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Power Allocation In Cognitive Radio

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Problem Description

One of the major challenges in design of wireless networks is the use of the frequency spectrum. Numerous studies on spectrum utilization (by FCC in the USA) show that 70% of the allocated spectrum is in fact not utilized. This discrepancy between allocation and usage provides the motivation for opportunistic use of the spectrum, giving rise to the concept of Cognitive Radio (CR). The basic idea here is that in a licensed frequency band, some unlicensed (secondary) users are permitted to operate without causing interference to the licensed (primary) user. Thus, the CR link intelligently detects the usage of a frequency segment in the radio spectrum, and jumps into any temporarily unused spectrum rapidly without interfering with communication between primary users. Use of power control is one efficient way to increase the sum capacity of the network by allowing secondary users to enter the network, and intelligently controlling their power transmissions in order to make sure that the primary users are unaffected. CR is currently a hot research area worldwide, and the aim of this project is to contribute to the research within this domain in order to provide more efficient use of the spectrum resources available. Matlab simulations will be performed to validate the obtained results.

Assignment given: 15. January 2008
Supervisor: Geir Egil Øien, IET

Acknowledgments

The report we are presenting here is the result of our Master Thesis work for the Universidad Politécnica de Valencia (UPV). We have carried out all our work in the Department of electronics and Telecommunications of the Norwegian University of Science and Technology (NTNU). We would like to thank this university for providing us the opportunity of living the great experience of a year in Trondheim, a city that has welcomed us with open arms. Also for providing us the necessary resources for the consecution of this Master Thesis, with which we have learnt a lot about the world of Wireless communications.

Special mention to our supervisors, Mariam Kaynia and Geir Øien, for their guidance, support and patience along the way.

We can not forget in this section our " second families", our friends in both Valencia and Trondheim. They have been really important in these past years, going through either good or bad situations. Without all of them, probably we would not be here now, and they are the most esteemed thing we will etch in our minds for the rest of our lives.

Finally we would like to thank our parents for their, and we can not emphasize this enough, endless support during our whole lives. Thanks to them we are what we are nowadays.

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Abstract

One of the major challenges in design of wireless networks is the use of the frequency spectrum. Numerous studies on spectrum utilization show that 70% of the allocated spectrum is in fact not utilized. This guides researchers to think about better ways for using the spectrum, giving rise to the concept of Cognitive Radio (CR).

Maybe one of the main goals when designing a CR system is to achieve the best way of deciding when a user should be active and when not. In this thesis, the performance of Binary Power Allocation protocol is deeply analyzed under different conditions for a defined network. The main metric used is probability of outage, studying the behavior of the system for a wide range of values for different transmission parameters such as rate, outage probability constraints, protection radius, power ratio and maximum transmission power.

All the studies will be performed with a network in which we have only one Primary User for each cell, communicating with a Base Station. This user will share this cell with N potential secondary users, randomly distributed in space, communicating with their respective secondary receivers, from which only M will be allowed to transmit according to the Binary Control Power protocol.

In order to widely analyze the system and guide the reader to a better comprehension of its behavior, different considerations are taken. Firstly an ideal model with no error in the channel information acquisition and random switching "off" of the user is presented. Secondly, we will try to improve the behavior of the system by developing some different methods in the decision of dropping a user when it is resulting harmful for the primary user communication. Besides this, more realistic approaches of the channel state information are performed, including Log-normal and Gaussian error distributions. Methods and modifications used to reach the obtained analytical results are presented in detail, and these results are followed by simulation performances. Some results that do

not accord with theoretical expectations are also presented and commented, in order to open further ways of developing and researching.

Contents

List of Figures

Nomenclature

ATC	Air Traffic Control
BPA	Binary Power Allocation
BPC	Binary Power Control
BS	Base Station
CPE	Customer Premises Equipment
CR	Cognitive Radio
CRS	Cognitive Radio System
CS	Cognitive System
CSI	Channel State Information
DFS	Dynamic Frequency Selection
IR	Interference Requirement
ISP	Intelligent Signal Processing
LE	Licence Exempt
MAC	Medium Access Control
NTNU	Norwegian University of Science and Technology
Ofcom	Office of communications. Regulator for UK communications
OSI	Open System Interconnection
QoS	Quality of Service

SDR	Software Defined Radio
SL	Secondary Licensed
UPV	Universidad Politécnica de Valencia
WiMax	Worlwide Interoperability for Microwave Access

Chapter 1

Introduction

Since mobile communications are nowadays widely used, radio spectrum scarcity has become an important issue in the research of new technologies and protocol designs. Current research is focusing on a more efficient use of the spectrum since only a small percentage is in fact being used (actual measurements show that more than 70% of the spectrum is unused [14]), as it can be seen in Fig. 1.1.

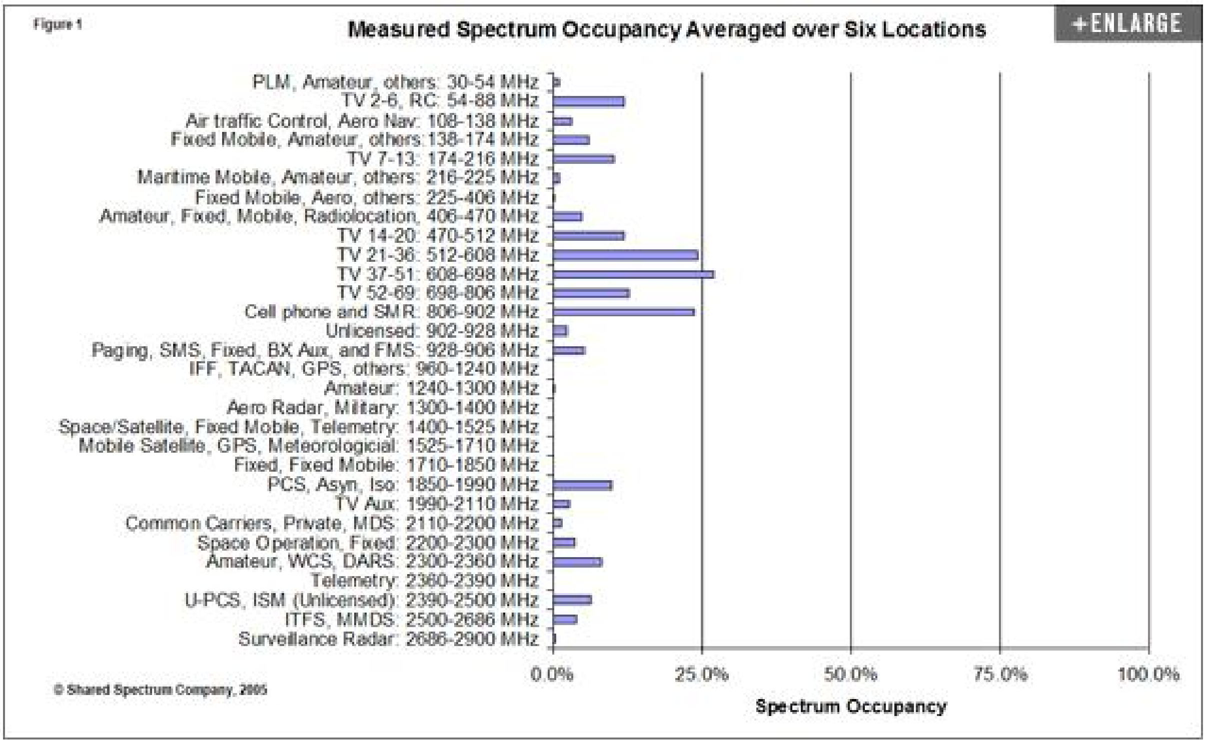

Figure 1.1: Spectrum availability by band averaged over the six locations of different characteristics around the USA.

Cognitive Radio Networks basically consist of ad-hoc networks, formed by several nodes (either transmitting or receiving) randomly distributed in space, able to perform simultaneously with a main licensed system and using the same spectrum without being harmful to that primary system. This obviously leads to a better way of using the radio spectrum since two systems can use the same resource.

On one hand, these CRNs present advantages such as fast deployment and reconfiguration, no installation and maintenance cost, and they achieve robustness due to the structure of these networks and their node redundancy. On the other hand, the fact of being unlicensed systems causes that they always perform underneath a primary (licensed) system.

One of the great challenges to face while designing CRNs is finding a proper MAC level solution so that both primary and secondary systems can co-operate in such a way that none of them is harmful to the other.

By having a deep knowledge of the different performing metrics of the system, the MAC layer can be designed bearing in mind some goals related to these metrics such as QoS, outage probability[1], capacity, etc

1.1 Problem Statement

In spite of the existence of some works related to cognitive radio like [14, 4, 5, 10, 12], and more specifically about binary power allocation, like [2] and [16], many aspects of the behaviour of these systems are still incomplete. Following the ideas and principles of [2], it could be important to get to a better comprehension of the behaviour of the system by carrying out some simulations with different fundamental parameters for the communication.

In this research, they propose a distributed cognitive radio coordination that maximizes the CRN sum rate while minimizing the interference to the primary users (PU). They achieve a primary-secondary system spectrum sharing by optimally allocating secondary users' (SU) transmit powers in order to maximize the total SU throughput under

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[1] *The probability that the required level of QoS (rate, range,...) can not be offered*

interference and noise impairments, and short term (minimum and peak) power constraints, while preserving the Quality of Service (QoS) of the primary system. The scenario in where it is developed has one PU, communicating with a primary receiver (PR) and an indefinite number of potential SUs that are allowed whether to transmit or not, depending on some operation constraints previously established for the primary user.

In relation to give the reader a more accurate comprehension of the binary control system, it is important to make all the performances in a more realistic scenario. In order to achieve this and seizing the work developed in [16], it is important to observe and analyze the behaviour of the system when some real factors, such us information acquisition imperfectness, enters in scene.

Apart from the wide analysis of the behaviour of the binary power control system, there are some important issues that are still unsolved. Based on the information taken from [2], and following its principles and ideas, as we said before, a possible improvement could be achieved if we are able to find the optimal way of deciding the SU that should be switched "off" when this action is necessary for the proper performance of the system. Since in the studies mentioned before the users are switched "off" randomly, we consider that implementing some different ways of deciding how to drop users could guide us to those better results we are looking for, and so we will do as our main goal in this Thesis in order to contribute to improve this field of action in cognitive radio systems.

1.2 Structure And Goal Of This Thesis

Since we need to achieve a better comprehension of the behaviour of the protocol under analysis, this report contains simulations with several parameters that can affect and define its behaviour.

Although the model still contains some simplifications in order to allow for the mathematical analysis to be carried out, these simplifications and assumptions will be justified and ,when needed, it will be shown through simulations that they do not affect the final results significantly, and that they are indeed reasonable.

This Thesis is structured as follows. Firstly, we will introduce the reader to some important and basic concepts related to cognitive radio and wireless systems, as well as presenting a general explanation of the binary power allocation algorithm. Secondly, we will describe the scenario in where this algorithm is applied. Thirdly we will present our results of the behaviour of the system by using different parameter modifications, thing that will guide us to a better comprehension of the original algorithm. Besides this, we will present our improvements to the original algorithm, which consists on a proper choice of the user who is dropped, dealing with different considerations, such as interference mitigation and capacity maximization. Up to this point, we have not considered channel information imperfectness, so from now on, we will introduce a new channel model, including error in the original algorithm, which will give our studies a more realistic point of view. Finally, explanations for all the results presented are given.

Chapter 2

Background And Related Work

2.1 Cognitive Radio Networks

Most of today's radio systems are not aware of their radio spectrum environment and operate in a specific frequency band using a specific spectrum access system. Investigations of spectrum utilisation indicate that not all the spectrum is used, as we saw in Fig. 1.1. A radio, therefore, that can sense and understand its local radio spectrum environment, to identify temporarily vacant spectrum and use it, has the potential to provide higher bandwidth services, increase spectrum efficiency and minimise the need for centralised spectrum management. This could be achieved by a radio that can make fast and autonomous decisions about its accesses to the spectrum. In this context, cognitive radio appears.

Such concepts are really well expressed in the definitions of cognitive radio given by two of the most renown researchers on this topic, Joseph Mitola and Simon Haykin, respectively.

"A radio that employs model based reasoning to achieve a specified level of competence in radio-related domains" [5].

"An intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier frequency, and modulation strategy) in real-time, with two

primary objectives in mind: (i.) highly reliable communication whenever and wherever needed and (ii.) efficient utilization of the radio spectrum" [4].

2.1.1 Definition Of Cognitive Radio

CR is the fusion of software defined radio (SDR) and intelligent signal processing (ISP). Main concepts of ISP and SDR have been investigated by researchers since the 1960s, with the most significant contributions being compiled in [23].

Combining the facets of radio flexibility, intelligence and spectral awareness, a full CR will adapt itself to changes in the environment, its user's requirements and the requirements of other radio users sharing the spectrum. Further researches will maybe lead us to the concept that Joseph Mitola called full CR, which will use long-term analysis to learn about its environment and adapt its own behavior to this knowledge.

CR implies ISP implementation at the physical layer of a wireless system. If we want to implement a full CR, it is clear that, as it is shown in Fig. 2.1, it has to have influence in all the 7 OSI layers. Ideally all seven layers need to be flexible if the CR's intelligence is to be fully exploited. Without optimization of all the layers, spectrum efficiency gains may not be optimized. This level of complexity, required for the full (Mitola) CR, may not be achievable for many years, we can say that it is utopian nowadays.

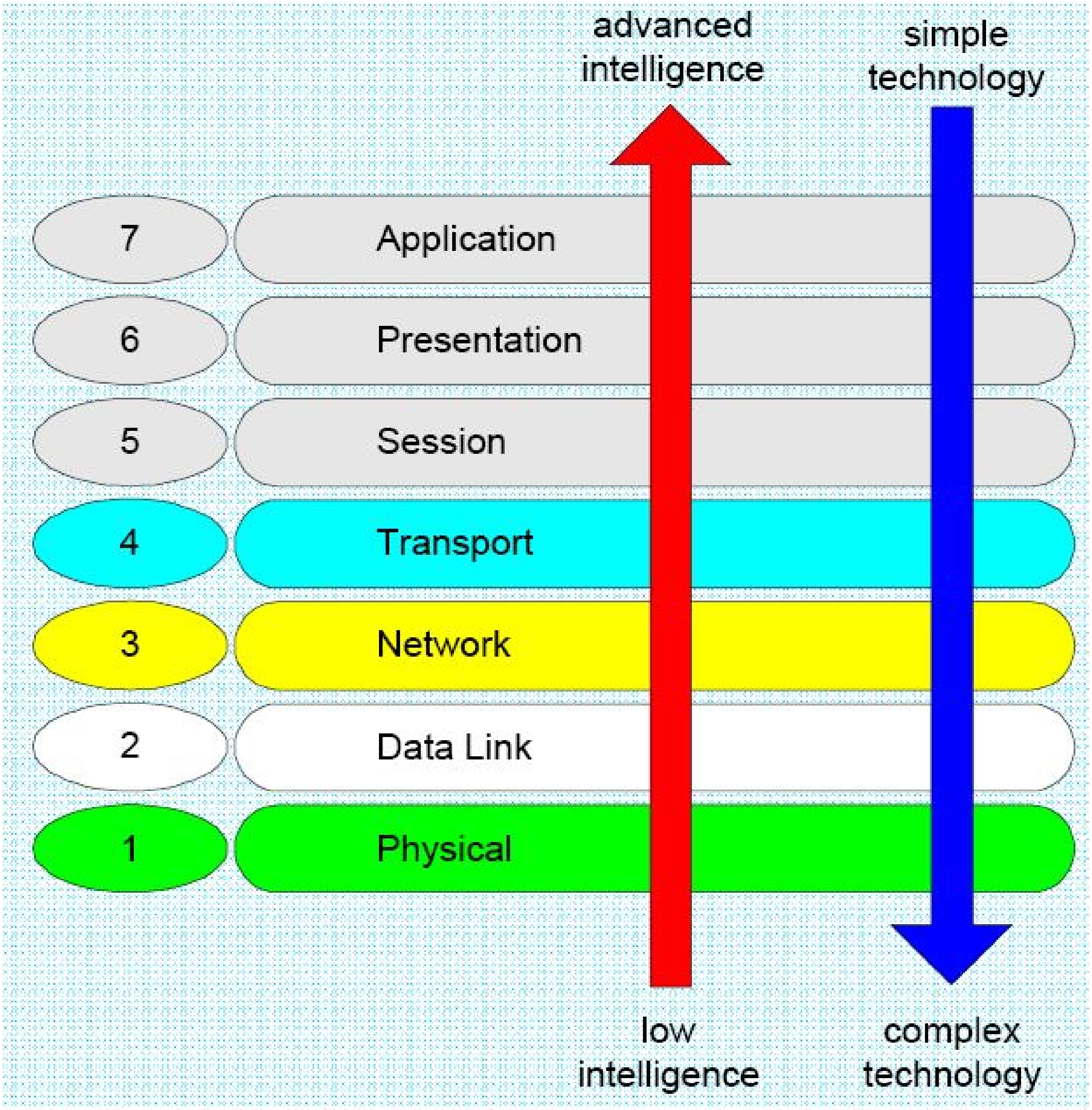


Figure 2.1: Complexity of ISP and Technology through the OSI Layers. For an optimized CR, intelligence and reconfigurability at all layers is ideally required.

2.1.2 Key Applications For CR And Its Spectrum Utilization

To go on with an introduction of a CR system, it is important to analyze potential applications of it as well as the potential bands where this systems could be deployed.

For this purpose we will focus in the results of an important reunion [39], which was held with various stakeholders including mobile service providers, manufacturers, cademics, Air Traffic Control (ATC) radar operators and regulators (MoD, Ofcom). There, it was highlighted that, for CR systems that are secondary users of the spectrum and need to coexist with primary systems, non-time sensitive services, could be more appropriate, due to some problems that could appear, such as hidden node, which will be properly explained in section 2.1.4.

After analysing economical and reliability resources, four promising applications were identified:

- Mobile multimedia downloads (for example, download of music/video files to portable players) which require moderate data rates and near-ubiquitous coverage.
- Emergency communications services that require a moderate data rate and localised coverage.
- Broadband wireless networking (for example, using nomadic laptops), which needs high data rates, but where users may be satisfied with localised "hot spot" services.
- Multimedia wireless networking services (e.g. audio/video distribution within homes) requiring high data rates.

After finding proper applications in where CR could be developed, it is important to check if they are realisable in practice. Because of this it is important to analyse the different bands in where this applications could be developed.

Spectrum activity in the analogue land mobile radio (e.g. between 148 – 470MHz), is considered to be low and has the advantage that base station locations are known and contemporary receivers are robust against interference, since they have short values of frequency in the spectrum.

The Digital Video Broadcasting-Terrestrial (DVB-T) band has a large amount of spectrum potentially available (e.g. bands 300–1000 MHz) and receivers are also reasonably robust against interference. Interleaved spectrum would enable wide coverage of CR services in this band. Maybe one of the most immediate applications that can come to the mind of the reader is Radar systems since we can affirm that they consume a considerable amount of spectrum in a intermittent manner. Because of their operation mode, radars may only point in one direction at a time. This could lead us to think that a lot of spectrum is wasted while using this service.

The 802.16 WiMax family of standards operates over a wide range of frequencies known as the Fixed Wireless Access Spectrum (e.g. between 2000 – 11000 MHz). Maybe the best characteristic of this band, apart from its robustness against interference, is that WiMax base stations and CPEs are geographically fixed. Then, a database of locations could provide a CR with WiMax base station and device locations. The CR could then listen to determine which specific channels were in use. As a conclusion, we have to say that CR is an emergent technology that is not still fully developed, and the application founds are according with this delay. This guides us to think that additional applications will be constantly emerge as CR technologies develop.

2.1.3 Advantages Of CR

It is clear that the main advantage of a CS is the spectrum efficiency gain achieved by sharing spectrum or using the spectrum opportunistically. CR could also reduce the need for centralised spectrum management.

While more and more companies are getting in the world of the wireless communications, they realise that the traditional spectrum management is obsolete, according to [39]. This guides to the creation of a new market-based approach using spectrum trading and spectrum liberalisation concepts.

The versatility of CR, with its potential for dynamic spectrum access, is a promising technology enabler which, alongside other regulatory mechanisms, could be used to allow the dynamic trading and usage of spectrum.

Another benefit, that at first glance is not so clear is, specially for regulation organisms, that CRs could be programmed to manage their own spectrum access using appropriate regulatory policies, as part of a CR configuration management practice. Service providers and spectrum owners would also benefit in theory from the improved spectrum efficiency enabled by CR.

Dealing again with economic markets, CRs are a great opportunity for new service providers and existing service providers to grow their businesses without being limited by the potential lack of spectrum, since secondary users can make opportunistic use of certain bands of spectrum. CR users could benefit from improved QoS compared to fixed frequency radio users.

Provided the CR spectrum pool is sufficiently large, the probability of all frequencies in the pool being occupied will be vanishingly small.

All the changes that are needed for adapting the environment to the new technologies, will guide equipment manufacturers to have the opportunity to create new markets for new equipment and benefit from reduced production costs, etc. From a regulatory perspective, changes in spectrum usage or policy could be implemented through software updates, which are much more simple that the actual process.

2.1.4 Key Challenges Of CR

As well as significant advantages of CR, there are several key challenges. Ideally a CR should have no impact on other radio users, but in reality some impact is expected, particularly on non-cognitive legacy radio users. Maybe the worst disadvantage of a CR system is that it is difficult to predict and control the spectrum behaviour. At present time, the main efforts of the researchers are focused on the hidden node problem. This situation arises when a CR is unable to detect all of the radios with which it might interfere, not because its own spectrum sensing is ineffective, but because some radios are hidden from it as shown in Fig. 2.2. Although techniques can be used to reduce the risks of interference with a hidden node, there is not complete solution that properly addresses all situations where the hidden node problem might occur.

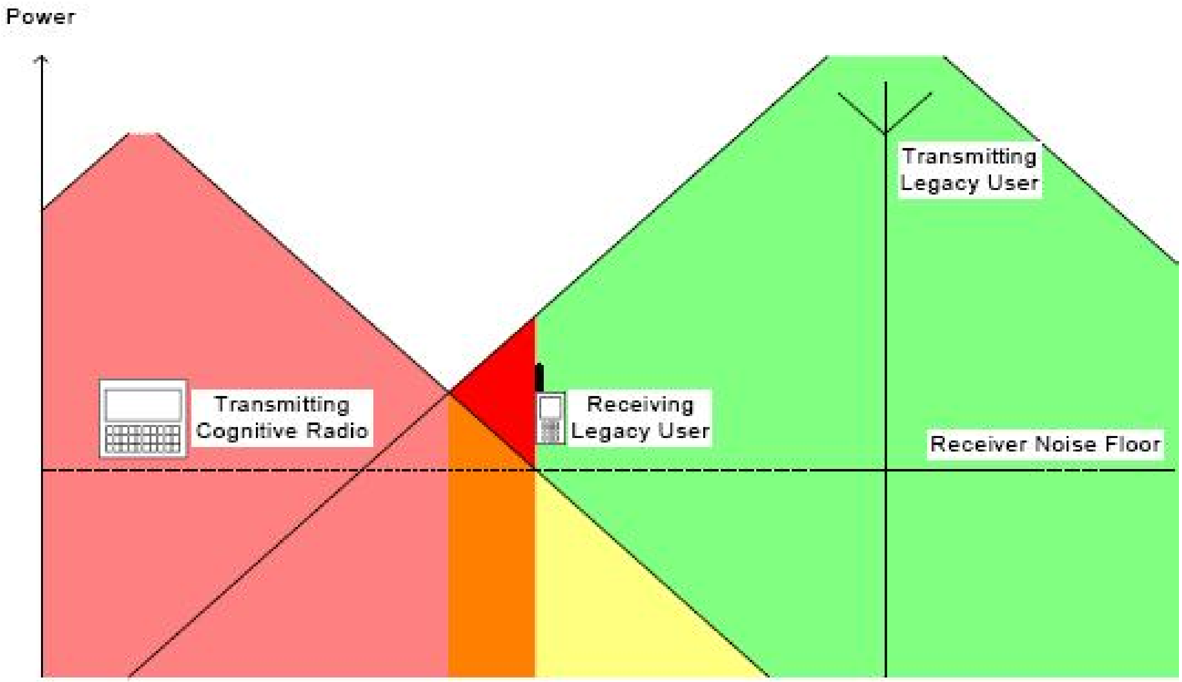
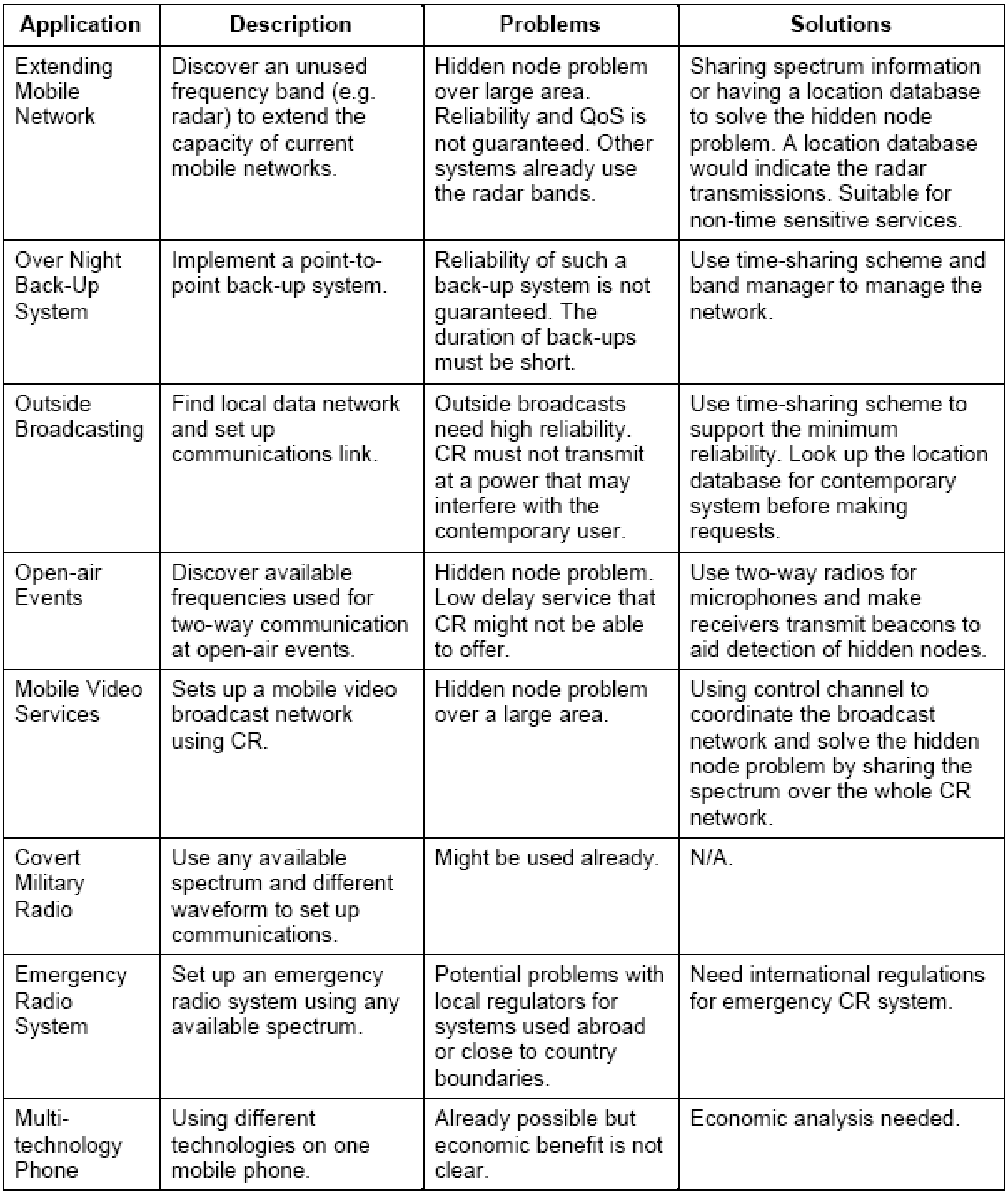


Figure 2.2: An example of hidden node problem taken from [39].

