automatically and there is no need to press the apply button to load the table. Finally, if the user needs to save the table, the save pushbutton must be pressed. A pop-up will appear to specify the location of the file and also the extension (normally in "csv" or "xls" format) to be saved.

IV.2.2 Results panel

When the simulation tab is pressed, the results panel is modified, with the results of the specific simulations.

The first result that is shown is the percentage of the CRU requests completed among the total of CRU requests.

$$\% \_cru\_request\_transmitted = \frac{cru\_requests\_transmitted}{total\_cru\_requests} \cdot 100 \qquad \textbf{(IV-1)}$$

This parameter specifies the efficiency of the proposed control system for the Centralized Cognitive Radio Network model.

Another important result that is shown is the spectrum efficiency, which is defined as in Equation IV-2.

$$specturm\_efficiency = \frac{(frequency\_slots \cdot time\_duration) - white\_spaces}{(frequency\_slots \cdot time\_duration)} \qquad \textbf{(IV-2)}$$

Another result that can be presented is the percentage of requests completed by each CRU. This result can be shown in a table and permits the user to know the efficiency of the system for each CRU.

The user simulation table let us show how the CRUs and their requests evolve during time. The rows are the frequency slots and the columns are the time slots. When the Next Time tab is pressed, a new time column appears with the cru id of the transmission in this specific time.

When we press the Show Graphic tab, the result is a pop up window that show us the distribution of the PUs, the CRUs and white spaces in the simulation. This means that is the output of the system or the transmission matrix. An example of this result is shown in Figure IV.7.
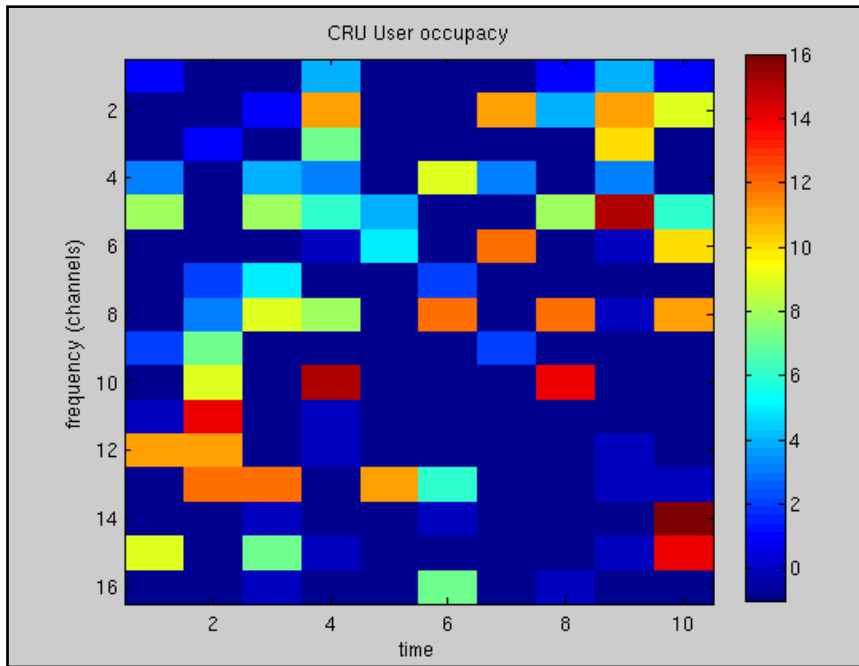
Figure IV.7 User interface graphic result when *Show Graphic* tab is pressed.

Finally, if we press Select User tab, a pop up window appears and let us to select one or more users. After that, the program graphically shows their behavior, meaning the evolution in time of the selected CRU requests.

Figure IV.8 shows an example of how to select different users and shows the result that is returned by the program.
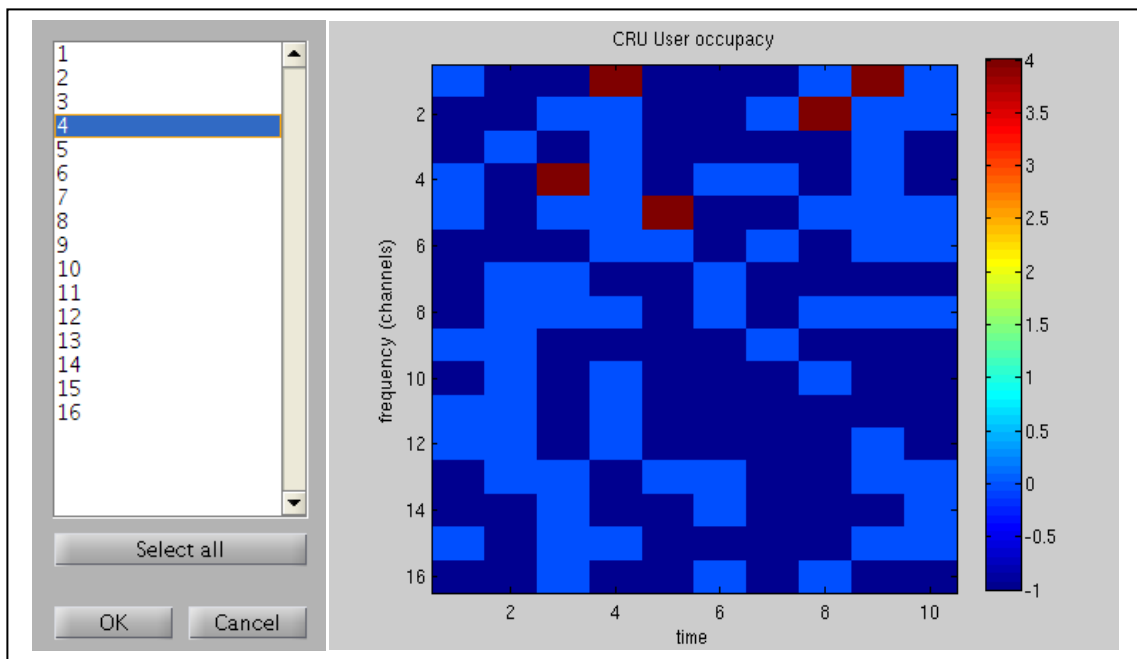

Figure IV.8 User interface results, selection to show user behavior

We can see that only the CRU 4, PUs with value of "-1" and white spaces with value 0 are shown.

