Dynamic Spectrum Sharing among Femtocells

Coping with Spectrum Scarcity in 4G and Beyond

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Dynamic Spectrum Sharing among Femtocells

– Coping with Spectrum Scarcity in 4G and Beyond –

PhD Thesis

by

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To my family.

Abstract

The demand for mobile broadband is now growing at an exponential rate, compelling operators to increase mobile network capacity very quickly. Since the inception of mobile networks, a number of factors have contributed to increase network capacity: more spectrum, better transmission techniques and the preeminent factor, spectrum reuse. In order to enhance even more the spectrum reuse this thesis considers small cells (femtocells) in combination with spectrum sharing, as a solution to the imminent spectrum scarcity and traffic demand explosion.

Small cells will lead to massive deployment with very high cell density. In addition to that, femtocells are expected to be mainly deployed by the end-user. These characteristics pose new challenges which favor the development of completely distributed and autonomous solutions for spectrum sharing. For this reason, this thesis investigates how each femtocell can autonomously select portions of the spectrum in order to achieve more spectral efficiency and fairness. The solutions also strive for scalability to a large number of cells, stability and limited complexity.

Inspired by both game theory and graph theory, this thesis proposes three main concepts which achieve balanced trade-offs of the established goals:

- Autonomous decision on the maximum number of channels which can be allocated at a particular instant of time, based on the most recent interference values and the history of sensed interference.
- A taxation mechanism where the channel allocation of each femtocell depends both on the actual sensed interference and the amount of

channels already allocated.

- Neighbor femtocells exchange messages in order to establish multi-lateral agreements on how to share the spectrum.

The first two concepts represent a significant advance in dynamic spectrum sharing among equals based on implicit coordination, i.e., when the different wireless networks cannot exchange signaling messages. The latter concept has a remarkable simplicity, robust performance and stability. These proposed approaches can be built upon existing mechanisms in 4G systems, facilitating their practical feasibility. The performance was evaluated through extensive multi-cell system-level simulations, comparing to different frequency reuses and a baseline state of the art method. As an example, such performance evaluation shows that one of the proposed solutions provides more than 500% outage throughput gain over reuse 1, at a 75% deployment ratio, while attaining the same average performance.

Altogether, the solutions proposed in this thesis will allow for plug and play configuration of spectrum allocation in femtocells, leading to an increased overall network capacity as well as a fairer distribution of the capacity. In contrast to the unmanaged situation, a minimum acceptable performance can be attained by each femtocell. Therefore, using these solutions, a large number of femtocells can interact within a geographical area without service disruptions.

Dansk Resumé[1]

Efterspørgslen efter mobilt bredbånd er nu vokset med en eksponentiel hastighed, hvilket gør det nødvendigt at øge den mobile netværkskapacitet meget hurtigt. Siden starten af mobile netværk har en række faktorer medvirket til at øge netværks-kapaciteten: Mere spektrum, bedre transmissions-teknikker og den fremragende faktor, spektrum- genbrug. For at øge spektrum-genbruget endnu mere, tager denne afhandling små celler (femtocells) i betragtning i kombination med frekvens-deling som en løsning på den forestående frekvensknaphed og eksplosion i trafik efterspørgsel. Små celler fører til en massiv anvendelse med meget høj celledensitet. Derudover forventes det, at femtoceller primært vil blive anvendt af slutbrugeren. Disse karakteristika skaber nye udfordringer, som fremmer udviklingen af fuldstændigt distribuerede og selvstændige løsninger til frekvens-deling. Af denne grund undersøger denne afhandling, hvor hver Femtocelle selvstændigt kan vælge dele af spektret med henblik på at opnå mere spektral effektivitet og fairness. Løsningerne stræber også efter skalerbarhed til et stort antal celler, stabilitet og begrænset kompleksitet. Inspireret af både spilteori og grafteori, foreslår denne afhandling tre hovedbegreber, som opnår en afbalanceret afvejning af de fastsatte mål:

- Selvstændig beslutning om den maksimale mængde af kanaler, der kan allokeres på et bestemt øjeblik af tid, baseret på de faktiske værdier og historien om den målte interferens.
- En fordelingsmodel, hvor tildelingen af hver Femtocell afhænger både af den faktisk målte interferens og antallet af kanaler der allerede er allokeret.

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[1] Translated by Jytte Larsen, Nokia Siemens Networks, Aalborg, Denmark.

- Nabo-femtoceller udveksler beskeder med henblik på at etablere multilaterale aftaler om hvordan man deler spektret.

De første to begreber udgør et betydeligt fremskridt i dynamisk spektrum deling blandt ligemænd baseret på implicit koordinering, dvs. når de forskellige trådløse netværk ikke kan udveksle signaleringsmeddelelser. Sidstnævnte begreb har en bemærkelsesværdig enkelhed, robust ydelse og stabilitet. Disse foreslåede tiltag kan bygges på eksisterende mekanismer i 4G-systemer, hvilket fremmer deres praktiske gennemførlighed. Udførelsen blev vurderet gennem omfattende multicelle systemniveau- simuleringer sammenlignet med forskellig frekvens-genbrug og en basislinie avanceret metode. Alt i alt vil de løsninger, der foreslås i denne afhandling, give mulighed for plug and play konfiguration af frekvensallokering i femtoceller, hvilket fører til en øget samlet netværk-kapacitet såvel som en bedre fordeling af kapaciteten. I modsætning til den ikke styrede situation kan en minimum acceptabel præstation opnås ved hver Femtocelle. Derfor, ved hjælp af disse løsninger, kan store mængder af femtocellerpåvirke hinanden inden for et geografisk område uden driftsforstyrrelser.

Preface and Acknowledgments

This Ph.D. thesis is the result of a three years research project. The project has been carried out at the Radio Access Technology (RATE) section, Institute of Electronic Systems, Aalborg University, Denmark. In addition to the research work I attended mandatory courses and I fulfilled teaching/working obligations required to obtain the Ph.D. degree. The research was co-financed by the Danish Agency for Science, Technology and Innovation, Nokia Siemens Networks Danmark A/S, and the Faculties of engineering, Science and Medicine at Aalborg University. The research was supervised by Professor Preben E. Mogensen (Aalborg University, Nokia Siemens Networks, Aalborg, Denmark) and Dr. Andrea F. Cattoni(Aalborg University, Aalborg, Denmark).

I first came to Aalborg to work on my M.Sc. thesis under the supervision of Dr. Nicola Marchetti (Aalborg University) and Dr. István Z. Kovács (Nokia Siemens Networks). My contribution to the research group was to investigate Game Theory (GT) applied to dynamic spectrum sharing. This line of work culminated 2 years later in the GT-based method of chapter 5. Other colleagues were also working in spectrum sharing from other perspectives and, of course, we have had many technical discussions. Curiously, the method of chapter 6 was born during an informal chat with my long-term friend and colleague Luis Guilherme U. Garcia. Creativity and inspiration have no formal schedule. Finally, the algorithm described in chapter 4 was designed based on the understanding of the problem provided by the other 2 solutions.

Here are my acknowledgments, even at the risk of leaving out someone who deserved my thankfulness. First and foremost, I want to thank God who gave me the breath of life and endowed me with all the talents which now I can use as a researcher.

My supervisors certainly deserve my gratefulness for sharing their experience with a passionate attitude and desire to make world-class research. Their guidance and knowledge have certainly been important and I really appreciate it. I extend this gratitude also to Dr. István Z. Kovács who followed the work. I give special thanks for the assessment committee for all their comments, questions and suggestions.

I would like to thank all the other colleagues from Nokia Siemens Networks and RATE group who created the ideal environment for a PhD. I want to thank Yuanye Wang, Sanjay Kumar, Klaus Pedersen and Nicola Marchetti for the early work together. Davide Catania for embracing simulator development with me. Lisbeth Schiønning Larsen, the secretary at RATE, who can solve insurmountable bureaucracy with the largest smile. Jytte Larsen, the secretary at Nokia Siemens Networks, for proofreading most of this thesis and related papers, as well as translating the abstract to Danish. Guillaume Monghal and Oumer Teyeb for playing together at the "RATE band" and the friendship. And a special thanks to Luis Guilherme for the discussions about all kinds of topics, including soccer and SOCCER. A method with such a name could not be conceived if not for team work.

I want also to show my deep gratitude to Prof. Paulo Henrique Portela de Carvalho, from Universidade de Brasília. During several years doing research under his supervision, I learned much about multi-objective optimization, wireless channels, graph theory and object-oriented programming. This thesis is a testimony that this knowledge is still giving fruits.

Words will never be enough to express my thankfulness to my beloved wife, Viviane Silva Teixeira. Her nearly selfless love and support have been essential to go through these years of research. Years which have not been short of challenges, nor achievements and great times. Likewise, I want to thank my parents and my brother. Even at distance you reside deep in my heart and I know you have been supporting me all this time. At last, but not least, a few months ago I received the news that I will become a father. My future child, still in the womb of the mother makes my days happier and motivated me to work harder during the writing of the thesis.

Contents

CHAPTER 1

Introduction

1.1 Introduction

Wireless technologies are now massively present in everyday life: mobile cellular networks, broadcast services such as radio and television, satellite navigation, and wireless local area networks. Moreover, wireless technologies are key enablers of services such as air traffic control and meteorological services.

All these services co-exist in the wireless medium. Traditionally, each service is statically allocated to a different portion of the electromagnetic spectrum. Each wireless transmitter is bound to respect out-of-band emissions, and each wireless receiver is tuned to the frequency of interest. The spectrum assignment of each system and enforcing regulatory policies are issued by government regulatory agencies. Cross-border and international alignment are handled by the International Telecommunications Union (ITU) at the World Radiocommunication Conference (WRC). This traditional approach is an effective way to avoid potentially harmful inter-system interference. Therefore such approach has been effective as long as the total demand for spectrum could be met with such orthogonal allocations.

However, the boom of cellular networks and Wireless Local Area

Networks (WLANs) has started putting pressure on this model. Over the years more and more spectrum has been identified and allocated for mobile networks. Still the auction prices of these bands remain high, and mobile network operators experience spectrum shortage. Instead of decelerating, the demand for mobile broadband communications is now growing at unprecedented rates, and simply refarming more spectrum to mobile broadband use will not meet the demand. An ITU report estimated the total demand for cellular spectrum to be between 1280 MHz and 1720 MHz[1] by 2020. Such high demand for spectrum will require very strong action from regulatory bodies to make enough spectrum available. While the exact numbers are debatable, extrapolations of current traffic demand growth trends lead to estimations of a thousand fold increase of mobile broadband traffic from 2010 to 2020 [2]. In light of such a demand explosion, spectrum shortage may become a major issue. The natural evolution of current services may not be accomplished and the next big innovation in wireless communications may be deferred due to spectrum scarcity.

The spectrum is, in principle, infinite. How is it possible that it is considered to be scarce? A key reason is that the spectrum between 300 MHz and 3 GHz is now considered to be prime. This has a number of reasons: favorable propagation conditions for most of the current applications, well developed transceiver technology, and reasonable antenna sizes. As one may suspect, all those aspects boil down to costs: costs of network deployment and maintenance as well as cost of device development and manufacturing. One should notice that the valuation of 300 MHz to 3 GHz spectrum can still vary a lot, especially due to extra coverage capabilities below 1 GHz.

The shortage exists because most of the considered prime spectrum has already been assigned in many countries. There are several ways of dealing with this prime spectrum scarcity, and one may expect that all of them will concur to alleviate the dearth of spectrum:

- Refarming of existing spectrum.
- Exploitation of higher frequencies, i.e., spectrum which is not considered to be prime.
- Increased spectral efficiency per area.
- Dynamic Spectrum Access (DSA).

All these possibilities are illustrated in Figure 1.1, along with a few examples. Next, each of these options for dealing with spectrum scarcity is briefly discussed.

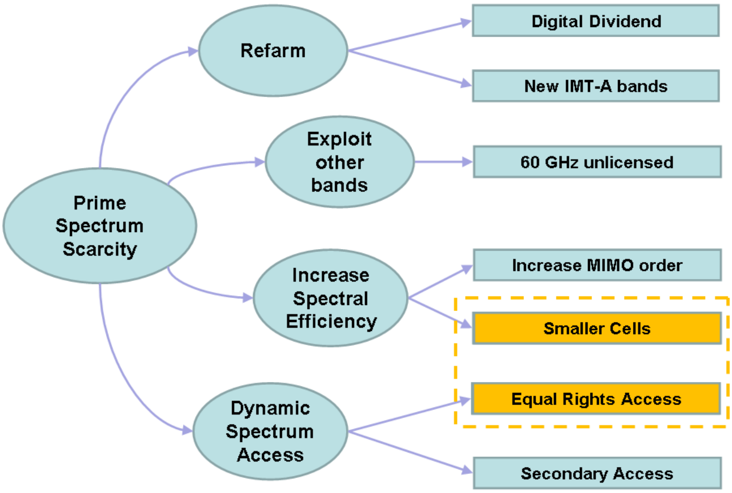

Fig. 1.1: The imminent prime spectrum shortage urges for a gamut of solutions (not extensively illustrated). The scope of this thesis is highlighted.

Spectrum refarming is a process in which a regulator changes the usage of a particular portion of the spectrum, e.g. allocating it to a different radiocommunication service. In general, spectrum refarming is a slow process which also implies extra cost such as equipment substitution and legacy device phasing out. One recent example is the digital dividend band, which consists of spectrum previously allocated to analog television, which was made available after the advent of digital television. The digital dividend and other bands have been identified in WRC 2007 as potential International Mobile Telecommunication – Advanced (IMT-A) bands.

The spectrum scarcity has been a motivation for exploiting more of spectrum which was not feasible with previous technology generations. In particular, the spectrum around 60 GHz has recently received more attention from the industry because of the availability of 7 to 9 GHz of unlicensed spectrum in most countries. Such a large amount of spectrum may lead to very high data rates, but the propagation in this band incurs high path loss. For this reason, the usable range at low transmission power levels is typically only a few meters. Furthermore, whether or not transceivers in this band will reach economics of a large scale remains to be seen.

The spectral efficiency per area can be increased by enhancing the capacity of a link or by changes in the architecture which enables more links to be supported concurrently. In the evolution of cellular networks both factors have been rather important. Nevertheless, the theoretical Shannon bound for a single link capacity has already been approached by 4G within a few decibels [3]. However, one should note that this observation is only valid within the usable Signal to Interference plus Noise Ratio (SINR) range, and it excludes the control channel overheads. Therefore, there is still room for improvement for the maximum spectral efficiency between a single transmitter and a single receiver. This can be achieved with higher order modulations, which extend the usable SINR range, higher order Multiple Input Multiple Output (MIMO), which effectively multiplies the number of links between a transmitter and a receiver, or reductions in the control channel overhead and real implementation losses. Still, such changes alone will probably fall short of meeting the increased demand for higher data rates. Thus, architectural changes enabling more concurrent links and increased bandwidths certainly need to be considered for future systems.

Among all architectural changes the one of particular interest in this thesis is the utilization of even smaller cells. Shrinking the cell size as a mean of achieving higher spectral efficiency has always been a key principle of cellular networks. In fact, while mobile radio technology improved a lot since 1950, the dominant factor in improving cellular capacity over this period has actually been the usage of smaller cells [4]. The new frontier now starts to be exploited with the usage of femtocells and picocells, where cell coverage spans only a few tens of meters, typically providing hotspot and indoor coverage. This trend continues and it may even be emphasized for the near future because of the increased difficulty in improving link capacity. Femtocells may actually be the key to achieve the data rates required by IMT-A [5] in low mobility. This thesis presents a view that future femtocells should incorporate autonomous channel selection capabilities, in order to optimize the area spectral efficiency. Femtocells are discussed in more detail in section 1.3 and throughout the thesis.

At last, but definitely not least, one may consider Dynamic Spectrum Access (DSA) in order to cope with the prime spectrum scarcity. The influential 2002 Federal Communications Commission (FCC) report [6] showed a striking difference between spectrum assignment and real usage. Even if the entirety of prime spectrum is allocated and assigned, the effective spectrum usage remains sparse in space and time even in major cities. Such observation indicates that spectrum can be reallocated to different networks on time scales much shorter than possible with spectrum refarming. In DSA solutions different wireless networks and systems should be able to dynamically reconfigure their spectrum allocations in order to maximize spectrum utilization. Such dynamic access can involve equal rights or tiered access with primary/secondary usage. These two paradigms are described in detail in the next chapter.

The remainder of this chapter is organized as follows. Sections 1.2 and 1.3 are brief descriptions of IMT-A and femtocells which help to contextualize this work. The scope and objectives of the thesis are set in section 1.4. Section 1.5 highlights why such a problem is far from trivial. Section 1.6 briefly covers the methodology whereas a list of contributions and publications is compiled in section 1.7. The organization of the thesis is described in section 1.8.

1.2 IMT-Advanced

In order to extend the access to high data rate services to wireless users, the International Telecommunications Union (ITU) established new requirements for future wireless communication technologies. The global standard for International Mobile Telecommunication – Advanced (IMT-A) specifies a very high peak data rate for the 4^{th} Generation of wireless systems. The peak data rate targets are: up to 1Gbps in low mobility and up to 100Mbps in high mobility conditions [5].

The high mobility target peak data rate can be achieved by technologies already in deployment, such as Long Term Evolution (LTE) Release 8 [7] and WiMax 802.16e [8]. Notwithstanding, the low-mobility IMT-A peak data rate and other IMT-A requirements will only be achievable with technology enhancements. For this reason, the Third Generation Partnership Project (3GPP) started developing LTE Advanced (LTE-A), and Institute of Electrical and Electronics Engineers (IEEE) standardized a new version of mobile WiMax: 802.16m. The following discussion focuses on LTE-A. Nevertheless, one should note that similar features are present in 802.16m.

One needs to understand the main characteristics of LTE Release 8 in order to appreciate the enhancements of LTE-A, which encompasses LTE Release 10 and beyond. LTE Release 8, hereafter simply referred to it as LTE, is an infrastructured Radio Access Technology (RAT). The transmissions and multiple access are based on Orthogonal Frequency Division Multiple Access (OFDMA) in downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) in uplink. LTE downlink supports transmission over multiple spatial streams up to 4x4 MIMO. The LTE User Equipments (UEs) only support transmission over a single spatial stream. The peak data rates of LTE Release 8 using 20 MHz of spectrum are roughly 300 Mbps in downlink (4x4 MIMO) and 75 Mbps in uplink.

One of the key characteristics of LTE is bandwidth and duplexing flexibility. LTE supports bandwidths ranging from 1.4 to 20 MHz and both Frequency

Division Duplexing (FDD) and Time Division Duplexing (TDD) operation modes. This flexibility allows for deployment in a rather fragmented spectrum and in different duplexing policies adopted in different countries.

The bandwidth flexibility of LTE is enhanced in LTE-A [9] by considering Carrier Aggregation (CA) [10]. CA allows the simultaneous transmission over several Component Carriers (CCs). For example, the target LTE-A band of 100 MHz can be achieved by aggregating 5 CCs of 20 MHz. In LTE Release 10 the standardization focus was on backward compatible CCs, i.e., one LTE-A CC is for most purposes identical to a Release 8 LTE carrier. Therefore, Release 8 UEs can access LTE-A CCs.

CA can largely boost user experience in low load conditions, but left unmanaged will do little under spectrum congestion [11]. The rationale is the following. In low load conditions the high peak data rate UEs will quickly complete their transmission, leaving more radio resources for the remaining UEs. However, when the load offered to the network is high, CA capable UEs will still be granted only a small fraction of the resources and, therefore, they will hold resources for a long time anyway. In fact, [11] compares the performance of two network configurations: independently configured LTE Release 8 carriers in contrast to aggregating two LTE-A CCs. The benefits of CA become evident at low load, but there is little difference between the two cases when the offered load is excessive. This is a reason why RATs should strive not only to boost peak data rates, but also average and outage spectral efficiency. And in the case of CA this means actively managing the CC allocation as discussed throughout this thesis.

CA can also be seen as an enabler of coordinated transmissions. Ideally, if different links use disjoint CC sets, then they can perform interference-free transmissions. This idea can even be extended to build system-agnostic spectrum sharing.

Apart from CA the other main peak data rate booster of LTE-A will be higher order MIMO. LTE-A will increase the maximum number of downlink spatial streams from 4 to 8 (8x8 MIMO), in comparison to LTE Release 8. In LTE-A uplink Single-user MIMO (SU-MIMO) is supported up to 4 spatial streams.

In addition to those, LTE-A also includes:

- Coordinated multipoint transmission.
- Relaying.
- Improved support for heterogeneous deployment, discussed in the next

section.

As previously illustrated in Figure 1.1 several of these techniques considered for LTE-A may be needed together in order to increase the spectral efficiency and, therefore, fulfill the IMT-A requirements.

1.3 Heterogeneous Cellular Deployment

In order to meet the predicted future traffic demand, it is necessary to improve the carrying capacity of today's cellular networks manyfold. Looking at the past history, the performance of cellular networks has been improved in several aspects: transmission and reception techniques, radio resource management and cell densification. Despite the huge technological advances in the other aspects, shrinking the cell size has played a key role in the improvement of cellular networks [4]. This trend continues and it may even be emphasized for the near future as illustrated in Figure 1.2.

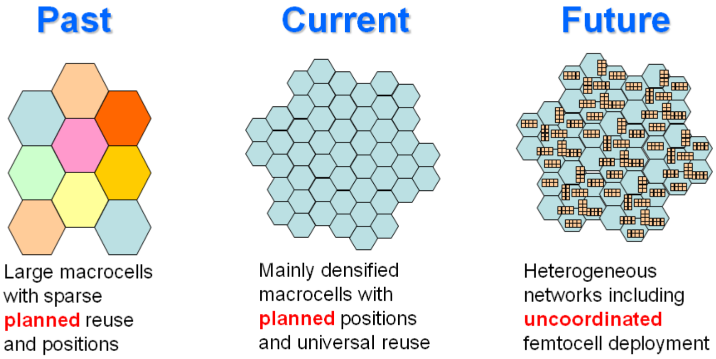

Fig. 1.2: Evolution of cellular network deployment: the trend has been both the densification of cells and tighter frequency reuse. Different colors illustrate different frequencies.

Heterogeneous cellular deployment consists of multi-layered cellular networks. One example of multi-layered cellular network is a dual band deployment where a macrocell layer , e.g. at 900 MHz, provides coverage and a much denser microcell layer, e.g. at 1800 MHz, provides extra capacity. The different layers of heterogenous networks are usually described from the sparsest to the densest as: macrocells, microcells, picocells and femtocells.

Noticeably, there has been increased interest from both the academia and the industry in heterogeneous cellular networks for a number of reasons. First, and foremost, the traffic demand pushes cellular densification towards much smaller cells: picocells and femtocells shall provide coverage in the order of tenths of meters. For this reason, there will be a much higher degree of heterogeneity in future networks than in existing macrocell/microcell deployments. A second aspect is that most of the high data rate traffic is produced when the user is at indoor locations [4]. Therefore, indoor coverage with femtocells is expected to become increasingly important. Third, there has been a lot of research trying to facilitate the reuse of the resources on all layers, instead of separate bands per layer. Again, the need for such reuse of frequencies in different layers arose from the spectrum scarcity.

Among the different layers in heterogeneous networks, femtocells can be contrasted to the remaining ones. Macrocells, microcells and picocells can be thought as increasingly denser cellular layers designed, planned, and deployed by operators. They are all part of the same network, and UEs can freely handover through the layers if needed. Important network parameters can be controlled and optimized. Backhaul can be properly dimensioned, and site acquisition and installation are performed by the operator. Femtocells, however, are of a different breed.

Femtocells are cost-effective, typically user-deployed, low-power base stations mostly providing indoor coverage. The femtocell concept is extremely enticing due to several potential benefits that it offers to operators and end-users:

- Improvement of indoor coverage and performance. When indoor users are covered by macrocell Base Stations (BSs), the UEs can experience poor coverage due to wall penetration from outdoor to indoor. In contrast to the usual indoor coverage issues of macrocells, with indoor femtocells the UEs can experience good coverage because they are close to the Femtocell Access Points (FAPs).
- Offload of the macro-cellular network [12]. Since a large part of total traffic is generated indoors, femtocells shall play an important role in capturing traffic which would otherwise be served by outdoor BS. In this way, the load of macrocells is relieved and the users attached to the macro network can experience better quality.
- Overall cost reductions [13], especially related to backhaul and site acquisition costs. Notice that if femtocells are user deployed, then site acquisition costs can be completely avoided, and the end-user may bear the costs of backhaul.

Nevertheless, femtocell deployment is not free of shortcomings. On the contrary, there are plenty of challenges.

Probably, the most important game changer in femtocells is the possibility of having Closed Subscriber Group (CSG) femtocells. In CSG femtocells, the FAP can only serve the UEs which are registered in the allowed list. One must remember that the whole cellular network concept is based on letting the UEs being connected to the serving cell with the most favorable geometry and load conditions. When CSG networks are introduced, these two characteristics are affected. For example, a UE may be forced to connect to a particular cell, while the signal strength received from another cell is much stronger. In case of macro-femto interaction such unfavorable geometry is known to cause coverage holes for the macrocell, in the near vicinity of the FAP[14]. In the case of femto to femto interaction the problem is less dramatic than in a macro-femto interaction. Still, the issue is considerable enough to cause poor performance of the victim UE attached to a FAP and interfered by another FAP [15].