Dealing with security, we have to face the problem of unexpected or problematic behaviour of individual CRs (sometimes, entire networks). The third challenge is the difficulty of controlling the use of spectrum by CR devices, especially those crossing international borders. Spectrum may be available for sharing in one area, but not in another. In summary, spectrally aware CR has significant user, market and regulatory benefits but many challenges, such as the hidden node, have yet to be overcome, and that is why it is not still an implanted system.

As a resume of this last 3 sub-sections, we present the table shown in Fig. 2.3, given in [24], where some possible applications are proposed, with the problems that can appear during their implementation and some possible solutions.



Application	Description	Problems	Solutions
Extending Mobile Network	Discover an unused frequency band (e.g. radar) to extend the capacity of current mobile networks.	Hidden node problem over large area. Reliability and QoS is not guaranteed. Other systems already use the radar bands.	Sharing spectrum information or having a location database to solve the hidden node problem. A location database would indicate the radar transmissions. Suitable for non-time sensitive services.
Over Night Back-Up System	Implement a point-to-point back-up system.	Reliability of such a back-up system is not guaranteed. The duration of back-ups must be short.	Use time-sharing scheme and band manager to manage the network.
Outside Broadcasting	Find local data network and set up communications link.	Outside broadcasts need high reliability. CR must not transmit at a power that may interfere with the contemporary user.	Use time-sharing scheme to support the minimum reliability. Look up the location database for contemporary system before making requests.
Open-air Events	Discover available frequencies used for two-way communication at open-air events.	Hidden node problem. Low delay service that CR might not be able to offer.	Use two-way radios for microphones and make receivers transmit beacons to aid detection of hidden nodes.
Mobile Video Services	Sets up a mobile video broadcast network using CR.	Hidden node problem over a large area.	Using control channel to coordinate the broadcast network and solve the hidden node problem by sharing the spectrum over the whole CR network.
Covert Military Radio	Use any available spectrum and different waveform to set up communications.	Might be used already.	N/A.
Emergency Radio System	Set up an emergency radio system using any available spectrum.	Potential problems with local regulators for systems used abroad or close to country boundaries.	Need international regulations for emergency CR system.
Multi-technology Phone	Using different technologies on one mobile phone.	Already possible but economic benefit is not clear.	Economic analysis needed.

Figure 2.3: Potential CR applications with their respective problems and solutions.

2.1.5 Regulatory Issues

One important thing that can come to the reader's mind while thinking about cognitive radio is asking himself if this technology can be held with the actual legislation. Here we find another advantage for CR technology, since it can be used currently without any changes to regulations, although subject to usage conditions as follows:

- by a licensee within their own spectrum.
- in License Exempt spectrum where such use is specified in the Interface Requirement.
- through leasing from licensees.

However, issues arise when CR users wish to gain access to spectrum which is already licensed to others. This is where the substantial benefits of CR are expected, as the user potentially has access to a huge amount of "unused" spectrum. There are two mechanisms by which this could be permitted, both of which would require changes to spectrum regulations:

- SL-CR: These systems would operate under secondary licences granted by Ofcom, without the specific agreement of the primary licensee. Secondary licensing is a common method for increasing spectrum utilisation: secondary users are allowed on a non-interference non-protection basis and are generally constrained to much lower powers than the primary user. For example radio microphones are secondary licensed in the spectrum used primarily by UHF TV broadcast.
- LE-CR: These systems would be allowed access to the spectrum on licence-exempt basis and subject only to Interface Requirements (IRs) specifying the constraints on maximum power, etc. An example of a system which could implement CR technology is the fixed wireless access system operating at 5.8GHz where Dynamic Frequency Selection (DFS) detection thresholds are required to avoid interference to radars.

2.2 Ad-Hoc Networks

We define the concept of ad-hoc network because somehow it is intimately linked with cognitive radio systems since the latter fit perfectly the philosophy of ad-hoc networks. This relationship is quite straight if the concept of cognitive radio introduced in section 2.1 is compared to the following definition of ad-hoc networks.

In [3], a really good explanation of ad-hoc networks is given. In this text, Ad-hoc is defined in two different ways—the first can be either "impromptu" or "using what is on hand," while the other is "for one specific purpose." Ad-hoc networks follow both definitions. They are formed as they are needed (impromptu), using resources on hand, and are configured to handle exactly what is needed by each user—a series of "one specific purpose" tasks.

The main feature of ad-hoc networks is that every node is aware of all other nodes within range, as pointed out in Fig. 2.4. The entire collection of nodes is interconnected in many different ways, "just as a physical mesh is made of many small connections to create a larger fabric".

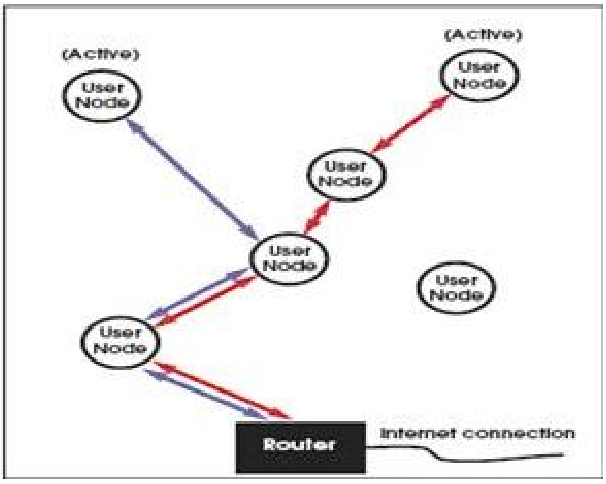


Figure 2.4: Basic structure of an ad hoc, or mesh, network. The path from the user's node to the destination node is provided by other users' devices acting as routers and at the same time all of them exchange information.

2.2.1 Advantages Of Ad-Hoc Networks

The principal advantages of an ad hoc network are the independence of all the devices involved in the connection. Since all of them are independent to make their own decision, they are self-configured, which allow the network to have a continuous re-configuration process. This feature gives the network a high grade of flexibility and scalability. Hence, this would also mean high robustness against failure.

2.2.2 Limitations Of Ad-Hoc Networks

While ad hoc networks are typically used where they have the greatest emphasis on its advantages, there are some limitations. Regarding to the fact that every node has to take its own decisions, we must assume that all of them should have full performance, which increments the complexity of the devices. In addition, we have to say that these kind of networks are really sensitive to high network load.

2.2.3 Key Applications

Although not many commercial applications for ad-hoc networks have been developed yet, we can find some really interesting applications. Ad-hoc networks have been used in some scenarios, which could be hardly accessible with other connection systems. This is possible because we can use repeater nodes to extend coverage to a large area, while user nodes can extend service in their locality.

Control systems (e.g. environmental controls) and industrial process monitoring and control are becoming major applications for mesh networking. These environments are difficult to serve with dedicated wiring, being spread over a large area, often with difficult access. Sensor networks from small-scale (e.g. household security monitoring) to large scale (e.g. wildlife tracking) are also being developed with ad hoc networking as the operational structure.

Developers of these and other applications have determined that ad hoc networks are the most efficient way to maintain system-wide communications.

2.3 Software Defined Radio

Before entering to the definition of the main subject of our Thesis, this is, Binary power allocation and Cognitive Radio, we consider that it is also interesting to define the technology of Software Defined Radio. We only want to give the reader a very general approach to this technology since, as we said before, it is not the main subject of this Thesis. Cognitive radio is a kind of evolution, a fusion for being more accurate, between SDR and some other technologies.

The reader could think that, along the evolution of radio communications, radio equipment has always had a software implementation. However, there is a huge difference between a radio that internally uses software for some of its functions and a radio that can be completely redefined in the field through modification of software. The latter is a software-defined radio.

A certain convergence occurs when multiple technologies align in time to make possible those things that once were only dreamed. Of course this convergence is also occurring in radio communications through digital signal processing (DSP) software to perform most radio functions at performance levels previously considered unattainable.

Incorporating DSPs to radio communications could be really useful not only for signal processing, thing that has as a result much better noise implementations and digital filtering performances. Of course they are not the only benefits that DSP can bring to radio communications. This guides us to software defined radios.

A software-defined radio is characterized by its flexibility: Simply modifying or replacing software programs can completely change its functionality. This allows easy upgrade to new modes and improved performance without the need to replace hardware. An SDR can also be easily modified to accommodate the operating needs of individual applications. All these possibilities are possible thanks to SDRs equiped with internal hardware and a processing device in order to make this hardware operate as necessary. As an example, an internal scheme of a generic SDR is shown in Fig. 2.5.

This SDR convergence is occurring because of advances in software that allow digital processing of radio-frequency signals. Many of these designs incorporate mathematical functions into hardware to perform all of the digitization, frequency selection, and down-conversion to base band.

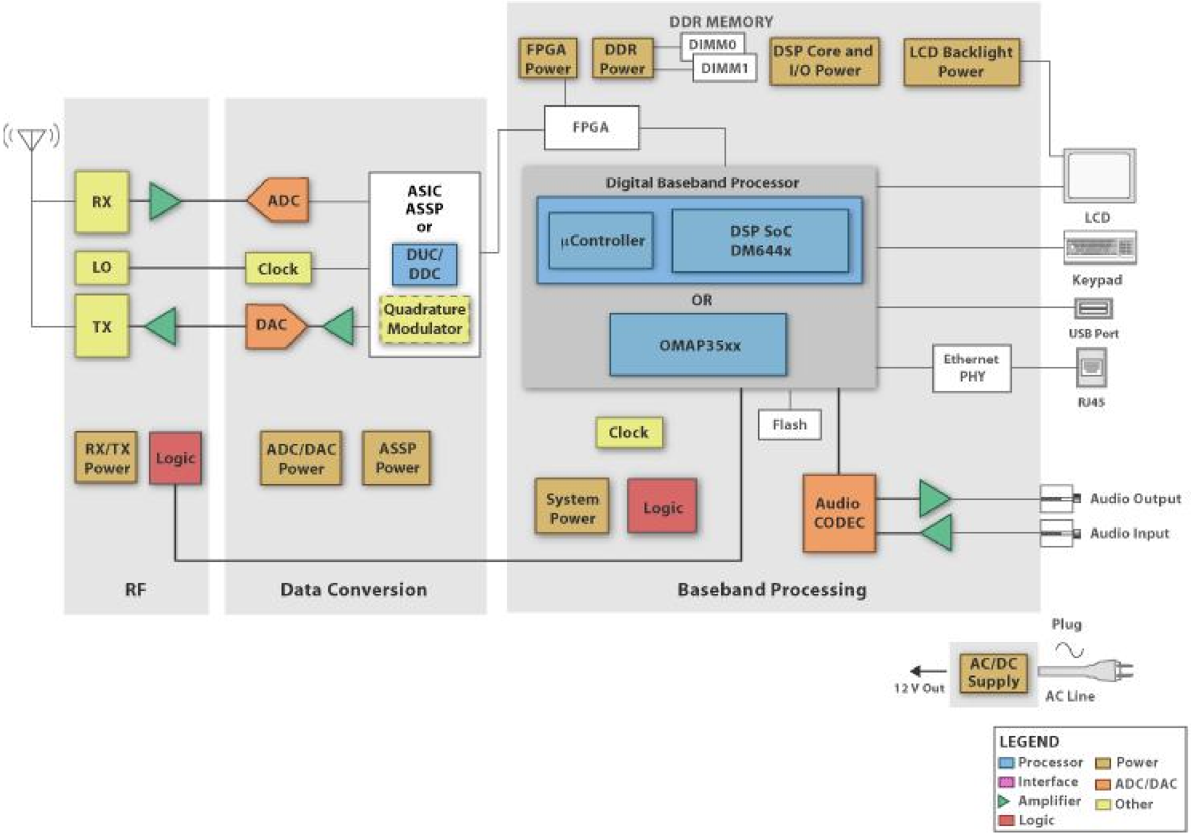


Figure 2.5: General bloc diagram of a SDR.

2.4 Related Work

Since we are dealing with a relatively new technology, many researches are being carried out nowadays. Hence, we consider that mentioning them in detail in this text would not be useful for the reader because each of them has different goals and are focused on different parameters, scenarios and criteria. Thus, we think that explaining some of them could lead to a misunderstanding. However, we introduce some of them just in order to enhance the amount and variety of power allocation schemes/algorithms and their philosophies:

- In [14] some fundamental requirements for a CR system that tries to avoid interference to potential primary users of a band are explored. It is firstly said that in order to deliver real gains, cognitive radios must be able to detect undecodable signals. Maybe this result a bit complex and unnecessary for the goals that we are trying to achieve in this thesis, but since it is the basis for a CR system, we considered important to mention it. To give a general idea of the content of this paper we will mention the two main conclusions to which they arrive:

  - In general, the performance of the optimal detector for detecting a weak unknown signal from a known zero-mean constellation is like that of the energy detector (radiometer). However we show that the presence of a known pilot signal can help greatly.
  - It is also shown that quantization combined with noise uncertainty can make the detection of signals by any detector absolutely impossible below a certain SNR threshold

- In [8] channel and power allocation models are designed with interference but without considering the protection of primary (licensed) users. We mention this paper just for the reader to realise that, while designing a cognitive radio power allocation scheme, many different philosophies and preferences are possible.

- In [9] They consider a cognitive radio network in which a set of base stations make opportunistic unlicensed spectrum access to transmit data to their subscribers. The spectrum of interest is licensed to another network (PU). Because of this, power and channel allocation must be carried out within the cognitive radio network in order not to cause excessive interference to the primary licensed users. Up to here, this study could result useful for cognitive radio. However, they do not consider a pure cognitive system, since the control for allocation is centralised in order to make some decisions for the communications. For this allocation decisions, a two-phase channel/power allocation scheme that improves the system throughput is proposed. With the aim of maximizing their total coverage while keeping the interference caused to each primary user below a predefined threshold, channels are allocated to base stations.

- In [10] the idea of using cognitive radios to reuse locally unused spectrum for their own transmissions is explored. The constraint imposed there is that they cannot generate unacceptable levels of interference to licensed systems on the same frequency. Up to this point, the goal and approach is similar to our scenario. However, the idea exposed in this document is to allow the SUs to vary their transmit power while maintaining a guarantee of service to primary users. Even starting from a different basis, some useful concepts are introduced and developed, such as considering the aggregate interference caused by multiple cognitive radios and showing that that aggregation causes a change in the effective decay rate of the interference. The effects of heterogeneous propagation path loss are examined and they try to demonstrate that under those conditions, the dynamic power of transmission can have proper conditions to be used. Apart from that, they prove a really important concept. This concept is that the fundamental constraint on a cognitive radio's transmit power is the minimum SNR and the effect of this capacity is explored.

- In [11], the multiuser power and channel allocation problem in cognitive radio is considered. It is focused though in a different way from the one in our scenario. They have based their paper analysis on game theory, modeling the problem into a non-cooperative game and proving that this problem is a supermodular game with the purpose to maximize the total system capacity of the network in which secondary users choose their power allocation in each channel according to their payoff function. This considers both the capacity gain of themselves and the loss of the others. It is easy to observe that we are dealing with a real cognitive radio system, since the users make their own decisions for allocating themselves. However, it is a more complex system for allocating than the one used in this Thesis, what does not mean that it will guide us to better results, as the reader can understand from papers like [16].

- In [12] the study is particularized for bands above 3 GHz, in which CR systems could have a better implantation. In this paper a Cognitive Radio approach is presented for usage of Virtual Unlicensed Spectrum (CORVUS). It is, in resume a vision of a Cognitive Radio (CR) based approach that uses allocated spectrum in an opportunistic manner to create "virtual unlicensed bands". These bands are shared with the primary users on a non-interfering basis. Dynamic spectrum management techniques are used to adapt to immediate local spectrum availability, allowing a user to transmit or not basing this decision on this spectrum analysis, which can comprise a whole band. This is different to what we studied in this Thesis, since we analyse the possibility of various users working simultaneously in the same frequency. However, some interesting concepts can be extrapolated and used for our further analysis.

- In [2] an Uplink Distributed Binary Power Allocation scheme is developed for a specific scenario, aiming to share the spectrum (PS-SS) in order to maximize the total SU throughput while preserving the QoS (in terms of outage probability) of the PS. Our work is mainly based on this last research, that is why we are introducing its basis and theory in chapter 3, obtaining some results from the original algorithm and after that modifying and improving some performance characteristics with the only goal of helping the original authors. Since this document will be properly introduced in section 3.1, we will not emphasize it anymore in this chapter.
- [4] is a general Cognitive radio view. There, CR is viewed as a novel approach for improving the utilization of a precious natural resource: the radio electromagnetic spectrum. The cognitive radio, built on a software-defined radio, is defined as an intelligent wireless communication system that is aware of its environment and learns from it. Two main objectives are set for CR:
  - Highly reliable communication whenever and wherever needed
  - Efficient utilization of the radio spectrum, explaining them with three important cognitive tasks:
    1. Radio-scene analysis.
    2. Channel-state estimation and predictive modeling.
    3. Transmit-power control and dynamic spectrum management.

Apart from the documents and researches we have mentioned before, we consider that is important to mention some other works, intimately linked with cognitive radio. In fact, some of them have established the basis for the development of the new technology under our study. Examples of this are some works like [5, 27, 28, 29] by Joseph Mitola, considered by many people father of the CR.

Another special mention can be given to some authors who have developed some important works, in similar scenarios than the one considered in this Thesis, such as [30] and [31], in where some efficiency parameters are analysed, giving as a conclusion some achievable parameters for a CR system. Works like those are crucial to give the reader an idea of how useful it can be to achieve CR system giving as a result the possible perspectives of implantation for real situations.

For the end of this section, we have reserved a work that was carried out under really similar conditions and scenarios used for the development of this thesis. In [37], we can see these really similar conditions we have mentioned before. However, the investigation of this paper goes in another direction, being its main object under study allocating users in different frequencies when these are not used inside a frequency band under study. In this paper, the idea of using cognitive radio to reuse locally unused spectrum for communications is investigated. A multiband/wideband system with two users in which the primary (licensed) user and the secondary (cognitive) user wish to communicate to the base station, subject to mutual interference is used. In this paper, the notion of the virtual noise-threshold, which represents a proxy for the primary user to allow cognitive communications, is introduced. Dealing with this, they determine, under the assumption that the primary user is oblivious to the presence of the cognitive user, the acceptable interference level within a given quality of service. Maybe what is more remarkable in this paper, even more that the things mentioned before, is the given way to acquire the primary user's side information. The proposed strategy is proved to be the optimal one that achieves the maximum rate for each of the two users, under the constraint that the secondary user maintains a guarantee of service to the primary user when cognitive communication is considered.

As the reader can guess, nowadays many other researches have been or are being carried out dealing with cognitive radio and power allocation schemes. Since it is really difficult to mention all of them, we just introduced the ones we considered significant and related with our scenario, system and/or goal.

Chapter 3

Uplink Distributed Binary Power Allocation For Cognitive Radio Networks

3.1 Introduction To Uplink Distributed Binary Power Allocation

The goal of this algorithm is, while preserving the QoS of the primary system (in terms of outage probability) and respecting interference and noise impairments and power constraints in the secondary system, accomplish a PS-SS spectrum sharing by searching for the optimal SUs transmit powers allocation in order to obtain the maximum total SU throughput. With this aim, it is set as important to find the optimal noise/interference threshold above which SUs can be able to transmit (if they decide so) without affecting the primary users' QoS.

3.1.1 The System Model

The system model can be slightly described as an uplink of a CRN with one PU and N SUs randomly distributed as described in Fig. 3.1. For the reader to understand further explanations and mathematical expressions, the notation used for every equation and reasoning is presented as follows:

- the index $j \epsilon [1, M]$ refers to the SUs in the SS.
- the channel gain between the PU indexed by pu and the desired user n is specified by $h_{\mathrm{pu,n}}$.
- $h_{\mathrm{j,n}}$ has an analogous meaning to $h_{\mathrm{pu,n}}$, but referred to the gain from the j^{th} to the desired user n.
- p_{pu} indicates the PU power level.
- the outgoing data from the j^{th} SU is transmitted with power p_{j}.