Chapter V.   Matlab simulations and results

In this chapter we describe the simulations and results of the system. These simulations are performed under diverse scenarios specifying different options for the traffic and user characteristics. The main parameter that we are interest on is the efficiency of the system using the control algorithm explained in the previous sections. The efficiency of the system in our case is the percentage of completed requests divided by the total requests of CRUs in the system. The spectrum efficiency is also important when analyzing the strategy used for CRU assignation.

V.1 Random model simulations results

The first scenario that we simulate is the behavior of the system when all the distributions of traffic are random. To perform this simulation, we change some of both the global parameters and some specific random parameters to see the responses change.

### V.1.1 Random model behavior results

The first simulation that we perform is the graphical response of the system when the PUs and CRU time definition are randomly distributed with a random parameter value of 0.5. The CRU frequency definition is also randomly distributed and the random parameter value is equal to 0.5.

Figure V.1 shows the response of the system, in a graphic manner, of the simulation with ten CRUs and time duration of sixteen.
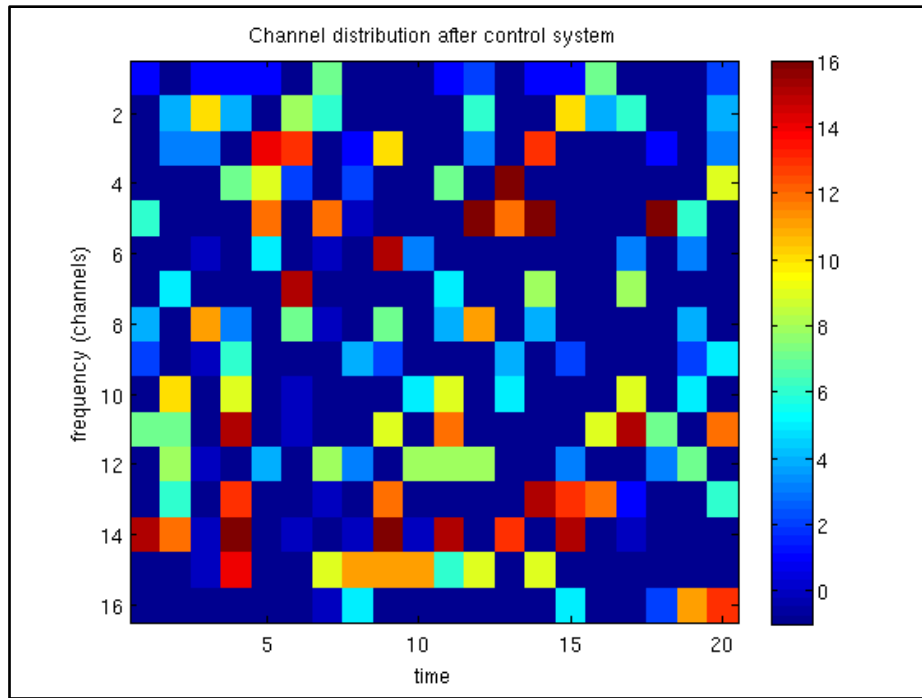
Figure V.1 Simulation result for random generation traffic with 16 PUs, 16 CRUs and 20 time slots

We could see that the graph shows how the PUs, CRUs and white spaces are distributed after applying the control algorithm to share the spectrum on opportunistic manner. The efficiency of the system in this case was 76.5 and the spectrum efficiency is 0.95. After that, we increase the number of available channels and CRUs in the network to 128. Time duration is also increased (100), to see the response of the system in a longer period of time. Figure V-2 shows the results of this simulation.
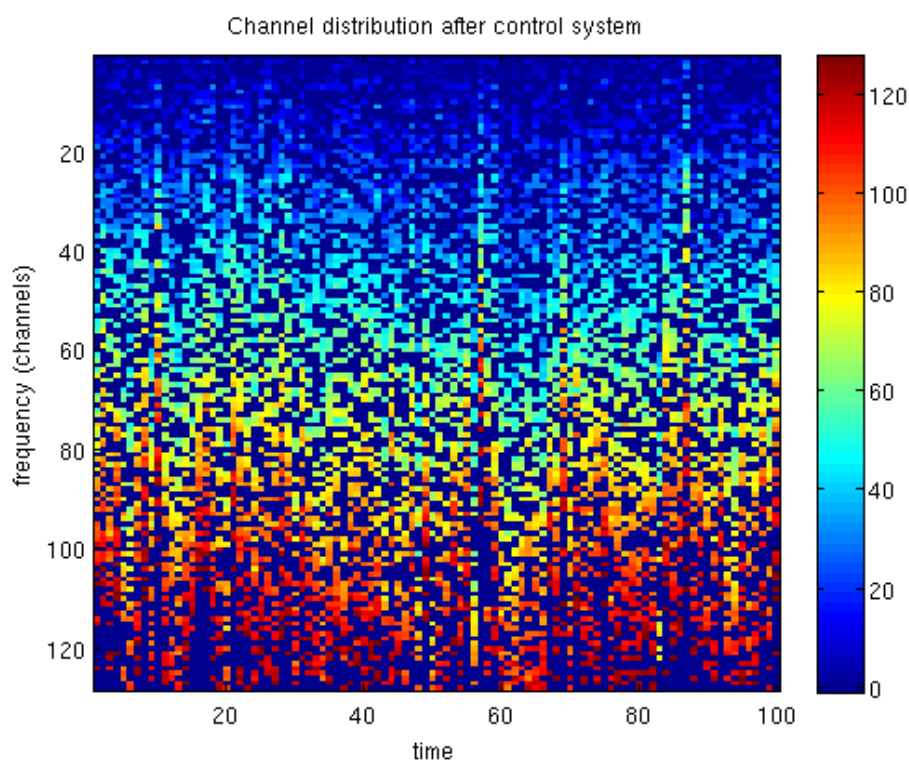
Figure V.2 Simulation result for random generation traffic with 128 PUs, 128 CRUs and 100 time slots

On Figure V.2 is shown the system behavior when we increase the number of frequency slots and also the CRUs. We can see in this case the strategy of assigning CRU to available frequencies. As we said in previous chapters, the first CRU that finds an available frequency slot will be assigned to transmit through that slot. As expected, we can see that the first CRUs in blue scale are assigned to the first frequencies while the higher CRU ids in red scale are assigned to the highest frequency slots. The efficiency in this case takes the value of 93.38 and the spectrum efficiency equal to 0.98.

For the next simulations, the global variables are fixed. The values of the global variables are 128 frequency slots, 100 CRUs and 100 time duration. The random traffic variables are modified to see the response of the system.