In addition to the CSG issue, there are still many other femtocell aspects which deserve attention. Overall, femtocell deployment poses significant challenges when compared to traditional cellular networks:

- *Massive deployment* - As illustrated in Figure 1.2, on the same geographical area that was covered by just a few cells on the past, the typical deployment today is much denser, and in the future it may be covered by thousands of femtocells. In fact, even though the femtocell density is still very low there are already more femtocells than macrocells [12]. As the number of cells explodes, planning, optimizing, and managing all cells may become too costly, unless a much higher degree of self-configuration and self-optimization is achieved. Ideally, femtocells should be completely plug and play.
- *Uncoordinated deployment* - As with WiFi Access-Points (APs) deployment, it can be expected that most femtocell deployments will be performed by the end users, with the exception of some enterprise solutions. Therefore, the location of FAP will typically be chosen by the end user. Nothing prevents placement of FAPs in locations that will generate very unfavorable geometry factors.
- *High density* - in the future, the number of femtocells per km^2 should be very high. For this reason, each cell can face a large number of interferers, and the interference footprint can be severely different from the one in traditional cellular deployment.

Such characteristics can lead to scenarios where the interference amongst neighbor femtocells is disruptive. For that reason, femtocell deployment demands some form of interference management [15, 14], especially in CSG deployment. In current femtocell deployments there is little concern about intra-tier interference because of the low deployment density. Often, the femtocells are even locked to a particular frequency. However, in the evolution of femtocells DSA should become an important technology component, as described in this thesis.

1.4 Scope and Objectives

The general problem addressed by this thesis is how to cope with the imminent spectrum scarcity. While the potential scope of solutions to that problem is very broad, the scope of the thesis is delimited as illustrated in Figure 1.1. The investigated solutions involve Dynamic Spectrum Access (DSA) among small cells with equal rights to spectrum access. More specifically, the aim of this research has been to design distributed algorithms which allow each femtocell to autonomously select the operating spectrum in an efficient and dynamic way.

The autonomous selection of resources is necessary in order to mitigate co-tier interference, i.e., from femtocell to femtocell. Due to the massive and dense deployment, solutions which are scalable to a large number of cells are of the utmost importance. For this reason, distributed methods are preferred, and the amount of signaling across different femtocells should be minimized. Such requirements, however, make it very challenging to achieve efficiency (high capacity), fairness and stability.

The aforementioned problem is a multi-objective optimization problem because the capacity of each cell should be maximized. Furthermore, the different objectives are conflicting because increasing the capacity of one cell may imply reducing the capacity from another one. In this context, the maximization of average cell throughput is an important global target, but it cannot be the only one. Otherwise the multi-objective nature of the problem is lost.

Another important goal is to attain a minimum performance for each femtocell. A particular costumer will be interested only on the performance of his own femtocell, not on the average throughput of all femtocells. Therefore, achieving a high area spectral efficiency is important, but how the capacity is distributed is equally, if not more, important. The main adopted Key Performance Indicator (KPI) to evaluate the distribution of throughput over cells is the 5^{th}-percentile of the cell throughput distribution, i.e., the throughput achievable by 95% of the cells.

In short, the key goal of this thesis is to design low complexity distributed algorithms which maximize the throughput of each femtocell by selecting the operating channels. In order to achieve this goal both the average throughput and attaining a minimum quality are important factors. Since these two objectives are conflicting, the design target is to derive solutions which have an efficient trade off of these goals.

1.5 Design Issues

In femtocell scenarios due to uncoordinated deployment, the interference scenarios between neighbor cells can be rather disruptive, and the proper selection of operating channels for each cell may be needed to meet minimum performance expectations. Frequency planning is unlikely to be feasible in user deployed scenarios. Thus, the spectrum configuration needs to be as plug and play as possible. In addition to that, even operator deployed FAPs should be self-optimizing in order to cope with the massive number of deployed cells. Otherwise the deployment cost may be prohibitive.

There are many ways to assign channels for different cells and links. In the past, the goal of the channel assignment problem was described as the minimization of Signal to Interference Ratio (SIR) [16], provided that a minimum SINR could be achieved. The rationale behind that was that communication was considered a rather binary problem. If a minimum SINR was reached, the communication was possible. Otherwise, the error rate was deemed excessively high. In such a binary decision problem, the goal was clearly to be able to communicate with the minimum SIR possible and consequently reuse the spectrum more often.

The continued adoption of efficient Link Adaptation (LA) procedures completely changed the game. This observation is especially true of Packet Switched (PS) systems, such as LTE, since some retransmissions can be tolerated, and therefore, LA can be complemented by Hybrid Automatic Repeat reQuest (HARQ). In such a scenario, from a single link perspective, the maximization of SINR increases the total link capacity. This clearly contrasts with the minimization of SIR done in the past. Remember, however, that in real systems there is a limit to the maximum capacity gain because wireless systems have a maximum Modulation and Coding Scheme (MCS). Increasing the SINR of a channel beyond the level where the maximum MCS can be decoded with low error probability is of no benefit for the link capacity. For this reason, in practice Radio Resource Management (RRM) has actually a limited operating dynamic range of interest for SINR.

When several links share the wireless medium, the situation becomes much more complex. The achievable SINR in each channel depends on the links sharing that channel. If the goal was simply to maximize the SINR per channel, making the allocation as orthogonal as possible would suffice. However, such allocation would leave the system with a very low bandwidth utilization. Instead, in order to maximize the spectral efficiency in the area of consideration, one has to strive for the right balance between high bandwidth utilization and interference. In a multi-cell scenario, these two goals relate in an intricate manner, especially during congestion times.

Considering a fixed channel allocation in other femtocells, a femtocell will usually benefit from the extra capacity provided by an additional channel. However, if this channel is used by other femtocells, then the interference generated to them is going to be increased, resulting in lower SINR and less capacity for them. In order to compensate for the capacity loss, these other femtocells may decide to allocate more channels as well. This effect may snowball, leading to a self-reinforced spectrum congestion. Therefore, interference has to be managed actively, but only to the extent that this process does not excessively hamper bandwidth utilization.

These examples show that on the one hand using many channels per cell implies large bandwidths with low SINR but on the other hand using few channels per cell can lead to high SINR, but low bandwidth availability. Consequently, finding the highest capacity is not a trivial problem, since both factors affect the capacity. The trade off between bandwidth utilization and SINR is an essential feature of the investigated problem. One can conclude, contrary to the channel assignment problem or a single link capacity optimization, the goal is neither to maximize nor minimize SIR. The goal is to find a sweet spot SIR operation point which allows both high capacity per channel and the utilization of many channels.

One of the goals is to design fully distributed solutions, where each femtocell can make autonomous decisions. Such a design enhances the scalability of the solutions to a larger number of cells, but designing distributed solutions always poses challenges in order to define who makes decisions and what information they exchange.

The decision makers need to acquire information in order to make good decisions. In general, more knowledge enables better decisions up to a certain extent. In practice, the knowledge a femtocell can gather is rather limited and imperfect because it has to be acquired with measurements and signaling. Retrieving more information can be quite costly: for example, when performing coherent measurements, the measuring node cannot receive data from other nodes. Furthermore, sending the information to the decision points can be even more costly and requires dedicated protocols and channels, consuming resources and adding complexity to the system. Additionally, when the information reaches the final decision point it may already be outdated, leading to wrong decisions.

One can roughly order the information in terms of increasing cost to the network:

1. Measurements made at the transmitter node.
2. Measurements made at the receiver node and signaled back to the transmitter node.
3. Measurements made by one femtocell and directly communicated to neighboring femtocells via a wired or wireless interface.
4. Forwarding measurements to central servers.
5. Forwarding measurements using multiple hops over the wireless interface.

The exact ordering would depend on the relative cost of using a wired or wireless interface for the exchange of measurements. In any case, efficient spectrum sharing should mostly be based on cheap information, and signaling should be avoided as much as possible. Moreover, since costly information can be updated less often, adaptations based on costly communication have to be done on coarser time-scales. Nevertheless, the relative importance of the knowledge should be considered as well. If costly measurements are justified by correspondingly large gains, then they should also be incorporated.

Two different information levels were considered in this thesis: 1) only information local to each femtocell is available or 2) neighbor femtocells can also exchange information. These two solutions lead to the different paradigms of DSA based on implicit and explicit coordination, as discussed in section 2.2.

Distributed solutions avoid expensive signaling and limits complexity, but they also raise concern about other issues, especially about stability. How does the addition of a new femtocell affect the operating ones? Does the solution provide a smooth transition from one state to another, or is it possible that a reconfiguration storm is caused? If reconfigurations of the operating channels are expensive procedures, stability is definitely a desirable goal. On the contrary, if the channels can be reconfigured easily, stability may not be a major concern. In the case of a LTE-A system, the reconfiguration of CCs is expected to take place slowly. However, Physical Resource Blocks (PRBs) are re-scheduled often. Thus, the relevance of the stability goal depends on the granularity where DSA is applied.

1.6 Methodology

Two important theoretic bases for this thesis were game theory and graph theory. The work also relies heavily on system-level simulations.

1.6.1 Game Theory

Game Theory (GT) is a set of mathematical tools with a primary focus on the analysis of the interaction among autonomous decision makers. GT is now regarded as one of the most appropriate tools for modeling and understanding DSA. In fact, GT perfectly fits the intrinsic nature of this problem, where the several decision makers involved in the scenario dynamically interact with each other. For this reason, GT has been increasingly applied to DSA, the closely related Cognitive Radio (CR) [17], and other wireless communication problems[18].

It should be noted that GT has actually been applied for spectrum allocation since governments started spectrum auctions. The auctioning theory is actually one important area in GT. The decision makers, named *players*, are the bidders and the auctioneer. GT provides several tools for understanding the auctioning process, and can ultimately help the auctioneer to design the auction format. The auctioneer typically wants to maximize the monetary revenue for society. Some DSA propositions are actually to scale down auctioning approaches to create secondary markets [19]. Nevertheless, there are challenges with auction driven DSA [20, 19]. In particular, auctioning may not be well suited for allocating spectrum over small geographical areas [19]. For this reason, spectrum auction approaches were not considered for investigation in this work.

While GT can be applied to maximize monetary revenue, it can also be used to maximize wireless communication KPIs. In general, two different uses can be foreseen for GT in wireless communication [18]:

1. Direct application: the investigated problem is modeled as a game, and GT is used to analyze it.
2. Engineering approach: GT is used to inspire practical designs.

Both approaches have pros and cons as discussed in [18]. In general, the GT model accuracy and tractability constrain the direct application. In fact, the most commonly used game models represent simple forms of mathematically tractable games. Most of this thesis is devoted to the second approach, where GT is seen as a valuable tool for inspiring the design of practical solutions for the DSA problem. In particular, the solution proposed in chapter 5 is the one most strongly rooted in GT.

The used methodology for GT application in this thesis can be described in three steps:

1. GT analysis provides insight into the problem.
2. Then, such insights were used to craft practical distributed algorithms.
3. When feasible, the resulting algorithms are analyzed in light of GT.

Analysis is at both ends of the process. Consequently, this process calls for a loop. In fact, over time, the analysis of existing methods spawned ideas for developing new solutions and this thesis is the fruit of many iterations.

GT is much more easily applicable to two-player problems than for an arbitrary number of players. It is important to notice that in the case of DSA, two-player analysis only tells part of the story, as described in chapter 3. For some classes of games there are well established results for an arbitrary number of players, such as: potential games [17], supermodular games [17] and canonical coalition games [21].

One distinctive feature of the work in this thesis was to flow through uncharted waters considering game classes with little previous application in wireless communication: submodular games [22] and some elements of Network Formation Games (NFG) [23]. However, less theoretical results are available for submodular games and NFG than for the aforementioned classes of games. In fact, these are active research areas in GT itself.

Rather than being a conscious decision, such more advanced modeling naturally arose for the following reasons:

1. Attempt to accurately model spectrum sharing among equals.
2. Focus on an arbitrary number of players.
3. Attempt to solidify theoretical background for good designs.

For this reason, I posit that there is an urgent need to advance GT itself in order to fully understand and characterize DSA theoretically.

1.6.2 Graph Theory

Graph theory is a mathematical subject where the *graph* abstraction is used to express the relations among objects. In particular, graph theory is well suited to analyze cases where the number of objects is large, but each object interacts with relatively few other objects. Thus, it is not a surprise that graph theory provides a powerful complement to game theoretic analysis in order to provide a more complete understanding of the issues addressed in this thesis.

Section 3.6 provides a graph theoretic analysis of the simulation scenario adopted for performance evaluation. Remarkably, such analysis explains why there is no need for very sparse reuse of resources.

Graph theory concepts strongly motivated the solution proposed in chapter 4, and they also provide deeper insight into the design discussed in chapter 6. The latter can be related to NFG, a class of games which includes graph concepts.

1.6.3 System-Level Simulations

Wireless communication systems are becoming increasingly complex. As a matter of fact, current systems are a rich and interwoven set of protocols and Radio Resource Management (RRM) procedures. In order to better understand and characterize the relations among these entities one should resort not only to theory, but also to simulations.

The work in this thesis relies largely on system-level performance evaluation. In the context of cellular networks, system-level simulations refer to the performance of an entire cell (single-cell simulations) or an entire cellular network (multi-cell system-level simulations), as opposed to a single link (link-level simulations). Naturally, investigating DSA requires multi-cell system-level simulations. In fact, investigating new systems and concepts may require new simulation techniques and, for this reason, this work used some approaches which are slightly different from traditional system-level simulations. Such development was also an important part of this work, and in fact a new simulator was built from scratch in order to support all the flexibility needed for the investigations in this thesis.

1.7 List of Contributions and Publications

The main contributions of this work are three novel methods for dynamic spectrum sharing introduced in chapters 4, 5 and 6. Some other contributions which can be highlighted are:

- Surveying of DSA among equals (section 2.5).
- The detailed analysis of the problem in chapter 3.
- The comparison of decisions based on symmetric or asymmetric interference information (sections 4.2 and 4.5).
- Comparison of altruistic and selfish decisions in chapter 6.

Here is a list of publications in international journals and conferences produced during the PhD in chronological order.

1. da Costa, G.W.O.; Cattoni, A.F.; Kovacs, I.Z.; Mogensen, P.E.; , "A Scalable Spectrum-Sharing Mechanism for Local Area Network Deployment," Vehicular Technology, IEEE Transactions on , vol.59, no.4, pp.1630-1645, May 2010

2. da Costa, G.W.O.; Cattoni, A.F.; Roig, V.A.; Mogensen, P.E.; , "Interference mitigation in cognitive femtocells," GLOBECOM Workshops (GC Wkshps), 2010 IEEE , vol., no., pp.721-725, 6-10 Dec. 2010

3. Garcia, L.G.U.; Costa, G.W.O.; Cattoni, A.F.; Pedersen, K.I.; Mogensen, P.E.; , "Self-Organizing Coalitions for Conflict Evaluation and Resolution in Femtocells," Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE , vol., no., pp.1-6, 6-10 Dec. 2010

4. Costa, G.W.O.; Garcia, L.G.U.; Cattoni, A.F.; Pedersen, K.I.; Mogensen, P.E.; , "Dynamic Spectrum Sharing in Femtocells: A Comparison of Selfish versus Altruistic Strategies," Vehicular Technology Conference (VTC Fall), 2011 IEEE , vol., no., pp.1-5, 5-8 Sept. 2011

5. Costa, Gustavo W. O.; Cattoni, Andrea F.; Kovacs, Istvan Z.; Mogensen, Preben E.; , "A fully distributed method for dynamic spectrum sharing in femtocells," Wireless Communications and Networking Conference Workshops (WCNCW), 2012 IEEE , vol., no., pp.87-92, 1-1 April 2012

6. Garcia, L.G.U.; Kovacs, I.Z.; Pedersen, K.I.; Costa, G.W.O.; Mogensen, P.E.; , "Autonomous Component Carrier Selection for 4G Femtocells — A Fresh Look at an Old Problem," Selected Areas in Communications, IEEE Journal on , vol.30, no.3, pp.525-537, April 2012 [1]

In addition to that, during this work five patent applications have been submitted through Nokia Siemens Networks' patents office. Furthermore, the work was disseminated in three short contributions for the workshops of COST Action IC0902 "Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks". At the time of writing two other submissions are planned: a journal paper based on the material of chapter 3 and a magazine paper based on chapter 6.

1.8 Thesis Organization and Outlook

The organization of this thesis is as follows:

Chapter 1 was an introduction discussing the relevance of dynamic spectrum sharing, IMT-A and femtocells. Dynamic Spectrum Access (DSA) among femtocells was proposed as a potential solution to the imminent spectrum scarcity. The scope of the investigated problem was delimited, setting up a more specific research question: how each femtocell can decide autonomously its own spectrum allocation in order to achieve high spectral efficiency while attaining fairness, stability, and scalability.

Chapter 2 discusses several spectrum access models and contextualizes the research to emerging Cognitive Radio (CR) technology. This chapter also includes the discussion of the state of the art, and the positioning of this work in relation to existing research and related problems.

Chapter 3 sets up the scene for the remainder of the thesis providing a detailed analysis of the problem in 3 parts: single link analysis, direct application of Game Theory (GT) for two femtocells and graph theoretic analysis for a large scenario. The problem is further characterized using system level simulations, which serves as a baseline and motivation for the remainder of the thesis.

Chapters 4, 5 and 6 correspond to the novel solutions proposed in this thesis. Chapter 4 discusses one proposed method to achieve efficient allocations with implicit coordination. Essentially the algorithm consists of the selection the

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[1] This work is not included in this Thesis

least interfered channels, and in case of persistent interference the algorithm changes the amount of usable spectrum. The issue of asymmetric information in interference coordination is also discussed and investigated through simulations.

The solution proposed in chapter 5 is also based on implicit coordination, being characterized by a game theoretic approach. The core definition is a utility function which emphasizes diminishing returns on allocated spectrum while striving for fairness and efficiency. The resulting framework is rather flexible.

In the concept discussed in chapter 6, cell to cell communication is possible, but considered to be rather limited, involving only neighbor femtocells. The possibility of explicit coordination is exploited to allow femtocells to negotiate whether to attain orthogonal allocations or not. The designed method is remarkably simple and efficient, and the underlying protocol is very lightweight.

Chapter 7 compares the approaches proposed in chapters 4, 5 and 6 in terms of network performance. Finally, in chapter 8 the overall conclusions of this work are discussed along with some recommendations, and future directions of investigation are pointed out.

CHAPTER 2

Dynamic Spectrum Access

2.1 Introduction

Chapter 1 highlighted the importance of more dynamic uses of spectrum, due to the imminent spectrum scarcity. The type of Dynamic Spectrum Access (DSA) considered here is among femtocells with equal rights, i.e., without prioritizing any femtocell. In order to provide understanding of this framework, spectrum access models, including DSA, are discussed in section 2.2 and Cognitive Radio (CR) technology is discussed in section 2.3. While emerging DSA concepts focus on spectrum sharing among wireless networks in different administrative domains, there are plenty of techniques which enhance the use of spectrum within a network. For this reason, section 2.4 presents such precursor technologies, and it contrasts such problems with DSA among femtocells. Section 2.5 is a survey of papers which are more closely related to this work. The chapter is wrapped up in section 2.6.

2.2 Spectrum Access Models

The set of spectrum access models is both rich and confusing and the same words are used with different meanings in the literature. For this reason, this section reviews some spectrum access models and taxonomy, setting the scene for the remainder of the thesis.

Usually, spectrum is assigned through spectrum licenses. Licensing the spectrum is a mechanism which provides exclusive rights to utilize a spectrum band in a particular region. The typical license defines the band and maximum effectively radiated power at a designated region, license duration and, in many cases, also the designated use [24]. Such a fixed use designation creates a barrier for efficient spectrum use. For example, a TV broadcaster with little audience can not use its spectrum band to deploy a cellular network, even though this is technically possible and potentially could lead to a better economical revenue. Many regulators are now turning fixed use spectrum licenses into flexible use ones, and reducing license rigidities which hinder technology neutrality.

Law enforced exclusive access to the spectrum is a very effective way of preventing interference [19]. Licensed systems need to be granted permission from regulatory bodies to operate. Therefore, licensing allows careful planning and analysis by regulatory bodies to assure that all licensed systems can be deployed without harmful impact on other systems. Nevertheless, this spectrum access model has rendered prime spectrum sparsely used [6]. Therefore, it is important to understand how such a model can be evolved to allow more dynamic spectrum access and what are the implications of doing so.

The seminal FCC report [6] of 2002 describes three spectrum access models: command-and-control, exclusive use and commons. Buddhikot [24] refreshes such view with the addition of one more model crafted for DSA: shared use of primary licensed spectrum. As described in [24], these four models can be ordered in terms of increased spectrum accessibility:

1. *Command-and-Control*: the regulatory body decides the spectrum allocation along with rules and policies. After that, the frequencies are assigned to the entity providing the service. The uses, requirements and eligibility may be defined in the license. In general the license is not transferable and the type of service (purpose of the license) is fixed.
2. *Exclusive use*: the licensee is granted exclusive access to the spectrum within a defined geographic area. The assignment is determined by a market mechanism such as an auction. This is the typical case of cellular

network bands. The key differences to command-and-control model are: flexible use and the fact that licensees are granted alienation rights over their licenses.

3. *Shared use of primary licensed spectrum*: secondary access to the spectrum where the impact on the primary user is minimized.

4. *Commons*: the access to a spectrum commons allows an unlimited number of users as long as they comply with some technical constraints such as power limitation and, potentially, spectrum etiquettes.

While auctions are now common, in many countries the spectrum allocation norm was until quite recently command-and-control. Many economists have been strong supporters in moving from regulation oriented command-and-control to market oriented exclusive use since the 1950s [25]. However, the recent success of unlicensed bands made several authors defend the allocation of more spectrum as commons [26, 27]. There has been a fierce spectrum debate about the allocation of more spectrum as exclusive use or commons. A few authors such as [28] attempt to reconcile the two views. Most of the spectrum debate focused on television spectrum, in particular, Television White Spaces (TVWS). Such spectrum has very favorable propagation conditions for a number of existing applications and the band is considered to be under-utilized. As a consequence, most of the current discussions about DSA focus on the shared use of primary licensed spectrum where a secondary system can access unused spectrum via spectrum underlay or spectrum overlay.

Buddhikot [24] gives a rather extensive sub-categorization of each spectrum model, describing several possibilities for DSA. In particular, he describes three types of ”Commons”:

- *Uncontrolled commons*: basically, this is an open access band. Still, one must recognize that the given examples in [24], the Industrial, Scientific and Medical (ISM) and Unlicensed National Information Infrastructure (U-NII) bands do have some lightweight management such as: emission power regulations, maximum channel holding time or the need for spread spectrum techniques. For these reasons, many authors say existing unlicensed bands are not commons, but rather state managed bands [29, 30]. More precisely, some management is also done by industry efforts such as IEEE standards.

- *Managed commons*: shared, unlicensed band where the devices can only have access if they fulfill some more stringent requirements such as compliance to a management protocol , commonly referred to as a spectrum etiquette.

- *Private commons*: similar to a managed commons, but managed by a licensee. Thus, the key difference is that the license holder can devise and enforce the rules. One example is a spectrum access provider which can selectively allow access for authorized users.

One should note that the provision of CSG femtocells by an operator constitutes a private commons [24, 31]. In fact, providing CSG service resembles spectrum leasing, which is also described in [24]. The spectrum "leaser" is the FAP owner, which is an operator's client. The spectrum used in a CSG femtocell will serve the "leaser", not other subscribers in the same area. As in any private commons, the operator has all the incentives to actively manage the commons in order to make the most efficient use of the resources. As such, the operator can enforce a particular protocol to be adopted to allow interference coordination among CSG femtocells. Furthermore, if the owner of the CSG FAP does not comply with the operator rules, the operator can purge the FAP from its network. After all, the spectrum is owned by the operator, not by the FAP owner.

Peha [19] offers another taxonomy of spectrum sharing based on 2 classifications:

- Spectrum sharing can be based on co-existence or cooperation.
- Spectrum sharing takes place among equals or a primary user is given priority over the secondary users.

When the spectrum is shared among equals, no device is given an explicit priority of spectrum access. Thus, there is no intrinsic reason why the spectrum should not be equally divided among users. In contrast, in primary-second sharing the access priority is clear: secondary devices must abide by the priority of primary devices. The secondary devices can use resources which the primary devices left unused in time and space. Nevertheless, the primary system has preemptive access to the spectrum and, therefore, the secondary may need to terminate the use of a band.

As noted in [19] there is not much difference between primary-primary sharing and secondary-secondary sharing. They are both spectrum sharing among equals. Both of them are commons if licenses are not exclusive, and in both cases the spectrum can be overused if left unmanaged. While the literature on primary-secondary sharing has grown vast very quickly, the issue of primary-primary or secondary-secondary sharing is often overlooked. This thesis aim at bridging such gap.

The second differentiation made in [19] is whether different networks (or conversely their devices) can explicitly exchange messages with each other or not. If the networks merely co-exist, they cannot exchange signaling messages. Therefore, co-existence relies on spectrum etiquettes and independent decisions.

When the networks/devices sharing the band can communicate to each other directly or via backhaul, this enables several cooperation possibilities such as: orthogonal allocation, joint (multicell) scheduling [32], network MIMO [33] and meshed networks [34]. One should note that Peha's definition entails that devices under different administrative domain *must* cooperate. One can also consider systems which *can* cooperate, i.e., they have the signaling capabilities, but they still have their own discretion to cooperate or not. This issue is studied in chapter 6. The conclusion of that study is that enforcement of cooperation may indeed be beneficial at a regulatory or standardization level.

As pointed out in [19] cooperation and co-existence can be strikingly different when applied to a commons band. Co-existence can be aided by the provision of a proper spectrum etiquette in order to avoid overuse. A poor choice of etiquette can slow down innovation or lead to inefficient designs. Cooperative commons, on the other hand, are less prone to overuse. Nevertheless, the challenges are inherent: need for altruism, trust, and especially the definition of communication protocols which must be common to all devices operating in the band.

