Aalborg Universitet (AAU)
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Study and Development of Power Control Schemes within a Cognitive Radio-based Game Theoretic Framework

by

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"Before anything else, preparation is the key to success"
Alexander Graham Bell (1847-1922)

Aalborg Universitet (AAU)

Abstract

Institut for Elektroniske Systemer
Radio Access Technology

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The requirements of the International Telecommunication Union (ITU) for the 4th generation of mobile devices raised up to 100 Mbps for high and 1Gbps for low mobility conditions. Reaching such challenging targets requires the deployment of picocells and femtocells. These techniques permit to achieve large cell capacity but also lead to difficulties in terms of interference. The GRACE algorithm, based on Cognitive Radio and Game Theory, has shown a fair balance between cell capacity and outage as well as short convergence time, low complexity and easy scalability. The aim of this work is to find an efficient power control algorithm that fits GRACE these goals. Therefore, a study of Cognitive Radio, Game Theory and Power Control algorithms is developed and a new power control algorithm is proposed. The simulation results show that the Fractional Power Control can increase notably the outage performance and the energy saving to the mobile devices.

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Abbreviations

AACR	**A**ware, **A**adaptive and **C**ognitive **R**adio
AP	**A**ccess **P**oint
BRD	**B**etter-**R**eply **D**ynamics
CC	**C**ognitive **C**ycle
CR	**C**ognitive **R**adio
CSI	**C**hannel **S**tate **I**nformation
DCA	**D**esired **C**apacity **A**lgorithm
eNB	**e**nhanced **N**ode**B**
FPC	**F**ractional **P**ower **C**ontrol
GRACE	**G**ame-based **R**esource **A**llocation in a **C**ognitive Radio **E**nvironment
GT	**G**ame **T**heory
IC-DSA	**I**inter-**C**ell **D**ynamic **S**pectrum **A**llocation
IMT	**I**nternational **M**obile **C**ommunication
MAC	**M**edium **A**ccess **C**ontrol
NE	**N**ash **E**quilibrium
OFDMA	**O**rthogonal **F**requency **D**ivision **M**ultiple **A**ccess
OLPC	**O**pen **L**oop **P**ower **C**ontrol
PC	**P**ower **C**ontrol
PRB	**P**hysical **R**esource **B**lock
PSD	**P**ower **S**pectral **D**ensity
PSNE	**P**ure **S**trategy **N**ash **E**quilibrium
QoS	**Q**uality **o**f **S**ervice
RRM	**R**adio **R**esource **M**anagement
SDR	**S**oftware **D**efined **R**adio
SINR	**S**ignal to **I**nterference plus **N**oise **R**atio

TP	**T**hrough**p**ut
UE	**U**ser **E**quipment

Dedicated to my family and my friends

Chapter 1

Introduction

1.1 The Wireless Communications Today

The fast evolution of technology is evident, among many others, in the field of wireless communications. In the last few years we witnessed the development of devices, networks, protocols and applications. The requirements of the International Telecommunication Union (ITU) for the 4^{th} generation of mobile devices raised up to 100 Mbps for high and 1Gbps for low mobility conditions [5]. Accordingly, the 3rd Generation Partnership Project (3GPP) also set the requirements for the release 10 of the Long Term Evolution, (or LTE-Advanced, LTE-A) in order to *meet or exceed IMT-Advanced requirements* [6].

Reaching such challenging targets requires the use of new techniques like the deployment of picocells and femtocells. Essentially this means reducing the coverage and increasing the number of the actual base stations of cellular systems. The advantages of this methodology are: for the operators, the low-cost and low power base stations that also provide indoor coverage and increase the network capacity; and for the users, more quality of service (QoS), the access to applications with more traffic demand and improving the battery life due to the reduced power radiation[7].

Picocells and femtocells have as disadvantages that they are not deployed by a telecommunications operator but by the owners of the buildings where they are set, which conforms an uncoordinated deployment. Therefore, some issues as the coverage can not be planned.

1.2 Motivation

The uncoordinated deployment design emphasizes the problem of the intra-cell interference and the need of latest frequency sharing and power control algorithms. Fortunately those new technologies, like Cognitive Radio, have already been studied deeply [8] and they are becoming reality.

The idea that a device which fits in your hand can provide high quality multimedia information and, at the same time, is able to adapt the way it is working internally to improve the system capacity and efficiency is something that sounds like a real breakthrough. This will soon be possible under the concept of Cognitive Radio.

New mobile devices have already some reconfiguration capabilities and also have enough computational power to process both user and environmental information. The objective of this work is to progress on the investigation of algorithms that use those capabilities towards the paradigm of Cognitive Radio.

This work takes a new developed algorithm called GRACE [2] as the fundamental framework. The GRACE algorithm is able to set the frequency allocation of radio devices using the measurements of interference in each frequency channel. In this way, GRACE is able to avoid interference in the chanels used and leads to an efficient spectrum sharing. This algorithm is designed to work in uncoordinated deployments because it adapts the allocation to the scenario depending on the spectrum occupancy.

Nevertheless GRACE does not define a power control algorithm. Power Control (PC) is a mandatory need specially in the environments where GRACE is meant to be applied. This work therefore aims to develop a study of different power allocation algorithms in order to find an optimal solution in terms of cell capacity, outage, energy saving and adaptability.

1.3 Problem Statement

In summary, the aim of this work is to find out the answer to the next research question: how is it possible to modify the GRACE algorithm in order to allow an effective inclusion of power control algorithms in its game theoretic flexible spectrum usage framework?

This resarch requires a study of the concepts of Cognitive Radio and game theory, the theoretical base of GRACE, to achieve a deep understanding of the way it works. Also a review of the power allocation systems will be done to identify which are the most suitable ones.

1.4 Thesis Structure

The document is organized as follows:

Chapter 2 gives an introduction to the idea of *Cognitive Radio* and then focuses on what are the potentials of this concept regarding the spectrum allocation and interference avoidance.

Chapter 3 presents *Game Theory* as a powerful tool that permits the analysis of systems in which each *player's* decision affects the decision of the others. Therefore Game Theory has recently become the way to analyse wireless systems through the definition of the *Interference Game*.

Chapter 4 describes GRACE, the inter-cell dynamic spectrum allocation algorithm that becomes the framework for this project in the further study of power control algorithms.

Chapter 5 introduces the function of power control in wireless systems and details the properties of three different power control algorithms: *Full path loss compensation*, *Water filling algorithm* and *Fractional Power Control*.

Chapter 6 focuses on *Fractional Power Control* and presents the *Desired Capacity Algorithm* as the implementated algorithms studied with GRACE.

Chapter 7 presents the results of the simulations done for both algorithms selected.

Chapter 8 summarises the results obtained and explains the conclusions achieved. It also depicts the directions to follow for future work.

Chapter 2

Cognitive Radio

2.1 History

The Global Standards Collaboration (GSC) a group from the ITU, proposed the following definition for Cognitive Radio (CR):

> *"A radio system employing technology that allows the system: to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained. "* [9]

This definition points out the two main features that characterise a CR. The first one is the ability to acquire the radio parameters from its surrounding space. Some important information that can be extracted from the air are the power levels in each frequency channel, i.e. the frequency occupancy. It can be used to make decisions about the best spectrum allocation. Other features can also be used to make decisions, for instance, the waveform properties or the modulation scheme can be relevant, as well as the geolocation of the device.

The second one is the possibility to adapt the transmission parameters. There are different advanced radio platforms whose behaviour approach is the one expected for a CR. The most important one is the Software Defined Radio (SDR) [10]. SDR is able to interoperate with multiple waveforms and has full software control of all signal processing, cryptographic and networking functions. A CR is supposed to add to these functions the possibility of learning about the environment and self configurating, or even experimenting with different settings [11].

Cognitive Radio arises from the combination of both last features, or in other words, from the ability of self and smartly modifying the radio parameters as function of its sensor inputs. The relation between these sensed inputs, the way of making decisions and the adaptation to the environment is explained by Joseph Mitola III. He is one of the main actors in the definition of the architecture of the CR. He defined the capabilities required for an Aware and Adaptive Cognitive Radio (AACR) node to be a cognitive entity, and represented them in a reactive sequence that is called a ″Cognitive Cycle″ [1].

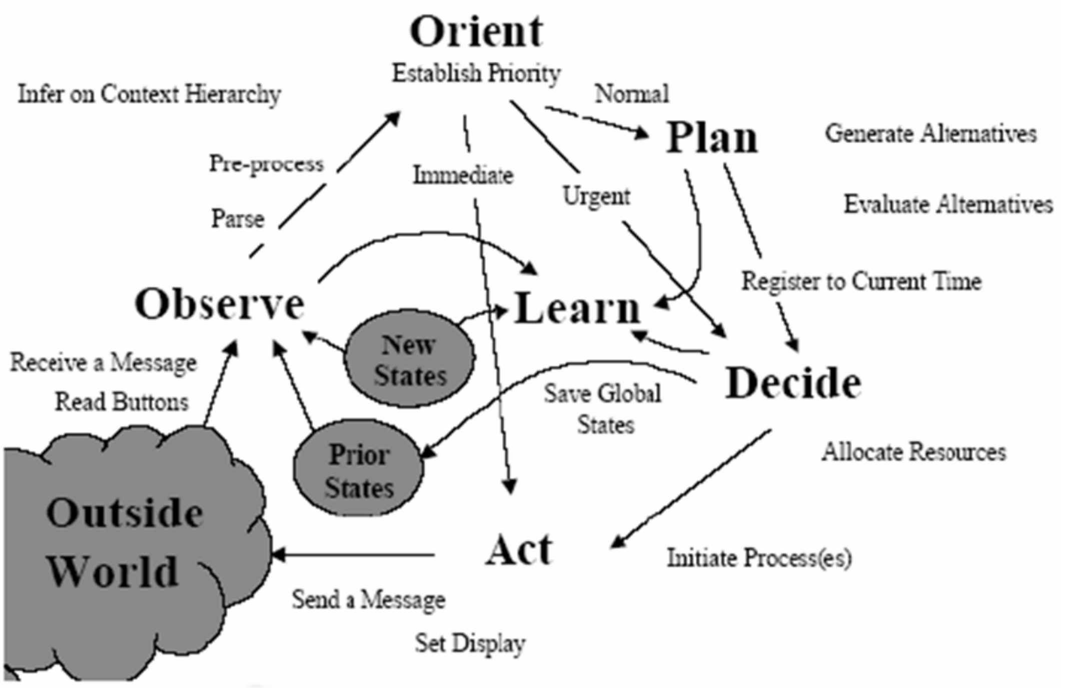

FIGURE 2.1: Mitola's Cognitive cycle, extracted from [1]

The concept of CR is rather new. Mitola's definition dates from the end of the 90's. Some technological steps had to be done before it became feasible. The evolution of the computing performance, by the semiconductor industry, made speed up the personal computers, but it also extended the capabilities of the mobile devices. At the same time the development of the signal data processing (DSP) made possible new processes that were totally impractical with analog signal processing. Other essential steps were the research in machine learning and neural networks, the research in wireless networking and the development of the SDR. Lately a new CR infrastructure had to be created as well as its standards and its business model [10].

2.2 Dynamic Spectrum Allocation

Traditionally the spectrum allocation followed fixed scheme methods as FDMA, which is a simple assignation of a frequency channel to each user. With OFDMA the spectrum was divided in several channels using orthogonal subcarriers, and this gave the possibility to make some adjustments in the spectrum allocation.