For the first set of the simulation, we modify the random parameter of the PU definition from 0 to 1, while the random parameter of both the CRU time definition and CRU frequency definition remains at 0.5.
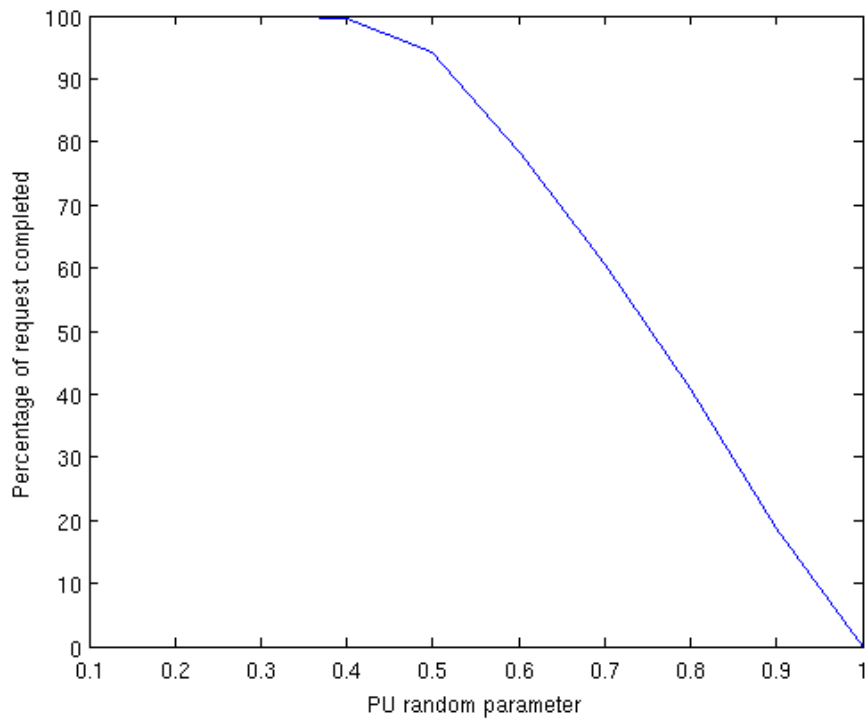
Figure V.3 Percentage of CRU request when PU random parameter changing

In Figure V.3, we can see that if the PU random parameter is low, i.e. means low PU presence, the percentage of completed CRU requests is close to 100 %. When the PU random parameter increases, i.e. more PU presence, the percentage of completed CRU requests decreases.
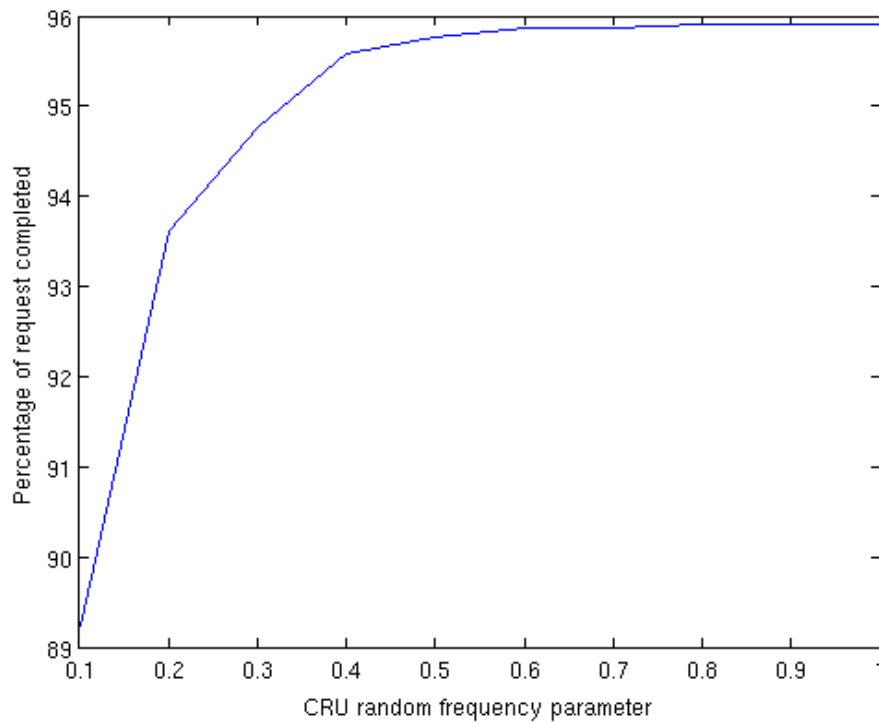
Now, we change the random parameter of CRU time definition, i.e. the distribution of the CRUs request in time, while the random parameter of PU definition and the random CRU frequency parameter remain at 0.5
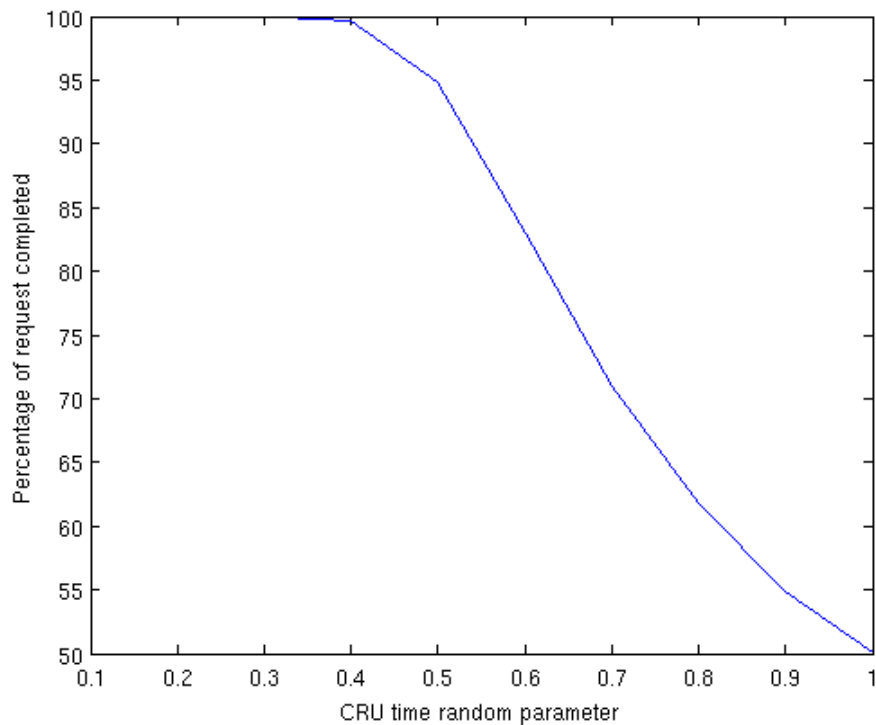
Figure V.4 Percentage of CRU request when random CRU time parameter changing

The same behavior as the previous case is observed in Figure V.4 if we change the random CRU time parameter. But in this case, when the value of the random parameter is 1, the percentage is at 50 %. This happens because the PU random parameter is fixed to 0.5, i.e. that exist 50 % of white spaces in the spectrum, while the random CRU time parameter at 1 means that all of the time the CRU would transmit. Considering that CRUs can only transmit through a white space, and the white spaces are 50 % of the spectrum, the best case scenario is to transmit into the 50 % of white spaces.