A shortcoming of this taxonomy is that it may lead to the idea that co-existence is opposed to cooperation. However, this is not the case. In general, cooperation is built into the spectrum etiquette. In fact, most co-existence spectrum sharing methods can be regarded as cooperative in the following sense: if a single system does not follow the spectrum etiquette, it may have capacity gains. Therefore, the diverse systems cooperate by sacrificing instantaneous gains in order to allow proper co-existence.

Because of these subtleties, a slightly different terminology is adopted in this thesis. Hereafter I refer to spectrum sharing based on either:

- *Implicit coordination*: networks under different administrative domains do not signal to each other (akin to Peha's definition of co-existence). Note that ***intra***-network signaling is not ruled out.

- *Explicit coordination*: inter-network signaling is possible, and therefore, it enables rich cooperation settings. If cooperation is mandated by policy this corresponds to Peha's definition of cooperation.

Figure 2.1 summarizes the possibilities of spectrum access as discussed in [24, 19] and this section.

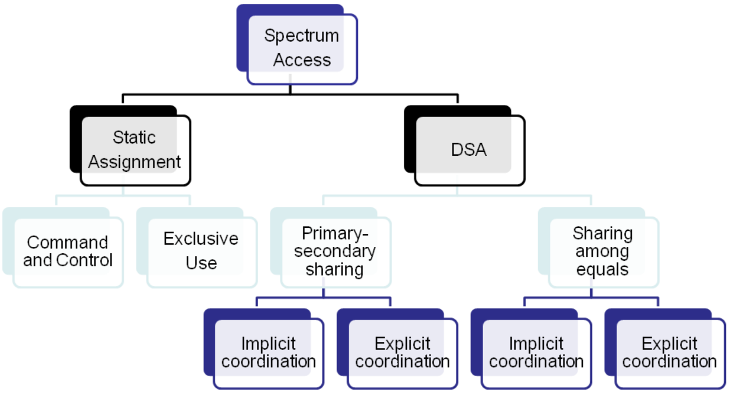


Fig. 2.1: Summary of the possibilities of spectrum access as discussed in this section.

In summary of this section, while spectrum access is a very broad topic, the scope of this thesis is to investigate DSA techniques, where spectrum sharing takes place among equals. In Buddhikot's taxonomy, such scope corresponds to access to a commons. The techniques of this thesis are particularly well suited for managed and private commons, because the corresponding protocols or etiquette compliance can be enforced at regulatory level, standardization process or by the licensee.

2.3 Cognitive Radio Technology

This thesis relates to CR technology, and the goal of this section is to clarify this relation. The original CR concept is described as follows:

> ”The term cognitive radio identifies the point at which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to: (a) detect user communications needs as a function of use context, and (b) to provide radio resources and wireless services most appropriate to those needs.” (J. Mitola III) [35]

One of the CR use cases proposed in [35, 36] is DSA based on spectrum pooling and spectrum etiquettes. This use case timely met the findings of spectrum under-utilization in [6] and the interest in CR and DSA has grown ever since. Over the years the research community started using CR and DSA terms interchangeably, as observed in [37]. The terms CR and DSA have often been used to mean primary-secondary spectrum sharing. Some authors advocated that focusing on more specific views of DSA as a standalone problem, apart from CR, would benefit the DSA development [24]. Unfortunately, such taxonomy ambiguity contributes to the still missing unified view on CR, as noted in [38]:

> "Unsurprisingly, various obstacles such as technical constraints, radio regulations, and the need to avoid interference to incumbent devices and systems imply that it may be many decades before the "full CR"/"Mitola radio" is realized. Various subsets of this concept are therefore often assumed, and there is much inventive improvisation in the research community as to what the concept of "CR" actually is. Perhaps the most prominent recent assumption is the so called "spectrum-sensing" CR, which currently has not so much to do with cognition but more with "opportunistic (secondary) spectrum access." " (J. Mitola et al) [38]

Since there are different CR views on the literature it is important to emphasize that even though CR is mostly discussed on primary-secondary spectrum sharing, CR technology could also be used for dynamic spectrum sharing among equals [19]. In addition to that, if one assumes that CRs are able to perfectly determine and counteract interference towards primary users, there still remains the need to share the spectrum holes among secondary users. Therefore, both views of CR are complementary. This concept is illustrated in Figure 2.2.

This thesis incorporates "light" CR capabilities into future femtocells contributing to the emerging view of *Cognitive Femtocell (CF)s*, built upon cognitive radio technology to address the interference problems in femtocell scenarios. The presented CF view is: self-optimizing femtocells empowered by limited-complexity, yet cognitive, FAPs capable of serving both legacy devices and cognitive ones.

Typical CR applications are node-centric, i.e., each node may make independent adaptations. In CFs, however, some cognitive decisions are more naturally made by the FAP, also on behalf of the UEs. Using measurement feedbacks from the UEs, the FAP can analyze the interference scenario for the whole cell. Therefore,

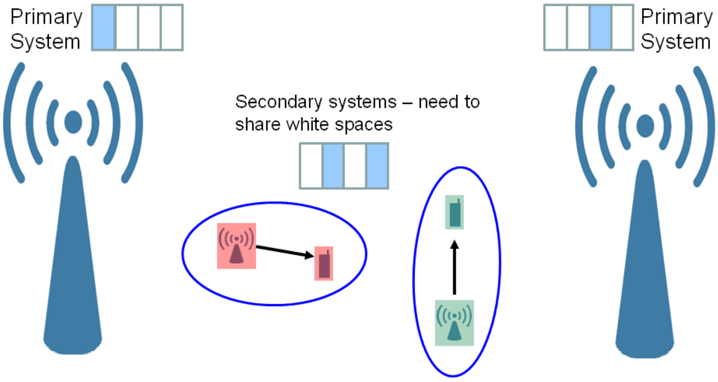


Fig. 2.2: Secondary-secondary sharing complements the primary/secondary sharing. Example where 4 channels are available. If secondary systems correctly select white spaces (channels 2 and 4 in the example), they still have to share such resources among secondary systems.

UEs assist on the spectrum sensing, while the FAP can concentrate most of the cognitive functions, coordinating medium and backhaul access.

There are different aspects of CR that can be reused in CFs: spectrum awareness, reconfigurability, learning capabilities, dynamic spectrum sharing and secondary (opportunistic) access. This latter aspect is the most prominent in CR literature [38], but it is not necessarily the most important aspect in CFs. In fact, there are several spectrum access options that can be considered for femtocells in general:

- Macro-cells and femtocells co-exist on the same licensed spectrum, typically with tight coordination. This scenario is common on initial femtocell deployment where the operator does not have other bands available.
- Femtocells use a separate fixed, licensed spectrum. In this case the two layers are completely separate, leading to easier deployment but the operator needs to have enough spectrum for each layer separately. When femtocell usage becomes more widespread, this separate spectrum implementation will become more attractive for two reasons: 1) Coordination with macro layer can become prohibitive and 2) intra-tier interference will increase significantly.
- Femtocells use license-exempt or unlicensed spectrum. Spectrum sharing among operators can potentially be beneficial in order to have access to

larger spectrum pools. The implicit coordination techniques developed throughout the thesis are particularly suitable for making such an operation more attractive.

- Femtocells make secondary access to other licensed bands. Due to the low transmission power and indoor usage, femtocells can be a feasible candidate for operating on a secondary basis.

2.4 Related Problems

Essentially, DSA allows multiple wireless networks to have access to a particular spectrum band at a specific location. Traditionally, wireless networks have been statically assigned separate spectrum bands and now due to spectrum scarcity dynamic spectrum sharing among networks is of increasing interest. While DSA is considered a new problem, it is noteworthy that there are plenty of techniques which allow wireless devices to access dynamically the spectrum *within* a wireless network, i.e. within the same administrative domain. Such techniques can be considered precursor and complementary technologies for DSA. Consequently, a brief description is worthy in order to clarify similarities and differences.

Multiple Access (MA) refers to multiple *users* accessing the same shared medium, in this case the wireless medium. If MA is a form of sharing the spectrum, what is the difference between DSA and MA? Typically, MA schemes are discussed in the context of several transmitter nodes communicating to a single receiver node or a single transmitter node sending data towards multiple receiver nodes. On the contrary, DSA refers to multiple wireless *networks* accessing the same shared medium. Therefore, DSA considers spectrum sharing among disjoint sets of transmitters and receivers. If such transmitters and receivers implement different technologies or belong to different administrative domains, they may not be able to communicate at all. Such issues make DSA much more complex than typical MA problems.

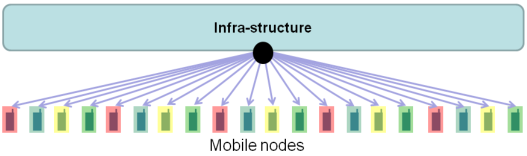
When the transmission decisions are done autonomously by a transmitting wireless node, the difference between MA and DSA becomes more blurry. In fact, in 802.11 networks Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) acts both as a MA mechanism and a DSA mechanism. In the basic Distributed Coordination Function (DCF), CSMA/CA is the MA scheme which allows multiple client stations to communicate to an AP. In addition to that, CSMA/CA is the DSA mechanism which allows multiple 802.11 networks co-exist in a near vicinity even when they use the same frequency by sharing that channel over time.

Another difference between MA and DSA is the practical implementation of underlying multiplexing mechanisms. Often, MA mechanisms are built upon signal multiplexing techniques which can divide the radio resources into smaller channels such as Frequency Division (FD), Time Division (TD), Code Division (CD) and combinations thereof. In principle, the same multiplexing techniques can be considered to build up DSA and divide the resources among different networks. However, the feasibility of the multiplexing signal processing needs to be checked case by case.

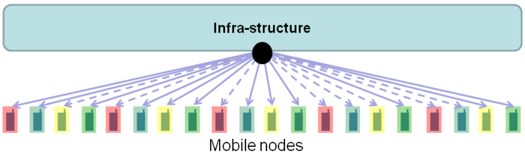
For example, synchronization is quite easy to attain when the transmission is done from one transmitter to many receivers, a typical MA downlink case. Synchronization is harder to achieve when multiple transmitters communicate to a single receiver, a typical MA uplink case. Nevertheless, in a DSA case where many transmitters are communicating to many receivers, any synchronization requirements become an even larger issue. One should note that in order to achieve channel orthogonality, TD and CD often have tight time synchronization requirements. If these requirements cannot be met, FD can still be used to create orthogonal channels even across disjoint sets of transmitter and receivers. This can be seen as one of the reasons why static spectrum allocation and assignment takes the form of FD. Another reason is that FD allows the co-existence of analog and digital systems.

Mobile networks use these physical layer multiplexing techniques in conjunction with advanced RRM in order to share the spectrum among a large number of transmitter and receivers. An overview of the evolution of some techniques of cellular networks helps to understand spectrum sharing among femtocells as a future evolutionary step. Mobile infra-structured networks have two key sets of wireless nodes: nodes attached to a wired infra-structure and mobile nodes. The traffic is oriented from the infrastructure to the mobile nodes or from the mobile nodes to the infrastructure. This regularity of traffic favors a special treatment of duplexing. In fact, in mobile networks there is, typically, a full separation of the two link directions, uplink and downlink, as in an FDD system or a synchronized TDD system. In such cases, the spatial footprint of interference can be analyzed separately.

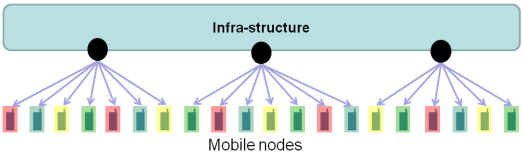
In the inception of mobile networks, if one would like to cover a large area, the approach was to use a single tower transmitting at very high power. This situation is illustrated in Figure 2.3a The mobile equipment also transmitted at high power and, therefore, it was usually mounted in cars. Simultaneous use was achieved in an FD approach and switching the channel was a manual operation. In such application, the number of served users was severely limited by the total spectrum availability. Two key developments allowed to multiply the user base that could be served in a particular band: automated trunking and cellular architecture. Altogether these two techniques were the key to bring



(a) Pre-cellular spectrum use: a large number of users sharing the spectrum and connecting to the same base station.



(b) Trunking concept: only active users occupy resources. (inactive users shown in dashed lines)



(c) Cellular network: Each cell serves less users than in the architecture of Figure 2.3a. Each mobile node is closer to the access point in the infrastructure

Fig. 2.3: Evolution of mobile networks towards more reuse in time and space domain.

mobile networks from niche applications to the masses in the first generation of cellular systems.

In trunked wireless systems the channels are assigned on demand for the users. Therefore, inactive users do not occupy the scarce spectral resources, as illustrated in Figure 2.3b. As long as the traffic pattern per user is sparse in time, trunking allows large gains in efficiency because the same spectral resources can be reused over time.

The cellular architecture allows an operator to reuse the same spectral resources over different areas. The coverage area of interest is divided into smaller areas, named cells. The division into cells lead to a number of effects. First, for a fixed number of users, fewer users are served per cell, as illustrated in 2.3c. Consequently, for the same cell capacity, a smaller cell can provide higher capacity per user. Conversely, the total number of users in the system can be increased for a fixed capacity per cell by increasing the number of cells.

Second, the transmission power can be reduced because, on average, each mobile node will be closer to the infra-structure. Finally, as a consequence of reduced power, distant cells can reuse the same set of channels. If neighbor cells have significant interference coupling, they need to use an orthogonal set of channels. Still, the net reuse offers significant gains.

The widespread use of the architecture shown in Figure 2.3c motivated a great of deal of research about the channel assignment problem, which is closely related to the problem tackled in this thesis. The channel assignment problem, also known as channel allocation problem, can be defined as follows. Given a set of desired links, e.g. as shown in Figure 2.3c, how can each active link be assigned *one* channel, in order to maximize the overall capacity and minimize blocking? Solutions to this problem fall into three main categories [16]:

- Fixed Channel Allocation (FCA) - Each cell is statically assigned a subset of the channels, which can be chosen for example via frequency planning. Then, for each link that is formed a cell has to choose one channel from its own pool.
- Dynamic Channel Allocation (DCA) - All channels are part of a common pool. The cells allocate the channels on demand, as new calls arrive. DCA can either be centralized or distributed.
- Hybrid Channel Allocation (HCA) - Hybrid approaches where part of the channels are cell specific and part of the channels can be dynamically allocated.

Naturally, DCA is a precursor technology to DSA. Actually, the femtocell DSA problem discussed here can be seen as DCA revisited with new working assumptions. Despite of the similarities, the classical DCA problem has also several differences to DSA among femtocells, summarized in table 2.1.

The proper assignment of a subset of channels for each cell has been of paramount importance for the deployment of cellular networks. In 1^{st} Generation (1G) and 2^{nd} Generation (2G) of cellular networks, the quality of the network has been assured by careful frequency planning, assigning different frequencies to each cell (typically statically, i.e., in a FCA fashion). However, over the years, cellular networks achieved tighter frequency reuses.

Because well planned Universal Mobile Telecommunications Systems (UMTS) and LTE macrocell networks can achieve a full frequency reuse in neighbor cells, an orthogonal allocation on an intercell level is not an imperative deployment strategy anymore. Instead, RRM procedures which manage

Table 2.1: Comparison of classical DCA and femtocell DSA.

Problem	Classical DCA	Femtocell DSA
Switching over air interface	Circuit Switched (CS)	Packet Switched (PS)
Figure of merit for a link	target SINR	maximum link capacity
Target channels per link	single channel	as many as possible
Cell selection	best server	locked to a cell (on CSG)
Deployment	coordinated	uncoordinated
Propagation characteristics	macrocellular	indoor
Central decision maker	usually available	usually not available
Number of users per cell	many	few

intercell interference on a reuse one scenario have been of great interest. In this context, dynamic packet scheduling emerged as a paradigm to handle the channels more efficiently within a cell. Channel-aware packet scheduling offers throughput gains due to multi-user diversity [39], by exploiting the time variation of the channel. In addition to that, each downlink receiver experiences different interference conditions and essentially this can be exploited by the packet scheduler by allocating UEs with robust links, with high Signal to Noise Ratio (SNR), on the most interfered resources. This property can be exploited more explicitly with the use of a technique known as Soft Frequency Reuse (SFR) [40]. Essentially, in a SFR approach some channels are assigned full transmit power but other channels operate at lower power levels. Neighbor cells use different patterns in order to coordinate which channels have higher or lower power. In this way, all channels are reused in all cells but the coverage of each channel is different within the same cell. A channel-aware packet scheduler will tend to allocate the cell-edge UEs on the channels with larger coverage and cell center UEs on the channels with limited coverage.

There are some caveats when relying solely on dynamic scheduling and SFR as techniques to manage the interference across femtocells. First and foremost, the number of users per cell is largely reduced compared to macrocells. In the extreme case, for example in a residential scenario, only one active user per cell is easy to conceive. In that case, there is no multi-user diversity gain and no possibility to exploit the fact that each UE experiences different interference conditions. A second aspect is that due to uncoordinated deployment the interference may be so disruptive that a very large power reduction may be needed in the SFR strategy in order not to block any UE from other cells. A potential solution for such blocking situations is the use of escape carriers [41].

2.5 State of Art

This section briefly surveys the literature on spectrum sharing among equals and co-tier interference management, with a focus on distributed solutions. Centralized approaches for channel assignment in cellular networks are rather extensively surveyed in [16], along with distributed and hybrid approaches.

This state of art description is organized as follows:

- References which perform analysis and characterization directly related to the problem described in this thesis. These works can mostly be related to chapter 3.
- Spectrum sharing solutions inspired by non-cooperative GT. Similar concepts and frameworks are used in chapters 4 and 5.
- DSA based on cooperative GT solutions, which can be contrasted to the solution proposed in chapter 6.
- Solutions designed for LTE and LTE-A, relevant to the whole thesis.
- A brief description of spectrum sharing in 802.11.

Each of these items corresponds to the following subsections.

2.5.1 Analysis

The work in [42] shows the performance of femtocells for diverse fixed frequency reuses applied to the Winner-II scenarios [43], when all cells are active. The studies are based on system level simulations. In case of the Winner-II indoor scenario, a reuse 2 approach showed attractive performance, while reuse 1 shows weak outage performance but good average performance. However, the optimal frequency reuse is shown to be highly dependent on the scenario and in a Manhattan scenario the situation is very different. In a Manhattan scenario the best average throughput was achieved by reuse 1, but the only reuse to provide high outage performance is reuse 4. Using a semi analytical approach [44] also concludes that the outage performance can be unacceptable for the 5x5 scenario proposed in 3GPP [45]. Therefore, co-tier interference has to be actively managed in femtocells.

2.5.2 Solutions Based on Non-cooperative Game Theory

In [17] GT is described as one of most promising approaches to study the interaction amongst CRs. Not surprisingly GT has often been used either as an analysis tool or as a source of inspiration to solve the spectrum sharing problem.

The problem of spectrum sharing in an unlicensed band is analyzed in light of GT [46], where maximizing data rates is the goal of each link. Under certain assumptions, it is shown that the full spread of power is the expected outcome, i.e., all links allocate all resources in a reuse 1 approach. The achievable rate region is discussed and compared to the full spread. More attractive allocations such as maximizing the sum rate or proportional fair allocation are justified using punishment mechanisms over repeated games. Notwithstanding there are limitations to such an approach. First, punishments are not enough incentives in case of very asymmetrical interference. Second, the game information is gathered using channel measurement and parameter exchanges, which causes overhead.

The work in [47] also considers repeated games as means to achieve cooperation among networks. In this framework the game is centralized in the hybrid coordinator of 802.11e capable networks. A distinctive feature of [47] is the use of a utility function with diverse Quality of Service (QoS) parameters: throughput, maximum delay and the period between transmission opportunities.

A number of proposals in the literature attempt to model spectrum sharing as potential games [48, 49, 50]. On the one hand, the advantage of such games is their attractive mathematical characteristics. Greedy adaptations over potential games always converge and a global function known as potential function is maximized [17]. On the other hand, there is one key disadvantage: potential game formulations often need some degree of symmetry of the problem, which leads to exchanges of information across networks or extra assumptions about the footprint of interference. Another aspect of these surveyed papers, [48, 49, 50], is that the reported results focus on minimization of interference. One needs to remember that interference minimization alone does not necessarily lead to the highest throughputs. Interference can be minimized by selecting fewer channels, but the decreased bandwidth has a large impact on the achievable rates. The generic framework proposed in [49] could in principle be used to formulate utility functions which are more closely related to capacity, but such development is not included.

In [48], a WLAN scenario is considered. The utility functions are defined based on interference, and the strategies consist of the possible selections of a single channel. Two cases are considered: a selfish utility which considers only the interference level at the player's own link and a cooperative utility where each player considers the incoming interference for herself and her neighbors. For the second case, the authors devised a protocol to exchange the needed information over a WLAN scenario. Also, they showed that two game-theoretic approaches, one based on potential game formulation and another based on no-regret learning, have the capacity to lead to better SINR distributions than a random allocation. In case exchange of parameters is possible, cooperation is achieved. This is one example that the utility function can be used as a design parameter to achieve more efficient protocols.

Greedy adaptations based on interference or SINR do not necessarily converge [49]. For that reason, the authors of that paper propose a general framework for convergent Interference Avoidance (IA) adaptations based on potential games. The key aspect of this framework is that each network should maximize a utility function consisting of three separable terms: a measure of the benefit of a particular transmission signature, the effect of incoming interference and the effect of outgoing interference. Explicit knowledge of the latter term, however, is translated as a need for explicit signaling among different networks. Furthermore, the application of such framework to maximize capacity directly faces some challenges, as the benefit of selecting some specific transmission signature usually depends on the interference.

Akin to [49], the work on [50] formulates distributed IA as a potential game. Because this work focuses on transmission over multiple channels and a cellular network scenario, the applicability of such an approach is very closely related to the problem discussed in this thesis. For this reason, this work has been selected as a baseline result. Another key contribution from [50] is to propose probabilistic updates, which avoid the need for any signaling among cells. However, [50] assumes both symmetric interference and a fixed demand for resources. Finding the proper resource allocation given a desired target number of resources is important but it is still a fraction of the complete problem. Discovering the number of channels that can be allocated during spectrum congestion is equally, if not more, important. Such difficulties are overcome by the method described in chapter 4 which can be seen as a generalization of [50] in order to cope with such issues.

In [51] the trade-off between efficiency and fairness is exploited using taxation mechanisms. CR nodes attempt to change their allocation autonomously based on a game theoretic formulation. Starting from capacity functions, taxation terms are added in order to prevent overuse of spectrum. The reported efficiency of this method is quite promising. Nevertheless, the parameters of the taxation mechanisms have to be optimized for a sweet spot operation on the given scenario. The formulation on [51] shares some similarities with the method proposed in chapter 5. An important difference is that the framework of chapter 5 applies non-linear taxes based on the Interference to Noise Ratio (INR).

The authors in [52] propose an iterative process where each link announces the interference price perceived at the receiver. In the case of multiple channels, that corresponds to a vector of interference prices, one for each channel. Then, at the next iteration, by assuming that the price of other links is fixed, one link can attempt to maximize the utility surplus, i.e, its own utility discounted by the effect caused on other receivers based on the interference price. For two players, this formulation can be related to supermodular games [17].

Another track of GT application into spectrum sharing is the utilization of auctioning mechanisms. For instance, in [53] primary users lease unused channels to secondary users. However, the direct application of auction mechanisms poses significant challenge in terms of signaling and trusted entities, such as spectrum brokers.

Auction mechanisms need competition of bidders in order to achieve efficiency. Therefore, the application of auctioning in a femtocell granularity could face problems since essentially there is only one potential customer per venue. So, whereas auctioning mechanisms are gaining acceptance [20, 19], they are most likely to be of more practical use to allocate spectrum over areas which are much larger than a femtocell network [19].

2.5.3 Solutions Based on Cooperative Game Theory

A prominent concept in the GT-based DSA literature is the application of Nash Bargaining Solution (NBS) [54, 55, 56]. The NBS has some attractive properties: uniqueness, Pareto efficiency and some embedded relative fairness [57]. The NBS allows maximizing system capacity directly, but there is a need of an underlying protocol for exchanging information among the players. In addition to that, computational complexity and scalability can be a concern when using NBS-based approaches. Another practical issue is that NBS only considers cooperation if no network suffers loss on their utility (capacity). Border cells with high SNR may not have any incentive to cooperate under a NBS framework and yet, in practice, one would like to mandate orthogonal allocations not to harm or completely block neighbor cells.

In [55, 56], a cooperative approach for spectrum sharing is taken. The game formulation is to consider the players as the transmitter-receiver pairs. There are K channels, and the possible strategies are the transmission powers allocated for each channel. The utility function is given by the aggregate Shannon capacity, based on the SINR of each channel. The authors show that the strategy space can be non-convex, but it becomes near convex as the number of channels, K, increases. Then, the use of NBS calculations is proposed to find the solution of the games. While the calculation of the exact NBS would involve information exchange involving all transmitters, the authors propose a distributed algorithm to approximate the NBS locally. They assume that there is an underlying method to exchange the needed information to calculate the NBS within two hops. Their solution achieves the second best average throughput, the second best outage throughput and the best fairness compared to other three algorithms: maximization of sum throughput, maximization of minimum throughput and a water-filling based approach.

The other main branch of cooperative GT deals with coalition formation [21]. Some applications in spectrum sharing can be found in [58, 59]. In the work of [58] each link can choose to cooperate with other links, forming coalitions. The links which are part of a coalition use an orthogonal allocation. The formation of coalitions is modeled as a Markov chain. When interference is relatively high for all links, the absorbing state of the Markov chain is the grand coalition, i.e., all links cooperate to have an orthogonal allocation. Simulation results are reported for links deployed in an ad-hoc manner over a 150 m x 150 m showing also the case where a coalition formation cost is considered.