Nevertheless, current conservative spectrum management methods (static spectrum assignments) are limited because they reduce the spatial reuse, preclude opportunistic utilization and delay wireless communication network deployment. Also recent measurements [12] [13] show that the spectrum occupancy is low when examined as a function of frequency, time and space.

A CR with spectrum sensing capability and cooperative opportunistic frequency selection is an enabling technology for faster deployment and increased spatial reuse. Furthermore, with the local spectrum utilization measurements it can create increased spectrum access opportunities and hopefully increase the spectrum occupancy [11].

Its worth saying that CDMA exists as an alternative. This scheme permits sharing the whole spectrum among the different users at the same time, using a pseudorandom code for every user that spreads the used bandwidth. As a drawback, CDMA has a lack of robustness towards frequency selectivity in wider bandwidths compared to OFDMA [14].

The Dynamic Spectrum Allocation Problem

The scenario of the femtocell deployment is similar to the actual WiFi scheme: There are several cells each one serving different users. The cells distribution is very variable. In city-like scenarios it is possible to find tenths of cells in the same building, but in rural-like scenarios the cell accumulation is much lower. Time is also an influencing factor since each cell activity changes depending on the time of the day. The purpose of the Dynamic Spectrum Allocation (or Flexible Spectrum Usage) is to be able to share the frequency channels while achieving the maximum efficiency in all different cell distributions.

The Rendezvous Problem One difficulty in Dynamic Spectrum Allocation appears when two devices must agree on which frequency channel to use. The sensing information that each one receives is different (as it happens in the *hidden* and *exposed* node problems) so the decision in allocation might be different as well. The problem then lies in defining an algorithm that both of them use to accord in a protocol in the shortest time possible [11]. Although this problem can be avoided if there is an infrastructure component existing, some optimal strategies are discussed in [15] and [16] for the cases without infrastructure.

The Opportunistic Access The opportunistic access is a solution to improve the spectrum usage efficiency. The way to achieve this is to permit unlicensed users to use licenced bandwidth on a non-interfering basis. In other words, secondary users may be allowed to use the temporarily unused licenced spectrum if they leave it free when the primary users want to access it. In [17], the authors pose the problems in radiometry such as the fact that power level detectors are vulnerable to noise, shadowing and fading.

2.3 Interference Management

2.3.1 The Interference Avoidance Problem

Spectrum and frequency managers assign the channels in order to ensure that the emissions from one do not harmfully impact others. As the example of [18] poses, this planning usually relies in the worst case, i.e. interfering signals will propagate the maximum possible range, while the desired signals will be received just with an acceptable link margin degradation. For instance, if propagation was a R^2 condition [1], and the receiver needed a 12 dB SNR, then the interference will affect a radius 4 times the one where the communication was intended. That means an interference area 16 times larger than the usable one. If we consider ground propagation, $R^{3.8}$, the interference area is just 4 times larger. But to consider the worst case we will suppose that the user is in a disadvantaged position (ground propagation model) and the potentially interfered users are in an advantaged position (free space propagation model). Furthermore, we have to take into account the worst-case multipath fade margin (up to 20 dB loss). Under these assumptions, the area of interference increases up to 150 times the area of reliable communications.

Once seen this example, it is obvious that the strategies of interference avoidance are mandatory when it comes to deal with efficient wireless networking. In [18], the author recognises two main approaches: the first one is the adaptation to the

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[1] Meaning that the power is decreasing proportionally to the square value of the distance, as it happens in free space conditions.

spectrum available, as it has been explained in the last section; the second one bears upon minimizing the *spectral footprint*, i.e. minimizing the radius of interference.

Interference Radius Minimization The proposed way for achieving such a minimization is to redefine the classical concept of spectrum efficiency. The metrics used to measure the spectrum efficiency of the modulations used has been always the number of bits per hertz, [$bits/Hz$]. These metrics presume that, within the Shanon's bound, infinite $bits/Hz$ can be reached as long as the energy per bit is high enough. The new metrics proposed combine the last one with the area radiated, so they take into account not only what is the radio link performance but also how the spectrum is shared by the different users[18].

2.3.2 Already Proposed Solutions

Spectrum Usage Reporting Another useful tool for the management of the interference would be continuous reporting of the bandwidth used, the interference received and the location to local neighbours or a local entity that behaves as spectrum manager. This reports would give to each member enough information to choose proper radio parameters to transmit. As a counterpoint, these reports would actually use part of the resources which means actually reducing the efficiency of the spectrum used in terms of overhead[18].

Interference Analysis The author in [18] defines two kinds of interference: the one with current communications taking place and the other with the unused channels. For the first one the author points out that CR can be very helpful for the mechanisms of the upper layers in order to correct the errors produced by this interference. The reason relies on the fact that CR devices are more interference-tolerant. For the second kind, the author shows that when attempting to use an transmission free channel we could be producing interference to the devices that actually are listening in the channel. In this case the author proposes mechanisms for the listening users to be able to mitigate the interference created by the CR users.

Chapter 3

Game Theory

3.1 Introduction

The most famous approximation to this subject must be the four times Oscar-awarded "A Beautiful Mind". The movie relates the life of the mathematician John Forbes Nash who worked, among others, in the field of Game Theory. One of the scenes of the movie symbolises the discovery of the non-cooperative equilibria, now called *Nash equilibria*. As a result of his work on this equilibria, Nash received the Nobel Memorial Prize in Economic Sciences in 1994 [19].

> *"The Game Theory is a collection of models and analytic tools used to study interactive decision-making processes."* [18]

This theory poses the situation in which different players interact with each other. Every player has a goal and a set of actions in order to achieve it. As the games usually do, there are also rules that define what is going to be the outcome when every player takes its action. In this scenario the decisions that every player makes will influence the rest of them, or from another point of view, the behaviour of every subject depend on the behaviour of the rest of them.

The classical application of the GT is to find what are the conditions under which the game achieves an equilibria. In such a stage of a game, the players have chosen a strategy and there are no possibilities to improve the outcome with an unilateral action so the strategy chosen will not change.

This theory was originally applied in economics to analyse and predict the behaviour of the different aspects such as bargaining, auctions or oligopolies. Afterwards its use was extended to a large variety of other fields, for instance: biology, engineering, international relations, philosophy and computer science.

The traditional techniques used to analyse dynamic systems (e.g. Dynamical Systems Theory, Optimization Theory, Parallel Processing and Markov Chain Theory) have some relevant limitations [20] compared to GT since the process of analysis becomes often too hard. The application of GT include the use of game models which simplify the work. Hence, the equilibria points are easier to find and also is possible the analysis of wide assortments of decision rules at the same time[20].

3.2 General Definitions

Games can be represented as Normal Games (or Strategy form) and Extended Games. We will focus on the first class which will be explained in the following text:

3.2.1 The Structure of a Normal Game

In [21] we can find that a Normal Game is a tuple composed by three elements: the set of players $\mathcal{P}$, identified by $i \in \mathcal{P} = \{1, \dots, |\mathcal{P}|\}$; a set of strategies to follow $(\Sigma_i)_{i \in \mathcal{P}}$; and the payoff functions u_i[1].

The representation of these games with two players is usually a matrix in which the columns correspond to the strategy of one of the players and the rows the strategy of the other. The values inside the matrix are the payoffs for every outcome of the game, i.e. for every pair of strategies chosen by both players. In the famous example of the prisoner's dilemma (developed by Merrill Flood and Melvin Dresher) this matrix would be:

TABLE 3.1: Payoffs of Prisoner's Dilemma, where $A > B > C > D$.

	Stay silent	Confess
Stay silent	B, B	A, D
Confess	D, A	C, C

In this example two prisoners are given the option of to confess or to not to do it. We can see the payoffs as a discount in the number os years that they have to spend in prison. A fast analysis of the payoff table 3.1 will show that both players' best situation is the one in they choose to confess and the other choose not to confess, since they

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[1] A common notation rule is to refer to all the players but i as $-i$.

would get A discount years. It is important to mention that every player is supposed to play completely rationally and will always chose the strategy that maximizes its own payoff function given the other's strategies (i.e. *non-cooperative* game, described in the next section). Therefore, if the game is played once, they both will probably choose to confess. Unfortunately this only will give them C discount years.

The situation changes dramatically if the game has to be played more than once, what is called a *repeated game* 3.2.2. In this case both know that choosing a greedy option may produce good payoffs in one game but not in the next. That causes the prisoners to change their strategies to avoid a bad reaction of the other player, and probably choose to staty silent.

We can see that even if the best overall outcome would be the case where neither of them confess, there is a high payoff in case they do confess, so depending on how many times the game is played, it is more likely that both of them confess to avoid the worst case (being the only one who didn't confess), or chose not to confess to avoid the other's confession in the next stage.

3.2.2 Game Characteristics

There are several rules to be defined as features of the game:

A *non-cooperative* game supposes that every player tries to maximise its own profit, even when it leads to improve the others profit as well. But if besides of the players, is there existing an outside party who obliges the players to take care of each other, it would be a *cooperative* game. We will focus from now on in the non-cooperative games.

Depending on how the payoffs are distributed other considerations must be taken. For instance, when the payoffs only depend on the strategy used but not in the identity of the player, then the game is called *symmetric*. On the contrary, if there is different roles for the players, and they earn different payoffs given the strategy of the others, then the game is *asymmetric*.

Another possible feature of the game shows up if the sum of all the payoffs is the same for any outcome. This is called a *constant sum* game. In this case the fact that a players wins implies that the others do not win as much as him[2]. Particularly, when the sum of the payoffs is zero, the game is called *zero sum* game and that means that if a player wins the others lose.

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[2] There is no convention for the gender that refers the players. The use of the male form follows the literature revised

A very interesting feature comes when the players know that the game is going to be played more than once, which is called a *repeated* game. The game can be repeated a finite or an infinite number of times. These kind of games allow the players choose strategies also depending on the outcomes from the past rounds, what creates the concept of *reputation* of a players, and also *punishment* actions can be taken if there has been betrayal among them. As it was shown with the prisoner's dilemma, this is a very important feature to decide present and future strategies.

For instance, the player can choose the *tit for tat* strategy, in which he will cooperate aslong as the other player does, assuming that the benefit will be larger than the one obtained for betraying, or he can select *defect first* if it is not.

Regarding the order of play, we can distinguish if the players make decisions at the same time (*simultaneous* game) or if there exist an order to do it (*synchronous* game). In this last case, if all the players are aware of the strategies played by the others, then the game is called *perfect information* game, otherwise it is called a game of *imperfect information*.

There are also features regarding the strategies. In first place, *pure* strategies are the strategies that are fixed given the behaviour of the rest of the players. Alternatively, *mixed* strategies denote the existence of a distribution among the strategies, which means that the moves have a certain probability of being chosen. If the strategy is chosen following a *Best Reply Dynamics*, the players will only choose the actions which are actually the best answer to the other player's moves. It could be also that the players follow a *Better Reply Dynamics* (BRD) and then the players would be satisfied to change their strategy into one which is better than the current one, not necessarily the "best" one.

Finally, we define an *equilibrium* or a *Nash equilibrium* (NE) as the set of strategies in which all the players see that a change in their current status-quo would represent a loss in the payoffs to obtain. Particularly, in the mixed strategies games, the players take into account the expected winnings of the distribution of strategies to play.

All these definitions follow the ones found in [22].