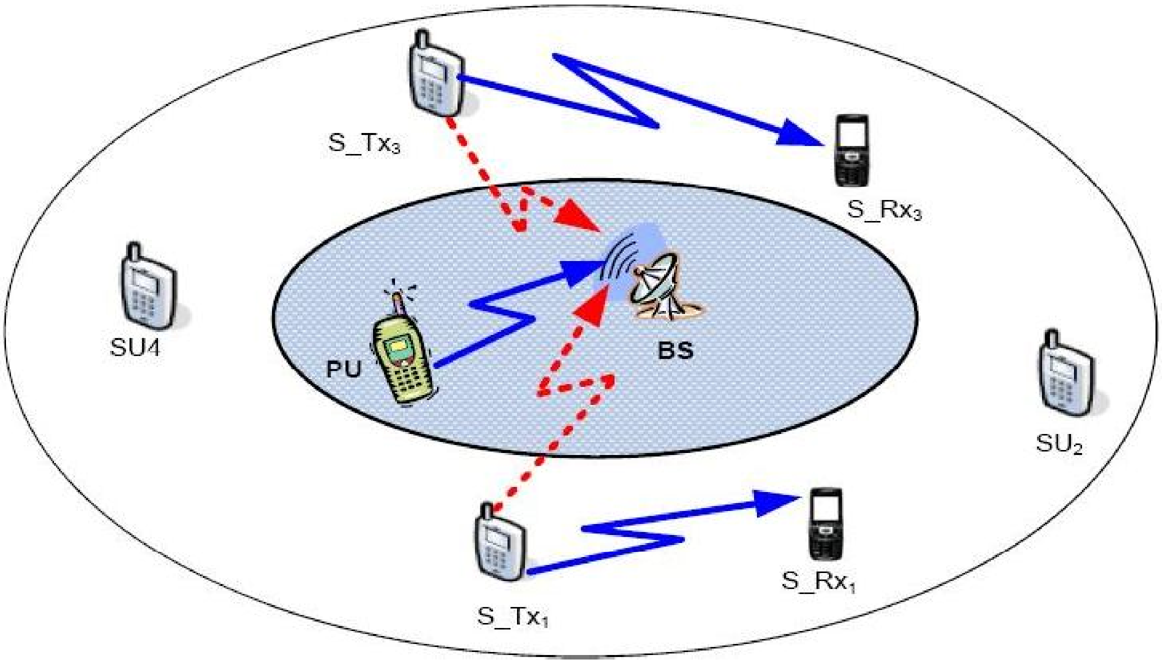


Figure 3.1: The Cognitive Radio Network with one primary user (PU) and M = 4 (example) secondary transmitters attempting to communicate with their respective receivers in an ad-hoc manner during an uplink transmission of the primary user, subject to mutual interference. [2]

We know that one of our main goals is achieving the biggest possible capacity for the SS. For this reason we have to make a deeper study of some expressions that will be useful in our work. We have to start with a generic multiprimary/multicognitive system expression for the instantaneous capacity in the i^{th} PU:

$$C_i = \log_2\left(1 + \frac{p_i \left|h_{i,i}\right|^2}{\sum_{k=1,k\neq i}^{N} p_k \left|h_{k,i}\right|^2 + \sum_{j=1}^{M} p_j \left|h_{j,i}\right|^2 + \sigma^2}\right) \quad i = 1...N \tag{3.1}$$

Our case is focused on an only frequency sub-band with one PU per sub-band. Thus, the previous expression is transformed into[1]:

$$C_{pu} = \log_2\left(1 + \frac{p_{pu} \left|h_{pu,pu}\right|^2}{\sum_{j=1}^{M} p_j \left|h_{j,pu}\right|^2 + \sigma^2}\right) = \log_2\left(1 + \mathrm{SINR_{pu}}\right) \tag{3.2}$$

Another important issue is the analysis of the capacity for the secondary users. We will start again with a generic expression for the j^{th} SU:

$$C_j = \log_2\left(1 + \frac{p_j \left|h_{j,j}\right|^2}{\sum_{k=1,k\neq j}^{M} p_j \left|h_{k,j}\right|^2 + \sum_{i=1}^{N} p_i \left|h_{i,j}\right|^2 + \sigma^2}\right) \tag{3.3}$$

By assuming, as we did before, the presence of only one PU in each sub-band we finally obtain the simplified expression:

$$C_j = \log_2\left(1 + \frac{p_j \left|h_{j,j}\right|^2}{\sum_{k=1,k\neq j}^{M} p_j \left|h_{k,j}\right|^2 + p_{pu} \left|h_{pu,j}\right|^2 + \sigma^2}\right) = \log_2\left(1 + \mathrm{SINR_j}\right) \tag{3.4}$$

At this point, and considering that we are looking for a maximum throughput for the SS (always respecting the conditions of QoS for the PU), we should think about maximizing any of the two following expressions:

$$C_{SS} = \sum_{j=1}^{\widetilde{M}} C_j \qquad \text{or} \qquad C_{su} = \frac{1}{\widetilde{M}} \sum_{j=1}^{\widetilde{M}} C_j \tag{3.5}$$

---

[1] This expression is similar to the previous one but without any other PUs interfering, we just have one PU per sub-band

where $\tilde{M}$ represents the number of active SUs.

Apart from focusing on one sub-band and only one PU in each sub-band, we have to assume some other conditions related with the information the SUs have about the channel and the coherence time. For the first issue we have to assume that every SU have all the necessary information about its own link, but nothing about other SUs' channel conditions. For the second one, we have to assume that the length is enough to be considered constant during each scheduling period. Moreover, power control for SU is included, but interference cancellation is not.

3.1.2 Binary Power Control Allocation

It is already known that, by taking profit of the cognitive features of the SUs, the overall performance of the system can be dynamically improved by changing the transmission parameters of the SUs.

In [2] they focus their research in finding both the cognitive system capacity and the maximum number of active cognitive users achievable in this situation. Thus the problem is expressed as follows:

$$\text{Find } \{p_1*, ..., p_M\} = \arg \max_{p_1, ..., p_M} C_{su} \tag{3.6}$$

subject to the previously mentioned conditions:

$$\begin{cases} 0 \leq p_j \leq P_{max} & for\ j = 1, ..., N \\ P_{out} = Prob\{C_{pu} \leq R_{pu} \mid R_{pu}, q\} \end{cases} \tag{3.7}$$

where q is the upper boundary for the outage probability P_{out}.

Based on a previous work [13], an on/off algorithm is used. This means that p_j is either 0 or P_{max}. Thus, SUs are switched "off" until the previously established conditions are accomplished. This leads to a situation with a certain number of SUs M among which only $\widetilde{M}$ are active.

As a conclusion, we can say that *"a SU should be deactivated if this action results in an increase in the cognitive capacity of SUs or if its transmission violates the PU outage constraint"*[2].

After a theoretical development, shown in [2], we can say that a SU denoted as m will be active if:

- At high SINR regime: $SIR_m > e$

- At low SINR regime: $SIR_m > 1$

However, since our main limitation is the outage probability of the primary user, we have to bear in mind that, even if the SU under study accomplishes any of the two SINR conditions, the condition $P_{out} < q$ should be respected.

According to the results obtained in the same research, the theoretical number of active secondary users $\widetilde{M}$ lies between these limits:

$$0 \leq \widetilde{M} \leq \frac{-\log(1-q)}{(2^{R_{pu}}-1)} . \frac{p_{pu}G_{pu}^2}{P_{max}G_{su}^2} - \frac{1}{SNR} \qquad \text{where } SNR = \frac{G_{su}^2 P_{max}}{\sigma^2} \tag{3.8}$$

After introducing the theoretical principles, a matlab code[2] for simulations was developed in [2] following the next scheme:

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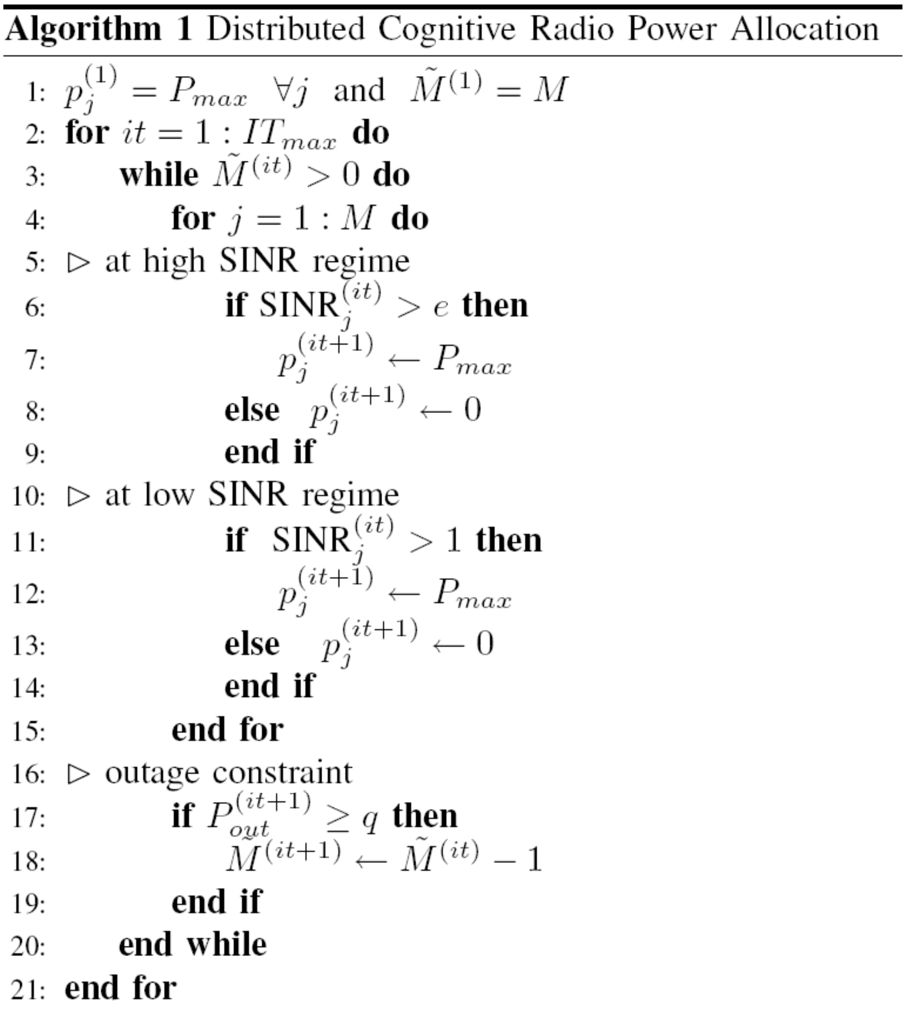
[2] Part of the original code is included in the appendix (A.1)



Algorithm 1 Distributed Cognitive Radio Power Allocation

```
$p_j^{(1)} = P_{max} \;\; \forall j$ and $\tilde{M}^{(1)} = M$
for $it = 1 : IT_{max}$ do
    while $\tilde{M}^{(it)} > 0$ do
        for $j = 1 : M$ do
▷ at high SINR regime
            if SINR$_j^{(it)} > e$ then
                $p_j^{(it+1)} \leftarrow P_{max}$
            else $p_j^{(it+1)} \leftarrow 0$
            end if
▷ at low SINR regime
            if SINR$_j^{(it)} > 1$ then
                $p_j^{(it+1)} \leftarrow P_{max}$
            else $p_j^{(it+1)} \leftarrow 0$
            end if
        end for
▷ outage constraint
        if $P_{out}^{(it+1)} \geq q$ then
            $\tilde{M}^{(it+1)} \leftarrow \tilde{M}^{(it)} - 1$
        end if
    end while
end for
```

Figure 3.2: Pseudo-code for the algorithm proposed in [2].

3.2 Results With The Original Code

In this section, we want to present some results obtained with the original code, result of an analysis of almost all the main parameters that have active part in a cognitive radio communication. This will guide the reader to a deeper comprehension of the behavior of a cognitive radio system which is, in fact, one of our goals with this Thesis.

We will start with a general simulation, only to give the reader a general idea of the results that can be obtained with common parameters in this kind of communications. As we mentioned before, our experiments are focused on uplink since the original algorithm was designed for that purpose. We consider a cognitive radio network as described in Fig. 3.1 with one PU and M secondary transmitters attempting to communicate with their respective receivers, subject to mutual interference. We will use a hexagonal cellular system functioning at 1.8 GHz with a primary cell of radius $R = 1000$ meters and a primary protection area of radius[3] $Rp = 600$ meters.

As well as commenting the main features of the original algorithm (we already did), we have to slightly mention the method used to calculate the channel gain losses. For this purpose, COST-231 path loss model introduced in [14] is used. It includes log-normal shadowing with standard deviation of 10 dB. For this first approach, the power constraint is given by the parameter P_{max} in the original code, in this case equal to 1 Watt.

Further in this section we will make a deeper analysis with different range of parameters to achieve some interesting results of the behavior of our system under extreme conditions. For the presentation of the results we decided plot the two parameters which we consider as the most significant in order to have an idea of either the good or bad behavior of the system. These parameters are, in order of presentation, the capacity per active SU versus the total amount of secondary users and the number of active SUs versus the total amount of secondary users.

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[3] This parameter means that each secondary user has to communicate with his respective receiver in a distance d $>$ Rp from the BS.

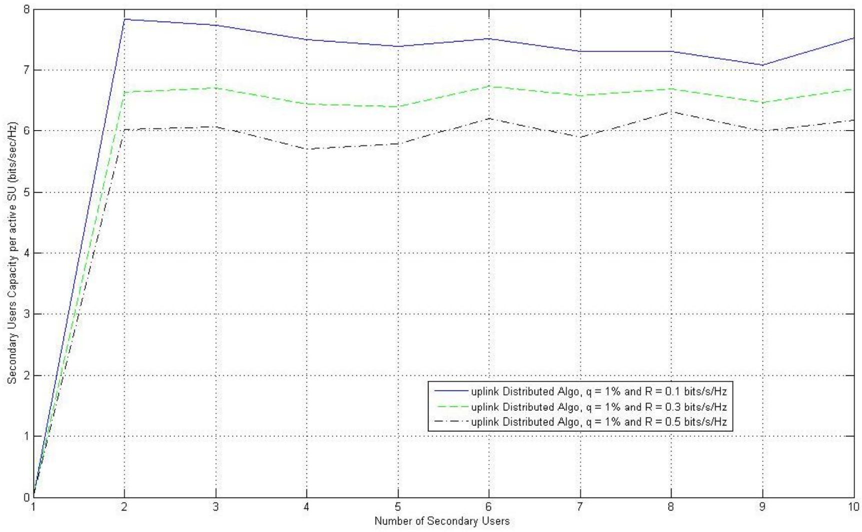

Figure 3.3: Capacity per SU vs Number of potential SUs, with lines for 3 different values of rate, for a CRN using the Uplink Distributed BPC algorithm with general communication conditions.

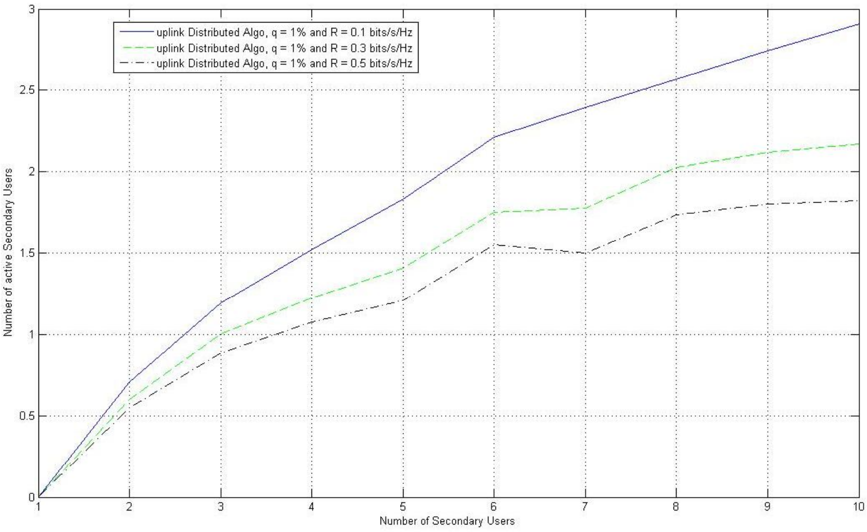

Figure 3.4: Number of active SUs vs Number of potential SUs, with lines for 3 different values of rate, for a CRN using the Uplink Distributed BPC algorithm with general communication conditions.

From this results we can reach some interesting general and, at the same point, obvious conclusions. Simulations and results for other concrete parameters will be analyzed further in this section. In Fig. 3.4 we can observe that increasing the number of potential secondary users brings with it an increase on the number of active secondary users. If we want to find a proper explanation we have to take a look at Eq. 3.8 introduced in section 3.1.2. Analyzing this expression we only find an explanation to this in the parameter G_{su}. Because of its nature[4], it makes the potential active users to grow. This will guide us to an interesting further analysis in order to find the limit of the asymptotic growth of the secondary active users.

Moreover, going on with the analysis of our first results we have to say that, as a trade-off, we can see in Fig. 3.3 that the SUs' individual cognitive capacity decreases, after reaching its maximum, as the number of SUs increases because there is more interference as the sum in the denominator of the equation 3.4 has more elements. However, this does not mean that the performance of the SS is getting worse as it could be deduced from the previous figures. In fact, the system's performance gets better due to new users contributing to the total throughput of the CRN.

This results and ideas suggest that we can not improve the total cognitive capacity and, at the same time, increase the number of "on" SUs, reaching both their maximum values simultaneously. When we try to maximize the number of "on" SUs, the cognitive capacity degrades. Because of this, if we want to develop a cognitive system, we have to analyze every different situation, depending on the preference of having either maximum capacity or maximum number of active secondary users, having to make then the decision of maximizing whether one or the other parameter.

Anyway, in sub-sections from 3.2.1 to 3.2.6 we will simulate the original algorithm with plenty of different conditions (different values for the different parameters defining the requirements of the system) to check how each of them affects the performance.

3.2.1 Different Rates

The rate parameter R represents the minimum rate at which the PU can transmit. It will be easy for the reader to understand that it is one of the main parameters of our

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[4] The parameter G_{su} is an interference average gain

simulations. If we take a look at the conditions for a cognitive radio system to work, exposed in Eq. 3.7, we can see that this parameter represents a constraint itself, which gives us an approach of its importance. We assume that SUs can be switched "on" as long as this action does not turn into a harmful interference to the PU, according to the conditions we mentioned before, which are fully dependent of this parameter.

As we did for the original code shown in section A.1, we simulate the algorithm with the same conditions, apart from the fact that we obviously change the rate value in order to check how the system behaves for a wide range of this parameter.

These rates lie between normal values and increase until reaching extreme values just to see how this affects the network. As it is shown in the legend in both figures 3.5 and 3.6, this simulation is made with 6 different rate values.

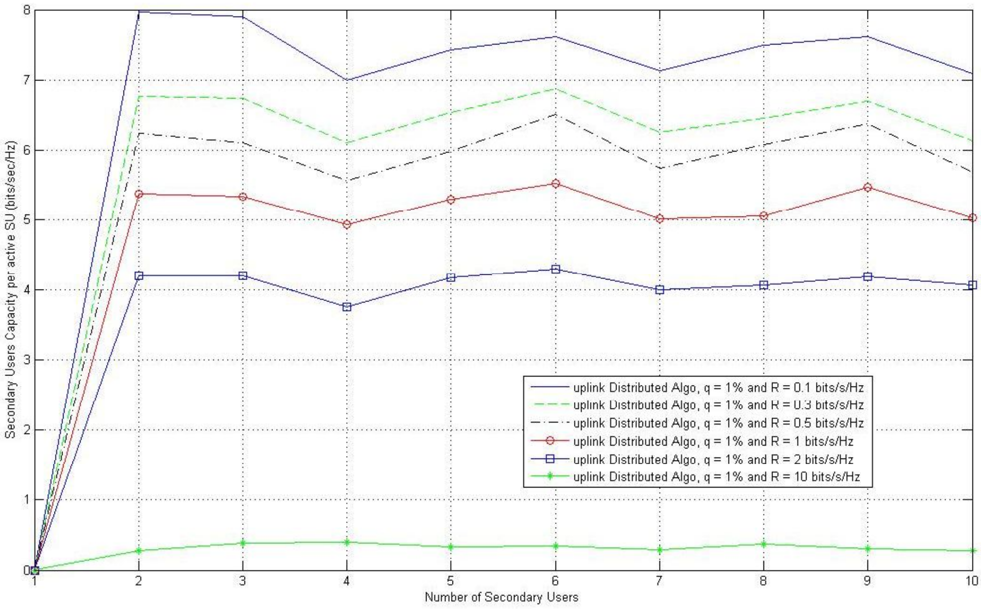

Figure 3.5: Capacity per SU vs Number of potential SUs, with lines for different values or rate, for a CRN using the Uplink Distributed BPC algorithm.

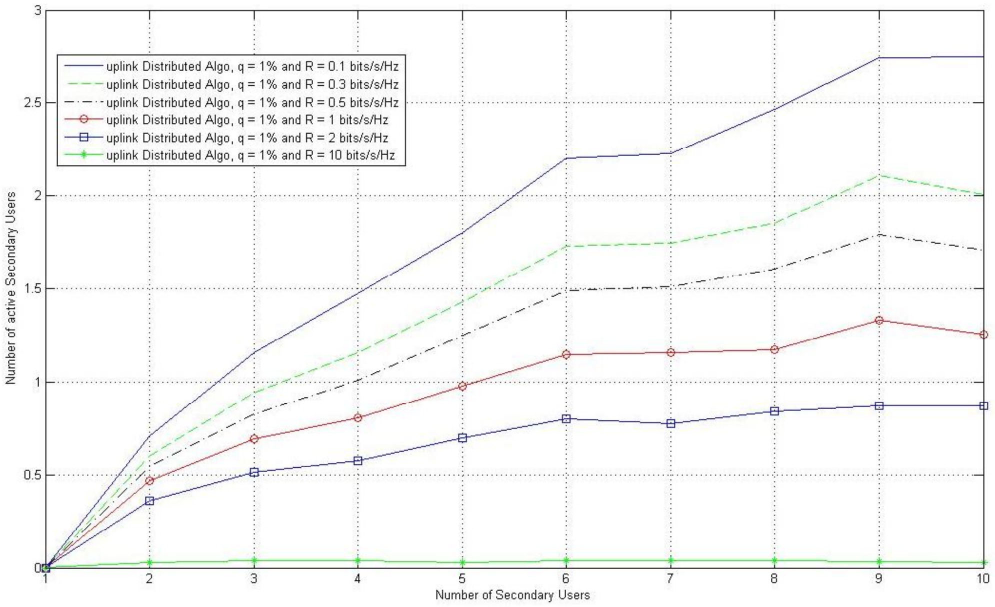

Figure 3.6: Number of active SUs vs Number of potential SUs, with lines for different values or rate, for a CRN using the Uplink Distributed BPC algorithm.

As intuition would expect and the plots in both figures confirm, as the rate is increased both the capacity per active secondary user shown in Fig. 3.5 and the number of active secondary users in Fig. 3.6 decreases. By simply taking a look to the Eq. 3.7 and Eq. 3.2, we can see that as more rate is required for the PU, it is easier for C_{pu} to fall below this boundary with a smaller number of SUs interfering on the PU. Since we need C_{pu} to be above R_{pu}, we have to reach a large value for this former parameter. According to Eq. 3.2, the only way of accomplishing this is by reducing the number of SUs interfering the PU. This action results into a decrease on the number of active secondary users and also a smaller value of the capacity per secondary user.

3.2.2 Different Values Of Outage Probability Limit "q"

When analyzing the behavior of a cognitive system, especially in our case, parameter q appears as maybe the most important one. We can say this because, as the reader can understand from the original code, all the decisions dealing with switching "off" a user are based on this parameter.

Specifically, this parameter refers to a given quality of service[5], established by the user itself. It is intimately linked with the outage probability, one of the main features of our analysis, since the decisions mentioned are basically carried out by comparing these two parameters. We can say then that q represents a constraint for the PU outage probability.

To give a mathematical support to this affirmations, the reader could take a look at the principles for operation in a cognitive radio system, exposed in the theoretical development in past sections.

Dealing with this parameter, we consider that representing the behaviour of the system for a couple of values is enough since it is easy to get the difference between the performance of the system for each of them. Thus, we simulted with q=1% and a more restrictive q just to see how the network reacted.

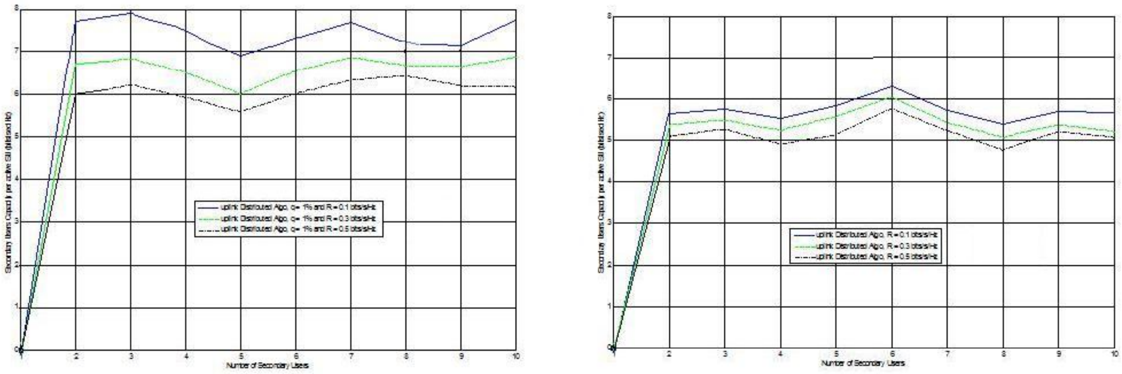

Figure 3.7: Capacity per SU vs Number of potential SUs. The left figure shows lines for 3 different rate values and q=1%. The figure on the right shows plot for the same 3 rate values, but now with a more restrictive q. Both simulations are for a CRN using the Uplink Distributed BPA algorithm.

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[5] In our case, q denotes a percentage and we are supposed to design a CRN in such a way that the probability of having $C_{pu} < R_{pu}$ is smaller than q.