Also using coalition formation games as the theoretical background, [59] consider femtocell cooperation where a cooperative set makes joint scheduling. The proposed cooperation algorithm attempts to form coalitions based on the recursive core concept. In the given examples, some femtocells start with just a fraction of the resources and by cooperating they make a common pool. So actually, by making coalitions some femtocells will have potential access to a larger bandwidth as well as coordinated interference due to the joint scheduling.

2.5.4 Concepts Designed for LTE/LTE-A

LTE release 8 also includes a signaling mechanism for Inter-cell Interference Coordination (ICIC) [60], based on frequency domain. This mechanism assumes the existence of a signaling interface from base station to base station, named X2. If the X2 interface is present, the ICIC signaling mechanism may facilitate the implementation of the concepts proposed in this thesis. Noteworthy, the solutions of chapter 4 and 5 can also be implemented without an X2 type of interface. In addition to that, the protocol for intercell signaling used to support the concept of chapter 6 is relatively lightweight. Therefore, over the air control signaling could also be feasible, avoiding the X2 requirement.

One of the limitations of the frequency domain LTE ICIC is that it is only applicable to traffic channels. Thus, control channels do not receive extra interference protection, and it does not avoid blocking situations. For this reason, the time domain ICIC [61] is included in LTE-A in order to cope with the fierce interference scenarios of heterogeneous networks. The solutions considered here are agnostic to the domain of multiplexing, as long as orthogonal channels can be created on an intercell level. Hence, both approaches can be considered precursor implementations for the solutions under proposal.

Besides the already standardized solutions described above, there are several proposals in the literature to cope with the inter-cell interference in LTE/LTE-A systems.

In the method proposed by [62], the spectrum allocation is done in two steps. In the first step, the femtocells apply iterative water filling in order to allocate the free spectrum in a balanced way. If some femtocells still demand more spectrum, they select the extra spectrum based on an SINR threshold in the second step. This approach shows large outage performance gains compared to reuse 1, but the result is still below reuse 2 performance at high offered loads. The outage throughput is shown to be enhanced by selecting restrictive thresholds but the average cell throughput can be affected. Still, even with the highest SINR threshold the method is strictly superior to a reuse 4 configuration.

The work in [63] proposes that each FAP should refrain from allocating too much spectrum in order to avoid excessive interference. First, the resources are ranked in terms of interference, measured in uplink for simplicity. Then, the capacity is estimated for the percentage of selected bandwidth, assuming that the less interfered resources are always the first ones to be selected. When the problem is posed in this way it becomes clear that the allocation of more resources provides diminishing returns. In one given example 50% of the bandwidth is enough to achieve 80% of the capacity which can be achieved by allocating 100% of the band. Thus the efficiency of allocating the first half of the band is much higher than the efficiency of allocating the second half. The key idea behind the proposed algorithm is to only select enough resources up to a percentage of the total. This is called the selfishness parameter. If all cells proceed this way, they will tend to only allocate less band, reducing the interference to others and increasing overall efficiency. The results are compared with reuse 1 and 2 approaches, showing considerable outage gain over reuse 1 in a full deployment.

The work in [64] investigates the effect of correlated frequency scheduling in macrocellular LTE scenarios in order to increase the SINR on fractional load conditions. In other words, when a cell has no need to use all resources, it leaves the unused resources to other cells. Some frequency transmission patterns are evaluated, and the role of measurement reports delay is investigated. The time correlation of the transmission pattern is shown to be very important in order to achieve interference coordination gains in a distributed way. While [64] focuses on fractional load given by the lack of traffic, the solutions proposed in this thesis enforce orthogonal use of resources, when the full reuse of resources is detrimental to capacity or a full reuse would imply having some receivers completely blocked. In this sense the proposed mechanisms try to determine the achievable rate and shape the traffic to that rate.

In [15] the authors study how femtocells can autonomously select CCs in an LTE-A system. Since a CC defines a cell in LTE-A, special attention is given to the so called primary CC. Each femtocell is endowed at startup to have a primary CC allocated with full coverage, and one of the key design goals is to provide extra protection against interference to primary CCs. When the femtocells need extra capacity, they allocate secondary CCs. The allocation of primary CCs is based on FAP to FAP measurements whereas the allocation of secondary CCs include UE measurements. In the latter case, SINR thresholds are applicable and the secondary CCs can only be allocated if these interference thresholds are respected. While such an approach protects the cells which already allocated primary and secondary CCs, it may render some cells without the possibility of allocating secondary CCs. This situation is particularly critical with large traffic variations since the cells have to allocate and relinquish CCs often, and even allocated CCs are not necessarily offered any traffic, just occupying resources that could be used by other cells. For this reason, this mechanism was extended in [65] where secondary CCs are allocated with lower transmit power, leading to an SFR approach. The exact power adjustments aim at maximizing the total network capacity trading off the loss of interfered cells for the gain of the cell acquiring more spectrum.

Graph theory is applied to the selection of primary CCs in [66], where distributed graph coloring is investigated as a way to achieve self-organization in LTE networks. Several distributed graph coloring algorithms were evaluated using system-level simulations. The number of CCs needed to have a conflict free assignment was between 5 to 7. Graph coloring is discussed in section 3.6.

2.5.5 Spectrum Sharing in 802.11

An overview of the state of the art would not be complete without considering CSMA/CA, which is a commercially available solution. CSMA/CA is a node centric MA scheme and, therefore, CSMA/CA does not discriminate duplexing, intra-cell multiplexing or inter-cell multiplexing. Still, CSMA/CA can be seen as a distributed solution which leads to time domain spectrum sharing, but as implemented , e.g. in 802.11 [67], it is not scalable to a large number of users [68]. The vast literature on CSMA/CA often focuses on the intracell interactions. Notable exceptions are [69, 70]. In [69], the authors show through a series of experimental and simulation settings that in a 802.11 system with unplanned deployment, adding more APs can actually be detrimental to the total area spectral efficiency, for a fixed number of served stations. They propose to mitigate such effects, by adapting CSMA/CA contention windows based on the number of active APs, instead of the traditional approach of adapting to unacknowledged transmissions. More closely related to the work in this thesis, [70] compares CSMA/CA to fixed frequency reuses. While CSMA/CA is shown to be able to provide a time domain sharing among cells, the resulting reuse is rather sparse and the performance can be largely boosted by using a static frequency reuse 2 scheme.

2.6 Conclusions

This chapter introduced diverse spectrum access models. According to these models, the type of DSA considered here can be classified as DSA among equals or access to a commons. While the literature about DSA is growing quickly, spectrum sharing among equals has received less attention than primary/secondary sharing, but as discussed in this chapter sharing among equals is needed as a complementary view.

Spectrum sharing within a network has been largely investigated over the years and a complete discussion of DSA should not overlook such developments. The channel assignment problem was presented as a related area which had great interest in the past. In this context DSA among femtocells appear as an evolutionary view of cellular networks and the solutions to this problem should replace frequency planning and centralized DCA approaches in order to minimize future femtocell deployment costs and maximize femtocell performance.

Existing solutions for DSA among femtocells or spectrum sharing among equals were surveyed including both prior art and developments done concurrently to this work. This survey will help to understand the contributions of this thesis in light of the existing literature.

CHAPTER 3

Problem Characterization

3.1 Introduction

Often, solutions to a problem can only be appreciated when the problem is fully understood, analyzed and characterized. This chapter is a thorough description and characterization of the investigated problem in order to provide enough insight which later substantiates the designed solutions.

The problem is described in section 3.2, along with a discussion of the system modeling and assumptions. Section 3.3 evaluates what the potential link capacity gain is for a link which is interference limited. Then the case of spectrum sharing between two femtocells is analyzed in light of GT in section 3.4. The scenario and simulation assumptions used throughout the majority of the thesis are introduced in section 3.5. In section 3.6 this scenario is analyzed using graph theory. Such analysis provides further insight into the nature of the problem when there are many networks. Finally, section 3.7 shows system level performance evaluations which serve as baseline results to which the methods proposed in the thesis are compared. The chapter is finalized with concluding remarks in section 3.8.

3.2 System Model and Assumptions

Consider two or more femtocells which share a particular spectrum band of interest with a total bandwidth of B MHz. The system bandwidth is divided into K orthogonal channels of B/K MHz. The channelization is common for all femtocells. The specific question addressed in this thesis is the following: how can each femtocell autonomously select a subset of the K channels for transmission in order to maximize the throughput of each femtocell?

A number of simplifying assumptions are adopted in order to investigate this problem, as much as possible, in isolation of other issues. The implications of such assumptions are discussed throughout the thesis along with expected outcomes of relaxing such working assumptions. Next, such simplifications are discussed.

There are no other wireless networks than the femtocells accessing the shared band during the time of interest. This assumption holds, e.g. if the spectrum band is licensed, or if the inter-system spectrum sharing problem is solved by another mechanism. All the FAPs and UEs are assumed to be able to transmit and receive over the whole band, i.e. over B MHz. In other words, different classes of UEs are not considered.

It is assumed that the duplexing provides full orthogonality of both directions, such as in an FDD system or a frame synchronized TDD system. This assumption allows us to consider a single link direction independently. Thus, the B MHz only has to be divided among links in one direction. Hereafter, downlink is taken as the main study case.

Since the channels are considered to be orthogonal, it is implicitly assumed that the receivers can mitigate Adjacent Channel Interference (ACI), whereas Co-channel interference (CCI) is treated as noise by the receivers. The Additive White Gaussian Noise (AWGN) model [71] is used to compute the effect of interference on each link. Each channel is considered to be decoded independently and, therefore, the effects of interference are separate for each channel. The capacity provided by a channel is assumed to be a non-decreasing function of SINR. However, a minimal SINR is required for decoding useful data rate. For example, below that SINR the radios are not even able to synchronize. In addition to that, a maximum implemented MCS limits the maximum achievable capacity when the SINR is high. For the purpose of evaluation, the following approximation of LTE system capacity is used in simulations and numerical examples [3]:

$$C(\gamma) = \begin{cases} 0 & \text{if } \gamma < \gamma_{min} \\ \frac{B}{K}\ B_{eff}\ log_2\left(1 + \frac{\gamma}{\gamma_{eff}}\right) & \text{if } \gamma_{min} \leq \gamma < \gamma_{max} \\ \frac{B}{K}\ B_{eff}\ log_2\left(1 + \frac{\gamma_{max}}{\gamma_{eff}}\right) & \text{if } \gamma \geq \gamma_{max} \end{cases} \tag{3.1}$$

Where γ represents the SINR in a linear scale and the other parameters are explained next. Equation (3.1) essentially defines a modified Shannon formula, where the gap between the raw channel capacity and the Shannon bound [72] is the factor γ_{eff}. In essence the parameter γ_{eff} measures how well the system is able to turn SINR into raw capacity. If γ_{eff} is equal to one, then the definition is the same as the Shannon bound. The term B_{eff} accounts for overheads such as guard bands, cyclic prefix and control channels as well as other adjustments which allow us to approximate γ_{eff} as constant throughout the whole SINR range [3]. γ_{min} is the minimum SINR in order to avoid complete blocking of a receiver. γ_{max} is the SINR at which the maximum MCS can be achieved with very low decoding error probability. Naturally, the channel capacity is scaled for the bandwidth, i.e., B/K MHz. Figure 3.1 shows a plot of the capacity formula from equation (3.1), using the following parameters $\gamma_{eff} = 2.0$ and $B_{eff} = 0.56$, which are values adjusted for LTE Single Input Single Output (SISO) [3]. γ_{max} is set in order to achieve the maximum LTE spectral efficiency (after discounting overheads), i.e. 75 Mbps over a band of 20 MHz, for a single spatial stream [7]. The threshold $\gamma_{min} = -7$ dB is a typical value for the minimum SINR so that a UE can synchronize to the serving FAP[66].

There is a control channel where UEs can send measurement reports to the FAP. The UEs are able to estimate the SINR and the sum interference in each channel while decoding useful data. If the interference needs to be discriminated according to the source transmitter, the UEs have to stop decoding incoming data and make dedicated coherent measurements of the received power from each interference source. These assumptions are in line with LTE receiver capabilities, though not all this information is feedback by default.

The FAP transmits with constant downlink power spectral density over the selected resources. Therefore the generated interference depends only on which resources are selected for transmission, not on which UE is scheduled.

In order to avoid the joint considerations with different packet schedulers and the inherent difficulties in choosing the feedback information from several UEs, the focus throughout most of the thesis on one UE per femtocell. For the purposes of practical application, it can be considered that only the information of the UE with the highest backlogged traffic or the UE experiencing the worst SINR

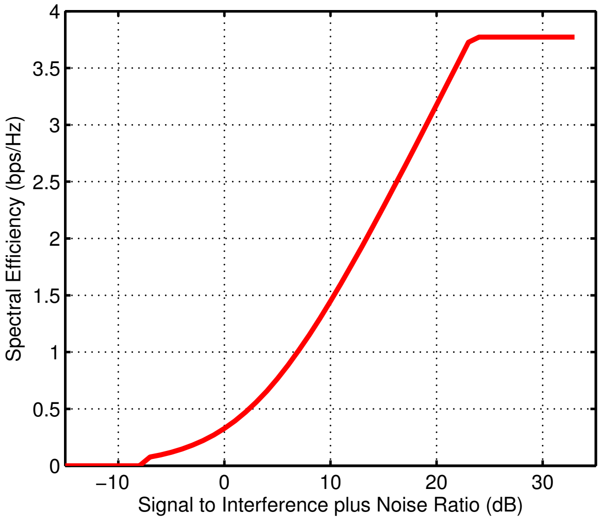


Fig. 3.1: Plot of the SINR to throughput mapping, as provided by equation (3.1) for the following parameters $\gamma_{eff} = 2.0$, $B_{eff} = 0.56$, $\gamma_{min} = -7$ dB, $\gamma_{max} \approx 23$ dB.

is used to make decisions.

Mobility and handovers are not considered. In general, local area mobility is infrequent and relatively slow compared to existing mobile networks. The femtocells operate on CSG mode and, consequently, handover considerations within the femtocell layer are not part of the investigation.

3.3 Potential Link Capacity Gain

The first analysis done here is to determine what is the potential capacity gain from a single link point of view. A basic comparison that can be made for a particular link is to evaluate what the capacity is if the transmission is free of interference and what the capacity is when interference is present. In particular, this comparison can be done when the SNR is very high such that $SNR \geq \gamma_{max}$. In this case, the received power is enough to achieve the highest MCS in case of interference free transmission. One should note that the condition $SNR \geq \gamma_{max}$ can often be fulfilled in a dense femtocell deployment, because, normally, the user will be close to the serving FAP. Using equation 3.1, under the condition $SNR \geq \gamma_{max}$, one can see that the capacity provided by one channel free of

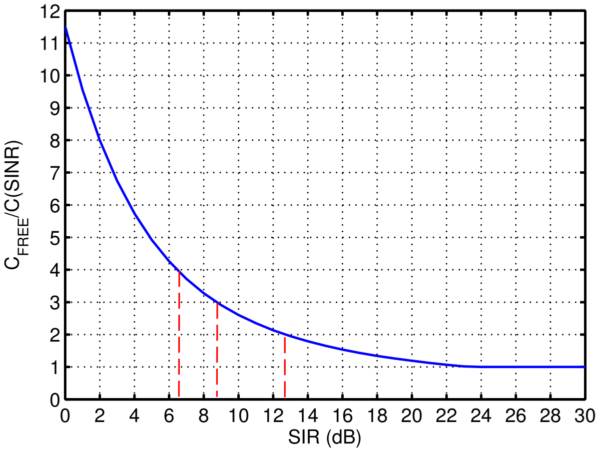


Fig. 3.2: The ratio of capacity between a clean channel and an interfered channel when SNR is very high. This illustrates the potential capacity gain per channel when interference is coordinated. Naturally, if the SIR is low, i.e. interference is strong, the potential gains are higher.

interference is given by:

$$C_{FREE} = \frac{B}{K} B_{eff} \, log_2 \left(1 + \frac{\gamma_{max}}{\gamma_{eff}} \right) \tag{3.2}$$

In an interference limited condition, a link can experience poor SINR even though the SNR is high. So, one important question is how C_{FREE} compares to the capacity of a channel which is impaired by interference. The answer of course depends on the relative strength of the interference. Figure 3.2 shows the ratio between C_{FREE} and $C(SINR)$ when the interference is varied. For low SIR, the capacity of an interfered channel is much lower than C_{FREE}, but for a high SIR the capacity of an interfered channel approximates C_{FREE}. Thus the potential gains that can be provided by mitigating interference depends heavily on the power ratio between desired signal and interference signals.

As previously mentioned in section 1.5 the trade-off between bandwidth utilization and SINR is an essential feature of the investigated problem. In general, when interference is coordinated it is possible to achieve higher SINR, but the price is that each link has to use fewer channels. Figure 3.2 allows us to assess which share of resources (channels) a particular link will need in order to have gains over the situation where it uses all channels. For example, if a link has $SIR \approx 12.5$dB when using all channels it will need to have at least $1/2$ of the channels totally free of interference in order to break even in total capacity. Conversely, if coordinating interference implies having access to only half the total number of channels, links where the original $SIR > 12.5$dB will certainly experience losses from interference coordination, whereas links where $SIR < 12.5$dB will potentially experience gains from interference coordination, assuming the interference can be mitigated. Since the total capacity depends directly on the number of allocated channels, as described in equation (3.1), it is of special importance to analyze the SIR at a reuse 1 condition, i.e. when all channels are reused by all links. The lower the reuse 1 SIR, the highest the potential gains of interference coordination.

While Figure 3.2 helps to visualize the potential gains of interference coordination from a single link perspective, it is the interaction and conflicts among different links which makes the problem challenging. These issues are addressed in the following sections.

3.4 Game Theoretic Analysis

A *game* [73] is any situation where the outcome of the choice made by each decision maker is affected by the choices made by other decision makers. Since the channel selection of each femtocell affects the decision of other femtocells through means of interference, the DSA problem among femtocells can be modeled as a game. In GT, a decision maker is called a *player*. In this spectrum sharing game formulation a player corresponds to a femtocell. Hereafter, the terms femtocell and player will be used interchangeably.

A *game in strategic form* Γ is a tuple $\Gamma = (\mathscr{I}, (\Sigma_i)_{i\in\mathscr{I}}, (\Pi_i)_{i\in\mathscr{I}})$ where, $\mathscr{I} = \{1, ..., |\mathscr{I}|\}$ is the set of players, Σ_i is the pure strategy space of player i, and it is defined for each player in $\mathscr{I}$. A strategy profile P is a particular selection of strategies for each player $P = \left\{s_1, ..., s_{|\mathscr{I}|}\right\}$, where s_i is a strategy of player i. The utility function $\Pi_i : P \to \mathbb{R}$ is a real valued function determining the preference of each player over the set of all possible strategy profiles.

A particular femtocell can have several communication links as illustrated in Figure 3.3. It is assumed that the nodes within a femtocell coordinate themselves to access the medium, providing the functions of duplexing and MA. The following formulation here deals only on how to share the spectrum among the femtocells. Let $\mathscr{K} = \{1, 2, ..., K\}$ be the pool of dynamically shared channels. Each player has access to all channels in the pool. Furthermore, the channels are orthogonal, i.e., there is no cross-interference between two

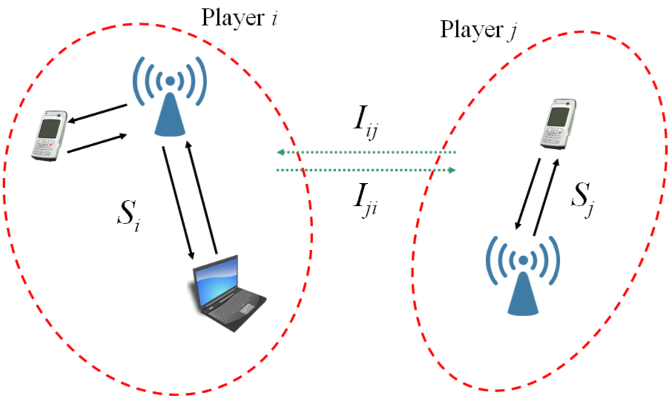


Fig. 3.3: Each femtocell is a player. Interference defines the interaction amongst players.

different channels. The strategy space of each player is the same and consists of all possible spectrum usage masks. In the following, $s_i(k)$ is a binary variable such that $s_i(k) = 1$ if the cell transmits at channel k and $s(k) = 0$ if there is no transmission at that channel. Hence, the spectrum usage mask $\mathbf{s_i}$ can be written as the binary vector:

$$\mathbf{s_i} = \left[s_i^{(1)}, \ldots, s_i^{(k)}, \ldots, s_i^{(K)} \right] \tag{3.3}$$

At least one channel must be selected, so that the femtocell can operate. Consequently the vector with a null channel selection is not considered to be part of the strategy space. The players only interact with each other by means of interference. The received interference power by player i, in channel k is:

$$I_i^{(k)} = \sum_{\substack{j=1 \\ j \neq i}}^{|\mathscr{I}|} s_j^{(k)} I_{ji}^{(k)} = \sum_{\substack{j=1 \\ j \neq i}}^{|\mathscr{I}|} s_j^{(k)} P_j^{(k)} G_{ji}^{(k)} \tag{3.4}$$

Where $I_{ji}^{(k)}$ is the incoming interference from player j to player i at channel k. $P_j^{(k)}$ is the transmit power player j allocated to channel k and $G_{ji}^{(k)}$ is the path gain between j's transmitter and i's receiver. Equation (3.4) also implies that there is no incoming interference from player j at channel k if that player does not transmit at channel k. Similarly, the received signal power of player i is represented by $S_i^{(k)}$ and the received power is only available if that channel is allocated:

$$S_i^{(k)} = \begin{cases} P_i^{(k)} G_{ii}^{(k)}, & \text{if } s_i(k) = 1 \\ 0, & \text{otherwise.} \end{cases} \tag{3.5}$$

Where $P_i^{(k)}$ is the transmit power used by player i, and $G_{ii}^{(k)}$ is the path gain between the transmitter and receiver in femtocell i. The utility function of each player is simply the sum capacity provided by all selected channels:

$$\Pi_i = \sum_{k=1}^{K} s_i^{(k)} \; C_i^{(k)} \tag{3.6}$$

Where $C_i^{(k)}$ is the channel capacity of channel k, and it represents the link level performance of the system. Using the AWGN assumption for the interference effect and equations (3.4) and (3.5) one can write:

$$\Pi_i = \sum_{k=1}^{K} s_i^{(k)} \; C \left(\frac{S_i^{(k)}}{\sum_{\substack{j=1 \\ j \neq i}}^{|\mathscr{I}|} s_j^{(k)} I_{ji}^{(k)} + N} \right) \tag{3.7}$$

Where $C(SINR)$ is a capacity function such as the one defined in equation (3.1), and N is the noise power measured over one channel. Note that $C(1) = 0$ in equation (3.1) and thus the case where $S_i^{(k)} = 0$ from equation (3.5) does not need special consideration.

The main goal of game theoretic analysis is to predict the behavior of each player when they pursue the maximization of their own utility function. The central concept of non-cooperative GT is the notion of Nash Equilibrium (NE), described next. In GT it is common to denote the set of strategies of all the players but i as s_{-i}, i.e., $s_{-i} = \left\{ s_1, ..., s_{i-1}, s_{i+1}, ..., s_{|\mathscr{I}|} \right\}$. An NE is a strategy profile where each strategy is the best response to the strategies of the other players. Formally, an NE is a a strategy profile where the following condition holds for every i:

$$\Pi_i(s_i, s_{-i}) \geq \Pi_i(\tilde{s}_i, s_{-i}) \text{ for } \forall \tilde{s}_i \tag{3.8}$$

Equation (3.8), explained in words, says that for a fixed strategy from the other players, s_{-i}, if player i selects strategy s_i his payoff will at least be as good as if any other strategy $\tilde{s}_i$ is selected. Since this condition holds for all players, in an NE no player has incentives for making unilateral deviations from the NE strategy profile.

Analyzing equation (3.7), a fixed strategy of other players s_{-i} implies in a fixed interference level $I_i^{(k)}$ on each channel. For a fixed interference level, the capacity can be maximized using a water filling approach for the distribution of the total power [71]. If the strategy of the other players is to select all channels with equal transmission power, and one assumes flat fading, then water filling application by a player will lead to the decision to select all channels as well. This leads to the conclusion that with such assumptions the strategy profile where all players select all channels is always an NE [46]. While flat fading is not a practical assumption, the average statistics of time-varying channels is usually regarded as the same within a band. This is equivalent to assume an average flat fading behavior over a very long time period.

Such a result is not particularly enticing, since such reuse 1 configuration can be inefficient and have unfair distribution of throughput. Other GT concepts can be applied in order to justify other solutions, such as repeated games [46] and NBS [56]. A deeper analysis of the two-player version of the spectrum sharing game helps to understand such concepts. In this version of the game, two players i and j can decide their channel allocation among two channels 1 and 2. Thus the strategy space of each player consists of the following 3 vectors: [0 1], [1 0], [1 1]. Recap that the selection [0 0] is ruled out, because an empty allocation would imply that the femtocell does not operate.

For simplicity, let the transmit power be doubled if both channels are selected. This situation could happen in reality if the transmit power is not limited, but the maximum power spectral density is limited by regulation. With such an assumption the received signal power and received interference power in each channel does not depend on the number of selected channels, but only if the channel is used or not. So, the game can be described in normal form as shown in Table 3.1. In the normal form, the game is represented as a matrix. Player i chooses among the rows, and player j chooses one of the columns. The first column shows the strategy space of player i, and the first row shows the strategy space of player j. Thus, each of the other entries correspond to a strategy profile. The values shown at these entries are the utility functions Π_i, Π_j, respectively, for that particular strategy profile.