3.3 Application to Wireless Communications

As for many other fields, Game Theory has also raised as a powerful tool to study wireless systems in telecommunications. In the frame of the Cognitive Radio networks, in which the devices can adapt most of the transmission parameters depending on radio measurements, a prediction of the complete behaviour of the whole system becomes tough. CR provides network designers with many game models to apply and find answers to questions about the performance of network and the stability of the adaptations.

The first step to do is to assign every item from the general theory to an element of the wireless networks. Players correspond to the devices of the network: cellular phones, laptops, wireless printers, routers, access points, base stations, etc. The actions that they might take are the different ways that they have to set the transmission: selecting band, modulation, power and coding schemes, bandwidth, routing algorithms and more. The outcome of the game becomes the performance of the network, represented essentially by the throughput achieved by every user. The rules that hold the game are divided in two different kinds: internal rules as, for instance, the maximum transmit power; and external rules as the nature of interference, the noise power or the fading that disturbs the device.

Utility Function In the process of making decisions game theorists usually compact the definition of preferences of each user into a expression called *Utility Function*. This function take as a inputs the knowledge of the state of the game, in this case, the inputs will be measurements from the environment, the rules of the game and the own player's strategy. The result of that function is a real value that represents the order in preference of the situation defined by the inputs. The aim of every player is to find which is the strategy to take that will provide the best outcome, and that now means, to find the maximum of the utility function.

In [23] the authors apply Game Theory to analise a *Random Access* Game. They show that desirable behaviour can be the result of autonomous selfish players. This was an encouraging for wireless networks designers but it does not completely apply in this work because the game definition is different. The definition for the game that applies in this work is following.

3.3.1 The Interference Game

This kind of game is characterized because the radio devices only take the interference read from the environment as the input parameter to make decisions.With all the elements showed so far, it is possible at this point to build the formal definition of an *Interference Game*.

Following the notation of [2], an Interference Game is a tuple $\Gamma = (\mathcal{P}, (\Sigma_i)_{i\in\mathcal{P}}, (\Pi_i)_{i\in\mathcal{P}})$ in which:

- $\mathcal{P} = \{1, \ldots, |\mathcal{P}|\}$ is the set of players
- Σ_i is the pure strategy space of player
  P= $\left\{s_1, \ldots, s_{|\mathcal{P}|}\right\}$ is a strategy profile and s_i is the strategy of the player i ($s_i \in \Sigma_i$).
- $\Pi_i : P \longrightarrow \mathbb{R}$ is the utility function.

The interference game is a non-cooperative game since all the players maximize greedily their own utility function to get the maximum profit possible. The properties of the distribution of the devices in the space and the different values of pathloss and fading among them turns this into an asymmetric game.

This is a repeated game because the radios update their status-quo every time that an improvement is possible, but it is not a simultaneous neither a synchronous game: the players don't play at the same time, and there is no existing order for updating the strategy. Another property defined by the pathloss is that the information is imperfect because not every radio can see all the others. Furthermore, even if a radio is able to perceive the response of several other radios, it won't be able to differentiate which of its neighbours is the cause of each change.

3.3.2 Supermodular & Submodular Games

At this point is necessary to introduce another property desirable in the interference game. A *submodular* game is, intuitively, a game in which strong strategies of some players cause a soft response by the others. This is desirable because if there is a player that, motivated by its low throughput, decides to allocate more resources then the others won't answer with the same attitude, but, tending to release some of the resources if possible. Contrarily, in a *supermodular* game players tend to respond with the same attitude to the behaviour of the other players. Supermodular games have another good property which is that always contain one pure strategy Nash equilibrium (PSNE) at least [24].

Formally, a submodular game has to hold the next three conditions for each player [2]

- Σ_i is a sublattice of $\mathbb{R}^K$
- Π_i has decreasing differences in (s_i, s_{-i})
- Π_i is supermodular in s_i

The first one will be accomplished if both operations among all the strategies possible result in an other strategy belonging to the set: i.e. $(s_i \wedge \tilde{s}_i) \in \Sigma_i$ and $(s_i \vee \tilde{s}_i) \in \Sigma_i$. The operation *meet* is defined as:

$$(s_i \wedge \tilde{s}_i) \equiv \left\{ min(s_i^1, \tilde{s}_i^1), \ldots, min(s_i^k, \tilde{s}_i^k) \right\} \tag{3.1}$$

And the *joint* operation is:

$$(s_i \vee \tilde{s}_i) \equiv \left\{ max(s_i^1, \tilde{s}_i^1), \ldots, max(s_i^k, \tilde{s}_i^k) \right\} \tag{3.2}$$

The second condition implies that:

$$\Pi\left(s_i \wedge \tilde{s}_i\right) + \Pi\left(s_i \vee \tilde{s}_i\right) \geq \Pi\left(s_i\right) + \Pi\left(\tilde{s}_i\right) \tag{3.3}$$

The third and last condition holds if

$$\Pi_i\left(s_i, s_{-i}\right) + \Pi_i\left(\tilde{s}_i, s_{-i}\right) \leq \Pi_i\left(s_i, \tilde{s}_{-i}\right) + \Pi_i\left(\tilde{s}_i, \tilde{s}_{-i}\right) \tag{3.4}$$

When $s_i \geq \tilde{s}_i$ and $s_{-i} \geq \tilde{s}_{-i}$

The presented theory is the tool used to analyse the behaviour of the GRACE algorithm, which is presented in the next chapter.

Chapter 4

GRACE

4.1 Overview

GRACE stands for Game-based Resource Allocation in a Cognitive radio Environment [2]. GRACE faces the problem of improving the throughput in LTE-like environments using both tools explained in the last chapters:

- Cognitive Radio means that both UE and eNB are constantly sensing the spectrum. They can use this information to determine how the spectrum is going to be used. Furthermore, GRACE is using only this information so it avoids the Intra-cell communication as well as the overhead needed to transfer this information. All these things together lead to a reduction of the complexity of the system.
- Game Theory is the tool that defines the behaviour of each user. This is the key to ensure that the behaviour of all the characters involved converge to a steady solution. This solution must maximize the efficiency of the resources used (i.e. the average capacity) but it also has to increase the user experience and fairness by keeping a minimum QoS for all the users.

The adaptation (instead of average capacity maximization) could make that in case of isolation maximum TP should be achieved. Contrarily, when all users are using the whole spectrum (Reuse 1), the TP must be comparable to the capacity achieved.

The spectrum sensing consists in a simple reading of the interference in each channel. This is one of the first steps in the algorithm and its simplicity turns it into one of the strong points of the algorithm. All the information needed to take decisions is taken from the normal transmissions of the other neighbours what means that there is no need to exchange information among the different cells. That fits completely with the existing close subscriber group structure (e.g. Wifi or cellular networks).

4.2 Definition

4.2.1 The Cognitive Cycle

GRACE is an Inter-Cell Dynamic Spectrum Allocation (IC-DSA) mechanism. Thus it operates close with RRM and MAC layers. The algorithm is based in an iterated optimization of a utility function (4.6). This iteration as well as the relation with RRM and MAC layers can be explained through two Cognitive Cycles in a mirror representation:

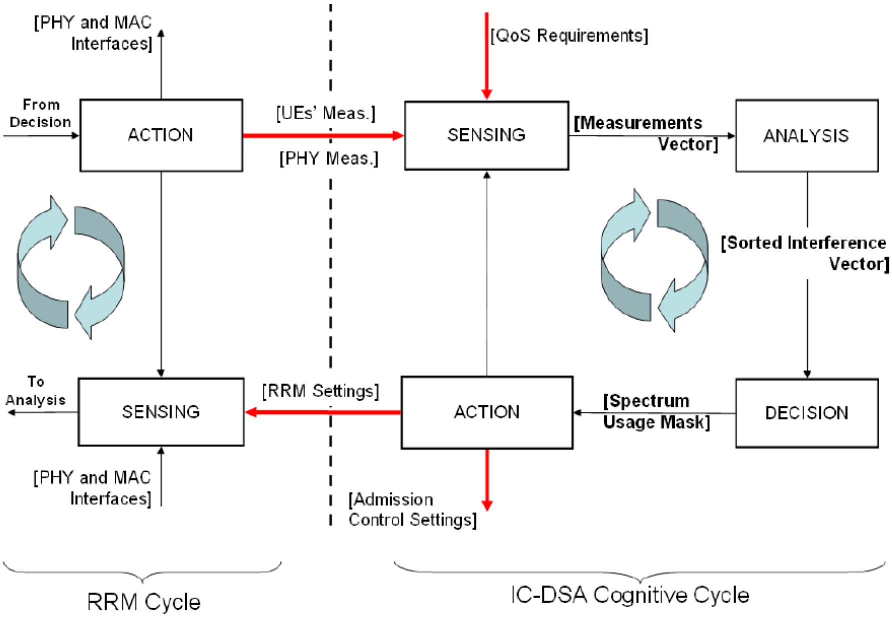

FIGURE 4.1: Cognitive cycle representation, extracted from [2]

In the RRM cycle, at the Sensing stage, the power measures are received from the Physical layer – when they are done at the same AP – or from MAC messages – when the measures are taken by the UEs. In the IC-DSA cycle, the sensing stage receives the QoS requirements through the Admission Control Layer. The measurements are passed then to the analysis stage. Every channel's interference is evaluated and the SINR and the INR are calculated. In the same stage the channels in the system bandwidth are sorted by the interference metric. This vector of channels sorted is used by the stage of decision to evaluate the utility function and generate a spectrum usage mask. Then the mask establishes the frequency resources available for RRM, AC and MAC layers. Finally, this mask is delivered to the action stage. The RRM and AC layers settings will be set up.

4.2.2 The Utility Function

The utility function is the parameter that the algorithm tries to optimize iteratively. In centralized structures the resources are distributed in order to achieve a global optimization. However in the frame of Game Theory, every player makes decisions to optimize greedily its own utility. The problem faced is to find a function which every C-cell uses to improve the performance locally but achieving a good overall performance at the same time. The global optimization is easier to reach in cases of fixed traffic demand than in cases when it is elastic. The principles that this function must follow are similar to the ones that traditional cellular networks apply, because a tight frequency reuse factor is used without degrading the SINR and also because part of the spectrum is leaved free for the use of the other cells. The aim of every cell should be:

- High bandwidth utilization
- Avoiding transmission over heavily interfered channels
- High spectral efficiency

The utility function derives from the comparison of the Shannon channel capacity in two different assumptions. The first one considers the scenario of reuse 1 where all the cells share the whole spectrum and cause interference to each other. The other is the one where FDM is applied and every cell is using just part of the spectrum without interference of the other cells.