Finally, we let the random PU parameter and the random CRU time parameter to 0.5, while the random CRU frequency parameter is changing from 0 to 1.

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Figure V.5 Percentage of CRU request when random CRU frequency parameter changing

We can see in Figure V.5 that the percentage of CRU request when the random CRU frequency is changing is increasing until approximately 0.96. An increase on this parameter means that more frequencies are available for CRU transmissions. When this parameter is equal to 1, means that all the frequencies are available for all CRU.

V.1.2 Percentage of request and spectrum efficiency

Figure V.6 shows the evolution of the percentage of CRU requests completed in the system if we increase the CRU number, fixing the frequency slots to 128 and the definition of PU and CRU with random distribution and the random parameters to 0.5. The result is specified as completed transmit petitions by CRU among the total CRU petitions requests.
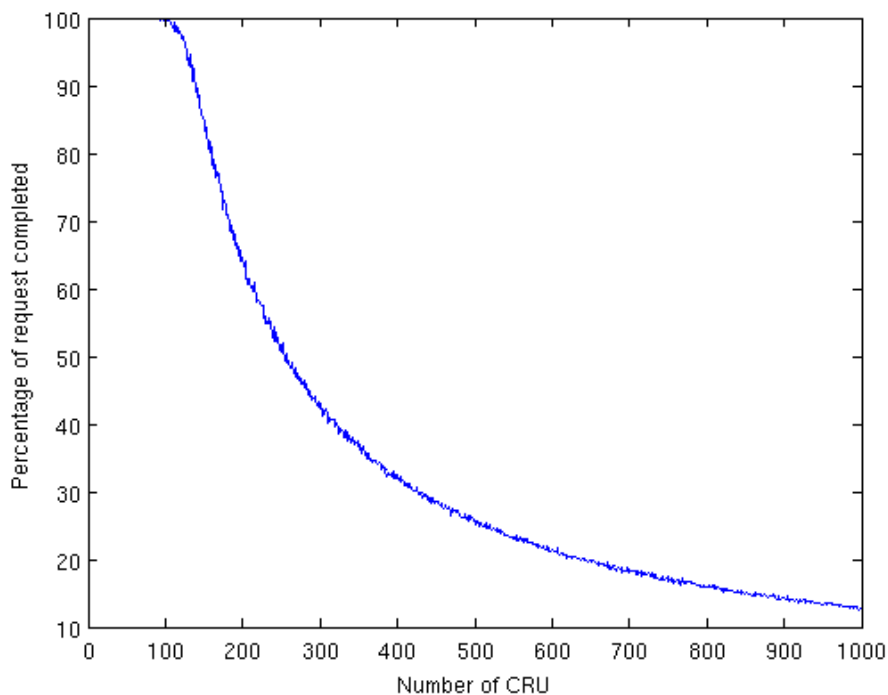
Figure V.6 Percentage of CRU requests completed when number of CRU is changing

As we can see, when the number of CRU is lower than the number of PU most of the requests of CRU can be processed and the percentage of the CRU request completed is close to 1. When the number of CRU is approximately at 0.75 of the PU, the percentage begins to decrease. When the CRU is equal to the number of PU, the percentage takes a value around 95 %. When the number of CRU increases above the number of PU, the percentage drastically decreases.

The percentage of CRU requests completed could be increased if the strategy of assigning the CRU to frequencies is different or the strategy considers memory. This means that if a CRU that request to transmit does not have an available frequency in the specified time slot of the request, the system could queue this request until an available frequency slot could be assigned on the next time slots. This becomes an improvement of the strategy of assigning frequencies to a CRU that will be study for further work.

Figure V.7 shows the spectrum efficiency of the system when the number of CRU is changed from 1 to 1000.
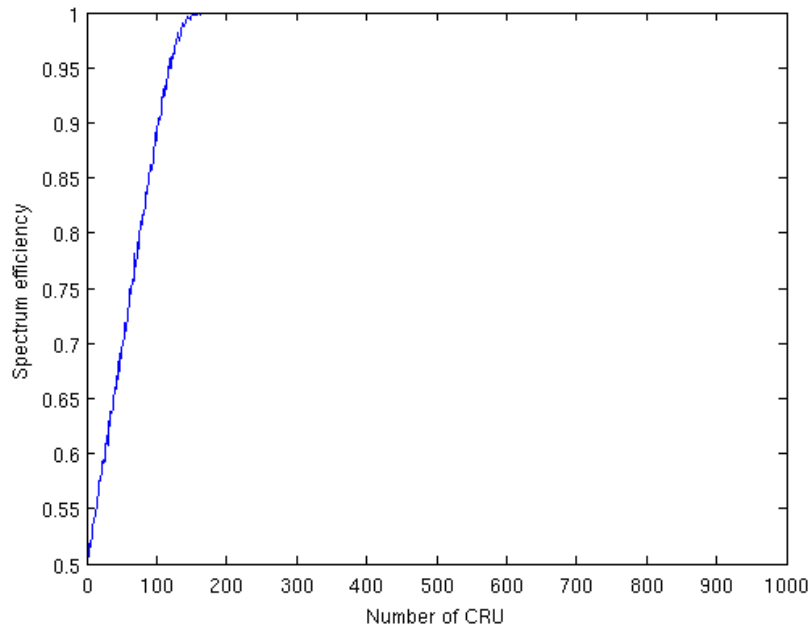
Figure V.7 Spectrum efficiency with random model distribution when the number of CRU is changing

We can see that the spectrum efficiency when the number of CRU is equal to 1 is about 50% because the PU is occupying the 50% of the spectrum and only 1 CRU is requesting to transmit. This occupancy is due to the PU random parameter that is 0.5, which means that the 50 % of the spectrum is occupied by PU.