Table 3.1: Two player spectrum sharing game in normal form. Player i chooses rows and player j chooses columns

j i	[1 0]	[0 1]	[1 1]
[1 0]	$C\left(\frac{S_i^{(1)}}{I_{ji}^{(1)}+N}\right),C\left(\frac{S_j^{(1)}}{I_{ij}^{(1)}+N}\right)$	$C\left(\frac{S_i^{(1)}}{N}\right),C\left(\frac{S_j^{(2)}}{N}\right)$	$C\left(\frac{S_i^{(1)}}{I_{ji}^{(1)}+N}\right),C\left(\frac{S_j^{(1)}}{I_{ij}^{(1)}+N}\right)+C\left(\frac{S_j^{(2)}}{N}\right)$
[0 1]	$C\left(\frac{S_i^{(2)}}{N}\right),C\left(\frac{S_j^{(1)}}{N}\right)$	$C\left(\frac{S_i^{(2)}}{I_{ji}^{(2)}+N}\right),C\left(\frac{S_j^{(2)}}{I_{ij}^{(2)}+N}\right)$	$C\left(\frac{S_i^{(2)}}{I_{ji}^{(2)}+N}\right),C\left(\frac{S_j^{(1)}}{N}\right)+C\left(\frac{S_j^{(2)}}{I_{ij}^{(2)}+N}\right)$
[1 1]	$C\left(\frac{S_i^{(1)}}{I_{ji}^{(1)}+N}\right)+C\left(\frac{S_i^{(2)}}{N}\right),C\left(\frac{S_j^{(1)}}{I_{ij}^{(1)}+N}\right)$	$C\left(\frac{S_i^{(1)}}{N}\right)+C\left(\frac{S_i^{(2)}}{I_{ji}^{(2)}+N}\right),C\left(\frac{S_j^{(2)}}{I_{ij}^{(2)}+N}\right)$	$C\left(\frac{S_i^{(1)}}{I_{ji}^{(1)}+N}\right)+C\left(\frac{S_i^{(2)}}{I_{ji}^{(2)}+N}\right),$ $C\left(\frac{S_j^{(1)}}{I_{ij}^{(1)}+N}\right)+C\left(\frac{S_j^{(2)}}{I_{ij}^{(2)}+N}\right)$

Table 3.2: Two player spectrum sharing game in normal form, simplified from the example in Table 3.1 for the case where both channels have the same path gain statistics.

j i	[1 0]	[0 1]	[1 1]
[1 0]	C_i^S,C_j^S	C_i^F,C_j^F	$C_i^S,C_j^S+C_j^F$
[0 1]	C_i^F,C_j^F	C_i^S,C_j^S	$C_i^S,C_j^S+C_j^F$
[1 1]	$C_i^S+C_i^F,\ C_j^S$	$C_i^S+C_i^F,\ C_j^S$	$2C_i^S,2C_j^S$

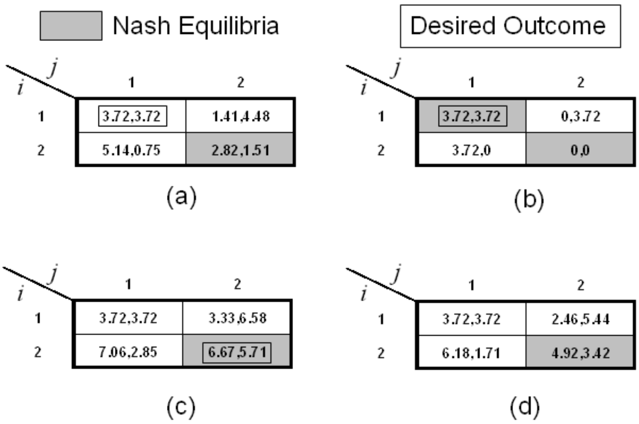
One conclusion that can easily be drawn from Table 3.1 is that the worst possible outcome is that both players select a single channel and they happen to select exactly the same channel. If the players select a single channel, but they could coordinate their transmissions in order to use different channels, then both players could achieve interference-free transmissions. Iterative Interference Avoidance (IA) methods can effectively rule out the selection of the same channel over time without the need for explicit signaling [50, 49]. More will be said about such IA procedures in chapter 4.

Even in such a simplified example, of Table 3.1 , the complexity of the utility function and a multi-dimensional strategy space overshadow the essence of the game. Hence, further simplification is needed in order to extract the core aspects of this problem. If the channel gains do not depend on the chosen channel, the picture can be much simplified. Let C_i^F and C_j^F be the channel capacities achievable in a channel which is free from interference. And let C_i^S and C_j^S be the capacities achievable in channels which are shared by both players. Then, the game of Table 3.1 can be rewritten as the game of Table 3.2. Now that the players give equal value to each channel, one can see that some of the game outcomes only depend on how many channels are allocated, not on which channels are allocated. Therefore, there are many equivalent strategies. Suppose that the worst case strategy profiles can always be ruled out using IA. Without loss of generality one can assume that player i will always choose the first channel, and player j will always select the second channel. Then it is possible to define a very minimal version of the two player spectrum sharing game where each player only has to decide whether to allocate 1 or 2 channels. This game is shown in Table 3.3.

Table 3.3: Two player spectrum sharing game in normal form, simplified from Table 3.2 for an alternative strategy space. Here, each player selects whether to allocate 1 or 2 channels.

j i	1	2
1	C_i^F,C_j^F	C_i^S,$C_j^S + C_j^F$
2	$C_i^S + C_i^F$, C_j^S	$2C_i^S$,$2C_j^S$

Figure 3.4 shows numerical examples for the game of Table 3.3. The links have very high SNR, a common condition in femtocells, but they are interference limited. The capacity is calculated using Equation (3.1), with parameters $\gamma_{eff} = 2.0$, $B_{eff} = 0.56$ and band per channel of 1 MHz. In Figure 3.4a, the resulting game is the well known prisoners' dilemma [73]. The prisoners' dilemma has only one NE: both players allocate all channels. However, the



(a)

i \ j	1	2
1	3.72,3.72	1.41,4.48
2	5.14,0.75	2.82,1.51

(b)

i \ j	1	2
1	3.72,3.72	0,3.72
2	3.72,0	0,0

(c)

i \ j	1	2
1	3.72,3.72	3.33,6.58
2	7.06,2.85	6.67,5.71

(d)

i \ j	1	2
1	3.72,3.72	2.46,5.44
2	6.18,1.71	4.92,3.42

Fig. 3.4: Numerical examples for the game of Table 3.3. The expected outcome NE is compared with the desired one. (a) A prisoner's dilemma SINR=10 dB and 5 dB. (b) A dummy game SINR = -15 dB and -10 dB. (c) A game where full reuse is highly desirable, SINR = 25 dB and 20 dB. (d) A game where the desired outcome depends on the network optimization criteria. SINR = 17 dB and 12 dB.

capacity of each player could be increased if they both used a single channel. This type of game is widely used as one example where greedy strategy selection is destructive. Starting from the orthogonal allocation, either player sees the benefit of allocating also the second channel. Notwithstanding, if both players choose to allocate the second channel, they will both be worse off than if they keep on cooperating by selecting a single channel. On a repeated game, the orthogonal allocation becomes an NE [73], because reuse 1 is Pareto dominated by the orthogonal allocation. Thus, in case the interference interaction between the two femtocells is long enough there are incentives to make the orthogonal allocation. Furthermore, in such a game the orthogonal allocation is the NBS of the game.

Figure 3.4b shows a case where the interference coupling is so large that the transmitters completely block the receivers in case of overlapping allocation. This is called a dummy game, because the blocked player decision cannot influence its own utility at all. In this game, where both players are blocked, cooperation is expected since the orthogonal allocation is also an NE. In reality, though, such observation could only be made if both transmitters know they are blocking each other receivers. Such knowledge may not be available in reality. If only one of the players is blocked, it cannot leave the blocking situation if the other player chooses to transmit in both channels. But the player which is not blocked would have incentives to transmit in both

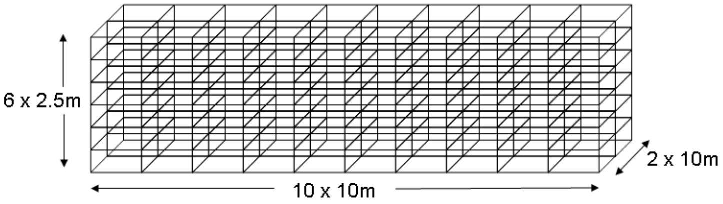


Fig. 3.5: Simulation scenario. A six floor building with 120 apartments.

channels. Ultimately, the blocked player depends on the kindness of the other player in order to be able to transmit anything. This is a strong reason why spectrum etiquettes need to be applied.

When the SINR is sufficiently high, the reuse of both channels is much more efficient than orthogonal allocation. One example is shown in Figure 3.4c. In this case, the desired outcome matches the NE of the game. Thus, a greedy strategy selection is not always destructive. There are also intermediate cases as illustrated in Figure 3.4d. In such cases, the definition of a desired outcome is blurry because the orthogonal allocation provides better outage performance whereas the reuse is more efficient in terms of sum throughput. These examples show the multiple nature of the DSA problem. The players should realize which type of game they are playing before making a decision between orthogonal allocation and reuse of resources. This is not a trivial task to do only with local information (implicit coordination case). In addition to that, for more than 2 players the interaction between each pair of players may be rather different, e.g., corresponding to one of the 4 cases exemplified in Figure 3.4. The interaction of many femtocells is further analyzed in section 3.6 in light of graph theory.

3.5 Simulation Scenario

The scenario adopted for performance evaluation in this thesis is a single building in a stripe format as illustrated in Figure 3.5. The building has six floors, and the floor height is 2.5 m. In each floor there are 20 apartments and the dimensions of an apartment are 10 m x 10 m x 2.5 m. Therefore, a total of 120 apartments are simulated. This single stripe scenario is similar to the 3GPP dual stripe scenario [45], except that a single building is considered.

In each simulation drop some apartments are randomly selected to have a femtocell deployment. The number of deployed femtocells was varied, in order to generate different deployment densities. The number of apartments with a deployed network was set to 1, 10, 20, 30, 60, 90 or 120, corresponding to different deployment ratios: 0.83%, 8.3%, 16.6%, 25%, 50%, 75% and 100%. When a femtocell is deployed, both the FAP and a corresponding UE are deployed within that apartment. Therefore, each apartment may contain a femtocell or not, and the femtocells are randomly distributed over the simulated scenario. The positions of both FAPs and UEs are selected randomly inside the apartment, since a user-deployed scenario is modeled. Each UE always remains connected to the FAP in the same apartment regardless of the signal and interference conditions, due to the CSG assumption.

In order to achieve statistical reliability the results were obtained in a Monte-Carlo approach. Each simulation drop corresponds to different random positions for FAPs and UEs. For each deployment ratio and simulated case many simulation drops were performed until samples from 6000 femtocells are available. The results shown throughout the thesis are statistics obtained from 6000 samples per configuration (simulation case and deployment ratio). This number of samples is enough to have the 95% confidence interval for the average throughput within ±2% of the absolute values, even in the simulated case with largest standard deviation of throughput (reuse 1).

Path loss and shadowing effects are calculated using the propagation model proposed in 3GPP [45], adjusted to a central frequency of 3450 MHz. This type of propagation model has 4 components of path loss:

$$\tilde{L} = L_{FS} + L_{LIN} + L_P + L_{FL} \tag{3.9}$$

Where $\tilde{L}$ is the total path loss, L_{FS} is the free space path loss, L_{LIN} is a linear attenuation for a given distance, L_W is the penetration loss of the crossed walls and L_{FL} is a floor to floor loss. All the values are in decibels. The free space path loss can be written as [43]:

$$L_{FS} = 20log_{10}(d) + 46.4 + 20log_{10}(f/5.0) \tag{3.10}$$

Where d is the distance in meters and f is the frequency in GHz. The linear attenuation term models the existence of obstacles, such as furniture, and internal walls within an apartment:

$$L_{LIN} = \alpha d \tag{3.11}$$

The constant α was set to 0.7 dB/m. L_P models the penetration loss in the walls between different apartments and it corresponds to:

$$L_P = n_W L_W \tag{3.12}$$

Where n_W is the number of crossed walls and $L_W = 5$ dB is the penetration loss of a single wall. Finally, L_{FL} models the extra path loss incurred from floor to floor [43]:

$$L_{FL} = 17 + 4(n_F - 1) \tag{3.13}$$

Where n_F is the number of floors between the transmitter and receiver. If the FAP and UE are on the same floor, then L_{FL} is set to zero.

Multipath fading is not explicitly modeled. Shadow fading is modeled by a log-normal distribution (in a linear scale). The shadow fading of each link is calculated independently, i.e. no spatial correlation of shadow fading is considered. When the FAP and UE are located in the same ambient the log-normal distribution is set to 3 dB standard deviation. Otherwise the standard deviation is 6 dB. A minimum coupling loss of 45 dB was assumed, and the final path loss is set to be at least as large as the free space path loss. Therefore, the path loss incurred in a link is:

$$L = min(\tilde{L} + L_{SF}, L_{FS}, 45) \tag{3.14}$$

Where L_{SF} is the shadow fading of a link, in dB, a randomly drawn value from a normal distribution with the aforementioned standard deviation.

The transmit power of FAPs and UEs was set to 24 dBm. This transmit power is only used over the channels selected by the DSA algorithms or the static channel allocations. The SINR is calculated for each channel using the AWGN model. Look-up tables map the SINR to corresponding throughput values according to a modified Shannon's formula from [3], expressed in equation (3.1).

The simulations assume perfectly elastic traffic, also known as full buffer traffic or queue saturation. This type of traffic has the characteristic of perfectly adapting to the physical layer capacity. On the one hand, full buffer traffic provides a worst case situation in terms of generating high interference constantly. On the other hand, assuming perfect elasticity can be a rather idealistic modeling of intermediate layers, such as Transmission Control Protocol (TCP). Nevertheless, the simplistic full buffer traffic assumption allows us to study the DSA problem in isolation of the upper layers' behavior.

The total system bandwidth is 60 MHz, starting at 3420 MHz and ending in 3480 MHz, configured for TDD. The downlink to uplink ratio is set to 7:3, and all femtocells are frame aligned. The band is divided into 12 orthogonal channels. In principle, the results should be independent of the method to achieve channel orthogonality, as long as full orthogonality among channels can be attained. The process of coding and decoding is assumed to be independent for each channel. This is true, for example, in LTE-A CCs. Even though 12 CCs is not a configuration currently in consideration in LTE-A, 12 channels allow us to define precisely reuses 1, 2, 3, 4 and 6 while maximizing co-channel distance. All throughput results are from downlink, and they were normalized by the maximum theoretical capacity of the system. Hence, a normalized throughput of 100% means transmission over the whole bandwidth at the maximum system spectral efficiency considering the MCS limitation.

In each snapshot 200 radio frames were simulated, where a radio frame lasts 10 ms as in an LTE-A system. The UE measurements are reported back to the FAP every radio frame. Unless otherwise stated, the throughput results were collected only in the last 50 frames, in order to allow for the convergence of the iterative methods.

3.6 Graph Theoretic Analysis

In this section, the simulation scenario is analyzed with the aid of graph theory concepts. A *graph* is a mathematical abstraction useful to express a set of objects and the relationship among them. A graph can be either directed or undirected depending on whether the relationship is asymmetric or symmetric. An *undirected graph* $G = (V, E)$ is defined by the set of *vertices*, V, and the set of edges E. Each edge is associated with a pair of vertices, and the presence or lack of an edge in the graph defines the relationship for that pair of vertices. A *directed graph* $G = (V, A)$ is defined similarly, the only difference is that the relation among two vertices is not symmetric. Thus, for each pair of vertices, v_1 and v_2, a directed graph has up to two *arcs*. One arc is directed from v_1 to v_2 and the other arc is directed from v_2 to v_1. By contrast, in an undirected graph an edge between v_1 and v_2 does not make any distinction of direction. A *weighted graph* has weights associated with each edge or arc. Therefore, weighted graphs are suitable to model problems where there is different intensity of relationship among the vertices.

Such graph definitions can be applied to model problems such as the channel assignment problem [74]. A wireless link or a cell corresponds to a vertex. Then, the potential interference among links or cells, can be characterized as an edge. As one example, let us consider the scenario shown in Figure 3.6a, which corresponds to one floor of the simulation scenario. The arrows illustrate the SINR of the victim if the channel is shared only with the interferer at the other end of the arrow. This scenario can be abstracted as the weighted directed graph of Figure 3.6b. Clearly, from such a abstraction, the interference relationship between each pair of cells can be quite asymmetric. Also, by comparing Figure 3.6a to Figure 3.6b, one can relate very low SINRs to the proximity of interferer and distance to the serving FAP. These two characteristics are due to user-deployment and CSG assumptions.

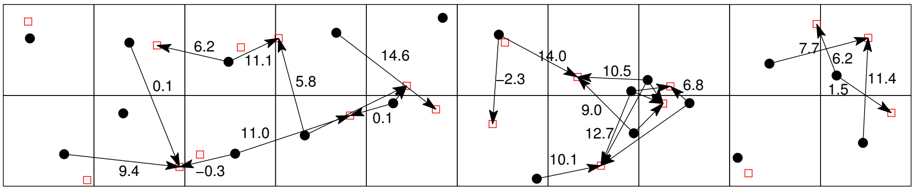
If one wants to express the conflicts, regardless of direction, a possible way is to select the most restrictive SINR, i.e. the lowest, to be an edge on a new graph. This process is illustrated by Figure 3.6c where the directed graph of Figure 3.6b is transformed into an undirected graph.

If one wants to mitigate all the interference, one should be able to assign orthogonal frequencies to each of the vertices of the graph which share an edge (highly interfered), while femtocells which do not share an edge in such a graph should be able to reuse the spectrum. Naturally, the difficulty is on defining what highly interfered means. This is illustrated in Figure 3.7, where the weights of the graph of Figure 3.6c can be removed by applying a SINR threshold. For different thresholds the density of the graph is very different.

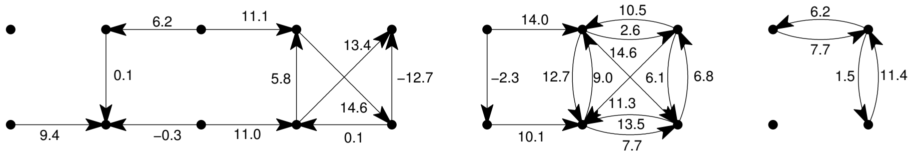
An undirected graph, like the ones shown in Figure 3.7, is a simple way of representing whether there is a conflict between each pair of femtocells. One relevant question is: how many channels (colors) are needed in order to assign one channel to each femtocell (vertex) so that no conflict remains? This problem is known as graph coloring [66]. In the case of a channel assignment problem, one channel corresponds to one color. A *proper coloring* is an assignment of a color to each vertex in such a way that no pair of vertices sharing an edge uses the same color. A graph is said to be *k-colorable* if k is the minimum number of colors needed to make a proper coloring.

A **lower bound** on the number of colors (channels) needed for a conflict free assignment can be determined by cliques. A *clique* is a subgraph such that all possible pair of vertices in that subgraph share an edge. Such definition excludes vertices with no incident edge, i.e., isolated vertices. Large cliques are, by definition, composed of smaller cliques. For example, a clique of size 3 is necessarily composed of 3 cliques of size 2. A *maximal clique* is a clique which is not included in any larger clique. Figure 3.8 shows examples of maximal cliques. The definition of maximal clique is important because it defines the densest spectrum reuse which can be achieved in a particular area while keeping an orthogonal channel allocation in femtocells with a relevant interference coupling. Notice from Figure 3.8 that the definition of a maximal clique size is local. In principle, nothing should preclude, for instance, an isolated vertex (femtocell) to allocate the whole spectrum.

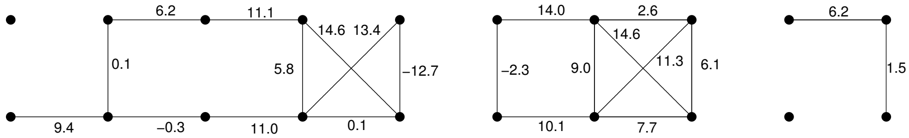
Note that each vertex of a graph can be part of multiple maximal cliques, as illustrated in Figure 3.8. For a particular femtocell, the maximal clique with highest cardinality determines the maximum number of channels that femtocell can have while: 1) Solving all interference conflicts in the clique by attaining an orthogonal allocation within the clique, and 2) assigning an equal



(a) Example of simulated scenario (one floor). The arrows point from the interferer (AP) to the victim (UE). The value near each arrow is the SINR of the victim if the channel is shared only with that interferer. Only SINR values below 15 dB are shown for clarity.



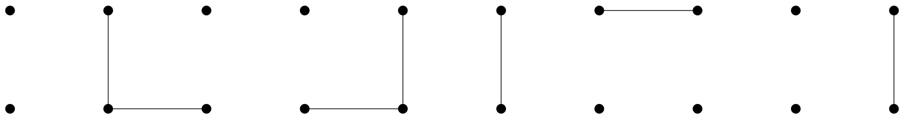
(b) Graph abstraction of the DSA problem from Figure 3.6a. Each wireless communication link can be abstracted as a node in a graph. The arcs can represent some conflict, as for example, SINR below 15 dB.



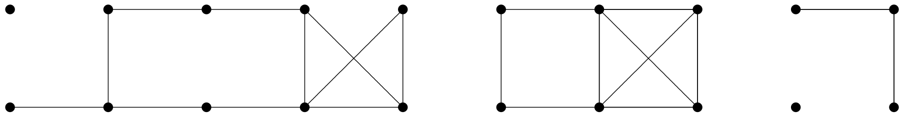
(c) Graph of Figure 3.6b where the direction was removed, by selecting the arc with the lowest SINR, to become an edge.

Fig. 3.6: Illustration of how a femtocell interference scenario can be abstracted to a graph.

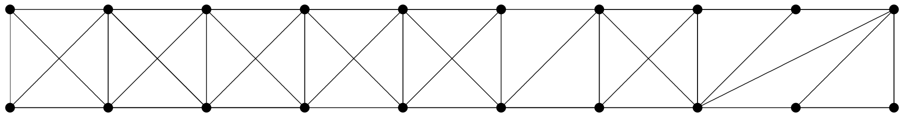
share of channels for each femtocell in each clique whenever possible. Therefore, the highest cardinality among the maximal cliques is an interesting figure for analysis. This metric is shown in Figure 3.9 for the investigated scenario, where the threshold to have an edge on the graph was set to 12 dB SINR. This value was chosen because it is roughly the SINR where half the maximum capacity is achieved (Figure 3.2). As expected, as the deployment ratio increases the distribution shifts towards having more maximal clique sizes of larger cardinality. Nonetheless, even at very high deployment ratio , the vast majority of interference conflicts can be locally solved by dividing the spectrum into 2 or 3 parts. What about the very few cliques of size 4 and 5? Are they always a concern? While it is true that more interference can be avoided by going to such larger reuses, this is not necessarily a desirable goal.



(a) Edges of the graph of Figure 3.6c where SINR is below 5 dB.



(b) Edges of the graph of Figure 3.6c where SINR is below 15 dB.



(c) Edges of the graph of Figure 3.6c where SINR is below 25 dB.

Fig. 3.7: The weights of the graph of Figure 3.6c can be removed by applying a SINR threshold. The density of the resulting graph depends heavily on such a threshold.

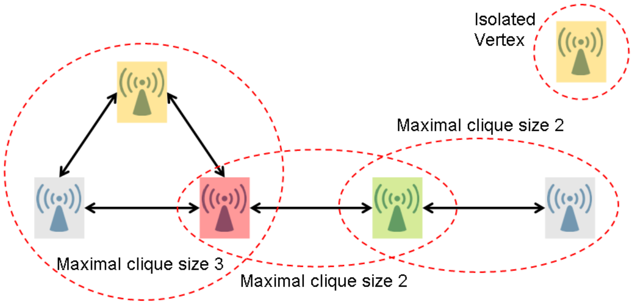
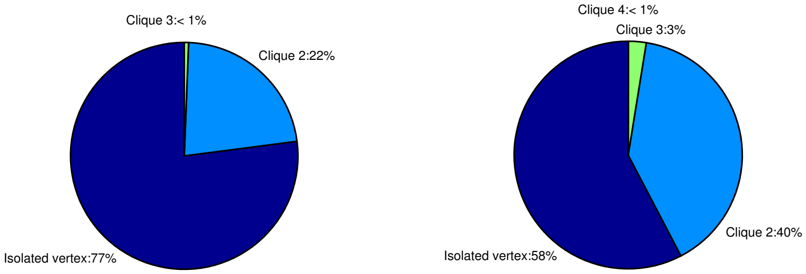
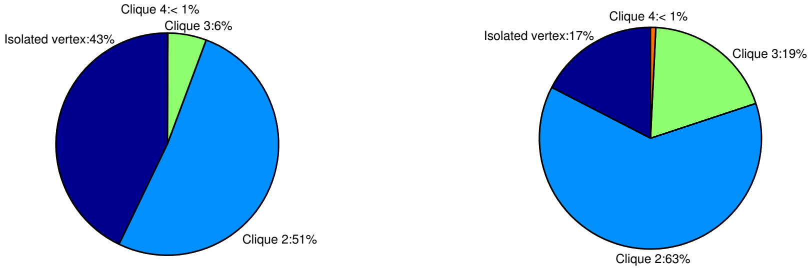


Fig. 3.8: Example of graph showing co-tier symmetric interference relationships. The presence of an edge between a pair of femtocells indicates a relevant interference coupling.