In the following inequality the left term stands for the capacity of a single interference free channel and the right one stands for the capacity of m interfered channels.

$$B\ \log_2\left(1+\frac{\tilde{S}}{N}\right) > m\ B\ \log_2\left(1+\frac{\tilde{S}}{\tilde{I}+N}\right) \tag{4.1}$$

Where $\tilde{S}$ is the average power received, N the noise power, $\tilde{I}$ the average interference and B the band. Whenever the inequality holds, the FDM solution will be chosen over the reuse. This equation can be derived to:

$$\log_2\left(1+\frac{\tilde{S}}{\tilde{I}+N}\right) - \frac{1}{m-1}\ \log_2\left(1+\frac{\tilde{I}}{N}\right) \leq 0 \tag{4.2}$$

If we redefine the reuse factor m as the total number of channels K divided by the number of channels allocated n_i:

$$\frac{1}{m-1} = \frac{1}{K/n_i - 1} = \frac{n_i/K}{1 - n_i/K} \tag{4.3}$$

The weighting function is defined then as a function of the percentage of used channels:

$$w\left(\frac{n_i}{K}\right) = \frac{n_i/K}{1 - n_i/K} \tag{4.4}$$

Now, using $C(x) = \log_2(1+x)$ in order to simplify the notation and substituting this and (4.4) in (4.2)

$$C\left(\frac{\tilde{S}}{\tilde{I}+N}\right) - w\left(\frac{n_i}{K}\right) C\left(\frac{\tilde{I}}{N}\right) \leq 0 \tag{4.5}$$

This equation could be used as the threshold in a frequency scheduling system. In that system the best scenario is the one where every node selects the maximum number of channels and generates the less interference, leading to the optimum performance of the network. Hence, the system would let the nodes keep on adding channels as long as the last equation keeps holding, i.e. the addition of a channel would be actually beneficial for them. This way, the system avoids that all the nodes select all the channels, but just the ones they need to have a good performance without harming the neighbours' one.

The extension of this simple case to more complicated topologies leads us to the definition of a general utility function:

$$\Pi_i = \sum_{k_i=1}^{K} s_i^{(k_i)} \left[C_i^{(k_i)} - w\left(\frac{k_i}{K}\right) \psi^{k_i} \right] \tag{4.6}$$

Where k_i is an ordaining of the channels in terms of increasing interference; $s_i^{(ki)}$ is just a binary value which is 1 if there is transmission in the channel k_i and 0 if there is not; $C_i^{(ki)}$ is the channel capacity given by the link level of the system; $\psi^{(ki)}$ is the term that measures the interference in the channel in order to know how much is it used. Equation (4.5) suggests to be the same function used to calculate the capacity so $\psi^{(ki)} = \log_2\left(1 + \frac{\tilde{I}}{N}\right)$; and $w\left(\frac{k_i}{K}\right)$ is the weighting function which is a design parameter. Equation (4.4) gives a possible definition.

The ordering of channels permits us to define the marginal utility as the extra utility achieved when selecting a new channel:

$$\frac{\Delta \Pi_i}{\Delta k_i} = C_i^{(k_i)} - w\left(\frac{k_i}{K}\right)\psi^{(k_i)} \tag{4.7}$$

This definition shows that maximizing the utility function (4.6) is equivalent to selecting the channels with positive marginal utility. We can also see that the definition of the weighting function is decisive in the behaviour of the algorithm. A good choice for that function will lead to many improvements:

- High Bandwidth utilization. In the case of low interference the utility function tends to be the channel capacity.
- Avoidance of heavily interfered channels. If a channel is highly interfered its marginal utility decreases so it will likely not be chosen.
- High spectral efficiency. The distribution of the channels among the different C-cells leads to the use of every free channel and that makes the system achieve a high spectral efficiency.

An example of weighting is the *Sigmoid* function. It has an 'S' behaviour so if the numbers of channels used is low, the interference on them is disregarded, otherwise the weighting is so high that the channels will be only chosen if they have very little interference. The sigmoid function is the one used for the simulations of GRACE.

$$w\left(\frac{k_i}{K}\right) = \frac{1}{1 + e^{\frac{-k_i}{K}}} \tag{4.8}$$

Another option in the design of the weighting function is a function learned dynamically, but it would affect the convergence of the whole algorithm.

4.3 Game Theoretical Analysis

GRACE uses the Game Theory to define the algorithm being used. Hence, GRACE is defined as a spectrum sharing game in which a player corresponds to a C-cell (both terms will be interchangeable from now on). Every C-cell can have different links established with different users, so it is important to clarify that GRACE deals with the spectrum shared among different C-cells but not with the spectrum shared by the users inside the cell.

Some auxiliary definitions must be done before the definition of a GRACE Spectrum Sharing Game.

Let $\mathcal{K} = 1, 2, .., K$ be the pool of dynamically shared channels. Every player has access to all channels in the pool and they are orthogonal, so there is no cross-interference between them. The strategy space is the same for every player and consists on all possible spectrum usage masks. The usage mask is defined by a binary vector, $s_i = \left[s_i^{(1)}, \ldots, s_i^{(k)}, \ldots, s_i^{(K)}\right]$ in which every component indicates if the associated channel k is used for the transmission $\left(s_i^{(k)} = 1\right)$ or not $\left(s_i^{(k)} = 0\right)$.

Each player reduces all the relevant information to just two values per channel. The first one is the received interference power:

$$I_i^{(k)} = \sum_{\substack{j=1 \\ j \neq 1}}^{|\mathcal{P}|} s_j^{(k)} I_{ji}^{(k)} \tag{4.9}$$

The second one is the received signal power:

$$S_i^{(k)} = \begin{cases} \tilde{S}_i^{(k)} & \text{if } s_i^{(k)} = 1, \\ 0 & \text{otherwise.} \end{cases}$$

The reduction of the information can be easily implemented by using the sensing information of the link with worst SINR. The next definition is the bijective function that orders the channels according to increased level of worse case of interference:

$$q_i(k) > q_i(k^*) \Leftrightarrow I_i^{(k)} > I_i^{(k^*)}$$

$$k_i = q_i(k),\ k_i \in K$$

With the last two values we can redefine the utility function as:

$$\Pi_i = \sum_{k_i=1}^{K} s_i^{(k_i)} \left[C\left(\frac{S_i^{(k_i)}}{I_i^{(k_i)} + N_i^{(k_i)}} \right) - w\left(\frac{k_i}{K}\right) C\left(\frac{S_i^{(k_i)}}{I_i^{(k_i)} +} \right) \right] \tag{4.10}$$

Where $N_i^{(k_i)}$ is the noise power and $C(x)$ is the link level mapping of the SINR to throughput.

Considering all these premises we can finally define a GRACE Spectrum Sharing Game Γ as a tuple $\left(\mathcal{P}, \mathcal{K}, (\Sigma_i)_{i\in\mathcal{P}}, I_{ij}^{(k)}, S_i^{(ki)}, (\Pi_i)_{i\in\mathcal{P}}\right)$ where,

- $\mathcal{P} = \{1, \ldots, |\mathcal{P}|\}$ is the set of players
- $\mathcal{K} = \{1, \ldots, K\}$ is the set of channels

- $(\Sigma_i)_{i \in \mathcal{P}}$ is the set of strategy spaces (i.e. all the possible combinations of channel allocations),
- $I_{ji}^{(k)}$ is the interference interaction at channel k from player j to player i.
- $S_{ji}^{(k)}$ is the received signal power by player i at channel k.
- And Π_i is the utility function defined in equation (4.10).

4.3.1 Game Statics

A Nash Equilibrium (NE) is the set of strategies in which no player achieves benefit by changing its own strategy. Therefore all players will keep the last strategy chosen before the NE is reached. As we see in [21] the NE existence is only ensured in the mixed strategy for finite strategic-form games.

The GRACE spectrum sharing game has a particular structure that does not change if the number of players is two or more. That is because from one player's point of view, the interference sensed (4.9) is the sum of the interference of all the other players, without taking into account which player is actually creating this interference. Therefore the adaptation to one player is the same as the adaptation to more than one player.

In a GRACE game the best reply selection can be implemented by selecting the channels which marginal utility is positive. In a two players GRACE game a best reply selection can be determined by the number of channels allocated by each player. This game has two features to highlight [2]:

- In the first place players try to minimize the overlapped resources. So if a player with few frequency channels assigned starts to increase them, the other tends to decrease the quantity that it is using. This is a property of submodular games and we will see that GRACE is so.
- In the second place GRACE creates a plateau on the best reply selection. This means that for some sets of strategies the reply does not change. For example when the interference is strong the players will reach a minimum of channels used. This is a feature important for the stability.

It is possible to prove that a two players GRACE game always has a PSNE as it is a submodular game which can be turned into a supermodular game. The key aspects to demonstrate it are:

- Σ_i , the set of strategies, must be a sublattice of $\mathbb{R}^K$. With the definition of the *meet* operator as a bitwise logical **AND** and the *join* operator as an **OR**, it is easy to see that the operation among the elements of Σ_i always produces another element of Σ_i.
- The utility, Π_i, must have decreasing differences in (s_i, s_{-i}) and be supermodular in s_i.

With the definition of utility given in (4.10) both propositions can be proved [2].

Although the existence of PSNE is not proved for a GRACE game with more than two players, all the simulations done have reached a fixed point as we show in the next section. It is still an open issue to find the general conditions that ensure PSNE existence in submodular games with more than two players. The latest advances in the topic can be found in [25].

4.3.2 Game Dynamics

The GRACE spectrum sharing game is played in several stages. In each one the players try to learn the equilibrium spectrum allocation based in the sensing information. This process is done through the better-reply dynamics (BRD) [26]. This means that in every stage of the game some players are selected to check their status-quo. Each player will update the status-quo just if the utility provided by the new strategy is greater than the one of the current stage. Otherwise the status-quo will be kept for the next stage.

There are two modifications made to BRD in order to improve the behavior of its convergence:

- The first one consists in a probability value, σ, to decide whether or not to update the status-quo [27]. This avoids coordination among players and permits a better scalability of the algorithm.
- The second is a maximum number of changes on the allocated channels every time the status-quo is changed, Δn_{max}. This modification stabilizes the sensing information, permits the RRM and AC layers to adapt more easily to the spectrum allocation changes and provides smother transitions on the transmission data rate to the upper layers. In addition the C-cells wait each other before doing large changes in allocation, so in the presence of several PSNE the symmetric equilibrium will be the most likely to be reached. The only negative side is the loss of spectrum agility. So the value of Δn_{max} has to be chosen sufficiently large so it is not disturbing the spectrum agility.

Chapter 5

Power Control

5.1 Definition of Power Control

The UTRAN-LTE defines 3 different levels in its Radio Resource Management (RRM): Radio Link Control (RLC), Medium Access Control (MAC) and Physical Layer (PHY) [28]. Figure 5.1 provides an overview of their functions.

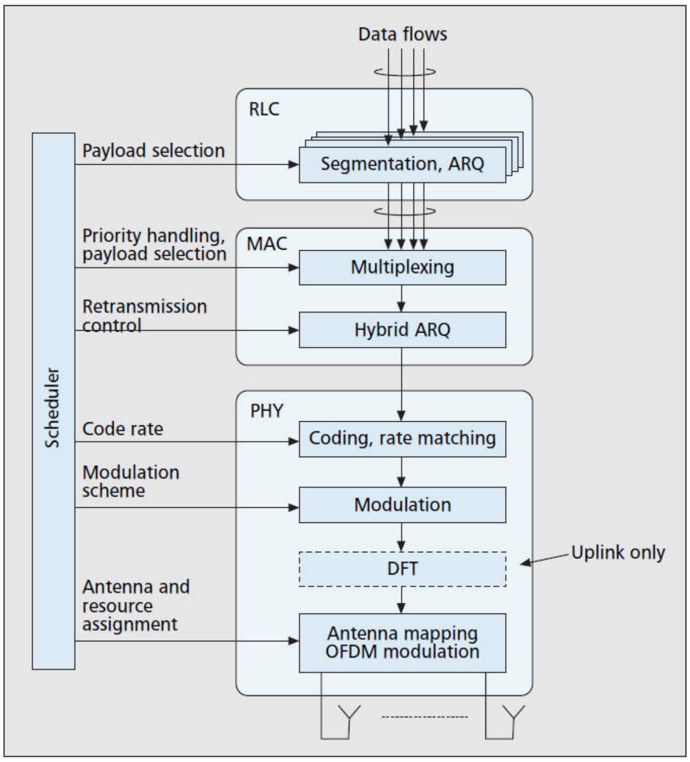

FIGURE 5.1: RRM Stack protocol of LTE extracted from [3]

The physical layer contains two main blocks: on the one hand the Link Adaptation Unit, which is responsible for the Modulation and Coding Schemes (MCS) selection. On the other the Packet Scheduler (PS) which sets the Time Transmission Interval (TTI) and performs the bandwidth and power allocation. This last feature, the power allocation, is the focus of this chapter.