When the number of CRU increases, the white spaces are reduced and the spectrum efficiency increases because these white spaces are filled with the CRU requests.

Looking at the percentage of CRU request completed and the spectrum efficiency, there is a region in which both the percentage of CRU request completed and the spectrum efficiency are high. This zone is comprised when the CRU number is among 80 and 130; this could be considered as the best performance region of the system for the PU and CRU traffic specification.

V.2 Distribution model simulation results

In this section we show the results of the simulations when the input traffic of PUs and CRUs are modeled by the specific distribution model explained in section IV.1.3, and a frequency band model distribution for CRU frequency definition explained in section IV.1.4. The organization of the results is the same as in the previous section, so we begin with the behavior results and finally the efficiency results.

V.2.1 Distribution model behavior results

In this case, the distribution model for PU definition and CRU time definition are fixed to 0.1 for mean arrival time and 8 for the duration of the interval in the distribution parameters. Also, the selected CRU frequency definition model is the band model with 8 frequency slots/band and the random assignation parameter of 0.3.

Figure V.8 shows the behavior of the system when a specific distribution is applied for 16 frequency slots or number of PUs, the number of CRU is fixed to 16, and the time duration is 20.
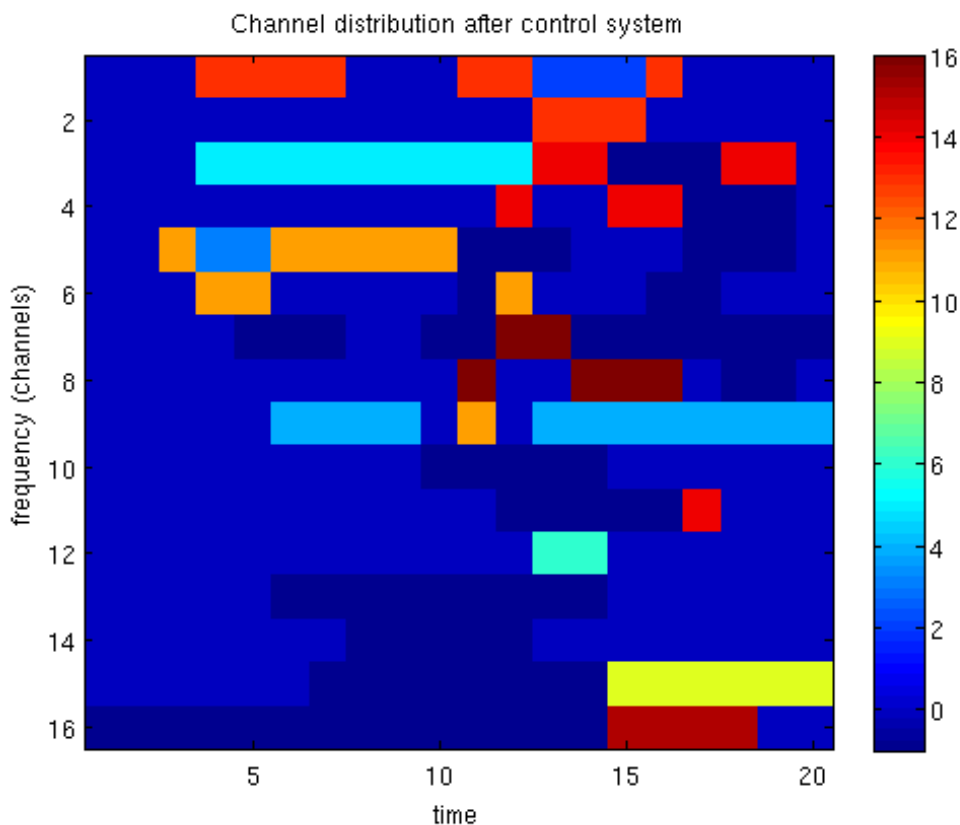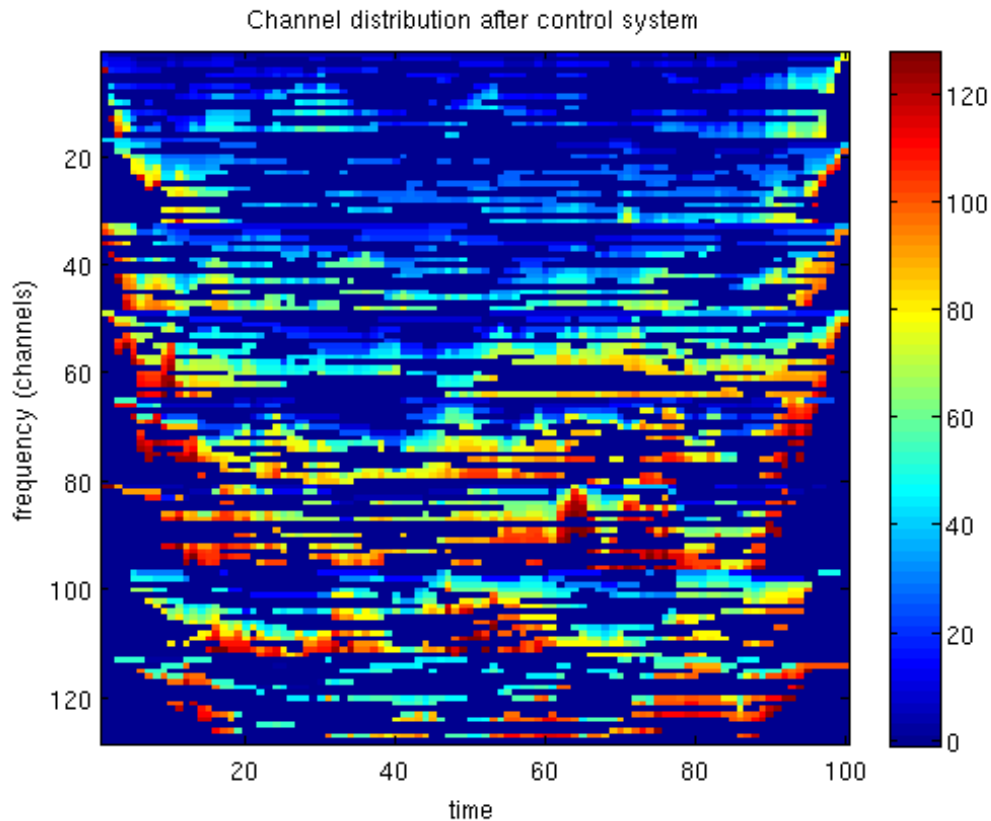

Figure V.8 Simulation result for distributed model generation traffic with 16 PUs, 16 CRUs and 20 time slots

We can see that applying this distribution, transmissions present longer durations. This is a more realistic approach. In this case, the efficiency is lower than using a totally random definition and its value for this particular case is 73.46. The efficiency of the spectrum is also lower at approximately 0.45.