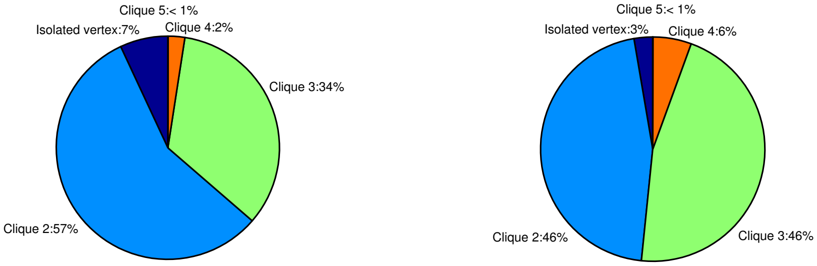
(a) Deployment ratio of 8.3% (10 networks over 120 apartments)

(b) Deployment ratio of 16.6% (20 networks over 120 apartments)



(c) Deployment ratio of 25% (30 networks over 120 apartments)

(d) Deployment ratio of 50% (60 networks over 120 apartments)



(e) Deployment ratio of 75% (90 networks over 120 apartments)

(f) Deployment ratio of 100% (all 120 apartments have a network)

Fig. 3.9: These graphs show the distribution for the following metric: for each femtocell the maximal cliques are analyzed. Then, the maximal clique with highest cardinality for that femtocell is taken as a sample. Isolated vertices are also included. Each graph corresponds to one of the different deployment ratios.

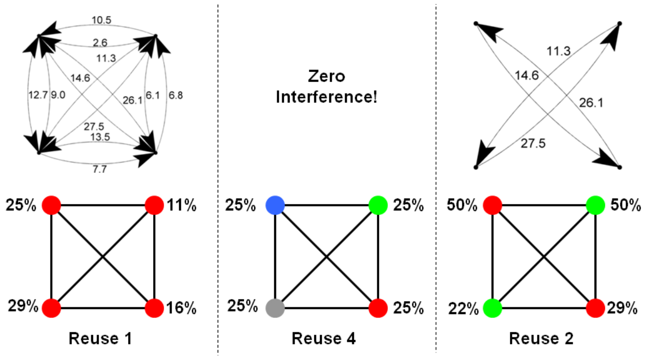
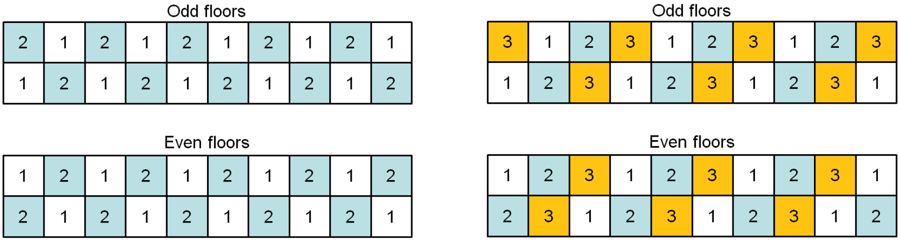


Fig. 3.10: Example of interference scenario with 4 femtocells. The interference can be fully mitigated by a completely orthogonal allocation (reuse 4), but a partially orthogonal allocation (reuse 2) may lead to higher average throughput.

The trade-off between mitigating all interference or not in larger cliques is easier to understand with an example. In Figure 3.10, the clique of size 4 from Figure 3.6b was isolated from the rest of the network. Then, Figure 3.10 shows the throughput achieved and the residual interference for reuse 1, 2 and 4. In the reuse 1 configuration, all the conflicts translate into summed interference. It can be seen that by mitigating all interference, all femtocells can achieve 25% of the maximum system throughput since they can use 1/4 of the channels at large SNR. This is actually a loss for one of the cells. In reuse 2, most interference is mitigated, but there is still residual interference between some links. The worst case throughput is reduced compared to reuse 4. However, in this scenario, reuse 2 provides a substantial increase of average throughput compared to reuse 4 configuration, because all cells have access to double of the bandwidth. Noticeably, the lower left cell loses even more capacity compared to reuse 1 and reuse 4. Assuming the default game theoretic behavior, and each cell maximizing its own capacity, such cell would never accept such type of reuse 2 solution. From an engineering point of view, however, reuse 2 is an attractive solution to the problem in Figure 3.10.

3.7 Baseline Results

The evaluation of performance using system-level simulations needs baseline results for comparison. Two channel assignment methods were chosen as baseline results:



Odd floors

2	1	2	1	2	1	2	1	2	1
1	2	1	2	1	2	1	2	1	2

Even floors

1	2	1	2	1	2	1	2	1	2
2	1	2	1	2	1	2	1	2	1

(a) Frequency plan for reuse 2.

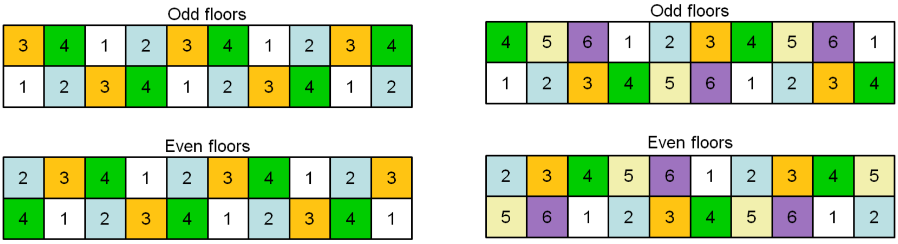
Odd floors

3	1	2	3	1	2	3	1	2	3
1	2	3	1	2	3	1	2	3	1

Even floors

1	2	3	1	2	3	1	2	3	1
2	3	1	2	3	1	2	3	1	2

(b) Frequency plan for reuse 3.



Odd floors

3	4	1	2	3	4	1	2	3	4
1	2	3	4	1	2	3	4	1	2

Even floors

2	3	4	1	2	3	4	1	2	3
4	1	2	3	4	1	2	3	4	1

(c) Frequency plan for reuse 4.

Odd floors

4	5	6	1	2	3	4	5	6	1
1	2	3	4	5	6	1	2	3	4

Even floors

2	3	4	5	6	1	2	3	4	5
5	6	1	2	3	4	5	6	1	2

(d) Frequency plan for reuse 6.

Fig. 3.11: Fixed frequency reuse plans used for baseline results

- FCA approaches, where each femtocell is statically assigned a set of frequency channels.
- The DSA method proposed in [50], which provides fixed frequency reuses but dynamic channel allocation.

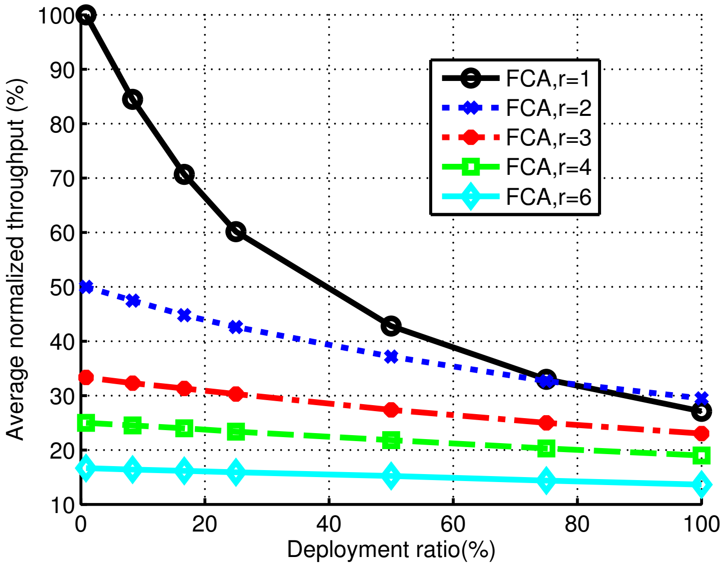
The static frequency plans are illustrated in Figure 3.11. Five reuse configurations were planned: reuses 1, 2, 3, 4 and 6. Since 12 channels are used, these configurations assign, respectively, 12, 6, 4, 3 and 2 channels to each femtocell. These frequency plans attempt to maximize the co-channel reuse distance within a floor, while displacing the floor planning in order to avoid co-channel deployment of apartments above or below the other apartment. Notice that these frequency plans are based solely on the apartment geometry, not on the actual location of FAPs and UEs, due to uncoordinated deployment. The exact locations of the wireless nodes vary in each simulation drop.

Figure 3.12a shows the normalized average cell throughput for the different frequency reuses of Figure 3.11. As the deployment ratio is increased, the average throughput is degraded due to increased interference as expected. However, the dominant factor to average throughput is the availability of more bandwidth. Only when the deployment becomes very dense, the interference is so destructive that the average throughput of reuse 2 is larger than the average throughput of reuse 1.

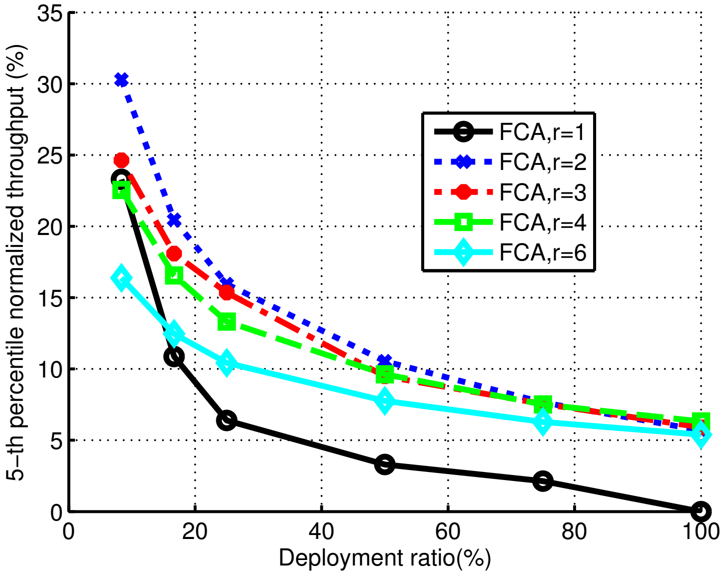
If average throughput was the only KPI of interest, the results of Figure 3.12a would make a strong case for a *laissez-faire* approach where each femtocell would simply allocate the whole band and use it as it wishes. Nevertheless, one has to think of each femtocell as a provided service, which needs a minimum quality even during congestion. As shown in Figure 3.12b, reuse 1 fails to provide a minimum throughput for more than 5% of the cells at a 100% deployment ratio. Even at low deployment ratios, the performance of reuse 1, in terms of 5^{th}-percentile of throughput, is significantly lower than other reuses. If the quality requirements are very stringent, reuse 1 performance has to be deemed unacceptable in any case. As little as 25% deployment ratio is enough to leave more than 1% of the cells in complete outage (zero throughput). One operator serving 25% of the apartments in a building is easy to conceive even if it has to compete with other operators for customers in that building.

The users whose networks have low performance are the ones complaining, returning products and switching to other operators. Therefore, attaining a minimal quality in each cell may be even more important than an overall high average throughput. Consequently, in the studied scenario, reuse 1 would be an unacceptable deployment strategy, whereas reuse 2 would be of significantly superior overall performance. However, as it will be seen throughout this thesis, DSA can do even better while avoiding the need for frequency planning at all. Even when the deployment is very dense, if only a few cells are active the effect is the same as having a low deployment ratio and some cells may be fairly isolated from other cells. Therefore, the ideal solutions will use all the channels whenever possible and switch to sparser reuses when needed, dynamically selecting the amount of used channels.

The DSA method described in [50] attempts to minimize interference for a given reuse configuration. Hereafter, this method is referred as Distributed Inter-cell Interference Coordination (D-ICIC), the title of the original paper. D-ICIC assumes that each cell demands a specific amount of resources. In these simulations, the demanded amount of channels m is the same for all cells. D-ICIC is summarized in algorithm 1. The implementation chosen here is a probabilistic version of the best-reply dynamics [50, 75]. Each femtocell updates its channel allocation autonomously according to a given probability ϵ, which was set to 50%. If the femtocell decides to update its allocation, then it selects the least interfered channels. This process is guaranteed to converge if the interference is symmetric between each pair of femtocells. The convergence without symmetry is discussed in section 4.2.



(a) Average throughput.



(b) 5$^{\text{th}}$ percentile of throughput.

Fig. 3.12: Achieved throughput by FCA approaches in different deployment ratios. These approaches provide fixed frequency reuses (indicated by 'r') with static channel allocation.

Algorithm 1 Distributed Inter-cell Interference Coordination (D-ICIC)
Parameter - Target frequency reuse r

```
# Some constants are assumed to be given.
# $K$ is the total number of channels (e.g. 12).
# $\epsilon$ is the status quo review probability.
$m \leftarrow K/r$                     # m is the target number of channels.
for each radio frame do
    $v \leftarrow U(0,1)$              # Sample a random number between [0,1].
    # With probability $\epsilon$
    if $v < \epsilon$ then
        Update interference measurements per channel.
        Order the channels in terms of increasing interference.
        Select the $m$ least interfered channels.
    end if
end for
```

D-ICIC can be used to define a target frequency reuse r, while using a dynamic channel allocation. The reuse is defined as the total number of channels on the band, 12, divided by the amount of demanded channels, m. In Figure 3.13a, D-ICIC is compared to the FCA approaches illustrated in Figure 3.11. This comparison provides an overview of fixed versus dynamic channel allocation in the studied scenario.

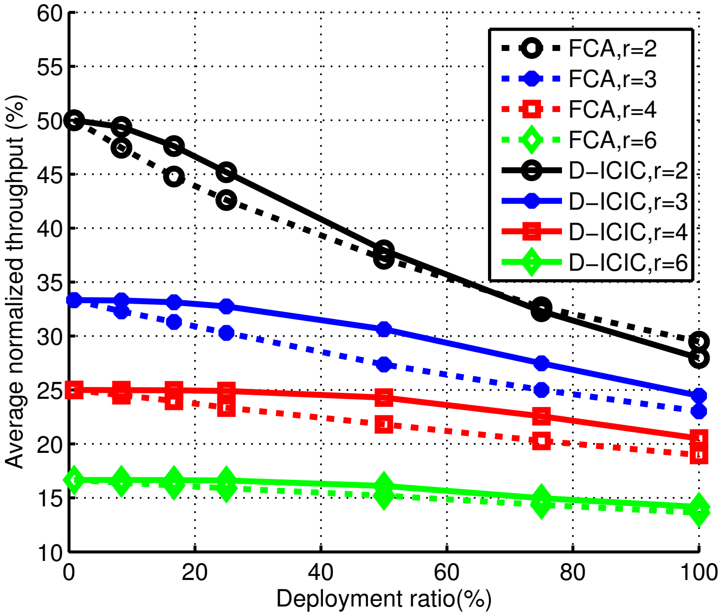
In a reuse $r = 2$ configuration, there is no clear winner in terms of average throughput between D-ICIC and the frequency plan in Figure 3.11a. At low deployment ratios, the dynamic channel allocation easily beats the fixed one. This is because in the fixed assignments different channels are allocated only in apartments which are adjacent. If for example, in the scenario of Figure 3.11a only the apartments with frequency plan 2 are active, then the fixed plan will be wasting half the resources. On the contrary, if the configuration is done dynamically, based on measurements, all resources can be put into use, and the interference can be minimized. On the other hand, when the deployment ratio reaches 100%, D-ICIC does not achieve the regular checkerboard pattern of Figure 3.11a, which has the advantage of avoiding co-channel deployment to any adjacent apartment. Instead, in D-ICIC, with $r = 2$, each femtocell tends to fend off its worst interferer, regardless of the remaining interferers, because the strongest interferer often dominates the total interference effect. This distributed process may reach deadlock situations where the configuration of adjacent cells is still co-channel, especially considering that the underlying conflict graph is not 2-colorable.

When the reuse is more sparse, the use of DCA is clearly superior to FCA for any deployment ratio. With more degrees of freedom, the final allocation becomes closer to a proper coloring and more than one interferer can easily be avoided. Another aspect which allows dynamic reuses 3, 4 and 6 to overperform their FCA counterparts is the floor to floor interaction. In the fixed reuses of Figure 3.11a, one apartment located exactly two floors above or below the other apartment is assigned a co-channel set. According to the model of equation (3.13), these apartments have at least 21 dB extra isolation due to floor to floor loss, on top of free space propagation loss. Despite of this isolation, depending on the relative locations of UEs and FAPs as well as the shadow fading of each link, the resulting interference coupling can still be rather significant in some cases.

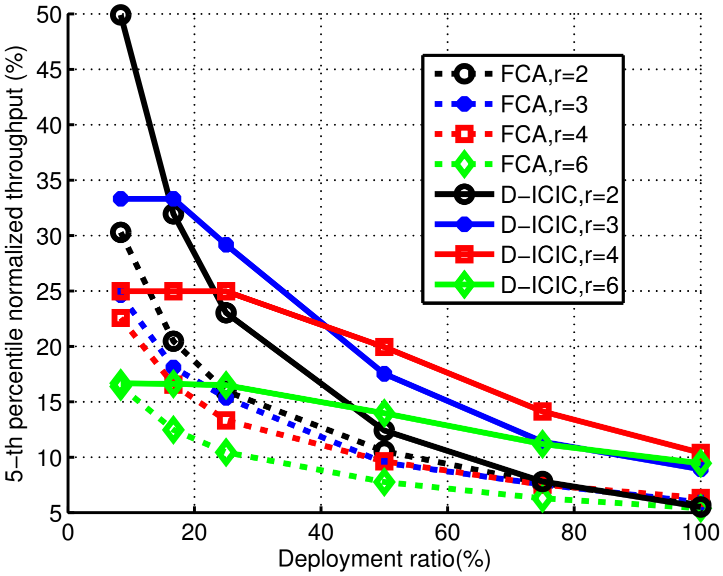
Figure 3.13b shows the 5^{th}-percentile of cell throughput D-ICIC. Here, one can see a different trend than in FCA. The dynamic reuses 3 and 4 are able to achieve significantly higher outage throughput than dynamic reuse 2 in high deployment ratios. Furthermore, one can conclude that the optimal frequency reuse in terms of outage is dependent on the deployment ratio. These results are in line with the analysis of cliques in the interference graph made in section 3.6. As an example, in Figure 3.9c it was shown that circa 6% of the cells are part of maximal cliques of size 3 at a 25% deployment ratio. And in fact, in 3.13b, D-ICIC with reuse 3 surpasses the outage throughput or D-ICIC with reuse 2. Note that in general, in terms of 5^{th}-percentile throughput D-ICIC is significantly superior to FCA. The exception is once again, a reuse 2 configuration for the same reasons explained above.

Since any number of target channels can be defined for D-ICIC, the method can also be used to generate non-integer reuses. Figure 3.14 depicts simulation results for several D-ICIC configurations with m channels demanded in each cell. Recap that $m = 6$ is a reuse 2 configuration and $m = 12$ is a reuse 1 deployment. Thus, the other curves in Figure 3.14 represent non-integer reuses between 1 and 2 with effective reuse $12/m$. These configurations essentially follow similar trends as reuses 1 and 2, while achieving intermediate trade-offs of 5^{th}-percentile and average throughput.

In light of the analyses of this section, the following methods have been chosen as a baseline for the remainder of the thesis: D-ICIC with reuses 2, 3 and 4, and FCA with reuse 1 and 2.



(a) Average throughput.



(b) 5^{th} percentile of throughput.

Fig. 3.13: Performance comparison between fixed and dynamic channel allocation (D-ICIC method) for different fixed reuses and deployment ratios.

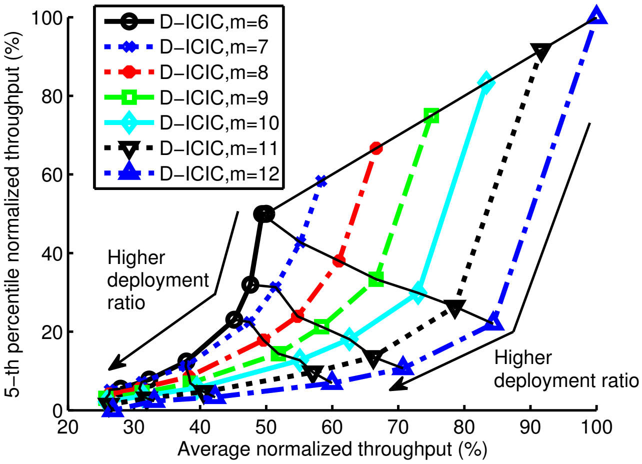


Fig. 3.14: Plot showing the trade-off of 5^{th}-percentile and average throughput for several D-ICIC configurations. The thin lines join the points with the same deployment ratio, helping to show the trend in sparse and dense networks.

3.8 Conclusions

This chapter provided a deep analysis of the investigated problem from different angles. First, from a single link perspective the potential gains were shown to be highly dependent on the relation between desired signal received power and the sum received power of interference signals. From such an analysis, it can be expected that some links can highly benefit from interference coordination while other links may experience some capacity losses.

Second, by using a game theoretic framework the problem was shown to have different characteristics depending on the SINR levels. Still, in most cases reuse 1 is Nash Equilibrium (NE) under certain assumptions. Reuse 1 may be Pareto dominated by other solutions, e.g. orthogonal allocation, but without signaling the players have the incentives, but not the knowledge, to decide the best allocation. Furthermore, asymmetric interference relations make the definition of desired allocation quite blurry. In the most extreme case one transmitter may be blocking the receiver from another link without even knowing about it. This is clearly a situation which is not desirable from an engineering point of view.

Then, graph theory was applied to provide a larger picture characterization of the problem in a dense scenario with up to 120 femtocells in one building.

From such an analysis it can be concluded that interference coordination is needed and it becomes more important as the deployment density is increased. Additionally, the analysis show that most of interference can be locally mitigated by coordinating the spectrum access with a few neighbor femtocells. The goal of such coordination should not be plainly to minimize interference. Actually, it can be counterproductive to excessively orthogonalize the allocation. The interference should only be mitigated as much as needed. Across the scenario different frequency reuses can be attained and reuses 1, 2, 3 and 4 should suffice in most of the cases.

Simulation results corroborate the findings of the previous analyses. The outage performance of a reuse 1 approach is unacceptable, even though the average performance is quite high. Sparser frequency reuses can largely improve the outage performance due to increased SINR, but they may also hinder the average performance. In the simulated scenario, reuse 6 was found to be inferior to reuse 4 in both KPIs which is in accordance to the aforementioned graph theoretic analysis.

Interestingly, in the investigated femtocell scenario, the logic of frequency planning is not only broken by massive deployment, but also by uncoordinated deployment. Massive deployment implies that the costs of doing frequency planning for each cell are prohibitive. In addition to that, uncoordinated deployment implies that the position of the FAP is not known. For this reason, some Fixed Channel Allocation (FCA) schemes which assign a frequency plan to each apartment were evaluated. They can still perform better than reuse 1, but the lack of FAP position information shows its toll when the performance is compared to other alternatives. A state of art method (D-ICIC [50]) which provides a fixed frequency reuse, but Dynamic Channel Allocation (DCA) provided a superior performance over the FCA approaches in most of the cases. These results will serve as baseline results to be compared with throughout the thesis. In conclusion, in an uncoordinated deployment it is better to have the channels selected dynamically rather than statically, because then the real interference information can be used in the decision making process. Such results motivate further investigations which lead to the dynamic selection of both the reuse and the operating channels.

CHAPTER 4

Timeout Based Reuse Selection

4.1 Introduction

The analysis in section 3.6 showed that the number of channels a particular femtocell should allocate is related to the maximal cliques which have that femtocell as a member. As a part of that analysis, the statistic depicted in Figure 3.9 motivates adapting among small integer reuses such as 1, 2, 3 and 4 to locally optimize the channel allocation. In addition to that, the baseline simulation results provided in section 3.7 corroborated such an analysis. These findings motivate us to define a method which not only avoids interference, but also adapts the amount of selected channels according to the interference conditions. This is the approach taken in this chapter, which has been named Timeout Based Reuse Selection (TBRS).

TBRS is built upon IA mechanisms. In general, IA refers to the selection of different waveforms to be used by transmitters, so that one or more receivers can avoid the effects of interference as much as possible. The term IA is often used in both intra-cell and inter-cell contexts corresponding to a single receiver or multiple receivers, respectively. Hereafter, the term IA implicitly means inter-cell IA.

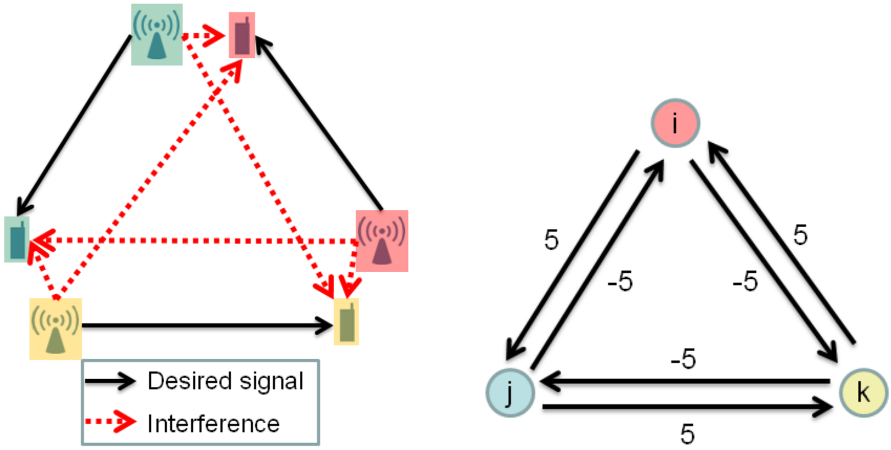
IA has been largely investigated in the literature. The basic idea behind IA can be described very simply as: select the least interfered channels according to some update dynamics. As one example, D-ICIC [50] was already introduced in algorithm 1 (section 3.7). Essentially, TBRS uses the same approach as D-ICIC, selecting the least interfered channels with probabilistic updates. But, in addition to that, TBRS attempts to figure out *how many* channels should be allocated. Motivated by the graph theoretic analysis done in section 3.6, TBRS tries to discover the densest frequency reuse which can be used locally. As previously discussed, the feasible frequency reuse is conceptually related to the largest maximal clique which contains the femtocell. This relation will be later shown in one TBRS example.