The power control (PC) system is needed, form the system point of view, to improve the system capacity and the coverage, and from the user point of view, to improve the Quality of Service and reducing the power consumption [29]. To achieve this, the PC has to find a commitment between the SINR that users can reach and the interference created.

There are two main possible structures: with the *Open Loop Power Control* (OLPC) the devices set their power depending on their own measures and the ones obtained from the eNB; for the *Closed Loop Power Control* (CLPC) UEs also send feedback to the eNB so they can receive more accurate corrections to set the transmission power.

Another feature of the PC is the speed of the changes that it has to correct. Therefore *slow PC* aims to correct for shadow fading or path loss changes and *fast PC* is meant for fast channel variations like fast fading.

It is worth saying that CLPC and fast PC require more complex procedures and more signaling than OLPC and slow PC, but they also provide the system with methods to defeat the channel conditions.

LTE PC algorithms work in terms of Power Spectral Density (PSD) rather than total power [30]. In traditional systems as 3G the spectrum used was fixed so total power was the usual term. Contrarily, LTE uses OFDMA [31] in which the available spectrum depends on the PRBs assigned so the PC is only capable to fix the power in each resource.

5.2 Examples of Power Control

5.2.1 Full Path Loss Compensation

Full path loss compensation is the first approach to the power control. It simply takes into account that the users which are further from the base station need more power than the ones which are closer. The aim then is to increase the transmission power with the value of path loss existing between the UE and the eNB.

The compensation of the PL causes that all the users transmit with the same SNR. This is also an advantage for the reception in the Base Station because the dynamic range in which the antennas work is smaller.

The value of PL can be obtained either by measuring it from the UE or as information received from the eNB if such an OLPC message is established.

5.2.2 Water Filling

This algorithm defines the way to distribute the power among the frequency channels. The main idea behind is to increase the capacity accumulating the power in the less interfered channels. The capacity maximization is reached by distributing the energy in a *water filling* manner. The figure 5.2 represents an example of how the algorithm works and shows the reason for its name: thinking of the noise and interference as the bottom of a container, the algorithm fills it with power as if it was a sort of liquid, leaving a flat surface on its top.

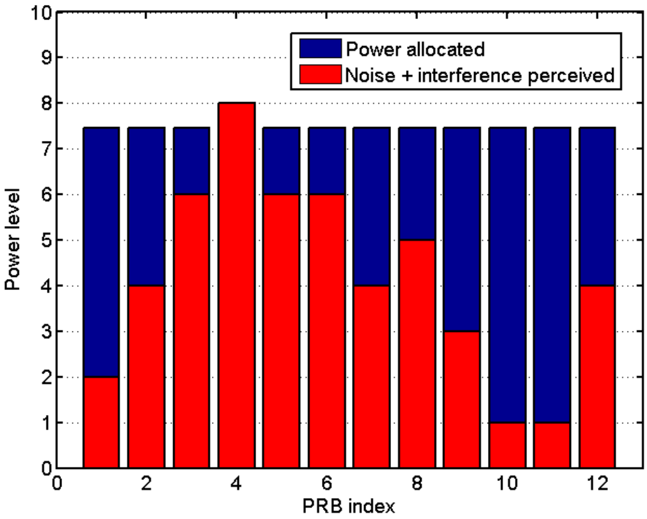

FIGURE 5.2: Example of the power allocated by a water filling algorithm

There are several implementations that can reach water filled solutions. The next one can be taken as an example:

```
N=length(interf_vec);

%first step of water filling
wline=min(interf_vec)+Pmax/N; %initial waterline
Palloc=sum(max(wline-interf_vec,0)); %total power allocated for current waterline

%gradual water filling
while abs(Pmax-Palloc)>error
    wline=wline+(Pmax-Palloc)/N;
    Palloc=sum(max(wline-interf_vec,0));
end
```

FIGURE 5.3: Example of Water Filling algorithm from [4]

The algorithm 5.3 needs the information about the interference (*interf_vec*) in each channel and the amount of power available (*Pmax*). As it is iterative, an *error* must be defined so the power allocated (*Palloc*) is close enough to the maximum power.

If applied in the interference game, each user considers the interference of the others as Gaussian noise. As the author points in [32], in case of low interference the solution achieved is equivalent to a Nash equilibrium for this Gaussian interference channel game.

A deeper analysis of the 2 players game is done in [32], where three different cases are depicted:

- If the frequency overlap is complete, there is only one existing solution in which the power is the same along all the frequency channels.
- If the frequency overlap is not complete, there are several solutions existing.
- If there is no overlap in the frequencies, there will be one solution if the interference is as large as the signal power. If the interference is larger than the desired signal, many solutions can be found.

In [33] water filling is compared to other power distributions as Equal Power allocated per PRB or Equal SINR for allocated PRBs. The authors conclude that although WF leads to the best average block TP, the SINR variability is high. This together with the also high complexity of the algorithm were the reasons to discard it as the best solution.

5.2.3 Fractional Power Control

This is the power control standard agreed in 3GPP for UTRAN LTE uplink [34]. The formula that defines the algorithm is the following:

$$P_{tx} = min\left(P_{max}, 10 \cdot \log_{10} M + P_0 + \alpha \cdot L + \Delta_{mcs} + f(\Delta_i)\right) \ \ [dBm] \tag{5.1}$$

Where,

- P_{tx} is the total transmission power allocated by the UE.
- P_{max} is the maximum power available in the device.
- M is the number of Physical Resource Blocks (PRB) allocated.
- P_0 is a cell specific parameter broadcasted by the eNB.
- α is the path loss compensation factor with a range of: $0 < \alpha < 1$.
- L is the DL path loss measured by the user[1].
- Δ_{mcs} is a UE specific parameter signaled by Radio Resource Control (RRC).
- Δ_i is an UE specific close-loop factor of correction.
- $f(\cdot)$ is signaled by the upper layers.

The path loss value is calculated by the UE means the measurement of the power level of the reference symbols. The analysis of the algorithm is done with the simplifications that come from focusing only in the OLPC, so from now on the close-loop corrections (Δ_{mcs} and $f(\Delta_i)$) will be dismissed. Then, the simplified formula for FPC is:

$$P_{tx} = min\left(P_{max}, 10 \cdot \log_{10} M + P_0 + \alpha \cdot L\right) \ \ [dBm] \tag{5.2}$$

Taking the *full path loss compensation* as a reference, the main idea behind the FPC is to decrease the inter-cell interference. The way to achieve this is to lower the transmit power of the UE which are at the edge of the cell, as those are the ones who damage the most their neighbour cells. The users in the cell edge are affected by a large path loss, what makes them to be the users transmitting more power in the full compensation algorithm.

The algorithm should improve the cell throughput without damaging the outage too much.

---

[1] The antenna gain and the shadowing effect are included

Effect on SNR

The user SNR is defined:

$$SNR = P - L - N \tag{5.3}$$

Applying (5.2), the ideal[2] SNR experienced by the users would be:

$$SNR = 10 \cdot \log_{10} M + P_0 + (\alpha - 1) \cdot L - N \tag{5.4}$$

Where N is the power of thermal noise.

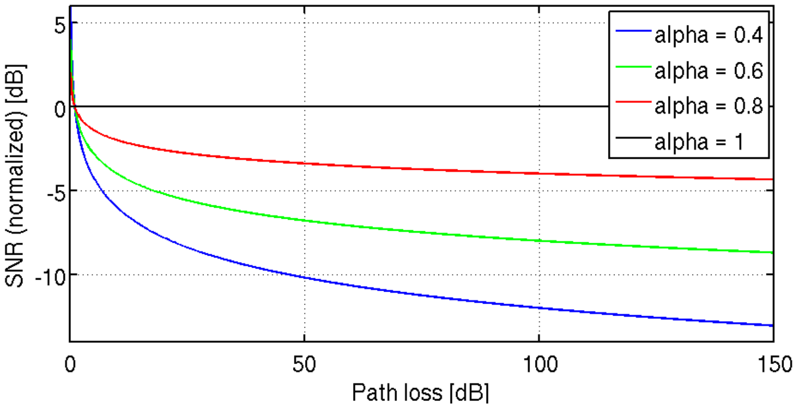

FIGURE 5.4: Expected SNR depending on the path loss of the UE, for different values of α

In figure 5.4 the ideal effects of the algorithm on the SNR are shown. The SNR values are referenced to the ones of the full PL compensation (or $\alpha = 1$). In this case, the SNR experienced for the users must be the same regardless of their PL. With the FPC algorithm, the following effects can be observed:

- The FPC SNR in much lower for all the UEs than for full compensation (even for the ones with low path loss).
- The SNR is lower when the PL increases.
- Decreasing the value of α also decreases the SNR and increases the slope of the curve, so the same difference of PL makes a larger difference in SNR.

The analysis done in [35] shows the effects expected in SINR and the results of a system-level simulator. The authors simulated two different environments:

---

[2] Assuming constant level of noise

Interference-limited Scenario Or Macro 1. In this case there is no limitation in power so the users can easily achieve the SINR required by the FPC. Large increase of cell capacity can be achieved at the expense of lowering the cell coverage. There is also the possibility to chose α and IoT[3] operating point so the increase in cell coverage is not so large but the loss in cell capacity is negligible.

Noise-limited Scenario Or Macro 3. In this case cell edge users are limited by the maximum transmitting power so they cannot achieve the SINR required. The cell gain that can be reached is very low but for some values of α and IoT the cell coverage is not penalized in excess.

As will be shown in the next chapter, this is the algorithm chosen to work as a Power Control because of its simple formulation and good performance, as well as because of its independence from the bandwidth allocated, what results convenient the convergence of the whole system.

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[3] Interference over Noise: $IoT = \frac{I+N}{N}$, lineal values.

Chapter 6

Power Optimized Application of GRACE

6.1 Problem Definition

The purpose of this work is to study different methods of power control that could fit the environment established by a spectrum allocation algorithm based in Cognitive Radio. The characteristics of GRACE as a frequency domain scheduler have been analysed and must be born in mind in order to find a proper PC algorithm.

It is necessary then to recall the most important goals that characterise GRACE:

- The algorithm is adaptable, distributed and scalable, meant to work in uncoordinated deployments.
- It has low complexity avoiding inter-cell signaling and extra overhead.
- It is meant to achieve high cell capacity with a minimum outage achieved.

Therefore, the behaviour of the PC algorithms should be in accordance with these characteristics or even improve them if possible. The next section, 6.2, explains how the FPC accomplishes these requirements, and in section 6.3 another algorithm called *Desired Capacity Algorithm* has been developed with the aim of achieving better results.

6.2 FPC Approach

The Fractional Power Control was chosen as a subject of study for this work because it satisfies the most important requisites.

In the first place, it has a simple formulation (5.1) and it is only dependant on intra-cell information (path loss measurements and close loop corrections). Other algorithms, like the one described in [30], propose to use information from other cells which increases the overhead and in some environments, like Wifi, implies agreements among different service providers to share this information.