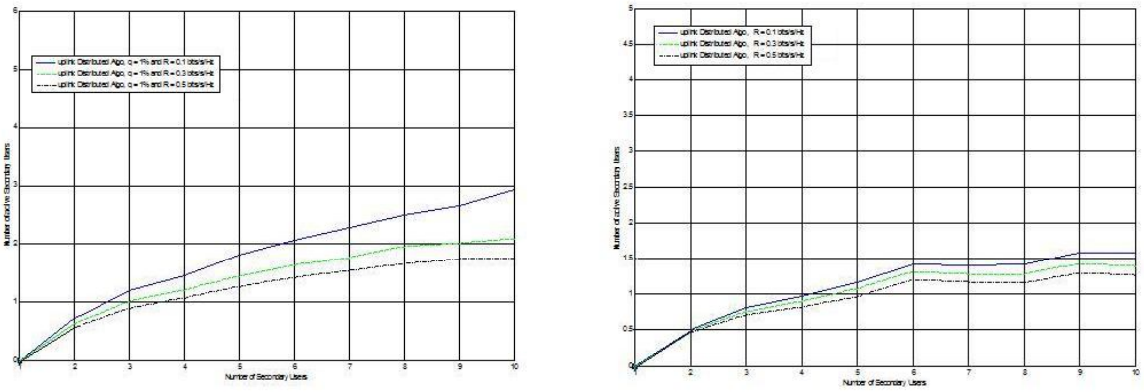

Figure 3.8: Number of active SUs vs Number of potential SUs. The left figure shows lines for 3 different rate values and q=1%. The figure on the right shows plot for the same 3 rate values, but now with a more restrictive q. Both simulations are for a CRN using the Uplink Distributed BPA algorithm.

During the whole analysis of our system, we have to deal with many parameters. Without any doubt, q is one of the most important ones dealing with possible changes in the results, since it is at the same time a constraint itself for our system and it plays an important role in the final expression to which we arrived at the end of our theoretical development.

Firstly we can analyse its impact on the capacity per user by checking Fig. 3.7. If the reader takes a look at the theoretical development in Eq. 3.7, q represents a limit for the probability of blocking, since it is a direct constraint for the outage probability. It is clear that the smaller the q is, the higher the exigency of the system is going to be, permitting with less probability the state in which $C_{pu} \leq R_{pu}$. The only way the system has to control this is by reducing the users capacity or the number of users, to make sure that the constraints we have imposed will be respected.

Apart from the capacity per user, a decrease in the number of active users is noticeable in Fig. 3.8. Analysing the expression 3.8 obtained at the end of the theoretical development in sub-section 3.1.2, the reader will be able to appreciate the importance of the parameter q and its role. For its better comprehension we can make a proper analysis of the expression, more especifically into: $-\log(1-q)$. There, if the value of our q tends to 0, what means that our system has no tolerance, the previous expression will tend to 0 and, as a result, the theoretical limit on the number of potential SUs will tend to

0 as well. On the other hand, if our parameter q tends to 1, which means exactly the opposite, this is, total tolerance, this expression will tend to infinite. This means that we will be able to have as many active SUs as we want[6], since the restriction for being harmful at the PU is inexistent.

This behaviour is represented in the graphs we have obtained. It is easy to observe in both Fig. 3.7 and Fig. 3.8 that, with the increase of the q parameter, more users are able to be active and consume more resources of our network, what means an increasing in both the capacity per active SU and the number of active SU.

3.2.3 Different Power Ratios

The power ratio parameter, which is not a real parameter indeed, represents a relation between the power of transmission of the primary and the secondary users. Specifically, it represents how many times bigger the PU transmission power is compared to the same parameter related to the SU.

As in past performances, we simulate the algorithm with normal condition parameters, obviously changing the ratio values while calling the function “dist_algo_CR_uplink.m” (shown in sub-section A.1.2) during the execution of “main.m” (included in sub-section A.1.1), in order to check how the system behaves for a wide range of this parameter. These rates lie between normal values and increase until reaching extreme values just to see how this affects the network. As it is shown in the legend of both Fig. 3.9 and Fig. 3.10, this simulation is made with 5 different rate values.

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[6] As many active SUs as we want in terms of q of the PS. Just remember that every system (cognitive or not) has a maximum number of active devices above which we reach a saturated situation.

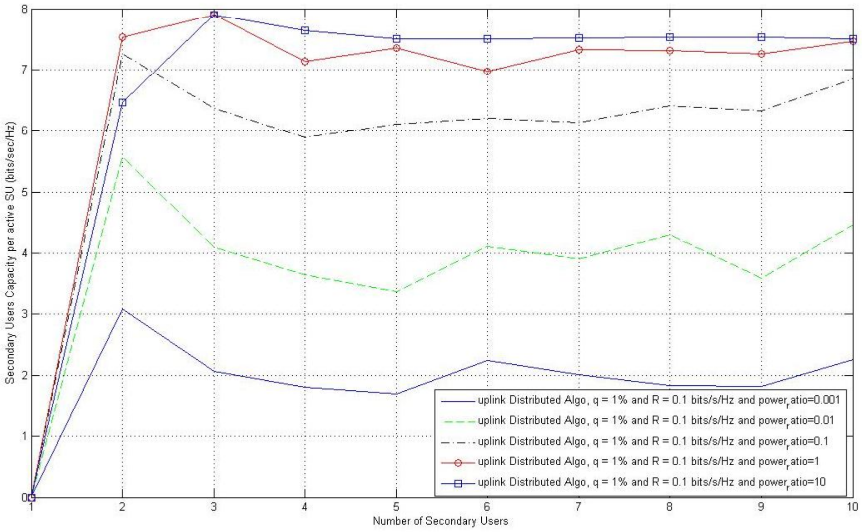

Figure 3.9: Capacity per SU vs Number of potential SUs, with lines for different values for PU/SU power ratio, for a CRN using the Uplink Distributed BPA algorithm.

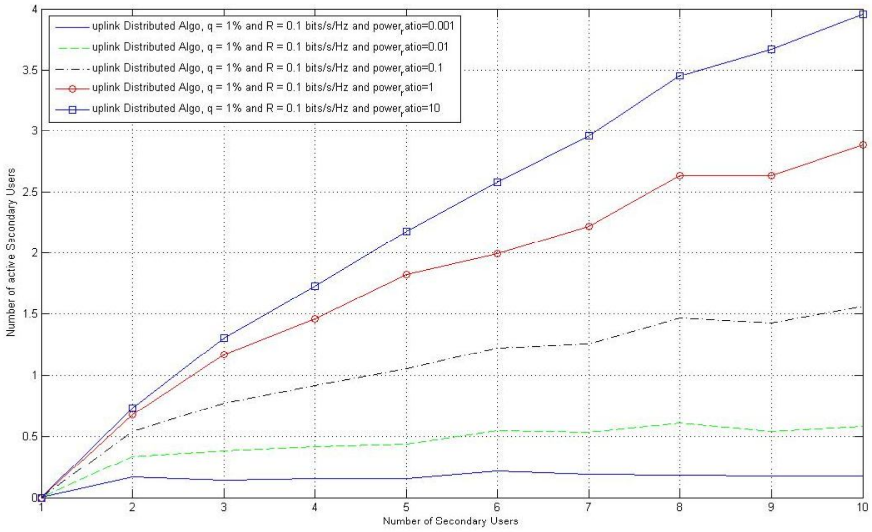

Figure 3.10: Number of active SUs vs Number of potential SUs, with lines for different values for PU/SU power ratio, for a CRN using the Uplink Distributed BPA algorithm.

After observing the results obtained, we can reach some conclusions about the reactions of our system to the changes related to the power ratio. At first glance the reader could think that a large value for the ratio value, which in short means a large value for the primary user's transmitting power, should lead to a decrease in the capacity per SU due to an increase in the interference affecting them, as it is deduced from the analysis of Eq. 3.4. Since the results obtained for these simulations say the opposite, we have to analyze this fact more thoroughly.

If we take a look at Fig. 3.9 and Fig. 3.10, it is clear that the behavior of the system, in terms of capacity per SU and number of active SU gets better while increasing the power ratio. This fact can be explained if we analyze the expression 3.2. It is clear that by increasing the PU transmission power, we are increasing the parameter C_{pu}. Since we need C_{pu} to be above R_{pu},the larger this parameter (power ratio) is, the bigger number of users will be possible to become activated. Doing this, it seems that we outweigh the negative effect of interfering more on secondary users.

3.2.4 Different Protection Radius

Another important parameter that needs to be considered is the protection radius for the PS. It is important to remember the meaning of this parameter, to which we gave an approximate definition in past sections. When we create the network for the simulations, with one PU communicating with a BS and M potential secondary users transmitting and receiving with other SUs through their own channel link, in order to preserve the integrity of the PU communications, we establish an area in where the multiple SU can not transmit.

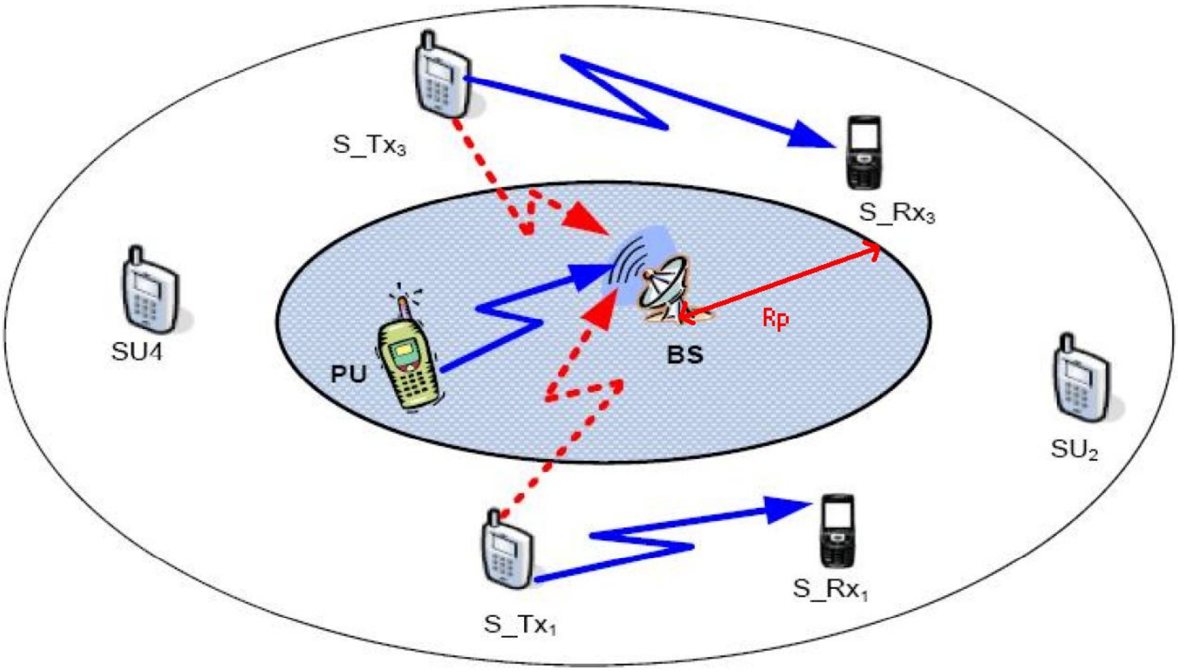

Figure 3.11: Our Cognitive Radio Network scenario, where R_p represents the protection radius, which specifies the dark area around the primary BS.

As we see in the figure above, we establish this area defining a value for its radius, since we assume that this area will be circular for our concrete scenario.

We considered simulating for different values of this parameter because we think that is important to realise how the system behaves when a user has either more or less space to fit in the system and try to communicate. This simulation could be considered intimately linked with the one for the saturation that will be taken in further sections. The study of the performance will be done for 6 different values, as the reader can see in the legend, under the same conditions of rate and q used in the general simulations performed in past chapters.

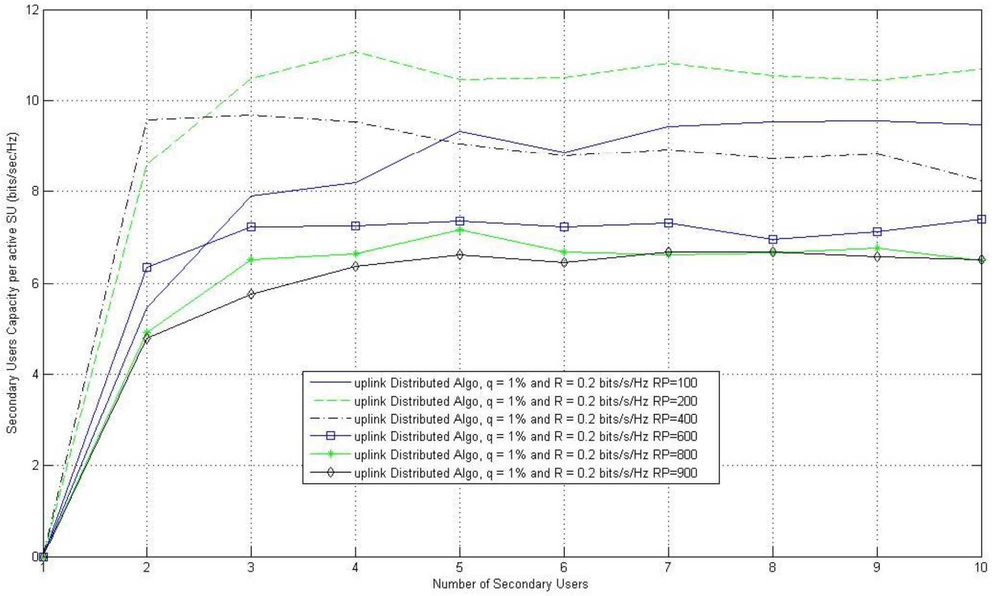

Figure 3.12: Capacity per SU vs Number of potential SUs, with lines for different values of the protection radius, for a CRN using the Uplink Distributed BPA algorithm.

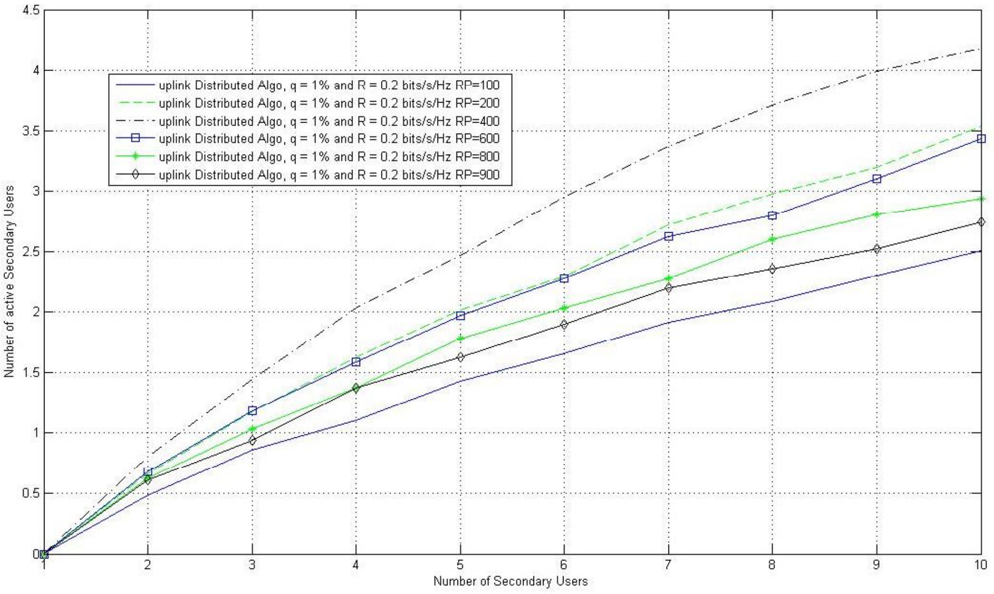

Figure 3.13: Number of active SUs vs Number of potential SUs, with lines for different values of the protection radius, for a CRN using the Uplink Distributed BPA algorithm.

At first, as intuition could expect we hoped that as the protection radius increases, the SUs have less space of the cell under study to develop their communication activities. The exact meaning of having less space to develop the cognitive activity results into a big probability of having more interference in the SUs even with a smaller number of active SUs spread in the area where they are allowed to transmit. That obviously should guide to a decrease in both the capacity per SU and active SUs as we increase the protection radius parameter.

However, taking a look at Fig. 3.12 and Fig. 3.13, the simulation does not guide us to the results we expected. At first glance, these results can look like random but if we analyze them properly, some interesting conclusions can be achieved. If we follow the results from the lowest value of radius to the highest one, we always start with an increase in both capacity and number of active SUs. However, at some point both values begin to decrease, following the behavior that we expected at first. This guides us to think, and this is a really interesting conclusion, that some configurations of the cell are optimal dealing with protection radius, or what is the same, that the lower value for the protection radius does not have necessarily to guide us to the best results. Taking a look at the previously mentioned graphs, we can set up approximately this optimal points, that does not have necessarily to be the same for both parameters (number of active SUs and capacity per SU). In fact, for the former we can set this point up in some point between a value of 400 and 600 for the protection radius, since as we see in the graph we obtain a maximum for 400 meters and from this point it begins to decrease, while that for the latter this point appears between 200 and 400, for the same reason mentioned above.

3.2.5 Different $\mathbf{P_{max}}$

As an introduction to the meaning of this parameter, in order to guide the reader to a proper comprehension of this analysis, it is important to remember the meaning itself of the power algorithm that we are developing in this Thesis, this is, binary power allocation. The most important feature of this algorithm is that, when a user is switched "on", it is transmitting with a fixed power value, establishing the possible transmitting values for the SU in the group {0, P}. The value of this P is what in the algorithm under analysis we call P_{max}, which is the main goal of analysis of this section.

At first glance, the reader could think that P_{max} could be an important parameter for the operation of a cognitive radio system. In fact, if we analyze the theoretical development exposed in sections 3.1.1 and 3.1.2 we will reach the conclusion that it is, dealing with the whole system capacity constraints, one of the most important parameters for the development of a real cognitive radio network.

Specifically, we can say this because taking a look to the capacity expressions 3.2 and 3.4, the reader can realise that the capacity is fully dependent of this parameter. In fact, if we fix the rest of the communication parameters and we consider a fix environment for the development of our cognitive system network, we can approximate the increasing of the capacity almost linearly with the increasing of the maximum power parameter. According to this, it could be considered important to simulate with a wide range of values for this parameter, since it has real importance while developing a real cognitive radio system. The simulations, as the past ones, are executed under conditions we consider normal for a cognitive radio communication process and for 6 different P_{max} values.

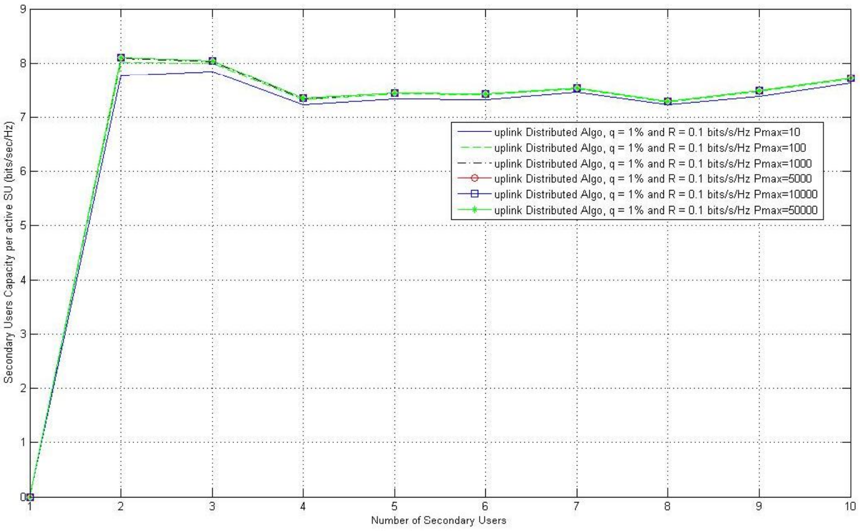

Figure 3.14: Capacity per SU vs Number of potential SUs, with lines for different values for $\mathrm{P_{max}}$, for a CRN using the Uplink Distributed BPA algorithm.

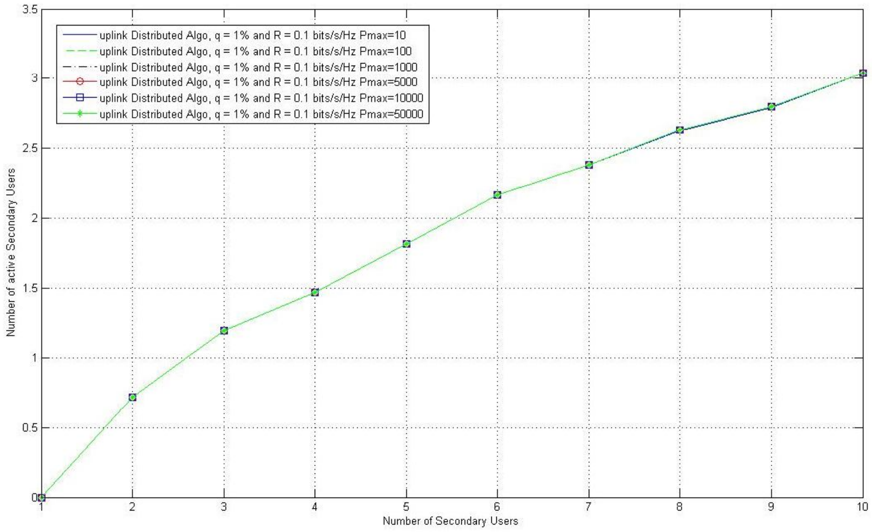

Figure 3.15: Number of active SUs vs Number of potential SUs, with lines for different values for P_{max}, for a CRN using the Uplink Distributed BPA algorithm.

The results that we have obtained for this simulation could be, at first impression, unexpected for the reader. At first, we expected an increasing in both the capacity per user and in the number of active SUs, up to a point in where we reach the system capacity limit. At this point, the number of secondary users and their capacity should begin to decrease, in order not to be harmful for the PU communications, since the capacity for the PU will be increasing as well[7].

As we said, the results obtained do not correspond with the expected ones, but by taking a look at the original code in section A.1, it will be easy for the reader to understand the reason to this. The thing is that in the mentioned original code, we do not establish any capacity saturation constraint, or what it is the same, we suppose that we can reach infinite capacity, being only limited by the QoS of the primary user. If we increase P_{max}, under this conditions, and taking into account that the transmission power for the PU will be increased in the same scale (because the power ratio remains with value 1), the limitations for QoS of the primary user will be the same, which guide us to the conclusion

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[7] We have obviated the fact that for our simulations, as we explained in past sections, the transmitting power for the PU is also increased with the increase of Pmax, since in our algorithm Pu transmission power is defined by RATIO*Pmax

that the behavior of the system is exactly the same for every value of P_{max}, as it is shown in the figures 3.14 and 3.15.

3.2.6 Saturation

Another important study that can be taken is the saturation of users in one cell. As we commented on past sections, this saturation could be reached due to two important reasons. The first is due to a capacity constraint, situation in where the sum of the capacities of the PU and the SU reaches the limit and some of the active SU are switched "off", in order not to "steal" resources for the PU (in this case, link capacity). The second one could be because of QoS of the primary user. Taking a look at the conditions for a cognitive radio communication, it is clear that C_{pu} has to remain above R_{pu} parameter, defined in sub-section 3.2.1. Taking a look at the theoretical analysis exposed in past sections, specifically to Eq. 3.2, while we add active SUs the denominator of this expression increases, due the addition of new terms in the summation of the interference. This guides us to a point in where it is impossible to maintain the constraint for the QoS for the primary users with the other parameters fixed, reaching then the point of saturation of the cell. Arrived at this point, we have the maximum number of SUs that can be in the state switched "on" at the same time in one cognitive network cell.

As we said in 3.2.5, since for our simulation we do not establish a maximum capacity constraint, we will focus the effort of our analysis in QoS for the PU.

To go even further in the QoS analysis, it is clear by taking a look at the theoretical development exposed in the expression 3.4, that even the individual capacity for the SUs decreases for every SU that is switched "on". That guides us to think that the saturation could also be reached by the capacity in this mentioned SU, in such a way that the achieved capacity per secondary user is smaller than the maximum[8].