Figure V.9 Simulation result for distributed model generation traffic with 128 PUs, 128 CRUs and 100 time slots

The system behavior if we increase the number of frequency slots up to 128, the number of CRU of 128 and the time duration of 100, is shown in Figure V.9. The value of the percentage of the CRU request completed is 73.11 and the spectrum efficiency of 0.9266.

The next simulations that present are based on the study of the behavior of the system when we fix the global variables, but we modify the specific parameters of the PU and CRU time distribution model definition.

First, we change the mean arrival time parameter, from 0.01 to 1 with an increment of 0.01, while the mean duration value is 4 time slots. The CRU time definitions remain fixed with mean arrival time of 0.1 and mean duration of 6 time slots. Figure V.10 shows how the percentage of CRU request completed change.
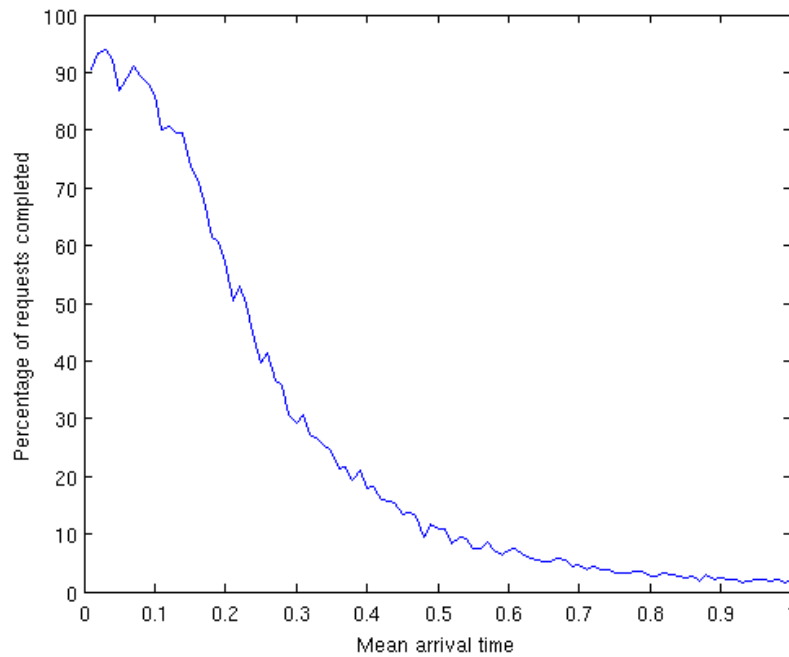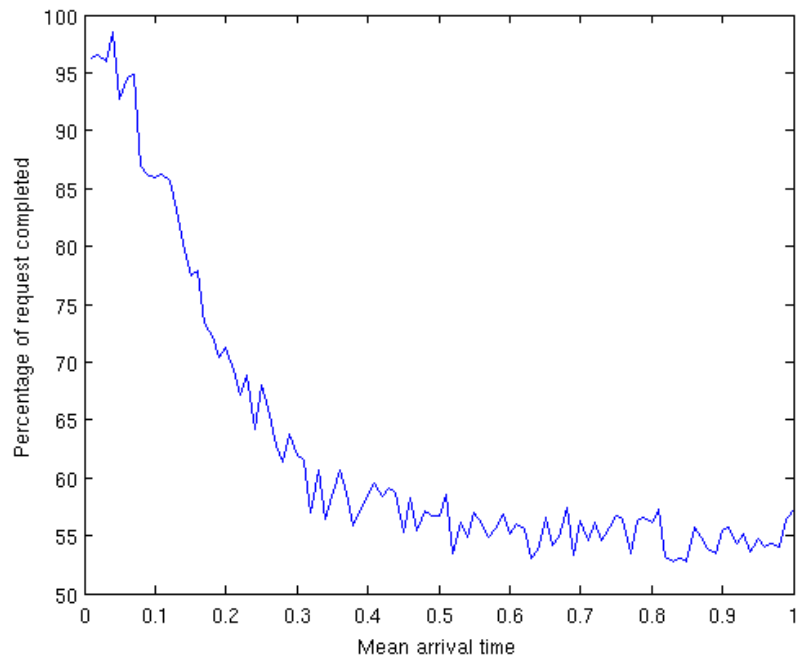
Figure V.10 Percentage of CRU request completed when PU mean arrival parameter is changing

In Figure V.10 we can see that the percentage of requests completed decrease when the mean arrival increase. This happens because an increment of mean arrival time in PU definition produce an increase of PUs, so lower white spaces are able to be occupied by CRUs.

If we perform the previous simulation but changing the PU mean duration parameter of the distribution model, the result is the same. When the mean duration is increased, most part of the spectrum is occupied by PUs and the transmissions of CRU cannot be performed; as a consequence, the CRU request completed decreases.

The next result that we present is how the response of the system is when the CRU time definition parameters are changing. We begin modifying the mean arrival time parameter of the CRU request. Figure V.11 shows this behavior.

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Figure V.11 Percentage of CRU request completed when CRU mean arrival parameter is changing.

We can see that when the mean arrival time parameter is increasing, the percentage of the request completed decreases. This is due to the increase of the total number of requests when the mean arrival time increases.

If we change the other parameter for CRU definition, the mean duration time, the behavior of the percentage of CRU request completed is the same: when the mean duration time increases, the percentage of CRU request completed decreases.