In the second place, the FPC does not affect to the convergence of GRACE since it simply assigns a PSD to each user so every user has a fixed power in each channel, and the actual total power assigned depends on the number of PRB assigned by GRACE. So the number of frames needed to achieve the best performance is the same as shown in [2], where GRACE is defined without power control.

The only property that was not studied by this work is if the FPC is also adaptable to uncoordinated deployments. The simulations realized only consider one specific layout which is defined in the next section.

The next flow diagram explains how both algorithms work together:

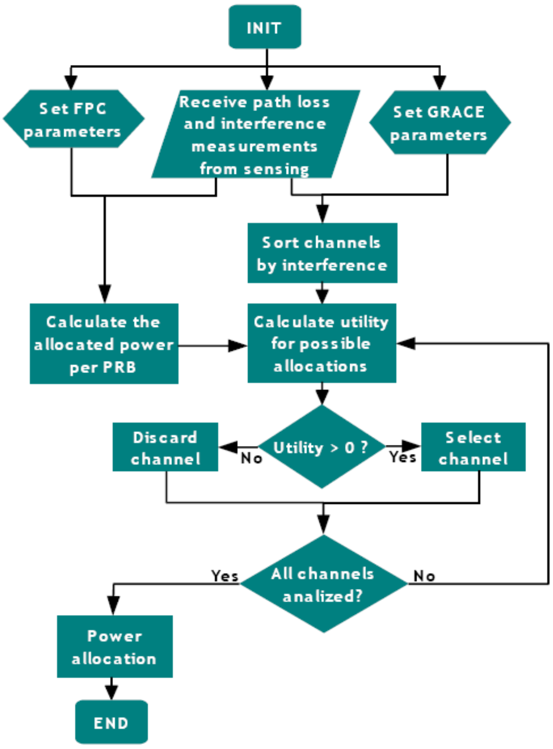

Figure 6.1: Flow diagram of FPC and GRACE

6.3 Desired Capacity Algorithm

On the way to design a new PC algorithm that improves the results of FPC, the first attempt was to follow the steps of the algorithm defined in [36]. In this algorithm each user establishes a price for its own power and updates the power depending on a utility function and the power price of the others. The value of the power price depends on the variation of this utility function over the measured interference. The problem found in applying a double optimization (power allocated and power price) is that the convergence of the whole algorithm takes more time since the parameters of both optimizations depend on each other.

The Desired Capacity Algorithm avoids then this double optimization. Alternatively, it follows the style of the FPC fixing a PSD. As its name suggests, the algorithm starts by setting a cell desired throughput (in Mbps) which is then translated into a value of SINR to be achieved. The power to be allocated is calculated with the following formula:

$$P_{tx} = min\left(P_{max}, SINR^{*} + L + 10 \cdot \log_{10}\left(I_w + N\right)\right) \quad [dBm] \tag{6.1}$$

Where P_{max} is the maximum power available, $SINR^{*}$ [dB] the desired SINR, L [dB] is the path loss measured and N [mW] is the noise power. I_w [mW] is called the *wideband interference* and it is the sum of the interference on all the frequency channels of the system (i.e. both used and not used). The fixed PSD is obtained by $\frac{P_{tx}}{M}$, with M being the total amount of frequency channels or PRBs.

Note that the algorithm is not aware of the amount of PRBs assigned, the PSD is fixed assuming that the whole bandwidth is available. In this way we avoid the dependency on GRACE optimization and the increase of time needed to achieve its solution. Note also that, unlike FPC, the algorithm takes into account both path loss and interference since the users will allocate more power if more interference is perceived. But as GRACE selects only the channels with less interference, the increase of power allocated will not disturb in excess the other users.

In the figure 6.2 a flow chart of the whole algorithm is shown.

Mapping the desired capacity into a SINR value The modification of the Shannon capacity bound of the paper [37] was considered in order to map throughput into SINR. The modification consists of two parameters, BW_{eff} and SNR_{eff}, that take into account the bandwidth and SNR efficiency for the UTRAN LTE air interfaces. Thus, the formula used to obtain the SINR is shown in equations (6.2) and (6.3).

$$SINR^* = \left(2^{\frac{C_{net}}{BW_{eff}}} - 1\right) \cdot SNR_{eff} \tag{6.2}$$

in which,

$$C_{net} = C^* \cdot \frac{S_t \; Sym}{S_u \; PRBs \; C_{PRB} \; C_s} \tag{6.3}$$

where we find C^*, the desired capacity and some system parameters as:

- S_t is the total number of slots and S_u, the used ones,
- Sym is the number of symbols per frame,
- $PRBs$ is the number of PRB's in the system,
- C_{PRB} is the number of carriers per PRB,
- and C_s, the carrier spacing.

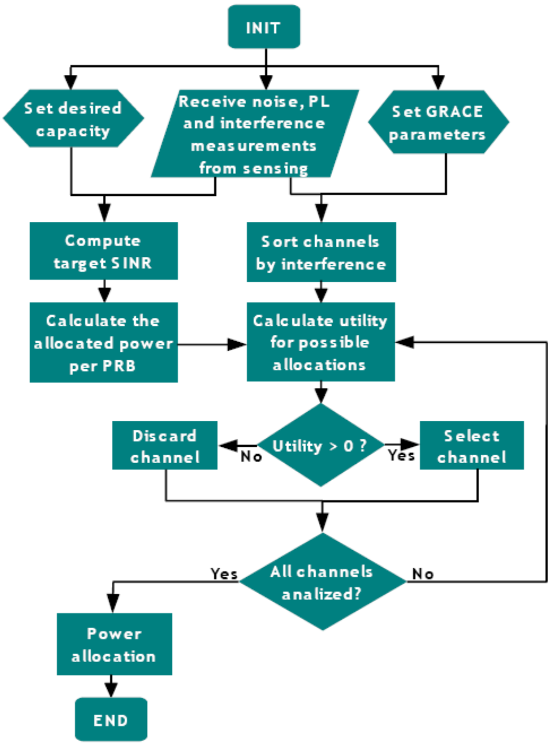

Figure 6.2: Flow diagram of DCA and GRACE

Chapter 7

Simulations, Results and Discussion

7.1 Simulation Framework

The simulator used to assess the performance of the algorithms is the same used in [2] and shares most of its settings. It is a system-level simulator which conforms an OFDMA access mode among different eNBs in a home scenario. All the simulations are done with the same *layout* structure (figure 7.1) which includes 16 cells, four rooms per cell, one user per cell and 2 corridors. The probability of users being active is 1.

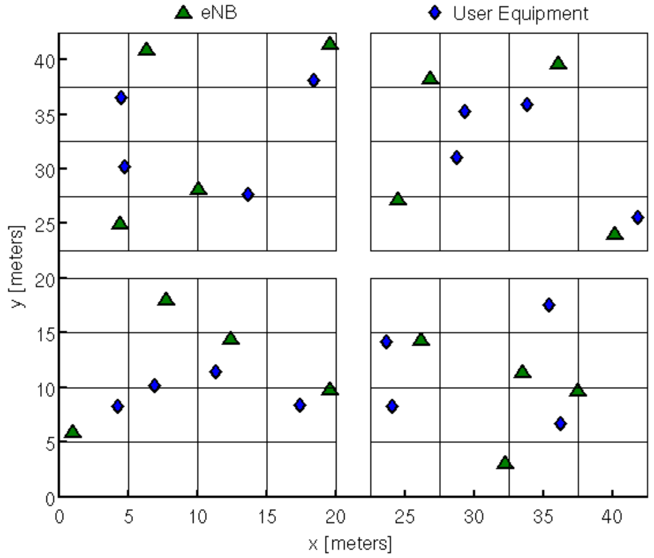

FIGURE 7.1: Example of home scenario: 16 cells (houses) with 4 rooms each

In every simulation several layouts and *drops* are generated. Every time a layout is generated the position of the eNBs is randomized. For every layout, several drops are simulated and, for each one, the position of the UEs is randomized as well, but the positions of the eNBs are steady until the next layout. For each simulation drop, 50 frames or game stages are computed. Each UE is connected to the corresponding eNB in the same house, in a closed subscriber group and there are no handovers considered.

The duplexing mode is TDD with UL/DL switching point fixed at 50%. Since the results in UP and DL are very similar only UL values are shown. The system Bandwidth is 100MHz, divided in 125 channels (or PRBs).

It is worth saying that there is no effect of fading considered and that power is set at P_{max} by default when there is no PC algorithm activated. In addition, if it is not specified, the simulations are done with the GRACE algorithm activated. More details of the configuration of the simulator can be checked in table 7.1.

TABLE 7.1: Common parameters used in the simulations

System Model		
Spectrum allocation	100 MHz centered at 3.5GHz	
eNB parameters	Max TX power	24 dBm
	Antenna System	Omni (3 dBi)
UE parameters	Max TX power	24 dBm
	Antenna System	Omni (0 dBi)
Access scheme	OFDMA	
Duplexing scheme	TDD	
PRBs	125	
Link Level Model		
3G-LTE approximation	SINR efficiency	[0.56 DL, 0.52 UL]
	Bandwidth efficiency	[2 DL, 2.34 UL]
Scenario Model		
Home scenario	Room size	5m x 5m
	Sidewalk width	2.5m
	eNB position	random
	UE position	random
Propagation Model: Winner II A1 Indoor		
Minimum coupling loss	45dB	
Home scenario	Internal walls	5dB attenuation
	External walls	10dB attenuation
	Shadow fading	no deviation
Traffic Model		
Data generation	Full buffer (there is always data for transmission)	

7.2 Applying FPC

The first simulations of the FPC have the purpose of showing an overview of the algorithm's performance or how this performance changes with the modification of the main parameters. Recalling the formula of the FPC in (5.2), only two parameters are involved: P_0 and α. These simulations are done with 25 random layouts and 25 random position for the UE in each, therefore 625 drops in total.

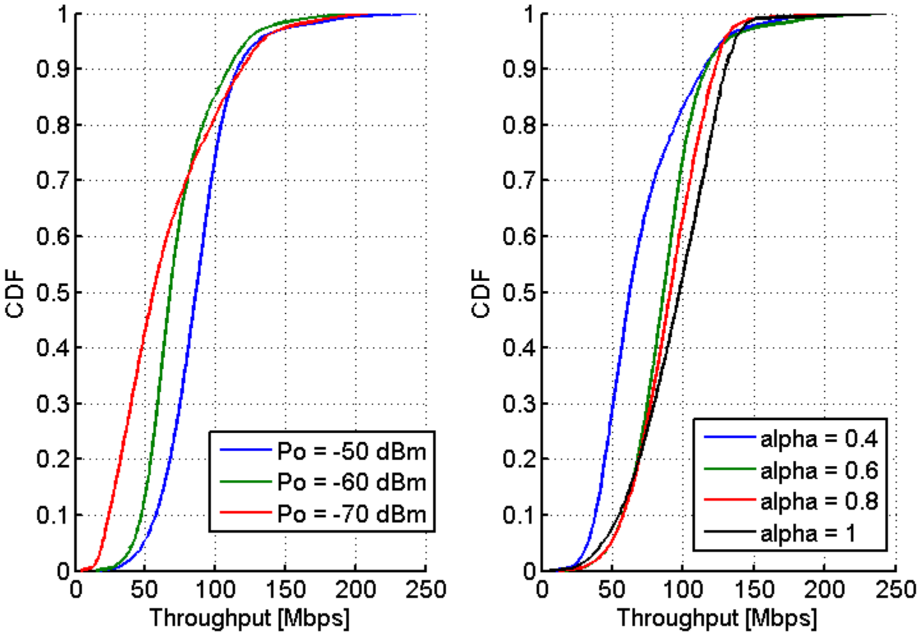

FIGURE 7.2: CDF of the cell throughput average. In (a) α is fixed to 0.6 and in (b) P_0 is fixed to -50 dBm.