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[8] Although it is obvious that our main goal with a cognitive radio system is not giving a high capacity for SU, we have to ensure a certain level for them, since if we don't do this the cognitive radio system loses its meaning

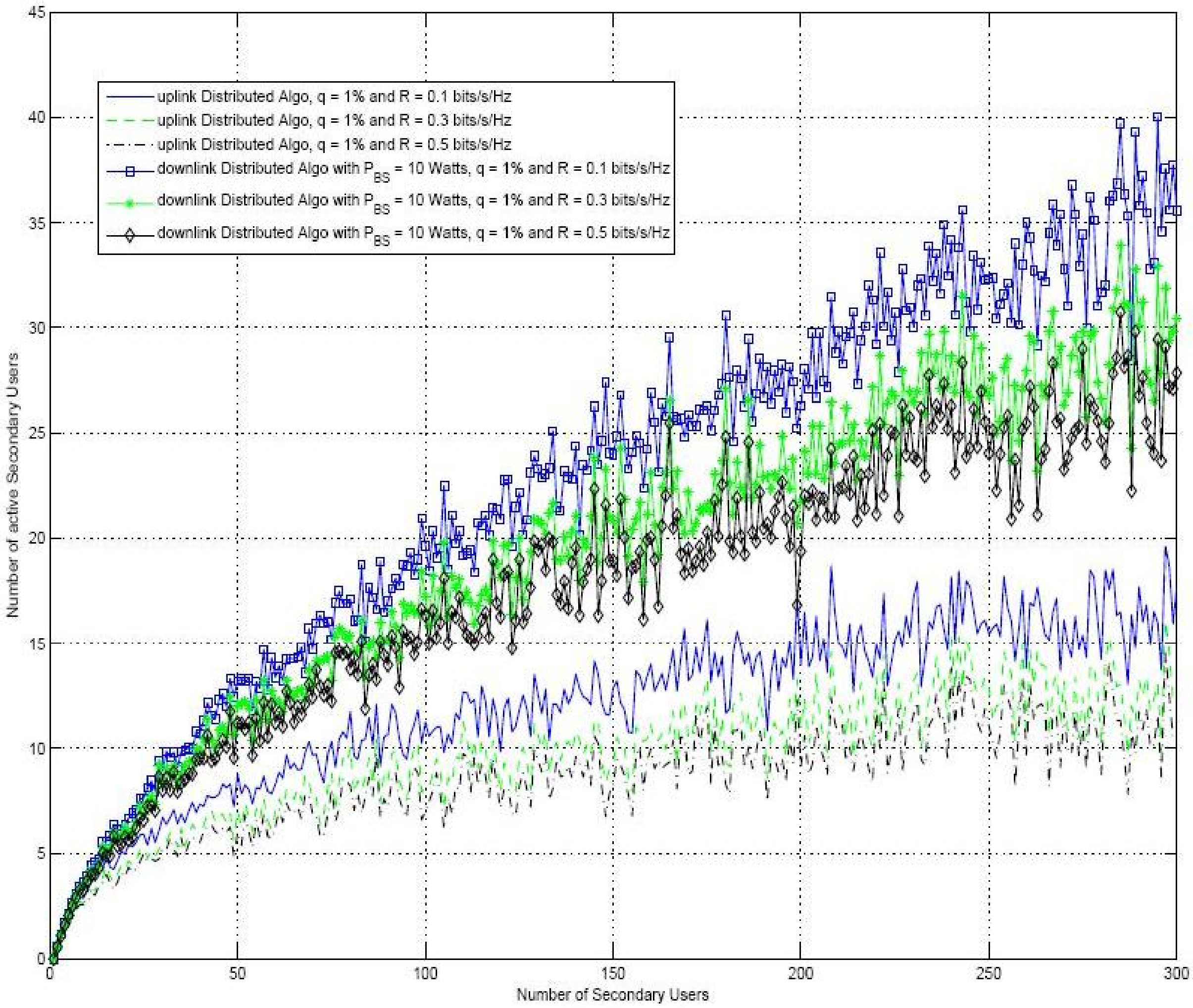

Figure 3.16: Number of active SUs vs number of active potential users, for values of the latter parameter reaching 300 potential users. This figure has been taken from [2].

We present as a result for this section a graphic taken from [2], obtained from the simulation under normal conditions of analysis, exposed in all the previous sections, only increasing the maximum number of potential secondary users to 300. If we observe this Fig. 3.16, the limit of the active secondary users is quite clearly defined since the behavior of the graphic tends asymptotically to a maximum value of active users. For the highest value of rate, we can fix the value between 15 and 20 users, not being possible to fix a clear value. It is important to remember that the results obtained are simulated for every fix number of users, being possible to have some fluctuations when dealing with great amounts of potential SUs.

3.3 Discussion

In this chapter, the behaviour of Binary power control has been studied. This study has been carried out with some simulations for some different parameters which are the most influential in a mobile communication. To be more concrete, a hexagonal cellular system functioning at 1.8 GHz is considered. Secondary transmitters may communicate with their respective receivers of distances d < Rp from the BS. Channel gains are based on the COST-231 path loss model [14] including log-normal shadowing with standard deviation of 10 dB, plus fast-fading assumed to be i.i.d. circularly symmetric with distribution CN(0, 1).

Firstly, the possible behaviour of our system was analytically presented. Based on this theoretical development, results according to it have been found. More specifically, rate, q, power ratio, P_{max} and radius of protection parameters have been studied.

All the results shown in this section are intimately linked with the nature of the parameters under study and the system behaved according to what we expected in the theoretical explanations.

In general terms, logical results have been obtained. Dealing with rate parameter, it is clear to see that the higher this value is, the more difficultly achievable the operation condition will be, entailing a decrease in both active SUs and capacity per SU. A similar case can be observed if we talk about q parameter, which is, as well, a constraint itself. If we establish a low value for this parameter, the requirements for the system will be greater (lower outage probability limit), and users have to be disconnected in order not to result harmful for the PU communication, which turns out in a decrease in the active SU.

If we talk about the protection radius, it was one of the parameters which generated more doubts at first. It was clear that, by increasing the power ratio, the PU was going to be more immune to interference. However, as a trade-off, it would generate more interference in other SUs. At last, as shown in our simulations in sub-section 3.2.3, it seems that the former effect results more important for the general behaviour of our system. As a conclusion we can say that increasing the value of the protection radius, we observe an increase on the capacity of the whole system.

Another important parameter from which some interesting results have been obtained is the protection radius. It is clear that the higher this parameter is, the less available space the SUs have for carrying out their communications. As expected, from the results obtained in sub-section 3.2.4 we can see that an increase on the value of the protection radius entails a worse behaviour in the system in general.

At last, we performed some simulations with the maximum power of transmission. In this case no conclusive result has been obtained since, as we already mentioned in sub-section 3.2.5, the algorithm under study does not include capacity constraints.

Maybe the reader could think that some results achieved and shown in this section are not so conclusive. However, at first glance all parameters seemed to be interesting and in fact we consider they are really interesting for giving the reader a more accurate approximation to the behaviour of the system under analysis, which seems to follow a logical pattern according to the theoretical principles introduced in sub-sections 3.1.1 and 3.1.2.

Chapter 4

Modifications To The Original Algorithm

After working with the original code, we have realized that some features could be improved and, that way, even the overall performance of the algorithm could become better.

As we already mentioned before, in this system the outage probability condition expressed by Eq. 3.7 has to be accomplished. For this reason, we need to turn "off" SUs in the system until we reach a value for the C_{pu} bigger than the required R_{pu}.

This leads us to think that one of the most important and, at the same time, most trivial issues to think about could be the way of choosing which SUs should be switched "off". In the original code attached in section A.1.2, this action is carried out by simply dropping a SU randomly, without taking into account if this user (position, transmission power, etc.) affects the overall performance of the system.

At this point, we think that following a logical policy while dropping a SU could result into better performance of the system. Across this chapter, we will introduce the different possible options with their respective implementations and also some interesting results and conclusions.

Basically, to reach our goal, we just followed two ways of thinking: relative to interference and relative to capacity contributions.

4.1 Capacity Maximization

Our first idea focuses on the most immediate way of increasing the total system throughput. Just realising that, according to Eq. 3.5, the total capacity of the secondary (cognitive) system is the sum of the capacities of every SU, it would be logical to think that by switching “off” the SU which contributes with less capacity to that total capacity could be a good solution for this improvement. As we did for the simulations in chapter 3, we consider a cognitive radio network as described in Fig. 3.1 with one PU and M secondary transmitters attempting to communicate with their respective receivers, subject to mutual interference. We will use a hexagonal cellular system functioning at 1.8 GHz with a primary cell of radius R = 1000 meters and a primary protection area of radius Rp = 600 meters is considered.

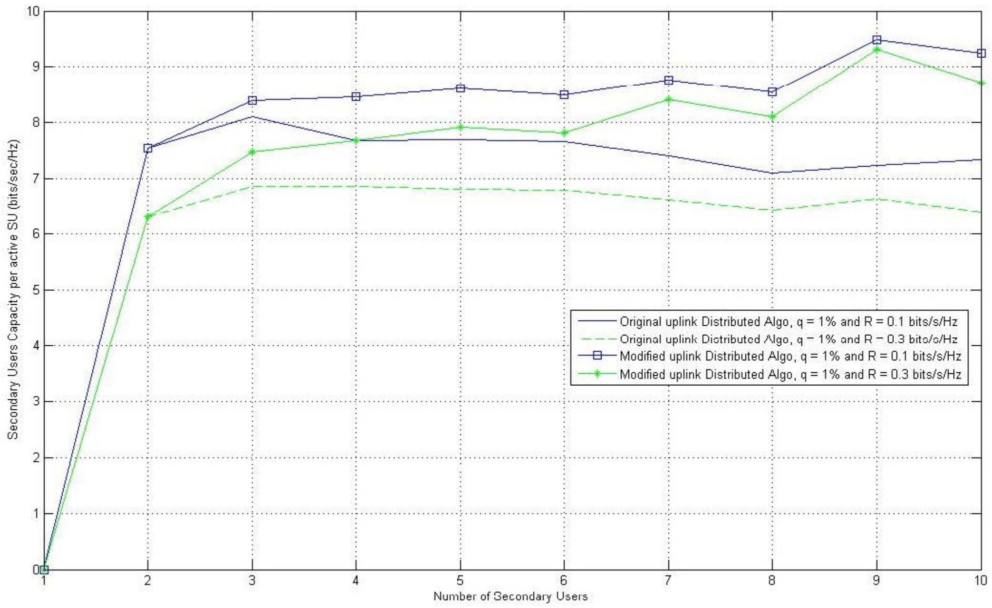

Figure 4.1: Capacity per SU vs Number of potential SUs, for both the original and the capacity improved algorithms using two rate values for each one.

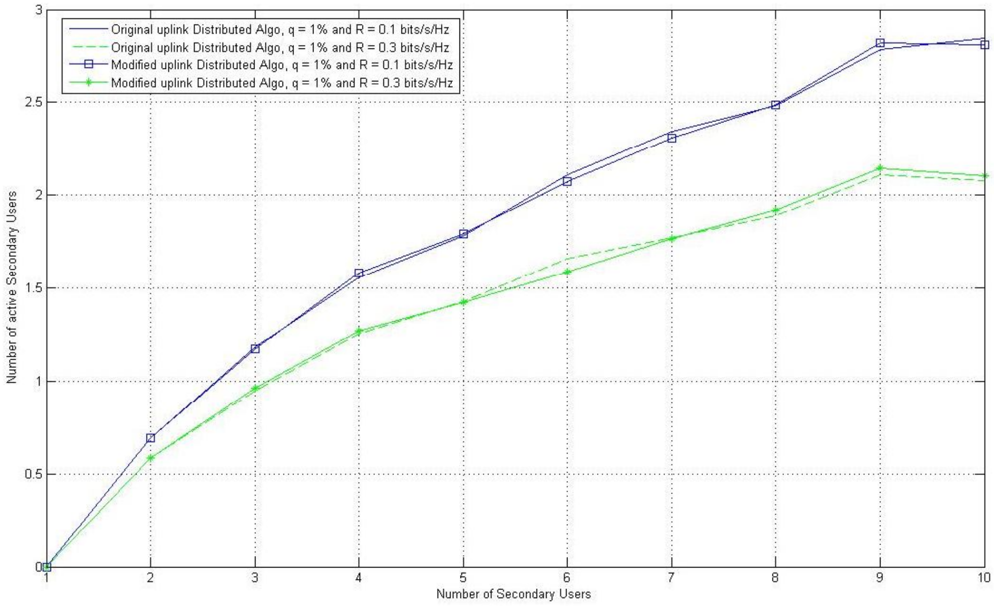

Figure 4.2: Number of active SUs vs Number of potential SUs, for both the original and the capacity improved algorithms using two rate values for each one.

From the results obtained with this performance, the reader can observe a clear improvement in the system behavior, especially if we talk about capacity per SU. We can observe in Fig. 4.1 that our system capacity increases with the increase of potential secondary users, achieving values of 26 per cent of improvement in comparison with the original implementation. As we can see in Fig. 4.2, this improvement does not entail an increase in the number of active secondary users, but the facts previously explained guides us to conclude that the general behavior of the system is improved by our implementation.

Another interesting study could be the one that can be made with the rates. However, in our case it does not represent any important difference. As seen in previous sections, the larger the rate for the primary user is, the worse behavior we will observe in our system.

If the reader takes a look at the theoretical development we presented in sections 3.1.1 and 3.1.2, it will be easy to find some reasons. Firstly we have to analyze the expression 3.7, which was one of the main conditions of operation of our system. By increasing R_{pu}, this operation condition is more difficult to accomplish. Secondly, if we analyze Eq. 3.8 we can see that R_{pu} plays an important role in limiting the number of active SU.

4.2 Interference Mitigation

Dealing with interference, there are three possibilities that could improve the performance of the algorithm. We consider switching "off" the SU which:

- Gets more overall interference.
- Generates more overall interference.
- Interferes more on the PU.

4.2.1 Switch "off" The SU Which Gets More Interference

As a first approach, we consider the case of switching off the user which gets more interference from the other users, including the primary. Having such an interfered user could be really harmful for the performance of the system, since the communication conditions for this user are not desirable.

At first glance we do not expect great results for this approach. Since we are dropping the most interfered user, it is easy to see that this improvement is not the best option for the uplink channel, as the interference for a user is more harmful while receiving (downlink).

For this simulation we assume the same conditions as the ones used for the first general simulation of the original code in section 3.2, since we consider that it is an appropriate environment for the study of our system.

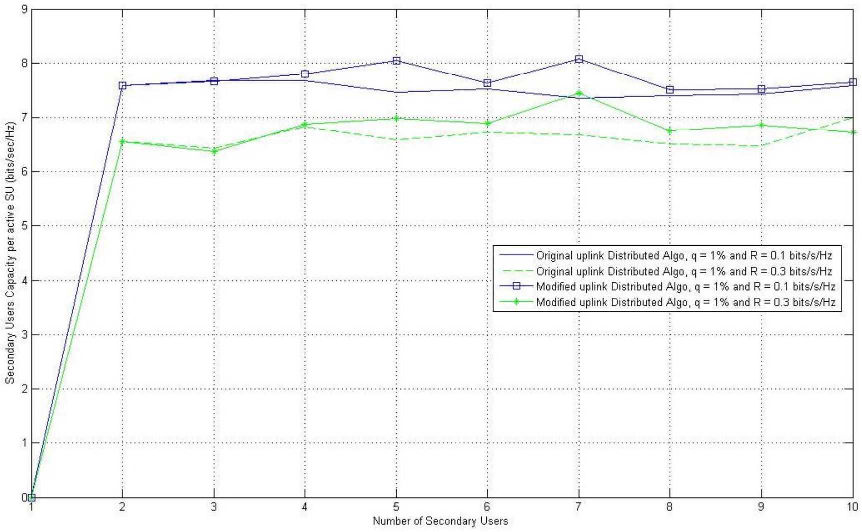

Figure 4.3: Capacity per SU vs Number of potential SUs, for both the original and the drop-the-most-interfered improvement algorithms using two rate values for each one.

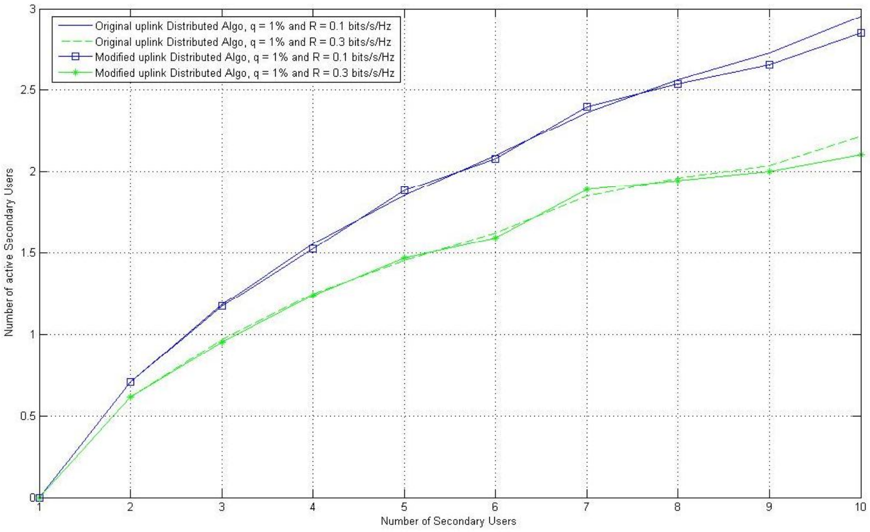

Figure 4.4: Number of active SUs vs Number of potential SUs, for both the original and the drop-the-most-interfered improvement algorithms using two rate values for each one.

As we expected, we did not obtain outstanding results. In fact, according to Fig. 4.4, the number of active SUs remains around the same values as with the original algorithm and in Fig. 4.3 we can see that the capacity per secondary user grows, but this increase is not very significant, even though we expected a better performance because of switching "off" the most interfered SU, what means, according to Eq. 3.4, deactivating a SU contributing with a low capacity to the system.

The behavior according with the rates does not present any important difference. As we explained in sub-section 3.2.1, the larger the rate for the primary user is, the worse behavior we will observe in our system. By taking a look at the theoretical development we presented in section 3.1, we can say that this is because of two reasons. For the first one we have to analyze Eq. 3.7, which was one of the main conditions of operation of our system. The reader would understand rapidly that with the increasing of R_{pu}, this operation condition is more difficultly achievable. Secondly, if we analyze Eq. 3.8 we can see that R_{pu} is one of the main factor for the theoretical limit of number of active SU. Observing the denominator, the reader will be able to see that the greater R_{pu} is, the more the denominator will increase, which is traduced at last in a decreasing on the theoretical limit for $\tilde{M}$, our theoretical limit for active SU.

4.2.2 Switch "off" The SU Which Generates More Interference

In contrast with the previous section 4.2.1, in this one we try disconnecting the user which generates more sum interference. It is quite logical to think that by disconnecting this user, the sum capacity of the SS as expressed in Eq. 3.5 can be increased since many of the individual capacities for SUs can grow. This fact is easy to deduce from Eq. 3.5 and Eq. 3.4 because, if we drop the most interfering user from $\sum_{j=1}^{M} p_j \left|h_{j,pu}\right|^2$ for each SU, all their SINR will be larger, what makes every SUs' capacity grow as well. Such growth in each SU's capacity would result into an overall increase of the SS throughput. Since the theoretical principles for this idea seem more reasonable, we expect even better results than the ones obtained in the previous section 4.2.1 assuming the same conditions.

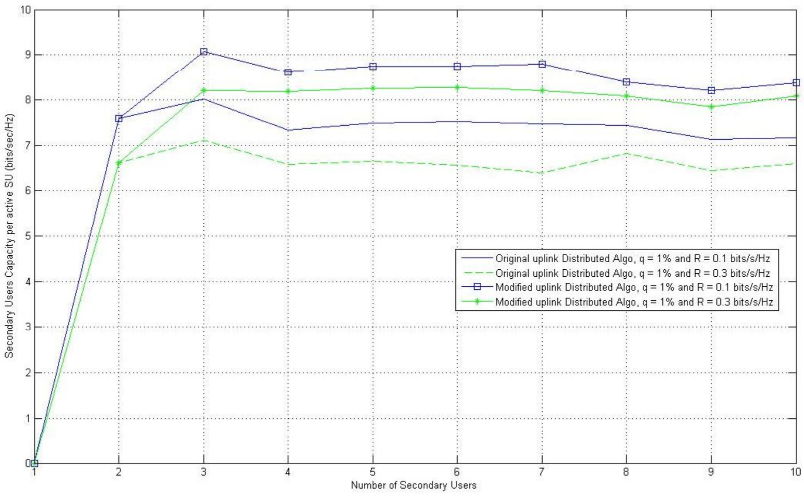

Figure 4.5: Capacity per SU vs Number of potential SUs, for both the original and the drop-the-most-interfering improvement algorithms using two rate values for each one.

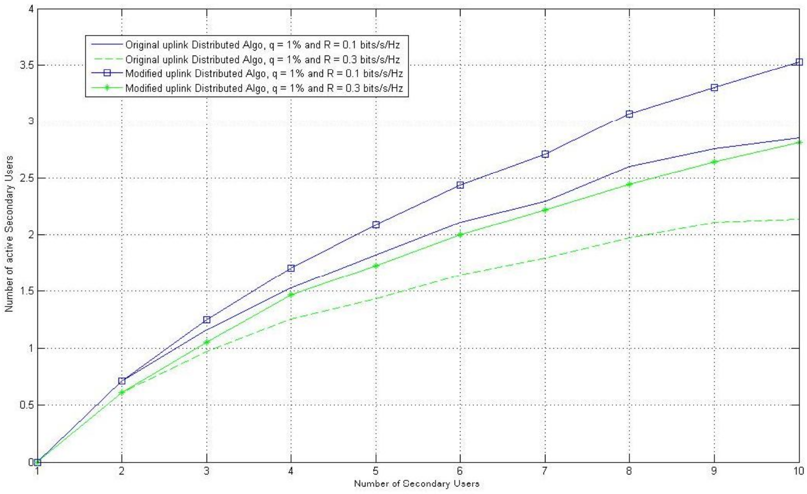

Figure 4.6: Number of active SUs vs Number of potential SUs, for both the original and the drop-the-most-interfering improvement algorithms using two rate values for each one.

As we expected, the improvement for this implementation is much greater, since the theoretical principles are stronger. Observing the graphs, we can see in some points an increase of 19 per cent over the original capacity for the lowest rate and around 22 per cent for the higher one in Fig. 4.5. Dealing with number of active users shown in Fig. 4.6, the percentage improvements are similar to the capacity ones. We can establish the improvement around a 20 per cent higher than the one obtained with the original code. Hence, an increase in both capacity per active SU and number of active SUs result into a huge improvement in the overall performance of the system.

Dealing with rates, all the assumptions made in section 4.2.1 are equally valid for this one. Apart from the facts proposed there, we can observe from the results of this last simulation that the whole behavior of our system, including capacity per SU and number of active SU, is better.

4.2.3 Switch "off" The SU Which Interferes More On The PU

As a last solution dealing with interference, disconnecting the SU which interferes the most on the PU arises as a possible approach. It does not seem to be any immediate reason to do this, but if we think about one of our main constraints, which is respecting the PU, this solution is logical. We already know that the desirable situation is having $C_{pu} \geq R_{pu}$, and the best way of achieving this is by simply increasing $\mathrm{SINR}_{\mathrm{pu}}$. The expression for $\mathrm{SINR}_{\mathrm{pu}}$ can be deduced from Eq. 3.2 as:

$$SINR_{pu} = \frac{p_{pu} \left|h_{pu,pu}\right|^2}{\sum_{j=1}^{M} p_j \left|h_{j,pu}\right|^2 + \sigma^2} \tag{4.1}$$

where j=1,...,M refers to the SUs in the system.

The fact is that our modified code departs with all the possible secondary users active, what forces the situation in which $C_{pu} < R_{pu}$, and disconnects SUs until the situation turns into $C_{pu} \geq R_{pu}$. From the equation 4.1 we can state that the only way[1] of increasing the PU's SINR and, therefore its capacity, is by reducing the interference on it. Moreover, we think that the optimal way of doing this is by switching "off" the SU which generates more interference on the PU because this will allow the system to reach $C_{pu} \geq R_{pu}$ by disconnecting the smallest number of secondary users.

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[1] Having already fixed the noise affecting the PU and the PU communication parameters (power and link gain).

Since the previous explanation for this idea seems the most reasonable, we expect the best results for it dealing with interference avoidance implementations, under the same conditions assumed for all the previous simulations. By simulating our modified code shown in section A.2.4, we obtain the following results:

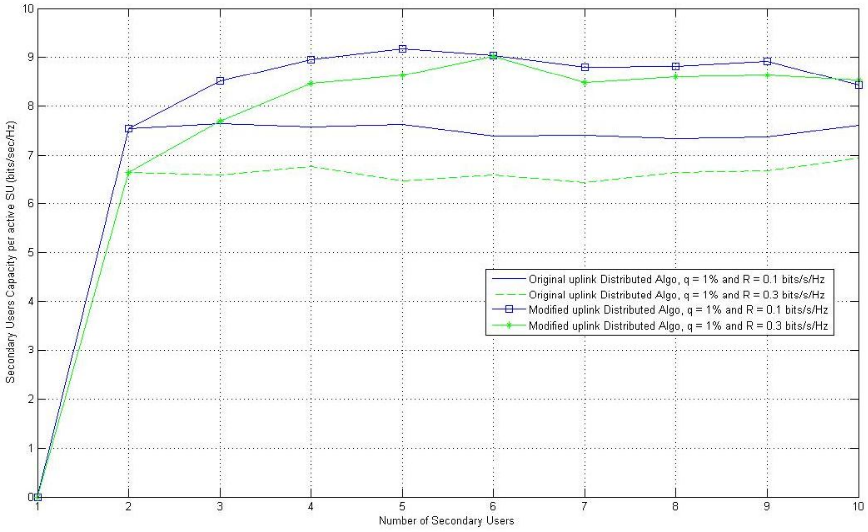

Figure 4.7: Capacity per SU vs Number of potential SUs, for both the original and the drop-the-most-interfering on PU improvement algorithms using two rate values for each one.