In the next lines, we study the difference in the system if the frequency distribution is based on random frequency model or based on band frequency model, with the same PU definition and also the same CRU time definition. Figure V.12 shows these differences in a graphical behavior with 128 frequency slots, 128 CRU and 100 time duration simulations variables.
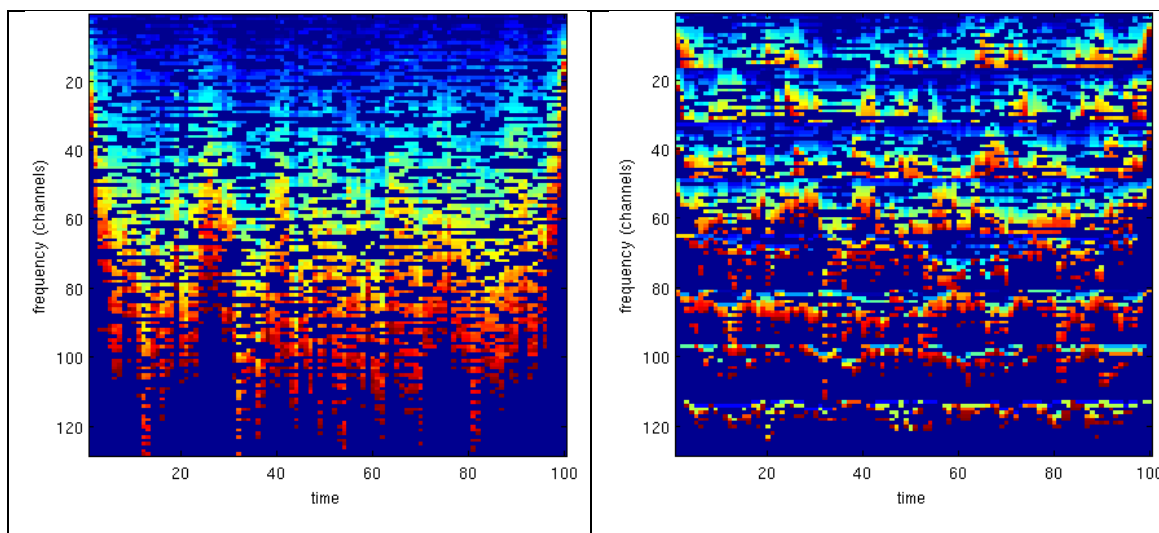
Figure V.12 a) CRU random frequency distribution selection. b) CRU band frequency distribution.

The frequency random distribution parameter of Figure V.12 a is 0.3 while the band frequency distribution variables for the simulations in Figure V.12 b are 8 bands of work to share randomly to the CRU and 128 frequency slots, so the frequency slots/band value is 16 and assigned randomly with parameter of value 0.3.

We can see in Figure V.12b how the bands are defined, for example the first band that goes from 1 to 16 is shown and the graphical composition changes. These is due to the specification of the band frequency distribution, because the CRU have some frequency values to choose from in their assigned frequency bands, and only these frequency slots could be used by the CRU to transmit its requests.

The strategy of assigning CRUs to the white spaces is the same, so the first CRU that could use the available frequency fit this frequency slot to transmit. So the degradation is maintained, meaning that the first CRU id are assigned firstly (to the first frequencies) while higher CRU ids are assigned to higher frequencies.

If we consider the percentage of CRU requests completed, the higher value is for the random frequency distribution with a value of 99.56 while using the band frequency model the request completed are 92.05 %. The spectrum efficiency for the first case is 86.85 and for band frequency distribution is 0.833.

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V.2.2 Percentage of request and spectrum efficiency

This section describes the results obtained from the point of view of the percentage of CRU requests completed and the spectrum efficiency when the distribution model is selected with specific values of 0.1 for mean arrival time and value of 8 time slots for the mean duration time, for both the PU definition and CRU time definition. A frequency band model is selected and fixed to 8 frequency slots/band and the random parameter of 0.3.

Figure V.13 shows the evolution of the percentage of CRU requests completed when the value of number of CRU is changing from 1 to 500.
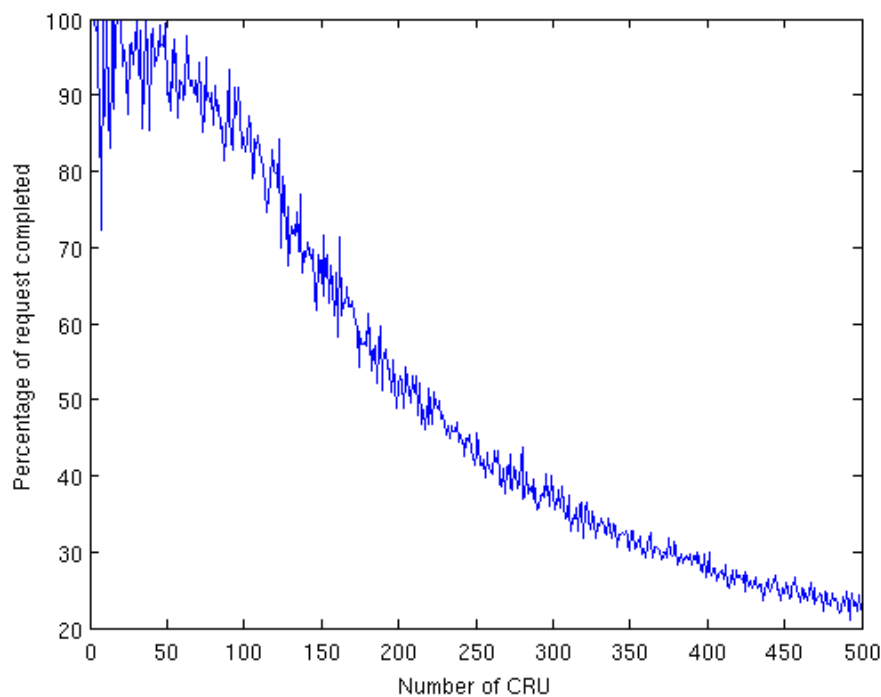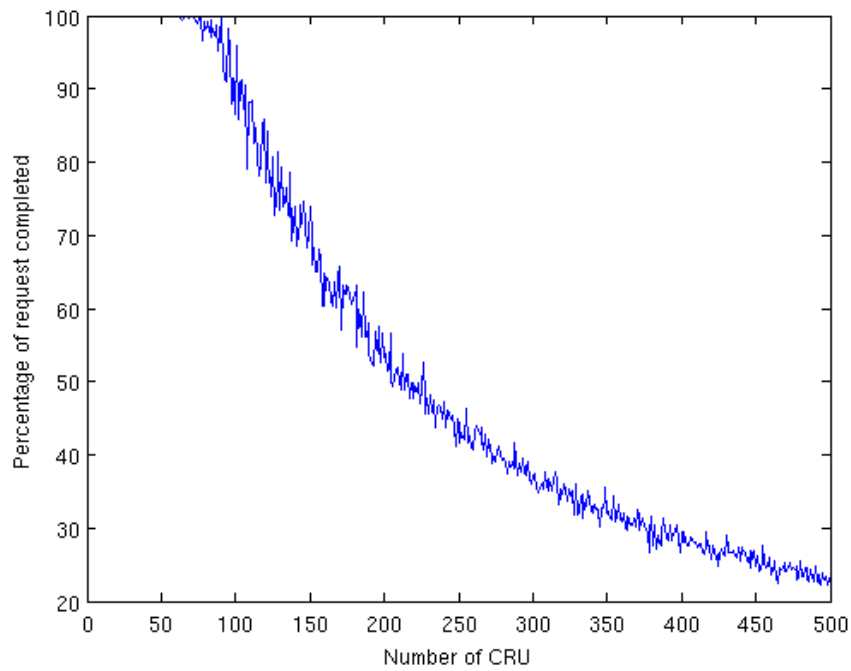