In the figure 7.2 we can see a CDF of the mean throughput achieved in each cell. Specifically, (a) shows the evolution of P_0 as α is fixed. The value of $-50dBm$ is definitely the one that permits the best throughput up to 90% of the users. In (b) α is changing with fixed P_0. In this case the best choice is not clear: $\alpha = 0.6$ and $\alpha = 0.8$ have the best performance in outage but $\alpha = 1$ achieves higher values of throughput.

As we can see in figure 7.3 the power allocated is significantly (around 18 dB) reduced when α is decreased. Such a reduction can be very interesting for battery fed devices since the power restriction is usually very important. That is the reason why the suboptimal configuration $P_0 = -50dBm$ and $\alpha = 0.6$ is the one chosen as a reference in extensive simulations. It is worth saying that the value of $\alpha = 0.6$ is also identified as a suboptimal in [35].

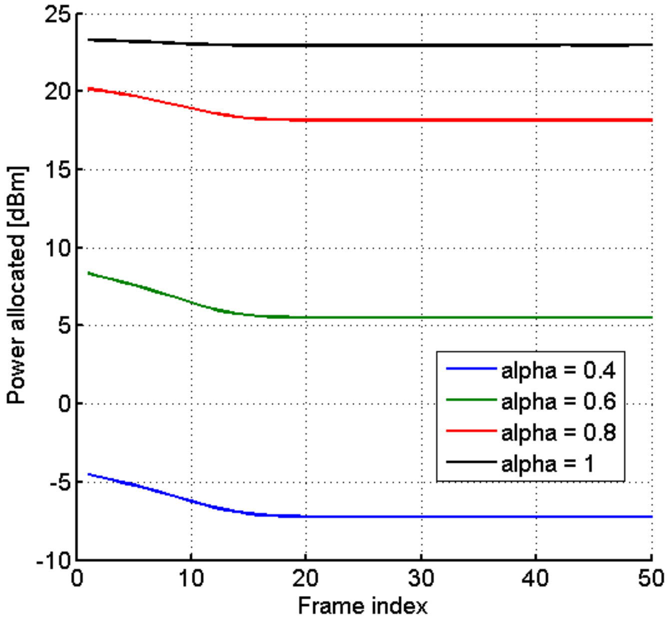

FIGURE 7.3: Power allocated with FPC for different values of α. P_0 is fixed to $-50dBm$

Beside the tests done with GRACE, FPC has been also tested with other spectrum distribution schemes as Reuse 1 (R1) and Reuse 2 (R2). In the fisrt case (R1) all the cells are using all the system bandwidth, and in the second (R2) the spectrum is divided in 2 parts between neighbour cells.

In figure 7.4 (a) we can see that applying FPC to both reuse 1 and reuse 2 makes the outage increase as happened with GRACE. In figure 7.4 (b) the values of power allocated are shown. As well as with GRACE the reduction in radiated power is significant. In both figures we can compare this behaviour with FPC applied to GRACE, wich performance is very close to the one of reuse 2 with FPC.

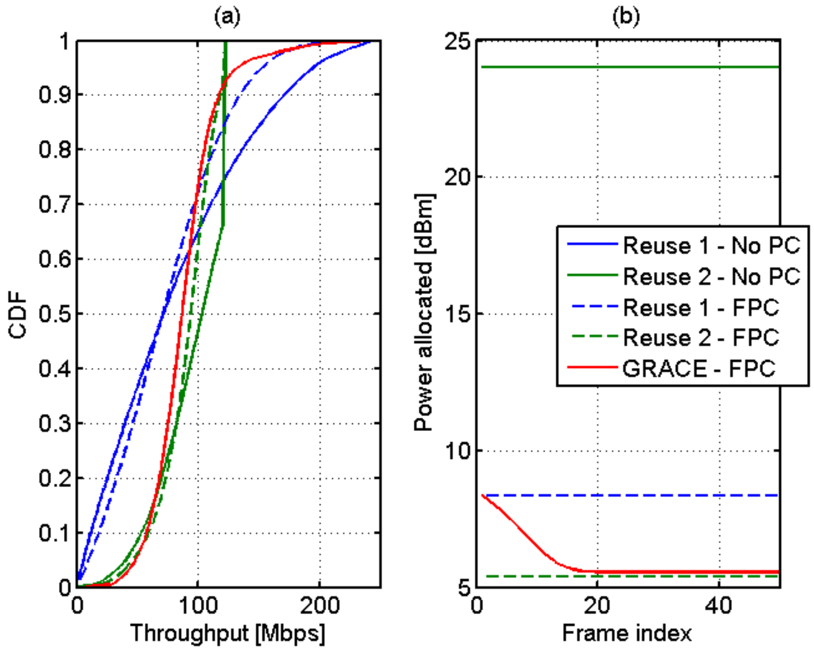

FIGURE 7.4: In (a) TP CDF of Reuse 1 and 2 with no PC and FPC. In (b) Power allocated.

The extensive simulations of FPC applied to GRACE were realized with 25 random layouts and 100 random positions for the UEs in each, what is 2500 drops in total.

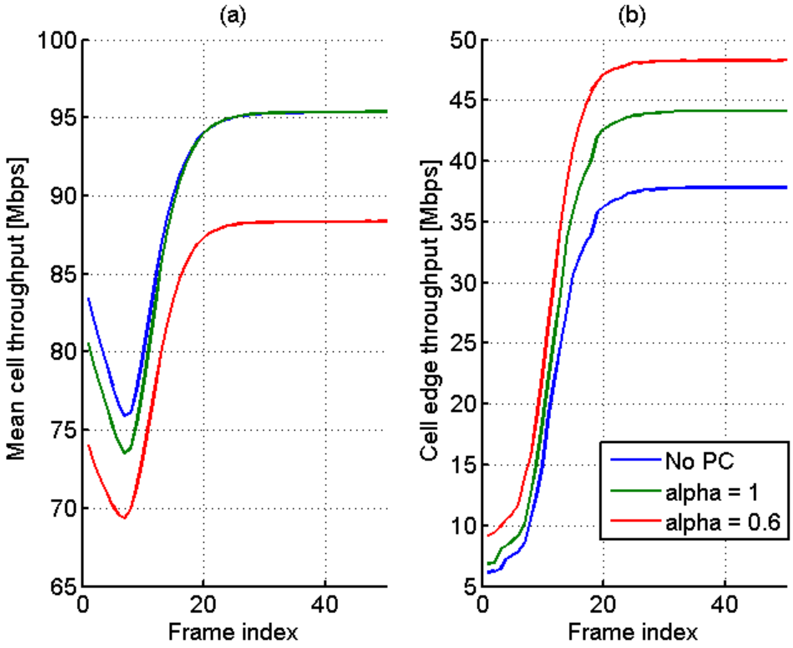

FIGURE 7.5: Evolution of the mean cell TP (a) and cell edge (b) TP over time

Figure 7.5 (b) shows the clear improvement in outage that FPC reaches: Compared to not using power control full path loss compensation ($\alpha = 1$) improves 16% and FPC ($\alpha = 0.6$) improves up to 27%. On the other hand FPC has a loss in mean cell TP of 7% while full compensation has no loss.

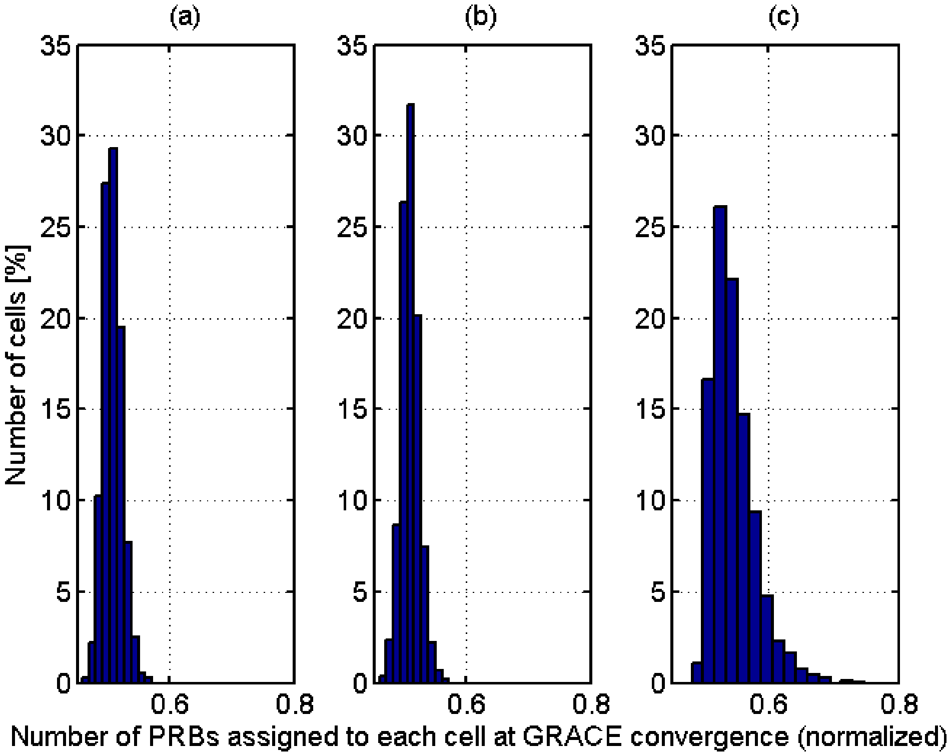

Figure 7.6: Histograms of the number of PRB's assigned at the convergence of GRACE. No PC in (a), full compensation in (b) and FPC in (c).

Figure 7.6 contains three histograms of the number of PRB's allocated by each cell in the last frame of the simulation, so when GRACE has converged. In histograms (a) and (b) (No PC and full compensation) the mean is around 50% of PRBs, with FPC it is slightly beyond.

The reduced transmission power of FPC decreases the interference among the different cells which explains that GRACE is able to allocate more PRB to every cell.

As we can see the application of FPC is increasing the outage TP when it is actually designed to decrease the transmission power of the edge users (respect to full path loss compensation). This effect is explained because the interference is combated by two different ways. On the one hand there is the reduction in power (specially in the cell edge) that FPC provides. On the other, GRACE establishes a proper distribution of the channels among the cells so they only use the ones with less interference. The sum of this two forces reduces drastically the interference perceived by all the users, as we can see in 7.7. In this figure, the slope shows how GRACE can reduce the value of noise power plus interference by about 10 dB and how the FPC lowers the entire curve about 20 dB more.