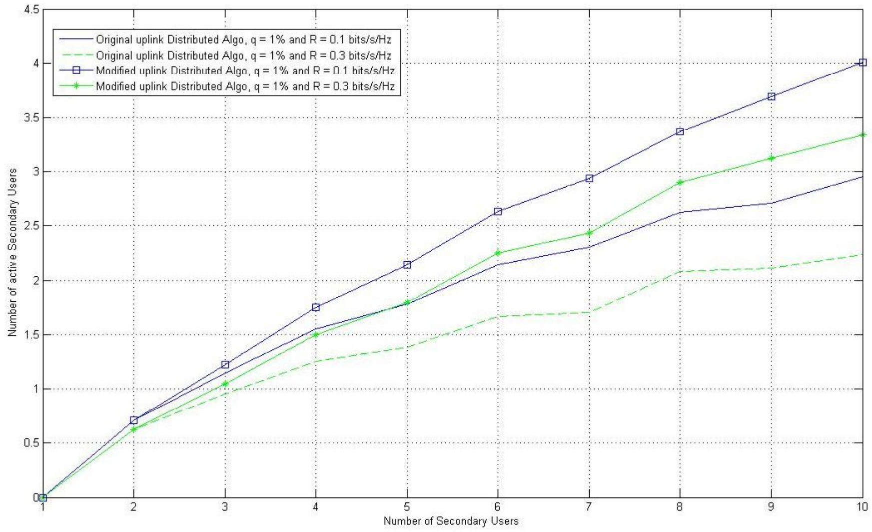

Figure 4.8: Number of active SUs vs Number of potential SUs, for both the original and the drop-the-most-interfering on PU improvement algorithms using two rate values for each one.

According to the theoretical analysis previously introduced in this section, this is the performance from which we expect the best results. As the reader can see in the graphs obtained, it has not disappointed us. Talking about capacity per user, from Fig. 4.7 we can set the average value of improvement near the 22 percent. At some points of the results we can observe improvements that are near to the 30 per cent, comparing of course with the original code implementation. As the reader can see, this improvements are really significant, which gives us an idea of the importance of the way of making the decision when we have to drop users. Observing in Fig. 4.8 the behavior of the system for the number of active SU, also a huge improvement in the performance can be observed. Thus, since these results entail a significant increase in both capacity per secondary user and number of active secondary users, we can state that this implementation performs outstandingly.

If we analyze the results for the different rates, we can not observe a huge difference between this implementation and the past ones, so we can consider all the assumptions made for them, avoiding as well the deep analysis in the difference of behavior between the different rates.

4.3 Discussion

As a result of our analysis and discussion about the original algorithm carried out in chapter 3, we considered important to introduce some improvements to the initial code.

If the reader analyses the general principles of the binary power control scheme introduced in section 3.1, it will be easy to see that one of its main features is that when we want to modify some parameters in order to accomplish our system constraints, a SU has to be switched "off". This guided us to think that the way of switching these users "off" is a really important issue for our system. According to this, some improvements to the original code were implemented and simulated.

The implementation of these improvements was mainly focused on two different points of view: according to interference and according to capacity. Dealing with theoretical basis, ideas related with dropping users because of their scarce capacity contribution or their excessive interference seemed to be reasonable to give us good results. This fact was stated when we obtained the graphs presented in sections 4.1 for capacity maximization and 4.2 for interference mitigation. Thus, for the capacity modification we observed in the figures included in 4.1 improvements near the 20 per cent, while in some cases of interference mitigation we reached improvements of a 30 per cent, talking about both active SU and capacity per each SU.

Improvements for interferences were performed for three different cases. Firstly we implemented the dropping for the user which received more interference from the other users. The improvements with this implementation are significant, achieving values between 5 and 15 per cent for the parameters under study as we can see in Fig. 4.3 and Fig. 4.4. However, the best results were obtained with the other two implementations, dropping the user which generates more interference and dropping the one who generates more interference on the PU. With the former, improvements of near the 25 per cent in the capacity for SUs and almost the same values for the number of active SUs are obtained according to Fig. 4.5 and Fig. 4.6. With the later, without any doubt the star of our improvements, we reached values higher than a 30 per cent for the capacity per SU at some points in Fig. 4.7, and almost 30 per cent for the number of active SU according to Fig. 4.8. Both increases together lead us to a system with a really outstanding performance. As the reader can imagine, talking about a communication system, in capacity this can represent an incredible difference.

As in past sections, a hexagonal cellular system functioning at 1.8 GHz is considered for the simulations. Secondary transmitters may communicate with their respective receivers of distances $d < Rp$ from the BS. Channel gains are based on the COST-231 path loss model in [14], including log-normal shadowing with standard deviation of 10 dB, plus fast-fading assumed to be i.i.d. circularly symmetric with distribution $CN(0, 1)$.

Chapter 5

Channel Information Imperfectness In Spectrum Sensing

All over our previous work, we have assumed that no error was present while sensing the channel state. That is why, across this chapter, we are looking for a more realistic approach concerning with this fact. More specifically, we consider the error during the acquisition of the link gain value, while deciding whether a SU can be active or not.

5.1 Introduction To Spectrum Sensing And Its Associated Error

Spectrum Sensing in CR is, according to [15], detecting the unused or not sufficiently used spectrum and share it without harmful interference with other users. Spectrum sensing techniques can be classified into three categories as it is shown in the next figure:

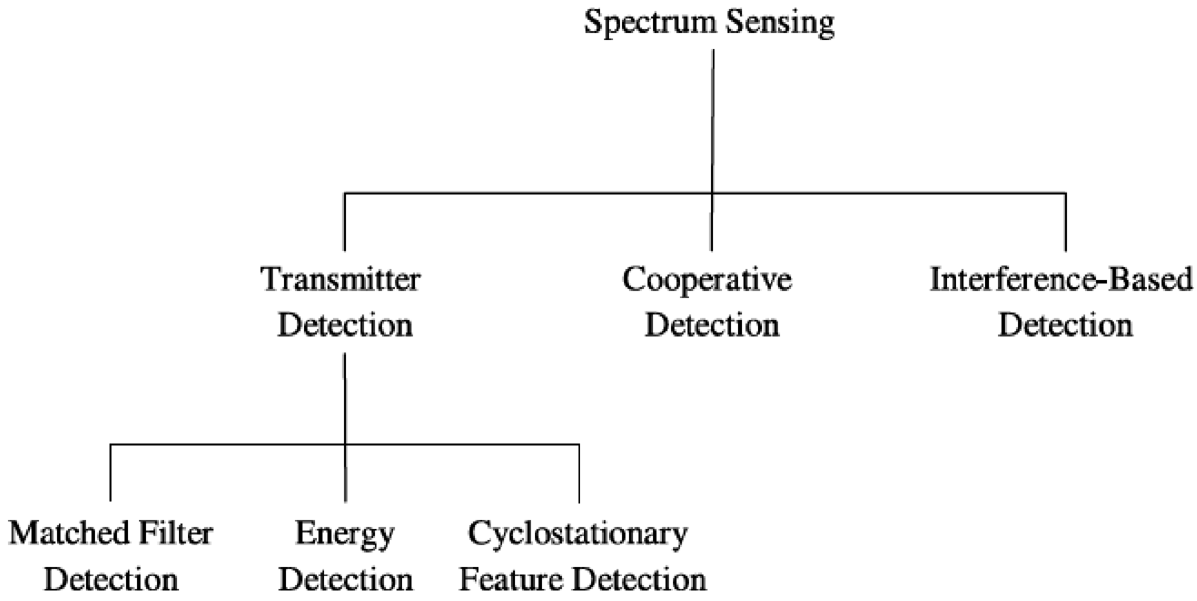

Figure 5.1: Different spectrum sensing techniques.

As it happens with every measurement, when a SU senses its link to check the channel state and decide whether to transmit or not, there is also an inherent error associated to this action. To apply this realistic fact to our previous work, we followed the research on the topic in [16], where two different error models (Zero-mean log-normal random variable and Zero-mean Gaussian random variable) are used to check how channel information imperfectness affects the performance of the system. Moreover, we want to underline that,according to [?], this acquisition of CSI can be affected by both magnitude and temporal errors, but we will only assume the presence of the magnitude error.

5.1.1 Error Models

As we mentioned before, we will introduce two different error models into the original Distributed Uplink Binary Power Allocation Algorithm for CR and see the difference between the ideal[1] and the realistic performance, as well as comparing the effect of both error models under the same system conditions. Therefore, we firstly introduce the reader

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[1] Ideal in terms of CSI.

to the principles of both error models in order to make the modifications on the original algorithm code understandable.

5.1.1.1 Log-normal Distribution

As it is said in [16] with reference to [18, 19, 20, 21], we can model the link gain measurement error as a log-normal random variable $\varepsilon_{n,j}$ with $E(\varepsilon_{n,j}) = 1$. Thus, we can express a link gain including this multiplicative error as follows:

$$\hat{G_{n,j}} = \varepsilon_{n,j}.G_{n,j} \tag{5.1}$$

where $\hat{G_{n,j}}$ represents the estimated link gain including error.

From this expression and knowing from [22] that $\log \varepsilon_{n,j}$ results in a normal random variable $\varepsilon_{n,j}^{(dB)}$, we can then see the previous expression of the estimated scalar link gain with additive error as:

$$\hat{G}_{n,j}^{(dB)} = G_{n,}^{(dB)} + \varepsilon_{n,j}^{(dB)} \tag{5.2}$$

where $\varepsilon_{n,j}^{(dB)}$ refers to a Gaussian (normal distributed) random variable with zero-mean and variance $\sigma^2_{\varepsilon_{n,j}}$ and ${G^{(dB)}}_{n,j}$ is the link gain in dB.

Therefore, as we proved before, we can say that a multiplicative log-normal error and an additive Gaussian error are equivalent for the scalar and the logarithmic expression of the link gain respectively.

In addition to this, it is important to underline that Eq. 5.1 implies a direct relationship between error and gain since the magnitude of the measurement error will be strongly dependent of the link gain magnitude.

5.1.1.2 Gaussian (Normal) Distribution

From [?] we can assume that the link gain error can be estimated as an independent Gaussian random variable $\varepsilon_{n,j}$ with zero-mean and variance $\sigma^2_{\varepsilon_{n,j}}$, what leads to the expression of the estimated link gain with an additive error in absolute value as follows:

$$\hat{G}_{n,j} = G_{n,} + \varepsilon_{n,j} \tag{5.3}$$

By taking a look into this equation and according to [16] it is easy deductible that the estimated gain $\hat{G_{n,j}}$ is only affected by the value of the error itself independently of the actual gain $G_{n,j}$. Moreover, it is also important to realise that, due to the randomness of $\varepsilon_{n,j}$, this expression of $\hat{G_{n,j}}$ could lead to negative values even if the original $G_{n,j}$ is positive. Whenever this happens in practice, we assume a value above 0 but really small ($\xi = 10^{-20}$) in such a way that the error distribution turns into a truncated Gaussian distribution.

5.2 Results

In this section, our main goal is to give the reader a more realistic view of the behavior of a CRS in which the original Binary Power Allocation scheme is implemented, by taking into account new factors that we did not consider in the previous ideal simulations. More specifically, what we have done is to introduce the concept of channel state information imperfectness. The real meaning of this concept for the algorithm arises while a SU is acquiring information about the channel gain.

Taking a look at section A.3, where the modifications done for this purpose to the original code are shown, it is easy to understand how this effect can affect to a cognitive radio system behavior.

The channel gain for each user link is calculated, according to the COST-231 path loss model in [14], as follows[2]:

$$\begin{cases} G_{ch} = L_{prop} + L_{shadowing} + 20\log h - G_{tx} - Grx & \text{logarithmic expression} \\ g_{ch} = 10^{(-G_{ch}/10)} & \text{linear expression} \end{cases} \tag{5.4}$$

---

[2] Including log-normal shadowing with standard deviation of 10 dB, plus fast-fading assumed to be i.i.d. circularly symmetric with distribution CN(0, 1).

Depending on the type of error distribution used, we have to add the error parameter either in linear (for additive Gaussian error) or logarithmic (for multiplicative log-normal error) including the error as shown in the next equations:

$$\begin{cases} G_{ch} = L_{prop} + L_{shadowing} + 20\log h - G_{tx} - Grx + \varepsilon_{n,j}^{(dB)} & \text{for multiplicative log-normal error} \\ g_{ch} = 10^{(-G_{ch}/10)} + \varepsilon_{n,j} & \text{for additive Gaussian error} \end{cases} \tag{5.5}$$

To be even more precise, we consider fundamental to give to the reader a proper explanation of the real conditions in where the error is introduced to our scenario. For every simulation, the original code creates a network with a primary user and M potential secondary users. The former is connected to a main BS and the latter have a secondary receiver each. Then, during the simulation we have to calculate several things that can be processed either with the ideal information or with the real one. It is obvious that for having a more realistic approach we have to choose the moments for using ones or the others.

For this simulation we will focus in the channel gain information acquisition. The process followed for the realistic approach is developed as follows. Once we have the mentioned network, we have to calculate both the actual[3] and the estimated[4] gain matrix, which represents the link gain among all the users in the network. Then, we will use the estimated for making all the decisions about switching “off” the users, but we will obtain the rest of the results (capacity per active SU and number of active SU) with the actual values. This fact will be normally traduced in a decreasing of the capacity and the secondary users.

5.2.1 Results For Log-normal Distributed Error

According to what we said in the introduction of this section and the theoretical principles shown in sub-section 5.1.1.1, a multiplicative log-normal error in linear scale is totally equivalent to an additive error in logarithmic scale with a Gaussian distribution.

---

[3] Without CSI error

[4] Including CSI error

For our implementation and the subsequent simulation we use the second option, expressed by the formula in the upper part of Eq. 5.5.

By introducing this concept into the code in (A.3.1), we obtain the results shown in the next figures. All the following simulations have been carried out under conditions that we consider normal for a cognitive system network. The values for the parameters are the same as the ones used for all the previous simulations, and we present the results for three different values of users fixed to 5, 10 and 15.

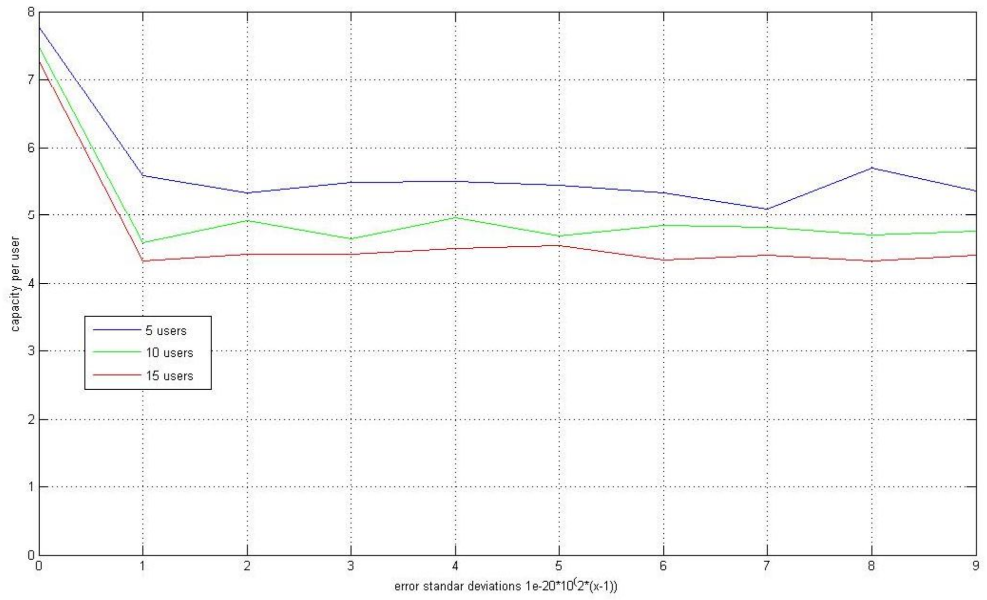

Figure 5.2: Capacity per SU vs error standard deviation of multiplicative log-normal distributed error, for 3 different values of potential users.

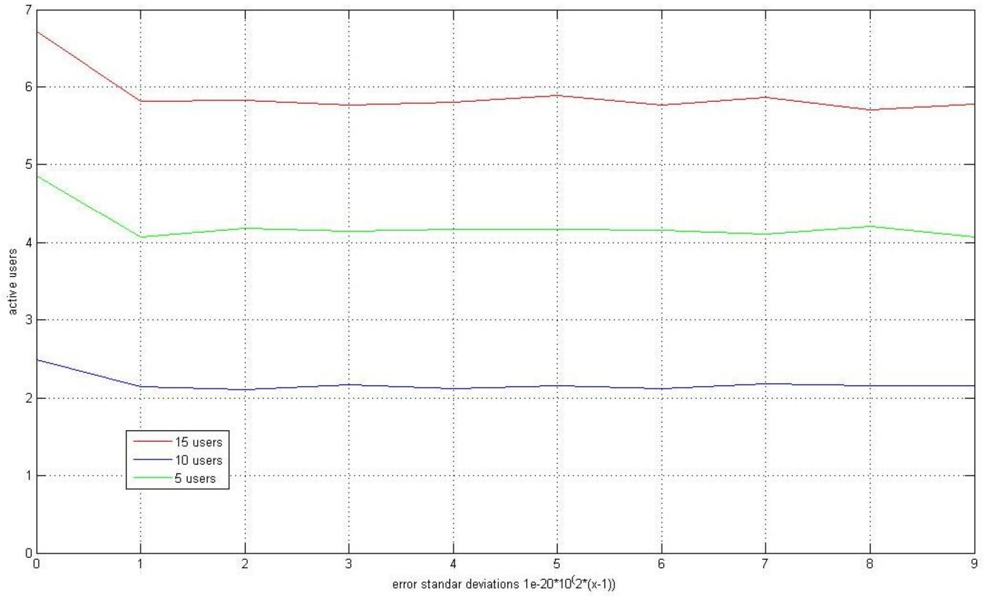

Figure 5.3: Number of active SUs vs error standard deviation of multiplicative log-normal distributed error, for 3 different values of potential users.

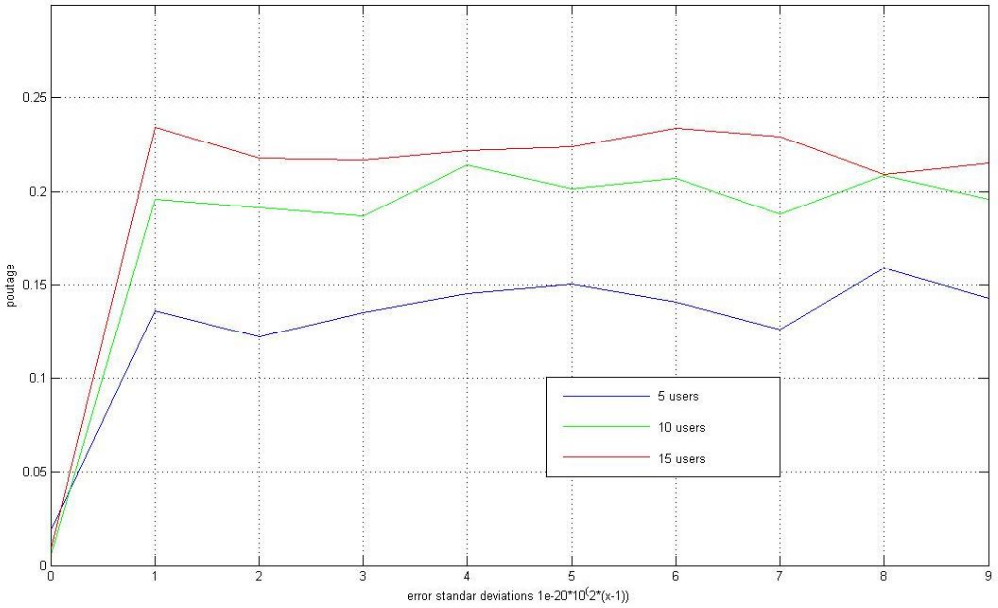

Figure 5.4: Outage probability vs error standard deviation of multiplicative log-normal distributed error, for 3 different values of potential users.

As we said, it was completely necessary for the reader to achieve a better comprehension of the behavior of our algorithm to perform some simulations under more realistic conditions. The reader could appreciate substantial changes for the results obtained either with or without error in channel information acquisition.

Talking about capacity per user we can observe in Fig. 5.2 changes of almost 30 per cent for the simulations with 5 users, reaching values near to 40 per cent of the original results for the simulation with 15 users. Lower differences are observed dealing with the number of active users shown in Fig. 5.3, in where the values for all simulations are around 14 per cent lower than the ideal case.

These changes, as the reader can imagine, especially if we consider them all together, represent a huge difference in comparison with the ideal conditions, which can guide us to think that maybe this is a really important issue to take in account when a realistic approach wants to be given.

Another important parameter to be analysed is the outage probability, according to which most of the decisions made along the code are based. This parameter is presented in Fig. 5.4, and as it shown there, it represents the percentage of the time that our system is not working properly, or what is the same, the percentage of the time our system is down. As it can be observed there, this value moves in a range between around 14 per cent for 5 users and 25 per cent for 15 users. These results are really interesting for our analysis, since they drop quite unacceptable values for non ideal conditions. It is clear that a real system can not be out of order a quarter of the time it is supposed to be working. This guide us to think , as it will be discussed in section 6.2, that this is a really important issue to be investigated and developed, in order to achieve a real implantation of the system of study in this thesis.

5.2.2 Results For Gaussian (Normal) Distributed Error

As a second approach, we consider a Gaussian distributed error. As we introduced in Sec. 5.1 and according to the theoretical principles shown in sub-Sec. 5.1.1.2, a Gaussian distributed error can be directly added to the actual link gain to obtain a more realistic approach as it is shown in the lower part of the expression 5.5.

By introducing this concept into the code in (A.3.2) and simulating under conditions that we consider normal for a cognitive system (same values as used in the simulation for the multiplicative log-normal error), we obtain the results shown in the next figures:

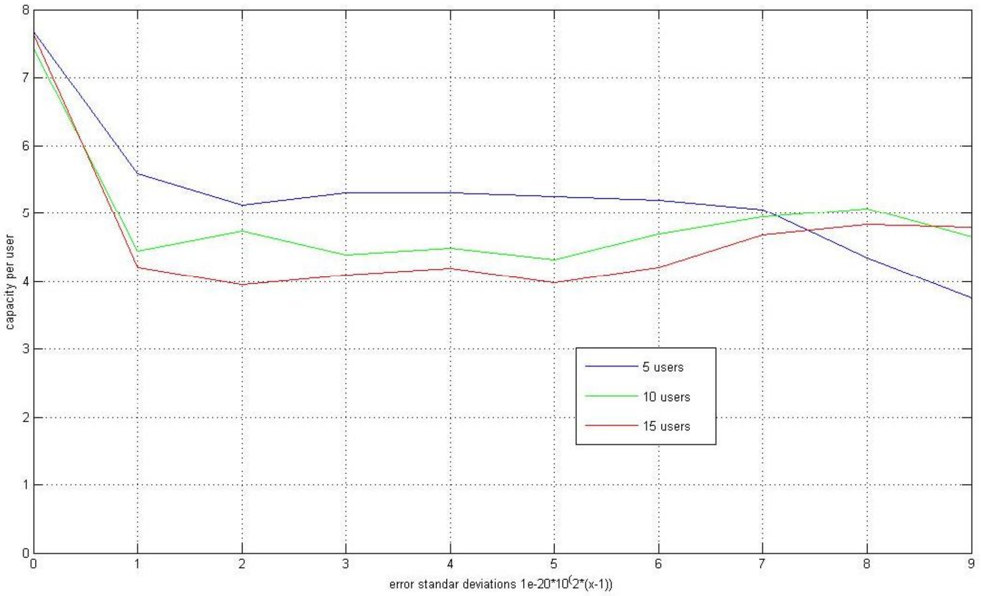

Figure 5.5: Capacity per SU vs error standard deviation of additive normal distributed error, for 3 different values of potential users.

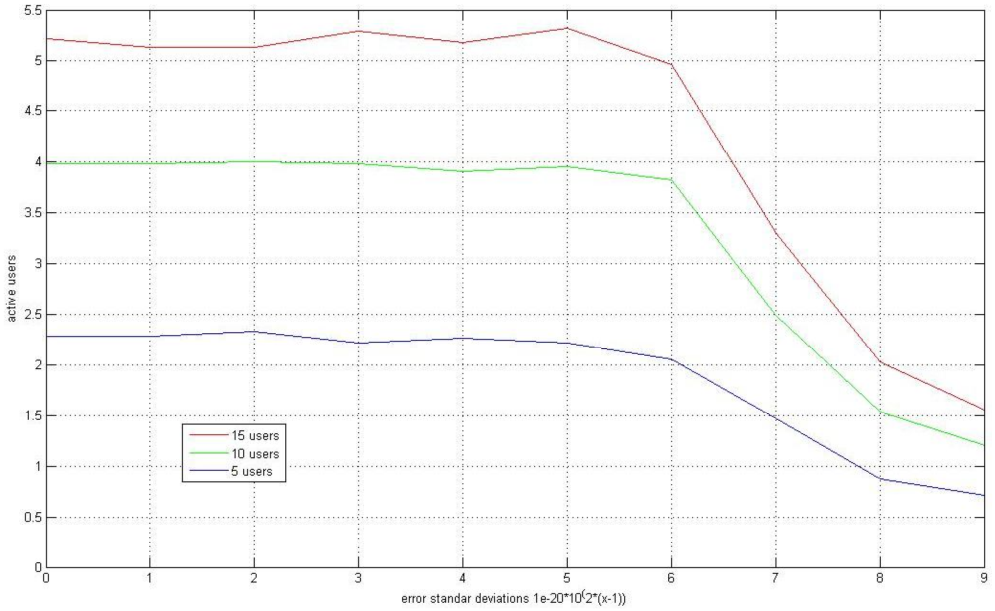

Figure 5.6: Number of active SUs vs error standard deviation of additive normal distributed error, for 3 different values of potential users.