The remainder of this chapter is organized as follows. Section 4.2 takes a closer look into the issues which can arise when doing independent IA adaptations. The section discusses one example from the literature, and further insight is provided, especially for the case where interference is not symmetric. TBRS is introduced in section 4.3. In section 4.4, the method is evaluated through system-level simulations. Then in section 4.5, the effect of having symmetric interference information is investigated and discussed. The chapter is finalized with conclusions in section 4.6.

4.2 Interference Avoidance Issues

Since TBRS is built upon IA, it is important to understand some of the challenges in the design of distributed IA methods. Intuitively, each femtocell should select the resources which are least interfered in order to maximize its own capacity. That is the rationale behind many IA algorithms. In one way or another, selecting the resources with lowest interference, or highest SINR, has been proposed by a number of authors, e.g. [49, 50, 63, 64]. Nevertheless, greedy adaptations based on interference or SINR do not necessarily converge. The following example is due to [49]. Three links interfere with each other as shown in Figure 4.1a. Each receiver is the victim of a near interferer and a far interferer. This problem can be described in terms of a SIR graph as in Figure 4.1b. In general, greedy adaptations attempt to mitigate the strongest interferer first, and only if possible other interferers are avoided. Figure 4.1b shows one potential trait of IA when only incoming interference is used for a decision: each player is mostly influenced by one player but harms another player the most.

Figure 4.2 shows how this cycle of influence from Figure 4.1 may lead to infinite looping. In Figure 4.2 the situation of desired and interference signals



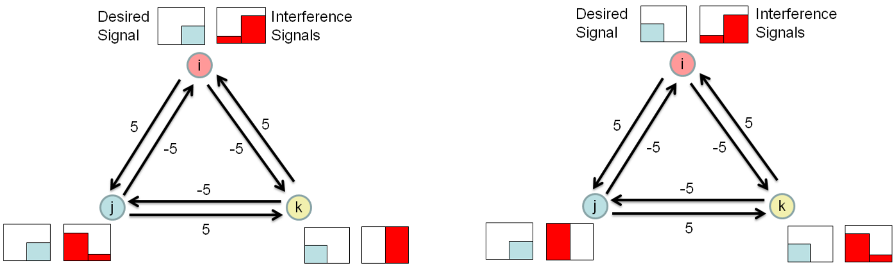
(a) The scenario conceptually.

(b) Scenario abstracted as a graph with SIR in dB as arcs.

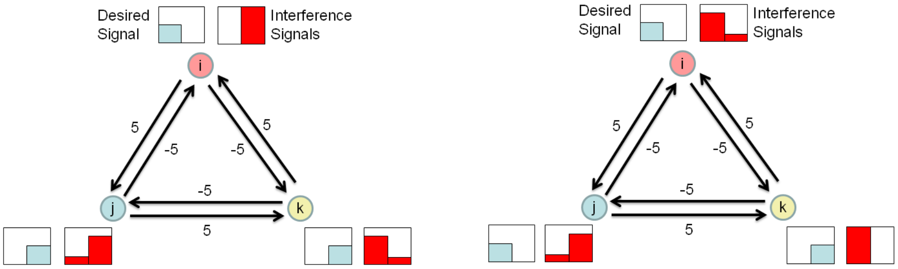
Fig. 4.1: Interference scenario described in [49]

is illustrated as seen in each receiver. Let us assume that each player only wants to allocate one channel and only two channels are available. In Figure 4.2a player i and player j are sharing the same resource (channel 2). Player i can increase its own SINR by switching to channel 1, leading to the situation in Figure 4.2b. But now, player k is the one experiencing a lot of interference while the other channel seems much less occupied. Thus, player k switches to channel 2, and after this adaptation the allocation becomes the one shown in Figure 4.2c. At this moment the burden of strong interference is on player j, and the logical decision is to move to channel 1. When the change is executed the interference scenario is as illustrated in Figure 4.2d. Comparing Figure 4.2a to Figure 4.2d, it can be concluded that the network only exchanged the allocation of channel 1 for the allocation of channel 2, a fruitless adaptation if both channels can be considered to have the same statistics on average. Since the first and last state are equivalent, such a sequence of steps characterize a loop and the adaptation process is expected to go on forever.

The effect of such non-convergence depends on the price of the adaptations needed to switch a channel, compared to the operation in low SINR. Notice that in all states in Figure 4.2 exactly one network is free of interference, one network is experiencing moderate interference, and the other is under fierce interference. So, in some sense the loop is akin to a token passed from one network to the next on the ring, changing the role of each network. Consequently, if switching channel is a cheap operation, the loop could be seen as a solution to having only two channels shared among three networks, instead of a problem. On the



(a) Player i is highly interfered. (b) Player k is highly interfered.



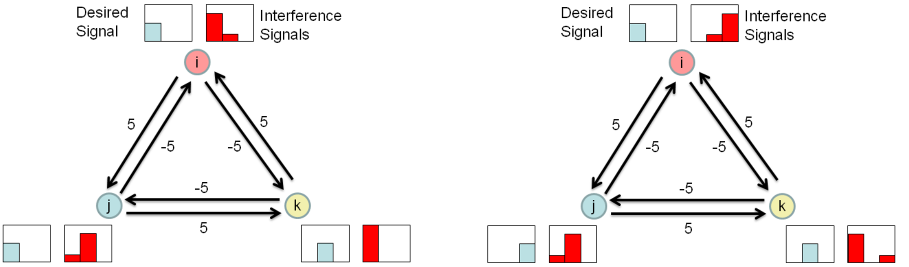
(c) Player j is highly interfered. (d) Player i is highly interfered again.

Fig. 4.2: Example where greedy SINR adaptation leads to an infinite loop ([49]). Note how the allocation in Figure 4.2d is exactly the allocation of Figure 4.2a mirrored.

other hand, if frequent channel changes have a high price, like making handover procedures for each UE, such loops should be avoided.

There are two key defining features on this non-convergence example from Figure 4.2. First, there are only 2 resources, while a proper solution would require at least 3 resources in order to effectively mitigate interference. This observation is particularly true if the interference level is high enough to avoid communication completely. Then, it is not only a matter of optimization of resources, but also a matter of enabling communication. If one considers this problem as a graph coloring problem, the issue is trying to color a graph that needs 3 colors with only two. Greedy graph coloring algorithms need to be able to add more colors to cope with such situations.

The second aspect of the non-convergence example is which femtocell has influence on the decision of other femtocells. Quite often in wireless links, most of the interference effect comes from only one or few other links.



(a) Player i is highly interfered. Player j is slightly interfered.

(b) Stable solution. All links are interference free.

Fig. 4.3: Similar to the example of Figure 4.2, but 3 channels are available. Convergence is easily achieved.

Therefore, the adaptations are essentially defined by these strong interferers, i.e., the influence of weak interferers on decisions is minimal and in some cases negligible. For example, if one of the interferers alone generates more interference than all the remaining ones, then making an orthogonal allocation towards the strongest interferer is a sensible choice regardless of the remaining interference. Of course, if a femtocell has enough degrees of freedom it would like to have an orthogonal allocation also towards other interferers. Therefore, the situation can change dramatically when there are enough choices for each femtocell. Figure 4.3 illustrates the previous example with the only difference that 3 channels are available. In this case there are no convergence issues. If either player i or player j selects the least interfered resource in the situation of Figure 4.3a, the new situation is like in Figure 4.3b. This example does not rule out the possibility of loops with more degrees of freedom. Instead, it serves to emphasize that a distributed IA process should not attempt to solve a problem which has no feasible solution, like coloring a graph with 2 colors if it is not 2-colorable. In order to avoid fruitless adaptations, some more extreme measures can be taken. For example, after a number of IA steps the allocation can be halted for some time.

The danger of looping can, in theory, be eliminated by considering symmetric interference information. In particular, [50] shows that under *symmetric* interference and considering a *fixed* amount of channels the process where each cell greedily selects the least interfered resources characterizes a potential game. In such a type of game, the sum of interference over all links is minimized in the Nash Equilibrium (NE). Furthermore the application of a distributed update process, such as best-reply dynamics [75] or better-reply dynamics[75] converges to the NE. Similarly, symmetry of the interference information is the key to define exact potential games in [49, 48].

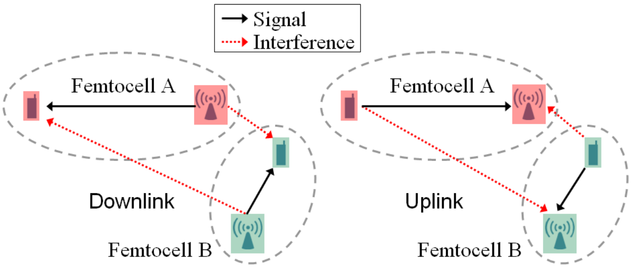


Fig. 4.4: Illustration of interference and signal paths in duplexed systems. Strong interference coupling is sensed by femtocell A in uplink and by femtocell B in downlink.

Unfortunately, symmetry of information may require exchange of signaling messages. However, using correlated information can be done without resorting to inter-cell signaling, as discussed next.

In infra-structured networks there is, typically, a full separation of the two link directions, uplink and downlink, as in a FDD system or a synchronized TDD system. In such cases, the spatial footprint of interference can be analyzed separately. This situation is illustrated in Figure 4.4, where signal and interference paths are shown for both uplink and downlink. In the example of Figure 4.4 femtocell B experiences high downlink interference from femtocell A, whereas the effect of femtocell B transmission on femtocell A is weak. In uplink, the role of victim and interferer is exchanged: femtocell A is the one experiencing high interference. This coupling comes from the close proximity of the FAP in femtocell A to the UE in femtocell B. In Open Subscriber Group (OSG) femtocells the problem is partially mitigated, as both UEs of Figure 4.4 could be served by the FAP of femtocell A, whereas the FAP of femtocell B could serve other users in more favorable geometries. In CSG femtocells, however, the UEs may be forced to operate in such unfavorable conditions.

The example of Figure 4.4 motivates us to use both downlink and uplink interference information in order to take spectrum decisions, because the worst case interference between a pair of cells will be correlated. In fact, if FAPs and UEs use similar transmit powers, the worst case interference will be nearly symmetric, especially in a TDD case. However, if power control is applied only in one link direction (e.g. uplink), such approach may not be feasible. In section 4.5 simulation results compare the throughput when only downlink interference information is used for decisions or when both uplink and downlink information are taken into account.

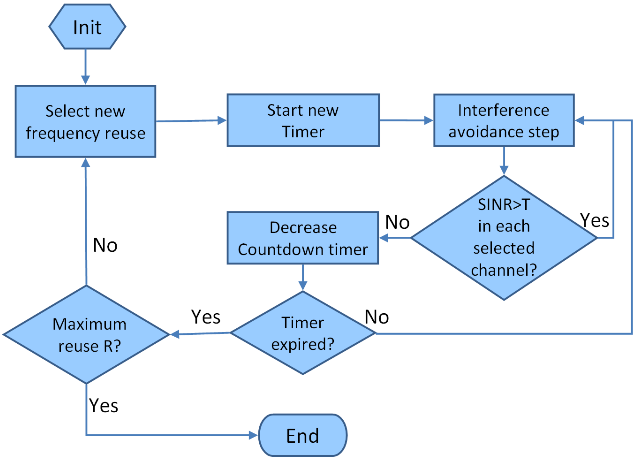


Fig. 4.5: Algorithm running on each femtocell to determine the densest reuse it can support. R is the sparsest allowed reuse. T is a SINR threshold.

4.3 Reuse Selection

TBRS is a distributed approach that tries to discover which is the densest frequency reuse possible in a particular area, as shown in Figure 4.5. Starting from a particular frequency reuse each femtocell attempts several steps for interference minimization, i.e. IA steps. As previously illustrated in the example of Figure 4.2 such steps may loop, or even at a stable situation the interference may be unbearable. If either situation is detected, each femtocell reduces the number of allocated resources. In essence by making such a reduction, the femtocells try to make the solution to the IA problem feasible, as exemplified by contrasting the examples of Figure 4.2 and Figure 4.3.

The number of IA steps which a femtocell attempts before changing the target reuse is controlled by a timer. Since a fully distributed operation is assumed, each femtocell has its own timer, and the effective reuse is flexible. For example, this timer can be a deadline to mitigate interference or a countdown timer. The latter approach is taken. Every time the SINR is detected to be below the threshold T in at least one used channel, the countdown timer is decreased, otherwise it remains halted. If the countdown timer expires and interference is not mitigated yet a sparser reuse is attempted. Hence, this approach is named Timeout Based Reuse Selection (TBRS). Note that such countdown timer procedure can detect a loop situation like the one in Figure 4.2.

Now the selection of the feasible frequency reuse is described. If the band is

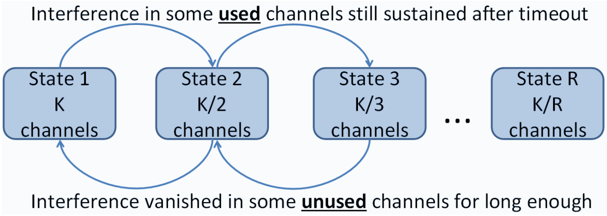


Fig. 4.6: TBRS as a finite state machine. Each state define a corresponding local reuse/amount of allocated channels. When there is interference in some used channels TBRS attempts to make reuse more sparse. TBRS falls back a state if interference in unused channels vanish for long enough.

divided into K channels, then one can define reuse r as: each femtocell has the right to allocate K/r channels, and the allocation of femtocells with considerable interference coupling is kept as orthogonal as possible. Such a definition allows for non-exact division K/r, but non-exact division may not be desirable. For example, consider a case where 5 channels have to be distributed amongst two femtocells with a strong interference coupling. Since they interfere with each other, if one strives for spectral efficiency, one would prefer an orthogonal allocation, i.e., $1 : 4$ or $2 : 3$ share of the channels which leave no possibility for fairness. If fairness is to be attained, one would consider $2 : 2$ or $3 : 3$ shares which are inefficient because one channel is either wasted or heavily interfered. Therefore, the division of a band into a number of channels which is exactly divisible by small integers is preferred and advisable. For example, with $K = 6$ channels, one can perfectly define reuses 1, 2 and 3. For $K = 12$ channels, then reuse 4 can also be perfectly defined.

The selection of the frequency reuse can be seen as a state machine composed with R states, where R is the maximum frequency reuse to be supported. This concept is illustrated in Figure 4.6. If one sticks only to integer reuses, the state machine has only a few states where the reuse of resources is pre-defined for each state: $K/1$, $K/2$, $K/3$ and so on. Notice that the state directly corresponds to the reuse a particular femtocell is attempting, i.e., in general reuse r is attempted in state r.

The feasibility of a particular reuse is tested by verifying the existence of severe interference or, conversely, a low SINR. When the interference is *sustained* the countdown timer expires, then the femtocell moves onto the next state. Figure 4.5 corresponds to traversing the states in Figure 4.6 from left to right, i.e., from a denser to a sparser reuse. Similarly, if low interference is sustained long enough, then the algorithm may fall back to a denser reuse as shown in Figure 4.6. This can be implemented by a second timer which ticks when low interference is detected on channels which are not currently use. The complete method is described in algorithm 2. In such implementation the same timer is used to tick in both directions. For example, if the *timeout* is set to 20 frames and the counter reaches 0 the femtocell will move to a sparser reuse. If the counter reaches 40 the femtocell will fall back one state to a denser reuse. Note that the IA part of algorithm 2 is essentially the same as in algorithm 1(D-ICIC, section 3.7).

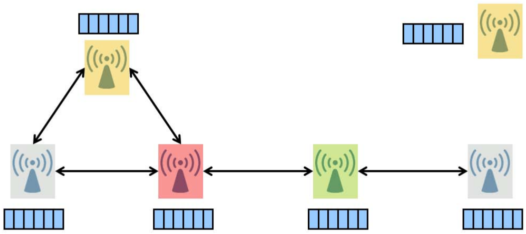
In every change to a sparser reuse, a femtocell will reduce its own total bandwidth without any immediate change to its own perceived interference level. The interesting effect is what the femtocells can achieve collectively when all of them are mitigating the interference to each other. Such interference mitigation effect is better understood by an example. Figure 4.7 revisits the scenario of Figure 3.8 applying TBRS in each femtocell. In Figure 4.7a all the femtocells are initialized to be on state 1. The bi-directional arrows illustrate strong mutual interference coupling. Therefore, femtocells sharing an arrow fiercely interfere with each other if they allocate the same channels. This is definitely the case on a reuse 1 approach and the femtocells start to sense a low SINR. Each femtocell starts a timer. After the timeout, if the SINR is still low, in any used channel, then the femtocell moves onto the next state.

When entering a new state a femtocell will reduce the number of channels it has allocated and restart the timer. When moving from state 1 to state 2 the femtocell has to discard half of the channels. The discarded channels are the ones with lowest SINR. Now, the inner loop of the algorithm, i.e. interference avoidance, starts to work again in order to make the allocations as orthogonal as possible.

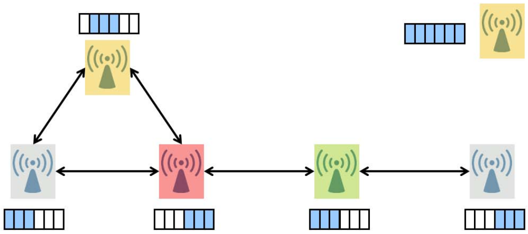
After the convergence, the situation shown in Figure 4.7b is achieved. Notice that the isolated femtocell never advanced to state 2 (because it never detected a low SINR in a used channel). The other cells moved onto state 2, and now there is much less interference compared to Figure 4.7a. Interference only remains on some channels of the leftmost cluster of 3 cells. After a new timeout, this interference triggers a change to state 3, only in those cells. Then the interference avoidance process takes care of making the allocation orthogonal. Finally, interference is mitigated and each femtocell gets a fair share of resources in an efficient way. The final allocation in the example is shown in Figure 4.7c. Such a distribution of resources is efficient and fair.

Algorithm 2 Timeout Based Reuse Selection (TBRS)
Parameters - SINR threshold T and maximum stage R

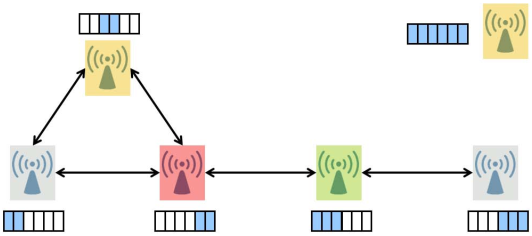
```
# Some constants are assumed to be given.
# $K$ is the total number of channels (e.g. 12).
# timeout - number of frames to expire the timer.
# $\epsilon$ is the status quo review probability.
$n \leftarrow K$                      # n is the current amount of channels.
$r \leftarrow 1$                      # r is the current stage.
$c \leftarrow timeout$                # c is the countdown/countup timer.
for each radio frame do
    Update SINR measurements per channel.
    if any allocated channel has $SINR < T$ then
        $c \leftarrow c - 1$
    else if $r > 1$ then
        if $K/(r-1) - n$ non allocated channels have $SINR > T$ then
            $c \leftarrow c + 1$
        end if
    end if
    if $c = 0$ then
        if $r < R$ then
            $r \leftarrow r + 1$          # Sustained interference. Use sparser reuse.
            $n \leftarrow K/r$
            $c \leftarrow timeout$
        end if
    else if $c = 2 * timeout$ then
        if $r > 1$ then
            $r \leftarrow r - 1$          # Interference vanished. Use tighter reuse.
            $n \leftarrow K/r$
            $c \leftarrow timeout$
        end if
    end if
    $v \leftarrow U(0,1)$                 # Sample a random number between [0,1].
    # With probability $\epsilon$
    if $v < \epsilon$ then
        Update interference measurements per channel.
        Order the channels in terms of increasing interference.
        Select the $n$ least interfered channels.

    end if
end for
```



(a) Example: all femtocells start at state 1 (reuse 1).



(b) The isolated cell remains with full resource allocation. All the other femtocells advance to state 2 (reuse 2) as a collective effort to mitigate interference. Note that the 3 femtocells on the left still interfere with each other in some channels.



(c) The cells which have a 3-way interference coupling advance to state 3 (reuse 3). The remaining cells can keep their larger bandwidth allocation since the interference was already mitigated.

Fig. 4.7: Example scenario and behavior of the proposed method. The arrows mean strong (mutual) interference coupling.

4.4 Results and Discussions

The results in this section were generated according to the simulation scenario described in section 3.5.

The method was simulated for several combinations of the two algorithm parameters: R, the number of states (maximum reuse) and the SINR threshold T. The maximum reuse R was varied from 2 to 4 and the SINR threshold T was varied for all the values 0, 5, 10, 15, 20 and 25 dB. The notation TBRS(R,T) is used to summarize the results. Several aspects on the parameter dependency will be discussed. The TBRS method is compared to the baseline results: a full resource allocation (reuse 1) and the D-ICIC method [50]. D-ICIC is parametrized by the amount of channels that each femtocell can allocate, or conversely a target frequency reuse. Here, the latter approach is used. Note that these two baseline methods can also be related to TBRS. Reuse 1 can be defined as TBRS(1,T) whereas D-ICIC will provide similar results to TBRS(R,∞). In the results of this section, the measurements are only done on the receiver side, i.e., the threshold is only applied to incoming interference. The next section presents simulation results which show the effects of using measurements from both link directions.

Figure 4.8b shows the 5th percentile of throughput for all combinations of parameters, R and T, for a deployment ratio of 25%. Notice that reuse 1 is included as the baseline, labeled as TBRS(1,T). At low deployment density, the probability that 2 neighbour cells measure the SINR below zero dB is rather small. For this reason, TBRS(R,0) essentially keeps the same allocation as reuse 1. The outage performance trend is quite clear in Figure 4.8b. As the SINR threshold is increased, the outage performance increases because the femtocells start to split the band and self-organize for interference avoidance. At this deployment density, the outage performance depends more on the SINR threshold T than on the maximum reuse R. This can be explained because in most cases splitting the resources by two, and applying IA, will solve nearly all the interference issues.

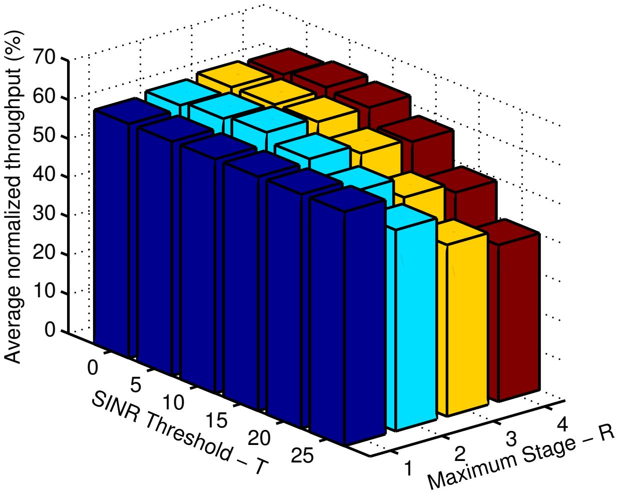
Figure 4.8a shows the average throughput performance for 25% deployment ratio. In general, the high gains on the 5th percentile come at the expense of some of the average performance. Still, the average throughput losses are quite limited up to the threshold of 15 dB SINR. Only for very high thresholds the average performance is significantly penalized, but those are also the configurations which provide the highest gains in terms of the 5th percentile of throughput. Also, notice that some configurations, such as TBRS(2,10), provide gains in both figures (average and outage performance).

When the deployment becomes denser, two effects occur. First, nearly all femtocells start to be affected by other cells. For this reason, most cells will move at least into the second stage. Second, a simple split of the resources by two fails to provide enough interference mitigation. These effects are illustrated in Figure 4.9, which shows TBRS results at 100% deployment ratio using reuse 1 as a baseline. Reuse 1 fails to provide any performance at all for more than 5% of the cells, but now several of these worst case issues are solved even by TBRS(R,0). Also in contrast to the results with 25% deployment ratio, the dependency of outage performance on the maximum stage becomes much clearer. More stages allow to split the resources until interference can mitigated by IA steps. The dependency on the threshold still exists, but it is mostly visible for $R = 3$ and $R = 4$. Instead, if only two stages are allowed, there is not enough room to mitigate interference. This can be related to Figure 3.9f, which showed that at 100% deployment ratio nearly 52% of the cells are part of cliques of size 3 or 4 (for an edge defined by SINR below 12 dB). In terms of average throughput the dependency of TBRS on the two parameters is not very different at 25% or 100% deployment ratio. Very large SINR threshold reduces the average performance, and some intermediate values, around 5-10 dB allow for average performance gains.