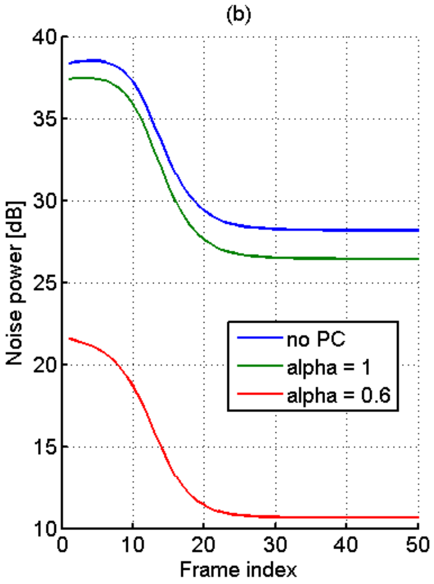

FIGURE 7.7: Noise rise evolution comparison

7.3 Applying Desired Capacity Algorithm

The results obtained so far by this algorithm are presented in this section. Different simulations were done to determine the impact of the cell capacity parameter on the performance. Figure 7.8 (a) shows the power allocated and (b) the Noise Rise Evolution. Compared to 7.3 the values are much higher.

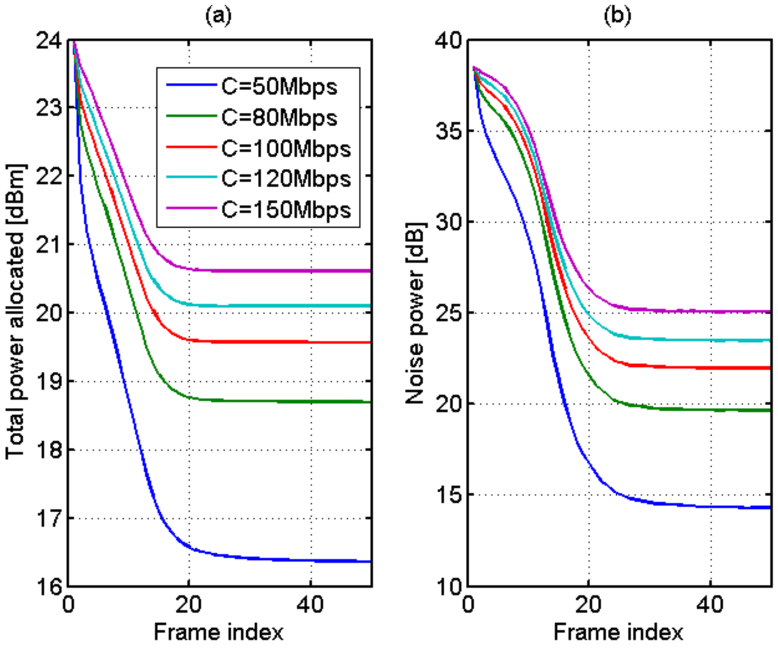

Figure 7.8: Power allocation (a) and NRE (b) for different values of C

In figure 7.9 we can see the histograms of allocation of PRBs. In the three cases the allocation is centered in 50% of the PRBs but for C=120Mbps the diversity of allocation is higher, so there are more cells with an allocation over and beyond that value.

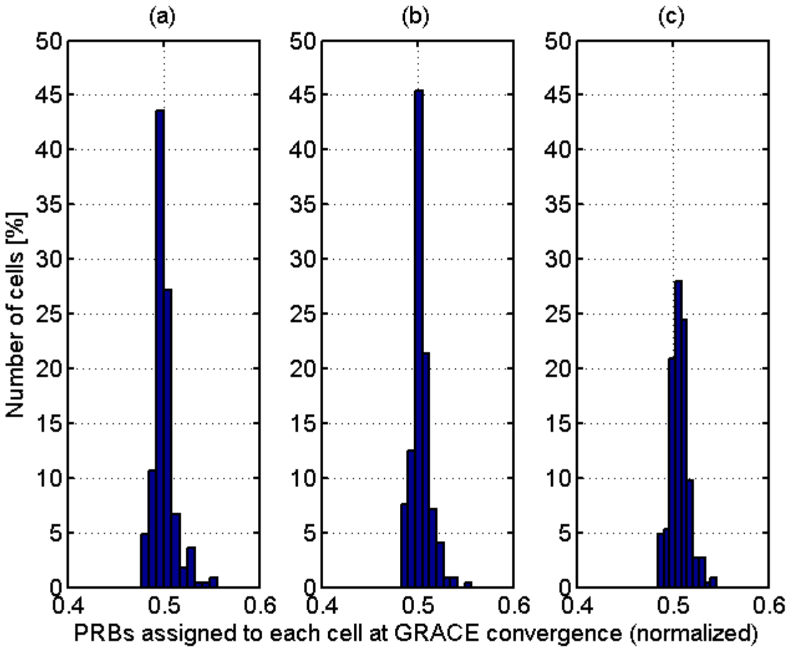

FIGURE 7.9: Histograms of the number of PRBs (normalized) allocated in GRACE convergence. C=80Mbps in (a), 100Mbps in (b) and 120Mbps in (c).

Finally, we can see in figure 7.10 the different throughput CDF curves. The worst performance is the one with C=50Mbps. About the others, 80 and 100 Mbps have a best outage performance and 120 and 150 a best mean cell throughput. The one chosen to be compared with the former results has been C=100Mbps because it shows the best balance between the two features.

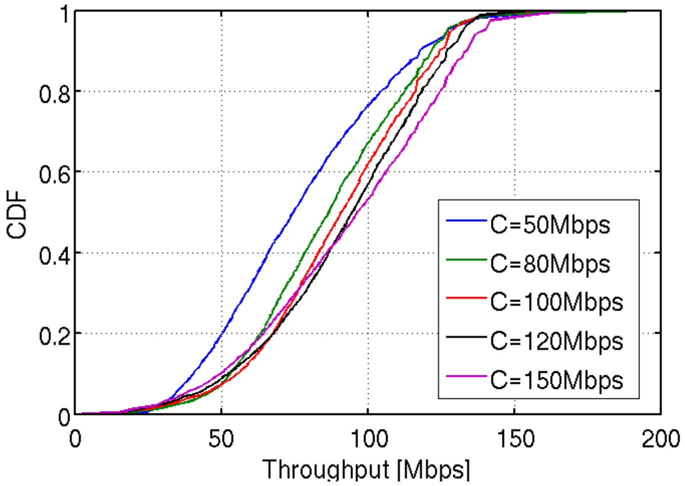

FIGURE 7.10: CDF of the throughput using different values of the desired capacity

Although the behaviour is good, in the comparison with the solutions analysed so far the DCA does not reach better results. In figure 7.11 we can see that DCA achieves more mean cell TP than FPC but just the same outage than full path loss compensation. The reason for this is that DCA does not have a parameter to differenciate cell edge users (as α does in FPC) so the interference created by this users is too high, and the frequency distribution provided by GRACE its not enough to reduce it.

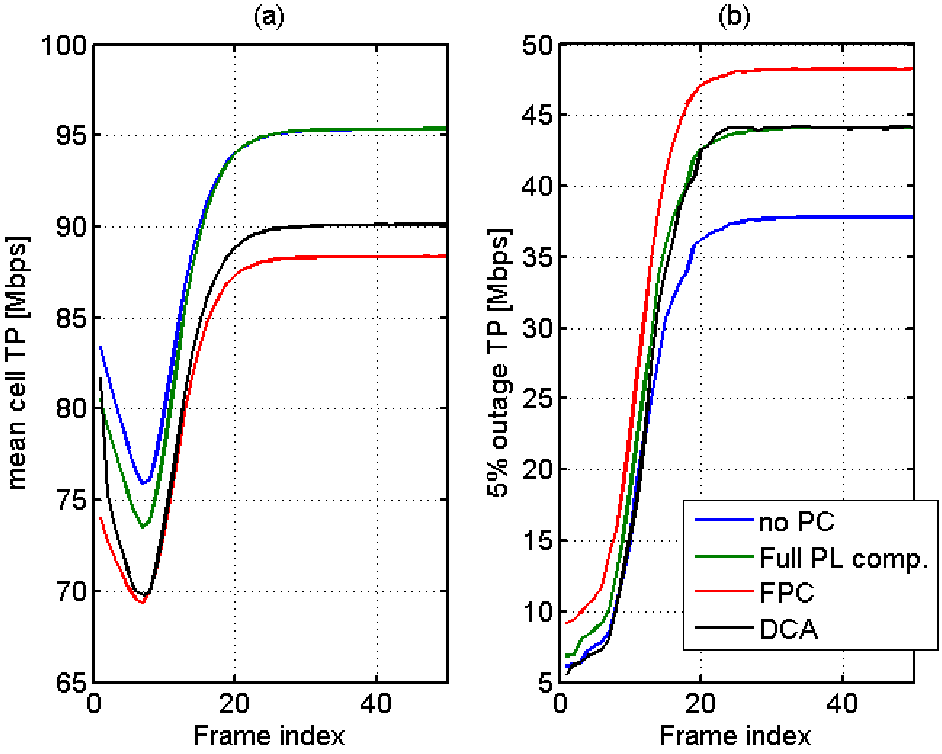

FIGURE 7.11: Comparison of the cell capacity (a) and outage throughput evolution

7.4 Results Summary

In the table 7.2 the numerical results achieved by the different solutions are shown referenced to the use of no power control:

Table 7.2: General comparison of results

Solution	**Mean TP UL**	**5% Outage TP UL**	**Mean power allocated**	**Mean PRB used**
No PC	100	100	100	100
Full PL comp.	100	117	95.8	100
FPC	89.5	128	22.9	108
DCA	94.5	117	81.3	99.3

The simulation results shown in this chapter manifest that applying Fractional Power Control to GRACE can improve significantly the throughput of the cell edge users without decreasing the cell capacity in excess. At the same time it permits to save a large quantity of power which is a very important aspect in this kind of wireless systems.

The results also showed that the proposed algorithm is a good approach but must be studied in the future to find better configurations.

Chapter 8

Conclusions

In the frame of Cognitive Radio and Game theory, GRACE is described as an IC-DSA mechanism that utilises the interference perceived in each frequency channel to select, efficiently, the less interfered channels for every user. GRACE is notable for its balance in cell capacity and outage achieved, its short convergence time, low complexity and easy scalability.

The aim of this thesis was to analyse the GRACE algorithm in order to find out in which way we can enable an effective power control algorithm. Different power allocation algorithms were studied to discover which features are the most relevant to achieve a performance that fits GRACE's goals. The water filling algorithm is able to achieve NE distributing the power among the less interfered channels. Nevertheless it needs a high computational effort in comparison to the results obtained. The full path loss compensation and FPC show large increases in the outage throughput with a very simple formulation.

The results have shown that the decisive factor in improving the throughput of the cell edge users is the reduction of used power. In the second place the distribution of the power among the different users is also important to increase the performance of the cell edge users minimizing the loss of the center cell users.

The FPC presented both features and showed two different configurations with notable results. On the one hand, setting $P_0 = -50dBm$ and $\alpha = 1$ results in the compensation of the whole path loss perceived by the device (full path loss compensation) and improves the performance in outage as well as cell capacity. On the other hand, $P_0 = -50dBm$ and $\alpha = 0.6$ slightly decreases the cell capacity at the time that achieves a large increment of the outage. Another important property of this second configuration is the great reduction in energy radiated also shown in the results.

The DCA has been proposed as an alternative to FPC aiming to improve the results by the addition of the interference as a factor for the calculations. DCA also keeps the simplicity that characterizes FPC, avoiding the optimization of any parameter so the convergence of the GRACE is not disturbed. Nevertheless the results obatined so far are not as good as the ones from FPC.

At the conclusion of this work the directions to follow in a future work would be analysing the adaptability of the system of GRACE with FPC subjected to different values of load of the environment, to asses what is the behaviour when the density of users is low. In addition, the DCA could be redefined and tested with a parameter that provides diversity of power allocation among the different users.

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