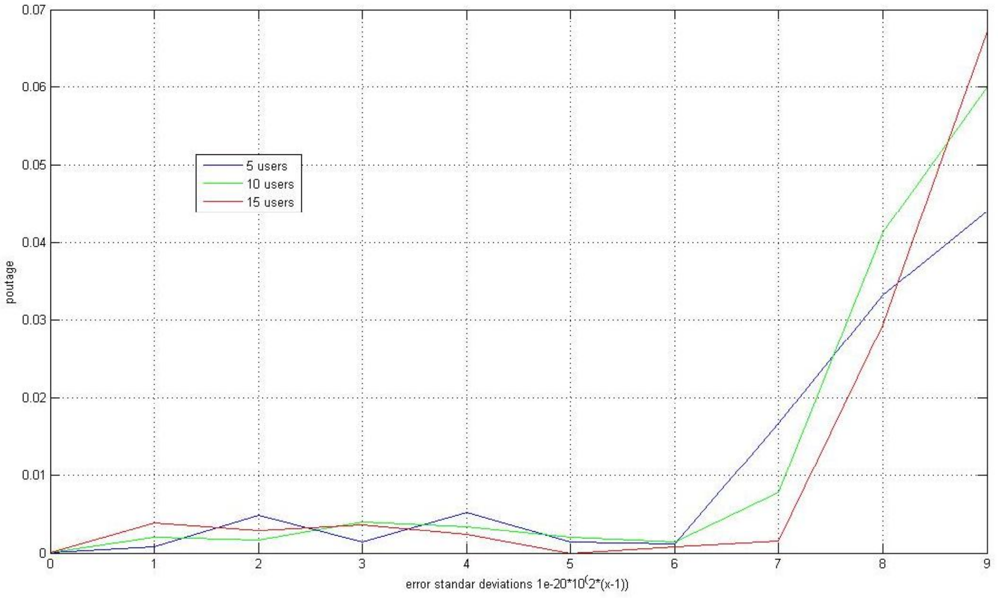

Figure 5.7: Outage probability vs error standard deviation of additive normal distributed error, for 3 different values of potential users.

From the results obtained in this section, and comparing them to the ones shown in sub-section 5.2.1, we can reach some interesting conclusions. First of all, dealing with capacity, the results obtained are quite similar compared to the ones obtained with the log-normal distributed error, with values fluctuating between a 30 per cent value in the 5 user simulation and a 40 per cent for the 15 one. However, in this results the curve obtained is more similar to the one expected. Results previously commented are presented in mean but the capacity goes decreasing while the variance value for the error gets a higher value, as it can be observed in Fig. 5.5.

Dealing with the number of active users, this study begins to be in some way critical. Although we observe a relative normality and stability for the first values of variance, the lower ones, the graphs in Fig. 5.6 show that, when this value increases, the decrease on the number of active users is more evident and exponential, reaching values that are in extreme cases more than a 60 per cent under the ones obtained under ideal conditions. As we said in the previous paragraph, these results are more similar to the ones that we expected, since they show a decrease on the communication parameters while the error variance grows.

As we did before, here it is really interesting to analyze the outage probability parameter for the results obtained, shown in Fig. 5.7. As it happened for the number of active SUs, the system presents an implicit robustness for low values of this kind of error. However, when the variance value begins to grow, this error seems to be more harmful to the operation of the system, not reaching though levels above 7 per cent for the range of variances under study. This value is more approximate to an acceptable condition of operation but it is not still valid. Apart from this, we have to consider some other factors, as the normal conditions for a communication system, in where the values of variance will not be so high. This fact will be discussed in section 5.3.

5.3 Discussion

As shown in sections 5.2.1 and 5.2.2, some interesting results have been obtained, with the main goal of giving the reader a real approach to the behavior of our algorithm. Both noise types studied turned out to be really harmful to our system. This guides us to think, as said before, that the correction of these error in the acquisition has to be one of the main issues in future researches.

However, it is also interesting to compare the behavior of both cases. The system has turned out to be more robust, in general terms, against Gaussian than against the log-normal distributed error. As commented in sections 5.2.1 and 5.2.2, the former is more constant in being harmful, since the results obtained are similar with all variances even with really high values of this parameter, while for the latter the behavior of the system is really good for low values of variance but as this value increases, the system becomes unstable. However, if the reader takes a look at the values under study, it is easy to realise that the values for which this behavior is unstable are not real values, since they are so great in comparison with normal conditions for a communication system.

If we take the previous comments into account, and analyze the results obtained in section 5.2.2, we can say that the binary power allocation algorithm is really strong against error with Gaussian distributions, since up to the point in where values for variance gets unreal we observe a decrease of less than 10 per cent for both capacity and number of active users and the outage probability reveals that the system is working almost 100 per cent of the time. On the contrary, it is obvious that the system has revealed itself really weak when we take in account some log normal distributed error, being unstable even for real values of variance in normal communications. Because of this, as we will mention further on, maybe this is one of the main issues to study in further researches dealing with binary power control allocation.

Chapter 6

Conclusions

In this chapter we will slightly review the results obtained in the previous chapters, as well as pointing out the main consequences and conclusions deduced from them.

6.1 Main Results And Conclusions

In chapter 3 we simulated the original Binary Power Allocation Algorithm with changing the different parameters involved in the system performance in such a way that we checked the behavior of the network under normal and extreme conditions. As we already said in all of the sub-sections (in chapter 3) dealing with each of the parameters, most of the simulations performed as we expected as the different parameters were changed, so we will not say to many things about this results though we will point out the robustness of the algorithm since the behavior of the systems, observed in the different plots, is quite regular and does not have any aggressive change.

Besides this, in chapter 5, we tried to introduce different distributions to model the channel state information error and try to see how this error affects the normal behavior of the system. Thus, we obtained some results although they are not really significant and we did not focus too much on this since it was not the main goal of this Thesis. Hence, we encourage further researchers to study this fact deeply, as we will comment in section 6.2.

Apart from the previous experiments, which were result of our intellectual curiosity and lack of previous researches in this field, we were really interested in improving the original scheme in order to help the original authors of the algorithm and so we did.

Thus, dealing with the different variations developed to improve the original code, we achieved really outstanding results. As we mentioned in chapter 4, all the different improvements we applied to the original code gave better results, what means a real success. Furthermore, if we take a look more thoroughly to the results obtained, we will realise that some of them do not entail great increases in the measurements, some of them perform quite well and some others are really outstanding. For instance, if we observe Fig. 4.3 and Fig. 4.4 for the "drop the most interfered" interference mitigation method, we realise that the values of both capacity per SU and number of active SUs respectively remain around the same values as the ones from the original algorithm. In contrast, by introducing the "drop the most interfering" interference mitigation method, we obtain better results compared to the original code, reaching increases of around 20% for both capacity per SU and number of active SU, according to Fig. 4.5 and Fig. 4.6 respectively. Moreover, with the capacity maximization method we achieved improvements around 25% for the capacity per SU, as shown in Fig. 4.3 but we did not see, in Fig. 4.4, any difference between this method and the original while dealing with the number of active SUs. Finally, we have a especial mention for the "drop the most interfering on the PU" interference mitigation method. Even we did not expect to obtain such good results, this variation turned out to be the most outstanding one, presenting huge increases in both capacity per SU and number of active SU. As we can see in Fig. 4.7, an average increase of approximately 22% on the original capacity per SU is achieved, while at some points this value reaches almost 30%. Dealing with the number of active SUs, by taking a look at Fig. 4.8 we can say that the difference between the original code and our improvement is even bigger than the difference noticed in capacity. Thus, we can strongly state that this last improvement performs really well and made of this research a really successful experience.

To finish with the conclusions, we will just point out another important issue accomplished by some of our improvements. If we take a look at the figures dealing with number of active SUs for both interference mitigation methods included in Sub-Sec. 4.2.2 and Sub-Sec. 4.2.3, the reader can realise that the difference between the original and the improved results become bigger as the number of potential SUs is bigger, what means that these methods can be even better in more populated networks. This fact together with the previously mentioned results make of our implementations really good options to deploy a cognitive radio network not only because of this results, but also due to the relative simplicity of the concepts involved.

6.2 Future Work

Due to the actual spectrum scarcity, it is clear that the future of wireless communications is the development of new systems that can optimize the spectrum utilization in order to correct this scarcity. In this context, cognitive radio has important things to say, since it is giving proper results in communications while achieving a much proper spectrum usage.

Hand in hand with cognitive radio comes binary power allocation, which has turned out to be probably one of the most optimum protocols to implement in this emergent technology. Along this thesis we have tried to give the reader a general idea of the behavior of this protocol. However, it has to be tested deeply, especially in some issues like the number of potential users, since it takes a huge computational cost to simulate for great amounts of this key parameter, only achievable with really powerful machines. For instance, we wanted to check the behavior of our improvements (specifically the ones in sub-sections 4.2.2 and 4.2.3) in a system with a large number of potential users, since in the plots shown form them we can see that the difference between their behavior and the original can become even bigger as the number of potential users increases.

Apart from this fact, and in order to make this system more realistic, it turns essential to test it under conditions in which we have more than one primary user, since the actual real conditions are considering this situation in the same cell and frequency bands.

Along this project, some weaknesses of the binary power control allocation protocol have been shown, such as its instability under channel state error conditions. As we said before, since this is a real problem when dealing with wireless communications, it has to be treated deeply if we want to turn a possible project in to a reality for the future communications, a future in where the spectrum scarcity could lead us to the introduction of emergent technologies such as cognitive radio.

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Appendix

In this appendix we only include some of the great amount of code we have work with during the development of this thesis. We consider that many of these codes are important for the reader to understand how the original algorithm works and how we have modified it in order to analyze its performance or apply our improvements.

A.1 Matlab Codes For The Original Binary Algorithm

In this section of the appendix we show the codes for the most important files while simulating our system: “main.m” in which the general structure of the execution is set, and “distalgoCRuplink.m” in which the BPA scheme is actually accomplished. Apart from this two codes, we also introduce the code to expound how the channel gain is calculated. This is important because in (A.3) we have some codes including error and across error introduction, the channel gain calculation file is very important and we want the reader to be able to notice the difference between this code and the ones in (A.3.1.2) and (A.3.2.2).

A.1.1 Original main.m

```
clear
clc
tic

%%%%%%%% cell parameters %%%%%%%%%%
R = 1000; % Outer radius of primary cell in meters
R_p = 600; % interference protection radius of primary cell in meters
alpha = 300; % interference protection radius of secondary Transmitter in meters
U_max = 11; % Max number of Users (PU+SUs)
Rate1 = .1;
Rate2 = .3;
Rate3 = .5;
q1 = .01;

for U = 2:U_max %in minimum we have 1 PU + 1 SU = 2

    boltz_const = 1.3806503*10^(-23);
```

```
    T_0 = 290; % ambient temperature in kelvins
    B = 1*10^(6); % equivalent bandwidth 1MHz

    %%%%%%%%%%% Propagation parameters %%%%%%%%%%%%
    maxBTStxPower_mW = 1000; %Pmax in mW
    maxBTStxPower_dBm = 10*log10(maxBTStxPower_mW); % Max.  BTS transmission power
in dBm for 1 W
    Gtx = 16; %Tx antenna gain in dB
    Grx = 6; % Rx antenna gain in dB
    thermnoisemW = boltz_const*T_0*B*1000; % thermal noise power in mW = N0 * B
    therm_noise_dBm = 10*log10(therm_noise_mW); % thermal noise power in dB
    d_Comb_CAP_sys = 0;
    Comb_CAP_sys=0;
    G = 4.5386e-010; %avg over all users
    SNR_avrage_mW = G * maxBTStxPower_mW / thermnoisemW;
    SNR_avrage_dBm = 10 * log10(SNR_avrage_mW);
    SNR_avrage_dB = SNR_avrage_dBm - 30;
    mc_it_max = 1e3;

    for mcit = 1:mc_it_max
        U
        mc_it


        gainmatrixuplink = channelgain_CR_uplink(R, R_p, U, alpha);
        %%%%%%%%% Received power from all possible transmissions %%%%%%%%%
        rxpwrmWuplink = maxBTStxPower_mW * gainmatrixuplink;


        [GDDACAPsys1(mcit), GDDAonusers1(mcit), ratioonSU1(mcit), dcellcombintpwr1(mcit)]
= distalgoCRuplink(gainmatrixuplink,rxpwrmWuplink,thermnoisemW, U,Rate1,q1,1);
        [GDDACAPsys2(mcit), GDDAonusers2(mcit), ratioonSU2(mcit), dcellcombintpwr2(mcit)]
= distalgoCRuplink(gainmatrixuplink,rxpwrmWuplink,thermnoisemW, U,Rate2,q1,1);
        [GDDACAPsys3(mcit), GDDAonusers3(mcit), ratioonSU3(mcit), dcellcombintpwr3(mcit)]
= distalgoCRuplink(gainmatrixuplink,rxpwrmWuplink,thermnoisemW, U,Rate3,q1,1);
    end
    avg_gd_dist_cap1(U) = mean(GD_DA_CAP_sys1);
    avg_gd_dist_cap2(U) = mean(GD_DA_CAP_sys2);
    avg_gd_dist_cap3(U) = mean(GD_DA_CAP_sys3);

    avg_gd_dist_on_users1(U) = mean(GD_DA_on_users1);
    avg_gd_dist_on_users2(U) = mean(GD_DA_on_users2);
    avg_gd_dist_on_users3(U) = mean(GD_DA_on_users3);
end
```

```
figure %capacity
plot([1:U_max-1], avg_gd_dist_cap1([1:U_max-1]),'b-')
hold on
plot([1:U_max-1],avg_gd_dist_cap2([1:U_max-1]),'g--')
plot([1:U_max-1],avg_gd_dist_cap3([1:U_max-1]),'k-.')

grid
xlabel('Number of Secondary Users')
ylabel('Secondary Users Capacity per active SU (bits/sec/Hz)');
legend('uplink Distributed Algo, q = 1% and R = 0.1 bits/s/Hz',...
'uplink Distributed Algo, q = 1% and R = 0.3 bits/s/Hz',...
'uplink Distributed Algo, q = 1% and R = 0.5 bits/s/Hz')


figure
plot([1:U_max-1],avg_gd_dist_on_users1([1:U_max-1]),'b-')
hold on
plot([1:U_max-1],avg_gd_dist_on_users2([1:U_max-1]),'g--')
plot([1:U_max-1],avg_gd_dist_on_users3([1:U_max-1]),'k-.')

grid
xlabel('Number of Secondary Users')
ylabel('Number of active Secondary Users')
legend( 'uplink Distributed Algo, q = 1% and R = 0.1 bits/s/Hz',...
'uplink Distributed Algo, q = 1% and R = 0.3 bits/s/Hz',...
'uplink Distributed Algo, q = 1% and R = 0.5 bits/s/Hz')

toc
```

A.1.2 Original distalgoCRuplink.m

```
function [CAPSU, nbonSU, ratioonSU, dcellcombintpwrSU] =
distalgoCR(gainmatrix,...
rxpwrmW,thermnoisemW,U,Rate,q,PBS);

% The vector P is initialized by ones (i.e., all users are supposed to be
% on).  We then compute the threshold depending on all the SINR we got.  We put the
% user "on" or "off" and compute the capacity with respect to the new
% vector P.
% U = total number of users (PU+SUs)
% Rate = Transmission rate
% q = outage probabilty.
% PBS = ratio between PBS and P_su especified in "main.m"

d_on_set(1,:)  = ones(1,U);
d_on_set(1) = PBS;
```

```
it_max = 20;
d_Comb_CAP_SU = zeros(1,it_max);
it_convergence = 5;

for it = 1:it_max
    nb_users = length(d_on_set(it,:));
    d_no_on_users(it) = sum(d_on_set(it,2:nb_users)==1);
    for u = 2:U
        d_on_set;
        d_sum_int(u) = 0;
        for m = 1:U
            if m ~= u
                d_sum_int(u) = d_sum_int(u) + gain_matrix(u,m)*d_on_set(it,m);
            end
        end
        d_gain_ratio(it,u) = gain_matrix(u,u)/d_sum_int(u);
        d_cell_ratio(it,u) = ((d_no_on_users(it))/(d_no_on_users(it)-1))^...
(d_no_on_users(it)-1);
        if (abs( log2(1 + d_gain_ratio(it,u)) - d_gain_ratio(it,u)) ) < 1e-3
            %disp('low SNR')
            if d_gain_ratio(it,u) < 1
                d_on_set(it,u) = 0;
            else
                d_on_set(it,u) = 1;
            end
        else %disp('high SNR')
            if d_gain_ratio(it,u) < d_cell_ratio(it,u)
                d_on_set(it,u) = 0;
            else
                d_on_set(it,u) = 1;
            end
        end
    end
    d_on_set(it+1,:)  = d_on_set(it,:);
    d_no_it = it;
    if it >= it_convergence
        if d_on_set(it,:)  == d_on_set(it-it_convergence+1,:)
            break
        end
    end
end

nb_users = length(d_on_set(1,:));
nb_on_SU = sum(d_on_set(1,2:nb_users)==1);
Pout = 0;
```

```
while(nb_on_SU > 0)
    for it = 1:d_no_it
        nb_users = length(d_on_set(it,:));
        nb_on_SU = sum(d_on_set(it,2:nb_users)==1);
        for u = 1:nb_users
            d_cell_comb_int_pwr(u) = 0;
            for m = 1:nb_users
                if m ~= u
                    d_cell_comb_int_pwr(u) = d_cell_comb_int_pwr(u) + ...
                    rx_pwr_mW(u,m)*d_on_set(it,m);
                end
            end
            d_cell_comb_SINR(it,u) = rx_pwr_mW(u,u) * d_on_set(it,u)/...
            (therm_noise_mW + d_cell_comb_int_pwr(u));
            d_cell_comb_CAP(it,u) = log2(1 + d_cell_comb_SINR(it,u));
        end
    end
    cap = d_cell_comb_CAP(it,:);
    nb_users = length(d_on_set(it,:)); %number of users is taken from
                                        the last iteration (it=d_no_it)
    nb_on_SU = sum(d_on_set(it,2:nb_users)==1);
    if nb_on_SU == 0%no SU can Tx
        d_Comb_CAP_SU = 0;
        Pout = 0;
        break
    end
    Pout = probab(d_cell_comb_CAP(:,1), Rate);
    if Pout <= q
        d_Comb_CAP_SU = sum(d_cell_comb_CAP(it,2:nb_users))/nb_on_SU;
        break
    else nb_users = nb_users - 1; %here we can choose the worst user to be deleted
in term of his interference contribution to the PU
        nb_on_SU = nb_on_SU - 1;
        if nb_on_SU == 0 %no SU can Tx
            d_Comb_CAP_SU = 0;
            Pout = 0;
            d_on_set = d_on_set(:,1); %there a no more SU in d_on_set
            break
        end
        for cc = 1:size(d_on_set,1)
            index_on_row(cc,:)  = find(d_on_set(cc,:));
            index_on = index_on_row(cc,1:end-1);
            temp(cc,:)  = zeros(1,nb_users);
            temp(cc,index_on) = 1;
            temp(:,1) = PBS;
            clear index_on_row
```

```
        end
        d_on_set = temp;
        clear temp;
    end
end

ratio_on_SU = nb_on_SU/(nb_users-1);
nb_on_SU;
CAP_SU = d_Comb_CAP_SU;

if nb_on_SU ~= 0
    d_cell_comb_int_pwr_SU = sum(d_cell_comb_int_pwr)/nb_users; %average interf.
else                                                            per user
    d_cell_comb_int_pwr_SU = 0;
    CAP_SU = 0;
end
```

A.1.3 Original channelgainCRuplink.m

```
function cg = channelgain_CR_uplink(R, R_p, U, alpha)


Gtx = 16; % Tx antenna gain in dB
Grx = 6; % Rx antenna gain in dB
mu = 0; % Mean for lognormal shadowing
sigma = 10; % S.D. for lognromal shadowing


[x,y] = PU_CU_cell_gen(R, R_p, U);
[distance_path_loss_dB, distUser] = propagation_model_CR_uplink(x, y,R_p,alpha);
shadowing_dB = randn(U).*sigma + mu;
h = abs(1 / sqrt(2) * (randn(U) + j * randn(U)));
PathLoss = distance_path_loss_dB + shadowing_dB + 20.*log10(h) - Gtx - Grx;
cg = 10.^(-PathLoss / 10);
```

A.2 Matlab Codes For The Improved Algorithm

A.2.1 Capacity Improved distalgoCRuplink.m

```
function [CAPSU, nbonSU, ratioonSU, dcellcombintpwrSU] =
distalgoCR(gainmatrix,rxpwrmW,thermnoisemW,U,Rate,q,PBS);

% The vector P is initialized by ones (i.e., all users are supposed to be
% on).  We then compute the threshold depending on all the SINR we got.  We put the
% user "on" or "off" and compute the capacity with respect to the new
% vector P.
% U = total number of users (PU+SUs)
% Rate = Transmission rate
% q = outage probabilty.

d_on_set(1,:)  = ones(1,U);
d_on_set(1) = P_BS;
it_max = 20;
d_Comb_CAP_SU = zeros(1,it_max);
it_convergence = 5;

for it = 1:it_max
    nb_users = length(d_on_set(it,:));
    d_no_on_users(it) = sum(d_on_set(it,2:nb_users)==1);
    for u = 2:U
        d_sum_int(u) = 0;
        for m = 1:U
            if m ~= u
                d_sum_int(u) = d_sum_int(u) + gain_matrix(u,m)*d_on_set(it,m);
            end
        end
        d_gain_ratio(it,u) = gain_matrix(u,u)/d_sum_int(u);
        d_cell_ratio(it,u) =
((d_no_on_users(it))/(d_no_on_users(it)-1))^(d_no_on_users(it)-1);
```

```
        if (abs( log2(1 + d_gain_ratio(it,u)) - d_gain_ratio(it,u)) ) < 1e-3
            %disp('low SNR')
            if d_gain_ratio(it,u) < 1
                d_on_set(it,u) = 0;
            else
                d_on_set(it,u) = 1;
            end
        else %disp('high SNR')
            if d_gain_ratio(it,u) < d_cell_ratio(it,u)
                d_on_set(it,u) = 0;
            else
                d_on_set(it,u) = 1;
            end
        end
    end
    d_no_it = it;
    if it >= it_convergence
        if d_on_set(it,:)  == d_on_set(it-it_convergence+1,:)
            break
        end
    end
    if it==it_max
        break
    end
    d_on_set(it+1,:)  = d_on_set(it,:);
end

nb_users = length(d_on_set(1,:));
nb_on_SU = sum(d_on_set(1,2:nb_users)==1);
Pout = 0;

while(nb_on_SU > 0)
    nb_users = length(d_on_set(d_no_it,:));
    nb_on_SU = sum(d_on_set(d_no_it,2:nb_users)==1);
    for u = 1:nb_users
        d_cell_comb_int_pwr(u) = 0;
        for m = 1:nb_users
            if m ~= u
                d_cell_comb_int_pwr(u) = d_cell_comb_int_pwr(u) + ...
                rx_pwr_mW(u,m)*d_on_set(d_no_it,m);
            end
        end
        d_cell_comb_SINR(u) = rx_pwr_mW(u,u) * d_on_set(d_no_it,u)/...
        (therm_noise_mW + d_cell_comb_int_pwr(u));
        d_cell_comb_CAP(u) = log2(1 + d_cell_comb_SINR(u));
    end
```

```
    capacity=d_cell_comb_CAP; %%%%%ADDED
    cap = d_cell_comb_CAP;
    nb_users = length(d_on_set(d_no_it,:)); %number of users is taken from
                                             the last iteration (it=d_no_it)
    nb_on_SU = sum(d_on_set(d_no_it,2:nb_users)==1);
    if nb_on_SU == 0%no SU can Tx
        d_Comb_CAP_SU = 0;
        Pout = 0;
        break
    end
    Pout = probab(d_cell_comb_CAP(:,1), Rate);
    if Pout <= q
        d_Comb_CAP_SU = sum(d_cell_comb_CAP(2:nb_users))/nb_on_SU;
        break
    else nb_users = nb_users - 1;
        nb_on_SU = nb_on_SU - 1
        if nb_on_SU == 0 %no SU can Tx
            d_Comb_CAP_SU = 0;
            Pout = 0;
            d_on_set = d_on_set(:,1);%there a no more SU in d_on_set
            break
        end
        indmincap=0;
        cap_min=max(capacity)
        for i=2:length(capacity)
            if capacity(i)~=0 && capacity(i)<=cap_min
                indmincap=i
                cap_min=capacity(i)
            end
        end
        d_on_set(:,indmincap)=0;
    end
end

ratio_on_SU = nb_on_SU/(nb_users-1);
nb_on_SU;
CAP_SU = d_Comb_CAP_SU;

if nb_on_SU ~= 0
    d_cell_comb_int_pwr_SU = sum(d_cell_comb_int_pwr)/nb_users; %average interf.
else                                                             per user
    d_cell_comb_int_pwr_SU = 0;
    CAP_SU = 0;
end
```