Figure V.13 Percentage of CRU request completed in distribution model when number of CRU is changing

In the distribution model case, the percentage of request when the number of CRUs is below the number of PU (or the number of frequency slots) is lower than in the random model. This happens because in the distribution model the requests of the PUs and CRUs have more duration in time and the frequency distribution restricts more the CRU utilization compared to the random case.
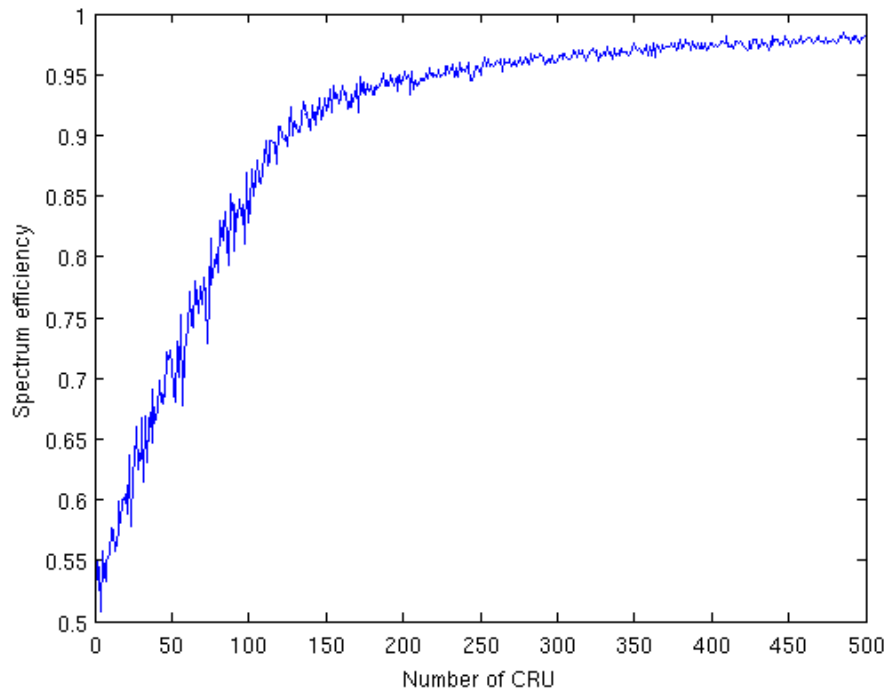
If we analyze the results when the CRU frequency definition is random, we obtain the result shown in the Figure V.14.

Figure V.14 Percentage of CRU request with distribution model for PU and CRU time definition and random model for CRU frequency definition

In this case we see that the CRU random frequency model increases the linearity of CRU request completed and when the number of CRU are below of the PUs or frequency slots the percentage is better and continuously close to 100 % compared to the abrupt changes in the band frequency model (Figure V.13 Percentage of CRU request completed in distribution model when number of CRU is changing). The spectrum efficiency of the same simulation is shown in Figure V.15.

Figure V.15Spectrum efficiency of CRU request completed in distribution model when number of CRU is changing

We see that the spectrum efficiency increase when the number of CRU increases. This result was expected because more CRU means that the spectrum is more occupied and the white spaces are reduced by the CRU requests. The same result is obtained when the CRU frequency definition is random.

If we analyze the results of the spectrum efficiency and the percentage of CRU request completed, we see that when the number of CRU is almost the number of PU or frequency slots, we obtain the best spectrum efficiency and the best percentage of CRU request completed. The region where the system has the best performance is when the CRU number is among 80 and 130 CRUs.

Chapter VI. Conclusions

In this project, we studied the basics of Cognitive Radio Networks, which is an actual under study telecommunications technology considered for efficiently sharing the wireless spectrum. The specific model studied, the Centralized Cognitive Radio Network with distributed control, plans to include different wireless technologies into the same CRN using CPCs for controlling the network.

The control algorithm that we study in this project shows that using a simple strategy to share the spectrum along the CRUs, without memory and assigning the frequency available to the first user in a priority-based system, contributes to increase the spectrum efficiency.

In this case, the CRU transmission efficiency is also good. Approximately 95 % of the CRU requests are completed when the relation of CRU requests with respect to the number PUs or frequency slots is about 75 %. When the CRU number begins to increase over the number of PUs, the efficiency of the system decreases as expected. These percentages would be better if the strategy of assigning frequencies to the CRUs allows memory, i.e. that the CRUs could wait some time slots for an available frequency to transmit the request if there are no frequency slots available for them in a specific time slot.

Personally, the experience to work with Nicolas Bolívar as an advisor of the project was amazing and the cooperation and collaboration between his PhD thesis work and my project was fantastic. The collaboration from the Universitat de Girona and, specifically the BCDS group and their director, José Luis Marzo, was also very rewarding.

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Chapter VII. Future work

In this final chapter, we remark the future works considered at the end of this project.

- For a complete analysis of the Centralized Cognitive Radio Network model, we need to integrate the modules that are not contemplated in this project to the simulator.

- In this project, two main types of PU definition and CRU definition were applied: a random and a specific distribution. For research purposes, the study of the behavior of new types of traffic and frequency distributions that fits the different standards that are currently available in Wireless telecommunication devices would be interesting.

- To increase the efficiency of the system, different algorithms for the assignation of CRUs to white spaces should be considered. Another improvement for the efficiency is to introduce algorithms that allow to queue in memory the requests and serve these petitions in different time instants.

- A method on how to sense the spectrum is also needed to allow the control algorithm to properly share the spectrum among the CRUs without affecting the PUs.

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