A.2.2 Drop The Most Interfered Improvement distalgoCRuplink.m

```
function [CAP_SU, nb_on_SU, ratio_on_SU, d_cell_comb_int_pwr_SU] =
dist_algo_CR(gain_matrix,rx_pwr_mW,therm_noise_mW,U,Rate,q,P_BS);

% Modified version and more true !!!
% The vector P is initialized by ones (i.e., all users are supposed to be
% on).  We then compute the threshold depending on all the SINR we got.  We put the
% user "on" or "off" and compute the capacity with respect to the new
% vector P.
% U = total number of users (PU+SUs)
% Rate = Transmission rate
% q = outage probabilty.

d_on_set(1,:)  = ones(1,U);
d_on_set(1) = P_BS;
it_max = 20;
d_Comb_CAP_SU = zeros(1,it_max);
it_convergence = 5;

for it = 1:it_max
    nb_users = length(d_on_set(it,:));
    d_no_on_users(it) = sum(d_on_set(it,2:nb_users)==1);
    for u = 2:U
        d_sum_int(u) = 0;
        for m = 1:U
            if m ~= u
                d_sum_int(u) = d_sum_int(u) + gain_matrix(u,m)*d_on_set(it,m);
            end
        end
        d_gain_ratio(it,u) = gain_matrix(u,u)/d_sum_int(u);
        d_cell_ratio(it,u) = ((d_no_on_users(it))/(d_no_on_users(it)-1))^...
        (d_no_on_users(it)-1);
        if (abs( log2(1 + d_gain_ratio(it,u)) - d_gain_ratio(it,u)) ) < 1e-3
            %disp('low SNR')
            if d_gain_ratio(it,u) < 1
                d_on_set(it,u) = 0;
            else
                d_on_set(it,u) = 1;
            end
        else %disp('high SNR')
            if d_gain_ratio(it,u) < d_cell_ratio(it,u)
                d_on_set(it,u) = 0;
```

```
            else
                d_on_set(it,u) = 1;
            end
        end
    end
    d_on_set(it+1,:)  = d_on_set(it,:);
    d_no_it = it;
    if it >= it_convergence
        if d_on_set(it,:)  == d_on_set(it-it_convergence+1,:)
            break
        end
    end
end

nb_users = length(d_on_set(1,:));
nb_on_SU = sum(d_on_set(1,2:nb_users)==1);
Pout = 0;
interf=zeros(nb_users,nb_users); %%%%ADDED

while(nb_on_SU > 0)
    for it = 1:d_no_it
        nb_users = length(d_on_set(it,:));
        nb_on_SU = sum(d_on_set(it,2:nb_users)==1);
        for u = 1:nb_users
            d_cell_comb_int_pwr(u) = 0;
            for m = 1:nb_users
                if m ~= u
                    d_cell_comb_int_pwr(u) = d_cell_comb_int_pwr(u) + ...
                    rx_pwr_mW(u,m)*d_on_set(it,m);
                    if it==d_no_it %%%%ADDED
                        interf(u,m)=rx_pwr_mW(u,m)*d_on_set(it,m); %%%%ADDED
                    end %%%%ADDED
                end
            end
            d_cell_comb_SINR(it,u) = rx_pwr_mW(u,u) * d_on_set(it,u)/...
            (therm_noise_mW + d_cell_comb_int_pwr(u));
            d_cell_comb_CAP(it,u) = log2(1 + d_cell_comb_SINR(it,u));
        end
    end
    cap = d_cell_comb_CAP(it,:);
    nb_users = length(d_on_set(it,:)); %number of users is taken from
                                        the last iteration (it=d_no_it)
    nb_on_SU = sum(d_on_set(it,2:nb_users)==1);
    int_on=sum(interf').*d_on_set(d_no_it,:)  %We use this to look for the SU which
is more interfered
    %int_of=sum(interf); To search for the SU which generates more interference
```

```
    %int_on_PU=interf(1,:); To search for the SU which interferes more to the PU
    if nb_on_SU == 0 %no SU can Tx
        d_Comb_CAP_SU = 0;
        Pout = 0;
        break
    end
    Pout = probab(d_cell_comb_CAP(:,1), Rate);
    if Pout <= q
        d_Comb_CAP_SU = sum(d_cell_comb_CAP(it,2:nb_users))/nb_on_SU;
        break
    else nb_users = nb_users - 1; %here we can choose the worst user to be deleted
in term of his interference contribution to the PU
        nb_on_SU = nb_on_SU - 1;
        if nb_on_SU == 0 %no SU can Tx
            d_Comb_CAP_SU = 0;
            Pout = 0;
            d_on_set = d_on_set(:,1); %there a no more SU in d_on_set
            break
        end
        [max_int,ind_max]=max(int_on(2:end)) %%%%ADDED
        ind_max=ind_max+1 %%%%ADDED
        d_on_set(:,ind_max)=0 %%%%ADDED
    end
end

ratio_on_SU = nb_on_SU/(nb_users-1);
CAP_SU = d_Comb_CAP_SU;

if nb_on_SU ~= 0
    d_cell_comb_int_pwr_SU = sum(d_cell_comb_int_pwr)/nb_users; %average interf.
else                                                                per user
    d_cell_comb_int_pwr_SU = 0;
    CAP_SU = 0;
end
```

A.2.3 Drop The Most Interfering Improvement distalgoCRuplink.m

```
function [CAP_SU, nb_on_SU, ratio_on_SU, d_cell_comb_int_pwr_SU] =
dist_algo_CR(gain_matrix,rx_pwr_mW,therm_noise_mW,U,Rate,q,P_BS);

% Modified version and more true !!!
```

```
% The vector P is initialized by ones (i.e., all users are supposed to be
% on).  We then compute the threshold depending on all the SINR we got.  We put the
% user "on" or "off" and compute the capacity with respect to the new
% vector P.
% U = total number of users (PU+SUs)
% Rate = Transmission rate
% q = outage probabilty.

d_on_set(1,:)  = ones(1,U);
d_on_set(1) = P_BS;
it_max = 20;
d_Comb_CAP_SU = zeros(1,it_max);
it_convergence = 5;

for it = 1:it_max
    nb_users = length(d_on_set(it,:));
    d_no_on_users(it) = sum(d_on_set(it,2:nb_users)==1);
    for u = 2:U
        d_sum_int(u) = 0;
        for m = 1:U
            if m ~= u
                d_sum_int(u) = d_sum_int(u) + gain_matrix(u,m)*d_on_set(it,m);
            end
        end
        d_gain_ratio(it,u) = gain_matrix(u,u)/d_sum_int(u);
        d_cell_ratio(it,u) = ((d_no_on_users(it))/(d_no_on_users(it)-1))^...
        (d_no_on_users(it)-1);
        if (abs( log2(1 + d_gain_ratio(it,u)) - d_gain_ratio(it,u)) ) < 1e-3
            %disp('low SNR')
            if d_gain_ratio(it,u) < 1
                d_on_set(it,u) = 0;
            else
                d_on_set(it,u) = 1;
            end
        else %disp('high SNR')
            if d_gain_ratio(it,u) < d_cell_ratio(it,u)
                d_on_set(it,u) = 0;
            else
                d_on_set(it,u) = 1;
            end
        end
    end
    d_on_set(it+1,:)  = d_on_set(it,:);
    d_no_it = it;
    if it >= it_convergence
        if d_on_set(it,:)  == d_on_set(it-it_convergence+1,:)
```

```
            break
        end
    end
end

nb_users = length(d_on_set(1,:));
nb_on_SU = sum(d_on_set(1,2:nb_users)==1);
Pout = 0;
interf=zeros(nb_users,nb_users); %%%%%ADDED

while(nb_on_SU > 0)
    for it = 1:d_no_it
        nb_users = length(d_on_set(it,:));
        nb_on_SU = sum(d_on_set(it,2:nb_users)==1);
        for u = 1:nb_users
            d_cell_comb_int_pwr(u) = 0;
            for m = 1:nb_users
                if m ~= u
                    d_cell_comb_int_pwr(u) = d_cell_comb_int_pwr(u) + ...
                    rx_pwr_mW(u,m)*d_on_set(it,m);
                    if it==d_no_it %%%%%ADDED
                        interf(u,m)=rx_pwr_mW(u,m)*d_on_set(it,m); %%%%%ADDED
                    end %%%%%ADDED
                end
            end
            d_cell_comb_SINR(it,u) = rx_pwr_mW(u,u) * d_on_set(it,u)/...
            (therm_noise_mW + d_cell_comb_int_pwr(u));
            d_cell_comb_CAP(it,u) = log2(1 + d_cell_comb_SINR(it,u));
        end
    end
    cap = d_cell_comb_CAP(it,:);
    nb_users = length(d_on_set(it,:)); %number of users is taken from the last iteration
(it=d_no_it)
    nb_on_SU = sum(d_on_set(it,2:nb_users)==1);
    % int_on=sum(interf').*d_on_set(d_no_it,:); To search for the SU which is more
interfered
    int_of=sum(interf).*d_on_set(d_no_it,:)  %%%%%To search for the SU which generates
more interference
    % int_on_PU=interf(1,:); To search for the SU which interferes more to the PU
    if nb_on_SU == 0 %no SU can Tx
        d_Comb_CAP_SU = 0;
        Pout = 0;
        break
    end
    Pout = probab(d_cell_comb_CAP(:,1), Rate);
    if Pout <= q
```

```
        d_Comb_CAP_SU = sum(d_cell_comb_CAP(it,2:nb_users))/nb_on_SU;
        break
    else nb_users = nb_users - 1; %here we can choose the worst user to be deleted
in term of his interference contribution to the PU
        nb_on_SU = nb_on_SU - 1;
        if nb_on_SU == 0%no SU can Tx
            d_Comb_CAP_SU = 0;
            Pout = 0;
            d_on_set = d_on_set(:,1); %there a no more SU in d_on_set
            break
        end
        [max_int,ind_max]=max(int_of(2:end)) %%%%ADDED
        ind_max=ind_max+1 %%%%ADDED
        d_on_set(:,ind_max)=0 %%%%ADDED
    end
end

ratio_on_SU = nb_on_SU/(nb_users-1);
nb_on_SU;
CAP_SU = d_Comb_CAP_SU;

if nb_on_SU ~= 0
    d_cell_comb_int_pwr_SU = sum(d_cell_comb_int_pwr)/nb_users; %average interf.
else                                                            per user
    d_cell_comb_int_pwr_SU = 0;
    CAP_SU = 0;
end
```

A.2.4 Drop The Most Interfering On PU Improvement distalgoCRuplink.m

```
function [CAP_SU, nb_on_SU, ratio_on_SU, d_cell_comb_int_pwr_SU] =
dist_algo_CR(gain_matrix,rx_pwr_mW,therm_noise_mW,U,Rate,q,P_BS);

% Modified version and more true !!!
% The vector P is initialized by ones (i.e., all users are supposed to be
% on).  We then compute the threshold depending on all the SINR we got.  We put the
% user "on" or "off" and compute the capacity with respect to the new
% vector P.
% U = total number of users (PU+SUs)
% Rate = Transmission rate
% q = outage probabilty.
```

```
d_on_set(1,:)  = ones(1,U);
d_on_set(1) = P_BS;
it_max = 20;
d_Comb_CAP_SU = zeros(1,it_max);
it_convergence = 5;

for it = 1:it_max
    nb_users = length(d_on_set(it,:));
    d_no_on_users(it) = sum(d_on_set(it,2:nb_users)==1);
    for u = 2:U
        d_sum_int(u) = 0;
        for m = 1:U
            if m ~= u
                d_sum_int(u) = d_sum_int(u) + gain_matrix(u,m)*d_on_set(it,m);
            end
        end
        d_gain_ratio(it,u) = gain_matrix(u,u)/d_sum_int(u);
        d_cell_ratio(it,u) = ((d_no_on_users(it))/(d_no_on_users(it)-1))^...
        (d_no_on_users(it)-1);
        if (abs( log2(1 + d_gain_ratio(it,u)) - d_gain_ratio(it,u)) ) < 1e-3
            %disp('low SNR')
            if d_gain_ratio(it,u) < 1
                d_on_set(it,u) = 0;
            else
                d_on_set(it,u) = 1;
            end
        else %disp('high SNR')
            if d_gain_ratio(it,u) < d_cell_ratio(it,u)
                d_on_set(it,u) = 0;
            else
                d_on_set(it,u) = 1;
            end
        end
    end
    d_on_set(it+1,:)  = d_on_set(it,:);
    d_no_it = it;
    if it >= it_convergence
        if d_on_set(it,:)  == d_on_set(it-it_convergence+1,:)
            break
        end
    end
end

nb_users = length(d_on_set(1,:));
nb_on_SU = sum(d_on_set(1,2:nb_users)==1);
Pout = 0;
```

```
interf=zeros(nb_users,nb_users); %%%%ADDED

while(nb_on_SU > 0)
    for it = 1:d_no_it
        nb_users = length(d_on_set(it,:));
        nb_on_SU = sum(d_on_set(it,2:nb_users)==1);
        for u = 1:nb_users
            d_cell_comb_int_pwr(u) = 0;
            for m = 1:nb_users
                if m ~= u
                    d_cell_comb_int_pwr(u) = d_cell_comb_int_pwr(u) + ...
                    rx_pwr_mW(u,m)*d_on_set(it,m);
                    if it==d_no_it %%%%ADDED
                        interf(u,m)=rx_pwr_mW(u,m)*d_on_set(it,m); %%%%ADDED
                    end %%%%ADDED
                end
            end
            d_cell_comb_SINR(it,u) = rx_pwr_mW(u,u) * d_on_set(it,u)/...
            (therm_noise_mW + d_cell_comb_int_pwr(u));
            d_cell_comb_CAP(it,u) = log2(1 + d_cell_comb_SINR(it,u));
        end
    end
    cap = d_cell_comb_CAP(it,:);
    nb_users = length(d_on_set(it,:)); %number of users is taken
from the last iteration (it=d_no_it)
    nb_on_SU = sum(d_on_set(it,2:nb_users)==1);
    %int_on=sum(interf').*d_on_set(d_no_it,:); %%%%To search for the SU
which is more interfered
    %int_of=sum(interf).*d_on_set(d_no_it,:); %%%%To search for the SU
which generates more interference
    int_on_PU=interf(1,:).*d_on_set(d_no_it,:)  %%%%To search for the SU
which interferes more to the PU
    if nb_on_SU == 0 %no SU can Tx
        d_Comb_CAP_SU = 0;
        Pout = 0;
        break
    end
    Pout = probab(d_cell_comb_CAP(:,1), Rate);
    if Pout <= q
        d_Comb_CAP_SU = sum(d_cell_comb_CAP(it,2:nb_users))/nb_on_SU;
        break
    else nb_users = nb_users - 1;
        nb_on_SU = nb_on_SU - 1;
        if nb_on_SU == 0%no SU can Tx
```

```
            d_Comb_CAP_SU = 0;
            Pout = 0;
            d_on_set = d_on_set(:,1); %there a no more SU in d_on_set
            break
        end
        [max_int,ind_max]=max(int_on_PU(2:end)) %%%%ADDED
        ind_max=ind_max+1 %%%%ADDED
        d_on_set(:,ind_max)=0 %%%%ADDED
    end
end

ratio_on_SU = nb_on_SU/(nb_users-1);
CAP_SU = d_Comb_CAP_SU;

if nb_on_SU ~= 0
    d_cell_comb_int_pwr_SU = sum(d_cell_comb_int_pwr)/nb_users;%average interference
per user
else
    d_cell_comb_int_pwr_SU = 0;
    CAP_SU = 0;
end
```

A.3 Matlab codes for CSI imperfectness

In this section we include, for both multiplicative log-normal error and Gaussian error, the codes of the codes we modified while introducing the error into the algorithm. These files are “distalgoCRuplink.m” and “channelgainCRuplink.m”. In “main.m” we make use of both previous functions to calculate capacity per SU and number of active SU, as we always do, but to obtain this values and also the outage probability, with CSI.

A.3.1 Codes For Additive Gaussian (Normal) Error

A.3.1.1 distalgoCRuplink_err.m

```
function [CAP_SU, nb_on_SU, ratio_on_SU, d_cell_comb_int_pwr_SU,Pout]=
dist_algo_CR_err(gain_matrix,rx_pwr_mW,gain_matrix_err,rx_pwr_mW_err,...
therm_noise_mW,U,Rate,q,P_BS);

% The vector P is initialized by ones (i.e., all users are supposed to be
% on).  We then compute the threshold depending on all the SINR we got.  We put the
% user "on" or "off" and compute the capacity with respect to the new
% vector P.
% U = total number of users (PU+SUs)
% Rate = Transmission rate
% q = outage probabilty.

d_on_set(1,:)  = ones(1,U);
d_on_set(1) = P_BS;
it_max = 20;
d_Comb_CAP_SU = zeros(1,it_max);
it_convergence = 5;

for it = 1:it_max
    nb_users = length(d_on_set(it,:));
    d_no_on_users(it) = sum(d_on_set(it,2:nb_users)==1);
    for u = 2:U
```

```
        d_sum_int(u) = 0;
        for m = 1:U
            if m ~= u
                d_sum_int(u) = d_sum_int(u) + gain_matrix_err(u,m)*d_on_set(it,m);
            end
        end
        d_gain_ratio(it,u) = gain_matrix_err(u,u)/d_sum_int(u);
        d_cell_ratio(it,u) = ((d_no_on_users(it))/(d_no_on_users(it)-1))^...
        (d_no_on_users(it)-1);
        if (abs( log2(1 + d_gain_ratio(it,u)) - d_gain_ratio(it,u)) ) < 1e-3
            if d_gain_ratio(it,u) < 1
                d_on_set(it,u) = 0;
            else
                d_on_set(it,u) = 1;
            end
        else %disp('high SNR')
            if d_gain_ratio(it,u) < d_cell_ratio(it,u)
                d_on_set(it,u) = 0;
            else
                d_on_set(it,u) = 1;
            end
        end
    end
    d_on_set(it+1,:)  = d_on_set(it,:);
    d_no_it = it;
    if it >= it_convergence
        if d_on_set(it,:)  == d_on_set(it-it_convergence+1,:)
            break
        end
    end
end

nb_users = length(d_on_set(1,:));
nb_on_SU = sum(d_on_set(1,2:nb_users)==1);
Pout = 0;

while(nb_on_SU > 0)
    for it = 1:d_no_it
        nb_users = length(d_on_set(it,:));
        nb_on_SU = sum(d_on_set(it,2:nb_users)==1);
        for u = 1:nb_users
            d_cell_comb_int_pwr(u) = 0;
            for m = 1:nb_users
                if m ~= u
                    d_cell_comb_int_pwr(u) = d_cell_comb_int_pwr(u) + ...
                    rx_pwr_mW_err(u,m)*d_on_set(it,m);
```

```
                end
            end
            d_cell_comb_SINR(it,u) = rx_pwr_mW_err(u,u) * d_on_set(it,u)/...
            (therm_noise_mW + d_cell_comb_int_pwr(u));
            d_cell_comb_CAP(it,u) = log2(1 + d_cell_comb_SINR(it,u));
        end
    end
    cap = d_cell_comb_CAP(it,:);
    nb_users = length(d_on_set(it,:)); % number of users is taken from
                                         the last iteration (it=d_no_it)
    nb_on_SU = sum(d_on_set(it,2:nb_users)==1);
    if nb_on_SU == 0%no SU can Tx
        d_Comb_CAP_SU = 0;
        Pout = 0;
        break
    end
    Pout = probab(d_cell_comb_CAP(:,1), Rate);
    if Pout <= q
        d_Comb_CAP_SU = sum(d_cell_comb_CAP(it,2:nb_users))/nb_on_SU;
        break
    else nb_users = nb_users - 1;
        nb_on_SU = nb_on_SU - 1;
        if nb_on_SU == 0%no SU can Tx
            d_Comb_CAP_SU = 0;
            Pout = 0;
            d_on_set = d_on_set(:,1);%there a no more SU in d_on_set
            break
        end
        for cc = 1:size(d_on_set,1)
            index_on_row(cc,:)  = find(d_on_set(cc,:));
            index_on = index_on_row(cc,1:end-1);
            temp(cc,:)  = zeros(1,nb_users);
            temp(cc,index_on) = 1;
            temp(:,1) = P_BS;
            clear index_on_row
        end
        d_on_set = temp;
        clear temp;
    end
end

for it = 1:d_no_it
    nb_users = length(d_on_set(it,:));
    nb_on_SU = sum(d_on_set(it,2:nb_users)==1);
    for u = 1:nb_users
        d_cell_comb_int_pwr(u) = 0;
```

```
        for m = 1:nb_users
            if m ~= u
                d_cell_comb_int_pwr(u) = d_cell_comb_int_pwr(u) + ...
                rx_pwr_mW(u,m)*d_on_set(it,m);
            end
        end
        d_cell_comb_SINR(it,u) = rx_pwr_mW(u,u) * d_on_set(it,u)/...
        (therm_noise_mW + d_cell_comb_int_pwr(u));
        d_cell_comb_CAP(it,u) = log2(1 + d_cell_comb_SINR(it,u));
    end
end

d_Comb_CAP_SU = sum(d_cell_comb_CAP(it,2:nb_users))/nb_on_SU; %%%%%
Pout = probab(d_cell_comb_CAP(:,1), Rate);
ratio_on_SU = nb_on_SU/(nb_users-1);
CAP_SU = d_Comb_CAP_SU;

if nb_on_SU ~= 0
    d_cell_comb_int_pwr_SU = sum(d_cell_comb_int_pwr)/nb_users; %average interference
per user
else
    d_cell_comb_int_pwr_SU = 0;
    CAP_SU = 0;
end
```

A.3.1.2 channelgainCRuplink_err.m

```
function cg = channelgain_CR_uplink_err(R, R_p, U, alpha,err_std_dev)

Gtx = 16; % Tx antenna gain in dB
Grx = 6; % Rx antenna gain in dB
mu = 0; % Mean for lognormal shadowing
sigma = 10; % S.D. for lognromal shadowing

[x,y] = PU_CU_cell_gen(R, R_p, U);
[distance_path_loss_dB, distUser] = propagation_model_CR_uplink(x, y,R_p,alpha);
shadowing_dB = randn(U).*sigma + mu;

%In the following line we generate the normal distributed error variable
%with zero-mean and standard deviation especified by the input parameter
%err_std_dev
info_imperf=randn(U)*err_std_dev;
%This kind of variable is also achieveable by using the command
% info_imperf=normrnd(media=0,desv std=1e-algo,fil,col) where
% “fil” and “col” are the same number and represent our number of users U
```

```
h = abs(1 / sqrt(2) * (randn(U) + j * randn(U)));
PathLoss = distance_path_loss_dB + shadowing_dB + 20.*log10(h) - Gtx - Grx;
cg = 10.^(-PathLoss / 10)+ info_imperf;

for fil=1:U %In case any of the channel gains became <0 because of the
    for col=1:U %error effect, we take a very small value above 0
        if cg(fil,col)<0
            cg(fil,col)=1e-20;
        end
    end
end
```

A.3.2 Codes For Multiplicative Log-normal Error

A.3.2.1 distalgoCRuplink_err.m

(Same code as the one in A.3.1.1 for Normal error)

A.3.2.2 channelgainCRuplink_err.m

```
function cg = channelgain_CR_uplink(R, R_p, U, alpha,varianza)


Gtx = 16;
Grx = 6;
mu = 0;
sigma = 10;


[x,y] = PU_CU_cell_gen(R, R_p, U);
[distance_path_loss_dB, distUser] = propagation_model_CR_uplink(x, y,R_p,alpha);
shadowing_dB = randn(U).*sigma + mu;
h = abs(1 / sqrt(2) * (randn(U) + j * randn(U)));
PathLoss = distance_path_loss_dB + shadowing_dB + 20.*log10(h) - Gtx - Grx;
tamano=size(PathLoss);


if tamano(1)==tamano(2)
    ruidoaditivo=(varianza).*randn(tamano(1));
    for i=1:tamano(1)
        for h=1:tamano(2)
            ruidoaditivo(i,h)
```

```
            if(ruidoaditivo(i,h)<0)
                ruidaditivo(i,h)=-10*log10(abs(ruidoaditivo(i,h)))
            else
                ruidaditivo(i,h)=10*log10(ruidoaditivo(i,h))
            end
        end
    end
else
    error('Something is not working :(')
end


PathLoss=PathLoss+ruidoaditivo;
cg = 10.^(-PathLoss / 10);
```