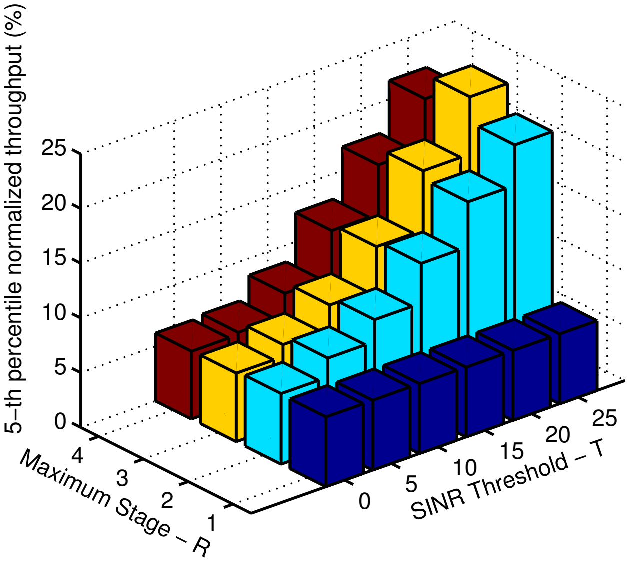
In order to understand the benefit of selecting how many channels can be used instead of pre-fixing the demand, one can compare D-ICIC to TBRS with a high threshold. TBRS(R,∞) always ends up in the maximum reuse R, since SINR is finite (there is always noise above zero absolute). Thus, TBRS(R,∞) would generate the same allocation as D-ICIC with $r = R$. If the SINR threshold was set to be exactly the SNR, then one is striving for zero interference, but achievable SINR. So, as long as the interference is detectable TBRS(R,SNR) would also keep on splitting the band , i.e., moving to the next stage until either reuse R is achieved or all interference can be avoided with a reuse less than R. More interestingly, the comparison of D-ICIC and TBRS(R,25) yields fruitful insights. The average throughput results of such comparison are summarized in Figure 4.10a.

The main drawback of capping the maximum spectrum utilization becomes evident: low average performance at a low deployment ratio. Since D-ICIC assumes a fixed bandwidth utilization, the femtocells cannot exploit opportunistic reuse even if the interference is virtually non-existent. On the other hand, TBRS adapts to such situations by keeping more dense reuses. As the deployment ratio increases TBRS will make the reuse more sparse in order to mitigate interference.

In nearly all deployment ratios, D-ICIC and TBRS(R,T) perform closely in terms of 5th percentile of the distribution, as shown in Figure 4.10b. One exception is actually when a single network is deployed per building, since

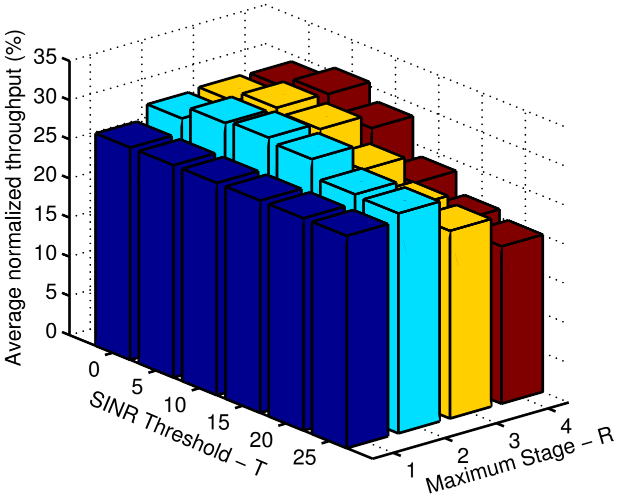


(a) Average throughput.

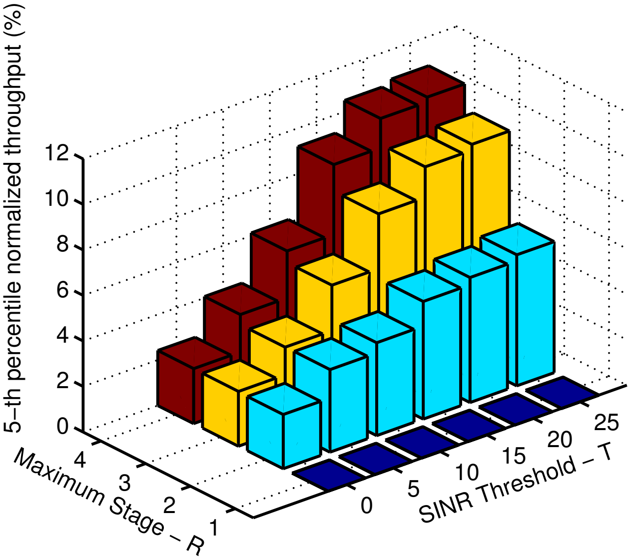


(b) 5^{th} percentile of throughput.

Fig. 4.8: TBRS performance for 25% deployment ratio.

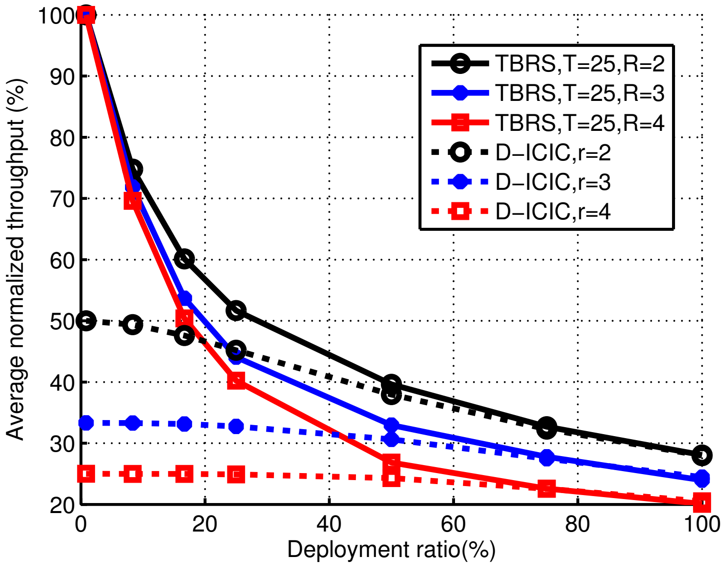


(a) Average throughput.

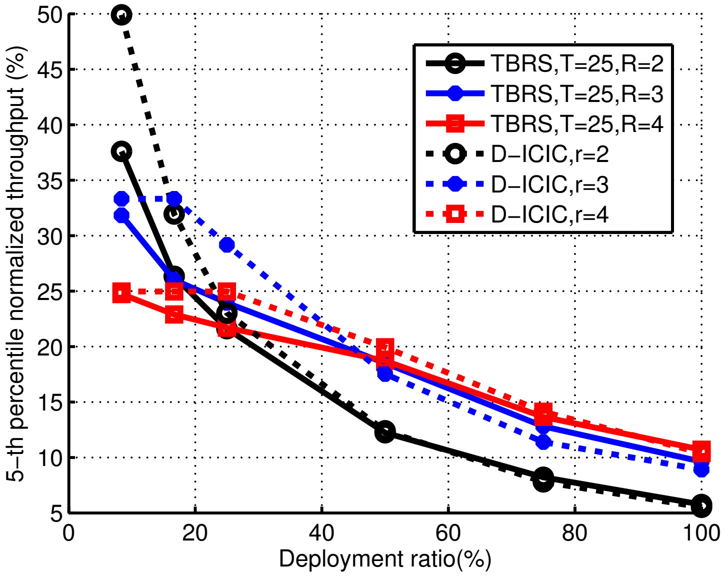


(b) 5^{th} percentile of throughput.

Fig. 4.9: TBRS performance for 100% deployment ratio.



(a) Average throughput.



(b) 5th percentile of throughput.

Fig. 4.10: Comparison of TBRS and D-ICIC average cell throughput performance for different deployment ratios.

TBRS uses the whole spectrum in this case, but D-ICIC is hard limited. This case was omitted from Figure 4.10b so that the differences among the curves could be seen more clearly. Also, the gap of outage performance between the two methods can be diminished by considering interference information from both link directions as studied in the next section. It can be concluded that in this scenario it is better to impose a strong measurement based limitation for spectrum access (e.g. 25 dB SINR) rather than hard limiting the number of selectable channels. Referring back to Figure 3.1 it is clear that at 25 dB the maximum MCS is reached. Thus, a femtocell which is already operating at more than 25 dB SINR in the selected channels will see no benefit of further splitting the spectrum. Notice that in the studied scenarios SNR$\geq$ 25 dB.

4.5 Symmetric Interference Information

Figure 4.4 motivates the use of the reverse link information in order to make the femtocells symmetrically aware of interference. While the SINR seen in both directions is not exactly the same, the downlink outgoing interference is correlated with the incoming uplink interference.

In this section, two cases are compared:

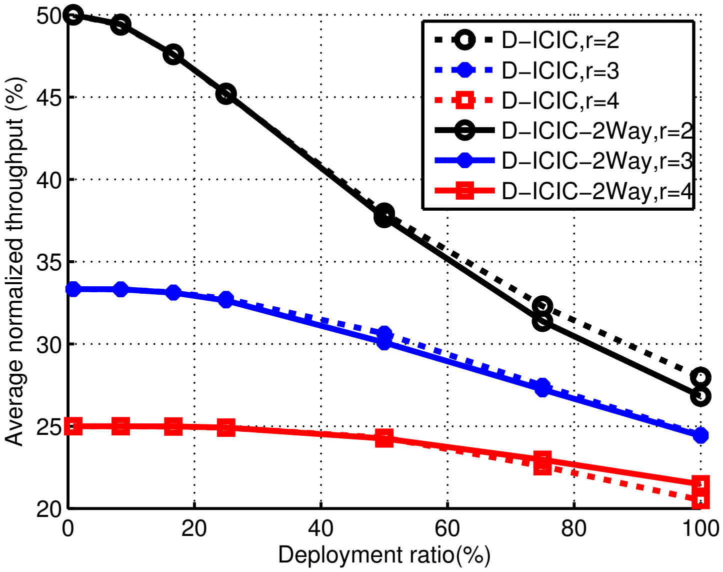
- When the femtocells make decision solely based on the measurements made at the receiver, i.e., downlink measurements.
- When the measurements are performed in both directions, i.e., downlink and uplink.

When the measurements are performed in both directions, the worst case interference (highest) is taken into account. The SINR to be compared with the threshold is calculated by using the received power of the desired signal from downlink and the worst case interference, between uplink and downlink. The figures 4.11a and 4.11b compare D-ICIC using single way or 2 way interference measurements. It can be concluded that D-ICIC is relatively insensitive to such extra information in the investigated scenarios. This can be explained relative to Figure 4.4. When the interference measurements are used only from one direction, cell A only perceives weak interference, but cell B perceives strong interference. Since from the very beginning D-ICIC limits the amount of channels allocated by cell A, cell B can make an orthogonal allocation and it does not matter much whether cell A is adapting or not, as long as at some point cell A stabilizes its allocation. The only difference when measurements are used in both directions is that cell A will also perceive strong interference (from the uplink) from cell B. Thus, cell A will tend to make an orthogonal allocation to cell B even if receives strong incoming interference from other cells.

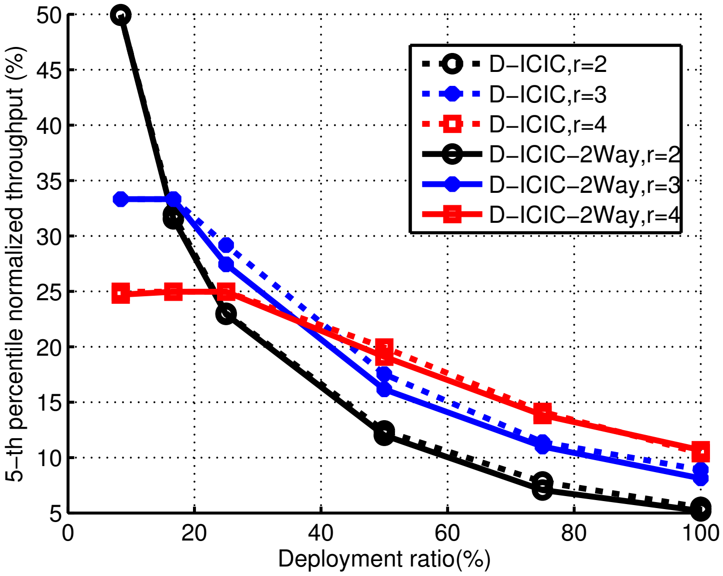
In addition to that, at a low deployment ratio, most femtocells have at a maximum 1 to 2 neighbors. In that case, even for an asymmetric scenario as shown in Figure 4.4 cell A and cell B may be the strongest interferers to each other. Thus, in this case, there is no difference between measuring one way or two way. As shown in Figures 4.11a and 4.11b the effect of measuring in both links is mostly relevant when the density is higher than 25%. The same argument for low deployment ratio is not valid for TBRS because the stage selection is affected. In fact, TBRS is quite sensitive to the presence or absence of some measurement of outgoing interference in low deployment ratio. This can be seen in Figure 4.12a which shows the average throughput and most noticeably in Figure 4.12b, in both cases comparing TBRS(R,4) with measurements in a single way or two way.

Referring once again to Figure 4.4, if the measurements are done only in downlink cell A may remain in a reuse 1 configuration, while cell B may move to further stages. In other words, cells transmitting over the whole spectrum may remain oblivious to the fact that they are causing a lot of trouble to neighbor cells. By using the reverse link information (uplink), such cells can actually detect such a situation and adapt accordingly. For example, cell A would be aware that it causes a lot of downlink interference because it perceives a lot of uplink interference. Therefore, having some measure of the outgoing interference helps outage throughput the most. Also, notice that when the SINR threshold is high, the method is less sensitive to asymmetries because even a small amount of interference will make TBRS move to further stages. Furthermore, the effect of measuring in both uplink and downlink is most apparent if several stages are available. This is the reason why 4 stages were used in this comparison.

Nevertheless, such approach of measuring in both directions has some drawbacks. First, the channels must be paired, i.e., one uplink channel must always correspond to another downlink channel. In case of a TDD system this is not a particular concern because the uplink and downlink channels are actually the same channel divided in time. But asymmetric CA [76] is under consideration for LTE-A FDD. With asymmetric CA the system can use a different number of CCs in downlink and uplink. Second, if power control is only applied to uplink, the interference information becomes much more asymmetric. In order to facilitate such approach either power control should be applied to both directions or none. At last, but definitely not least, if the traffic of uplink and downlink are relatively decoupled, the interference



(a) Average throughput.



(b) 5^{th} percentile of throughput.

Fig. 4.11: Comparison of D-ICIC throughput in 2 situations: when only the direct link (downlink) information is used or if the interference information is sensed from both ways (uplink and downlink).

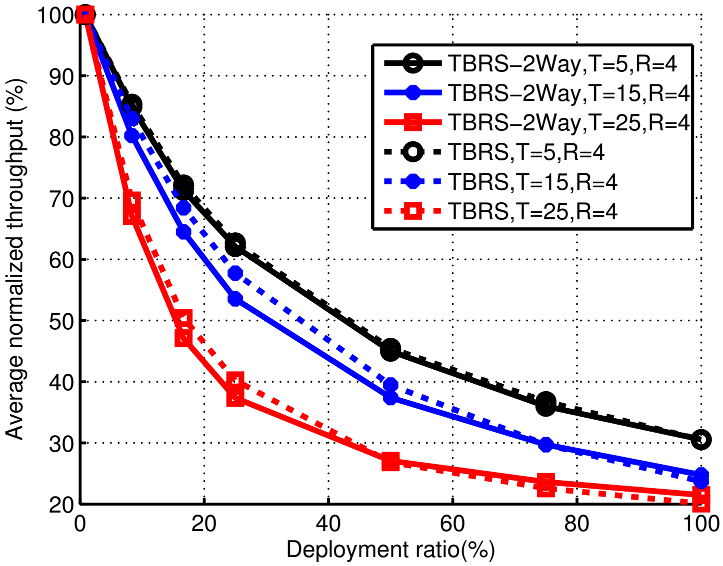
information in one direction also becomes uncorrelated to the information in the other direction. However, this does not prevent the cell to detect worst case uplink interference as a way to be aware at least that it should move to stage 2, i.e., leave some free channels for those links who are being highly interfered.

Since D-ICIC is quite insensitive to outgoing interference information whereas TBRS is more sensitive it is worth to revisit the comparison of both methods. The relative behavior of average throughput is still pretty much the same in Figure 4.13a as the one previously shown in Figure 4.10a. However, in terms of 5th percentile of throughput, TBRS(R,25) closes the gap to D-ICIC in lower deployment ratios, reinforcing the idea that hard limits to spectrum utilization are not really necessary in these femtocell scenarios. Note that the simulations were performed with full buffer traffic. If the traffic pattern is bursty a method which adapts the amount of allocated channels can provide higher gains. In principle, when the traffic on other cells vanish, TBRS can exploit a larger bandwidth, but D-ICIC cannot. If even on the worst interference case, which is full buffer traffic, the outage performance can be attained by a method which is adapting the total transmit bandwidth and providing more average efficiency then there is no reason to have a cap on spectrum accessibility.

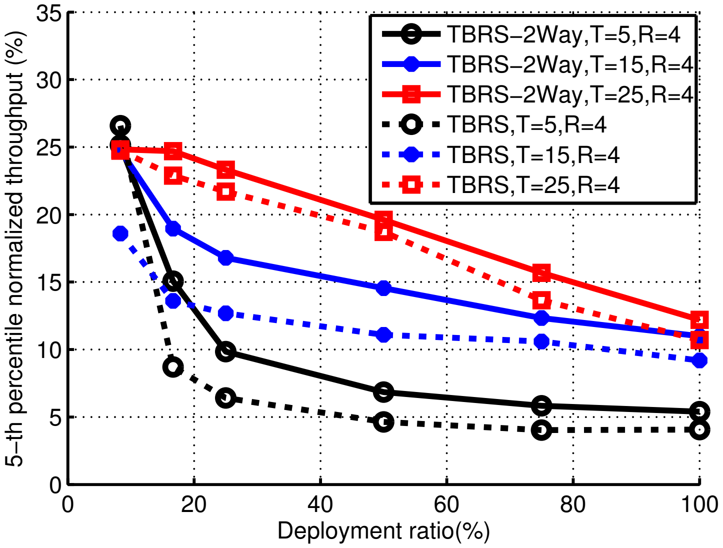
Finally, some selected cases of TBRS are compared to static frequency allocations for all deployment ratios in Figure 4.14. TBRS(4,5) shows both average and outage throughput gains. Such approach can be understood as: solve only the worst interference cases. Notice that this was a configuration which was heavily favored by using information of both links. TBRS(2,25) shows very strong outage performance in low deployment ratios, at the sacrifice of some average throughput. In practice, due to the varying nature of traffic the operating point should be low deployment ratios most of the time. Not surprisingly, TBRS(3,15) provides an intermediate trade-off between TBRS(4,5) and TBRS(2,25), with some extra gains on high deployment density, when more channels are needed to mitigate interference.

4.6 Conclusions

This chapter introduced a simple, yet efficient, method to determine the densest reuse each femtocell can achieve. The method is completely distributed and there is no signaling among femtocells. The Timeout Based Reuse Selection (TBRS) approach consists in: adapting the target reuse which can be achieved locally and coordinating the allocation by selecting the channels with less interference. The convergence issues of such a distributed

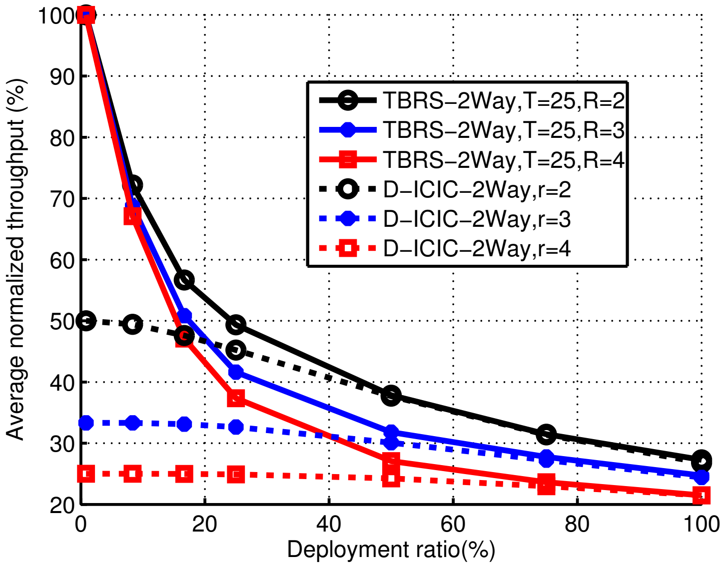


(a) Average throughput.

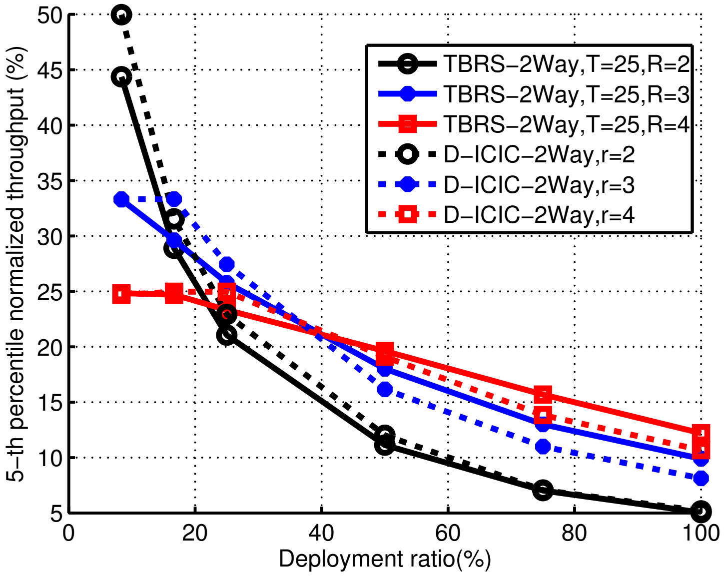


(b) 5^{th} percentile of throughput.

Fig. 4.12: Comparison of TBRS(R,4) throughput in 2 situations: when only the direct link (downlink) information is used or if the interference information is sensed from both ways (uplink and downlink).

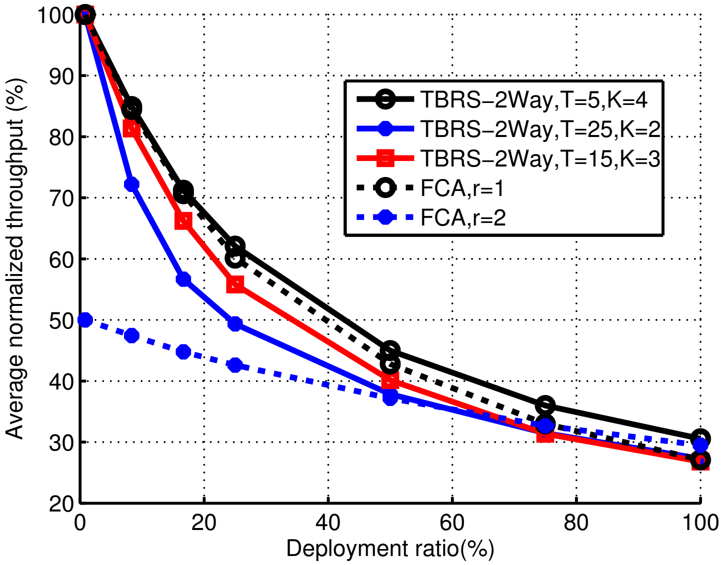


(a) Average throughput.

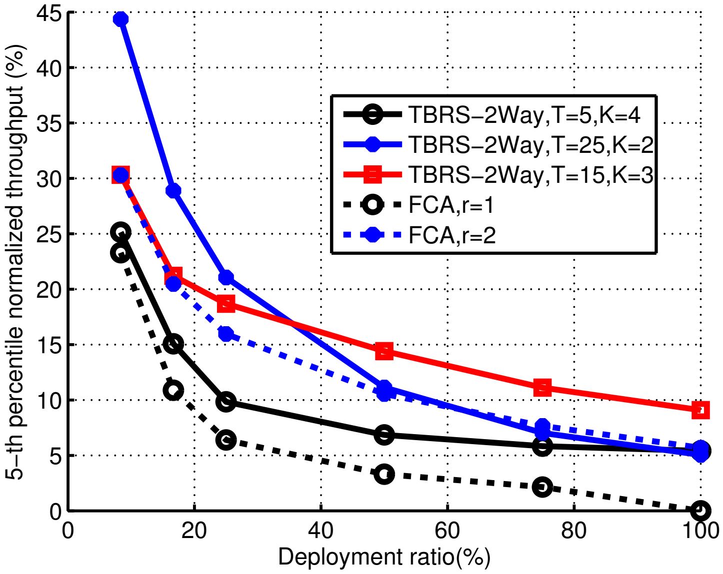


(b) 5th percentile of throughput.

Fig. 4.13: Comparison of TBRS(R,25) and D-ICIC when both uplink and downlink measurements are used to decide the downlink spectrum allocation.



(a) Average throughput.



(b) 5th percentile of throughput.

Fig. 4.14: Comparison of FCA and TBRS when both uplink and downlink measurements are used to decide the downlink spectrum allocation.

channel selection was discussed.

The simulation results showed considerable gains, over reuse 1 deployments, for the users in poor geometry conditions. Furthermore, the method was shown to be superior to just selecting the channels dynamically for a fixed reuse (D-ICIC) One key conclusion is that it is possible to define soft limits on spectrum utilization which perform as good as hard limits when the deployment is very dense, while allowing much higher spectral utilization and efficiency in sparser deployments. One can also infer that such adaptability is even more necessary when considering bursty traffic.

At last, but not least, the effect of having symmetric or asymmetric interference information was investigated through system level simulations. As a practical implementation, the incoming uplink interference information was used to estimate the outgoing downlink interference. The results show that the asymmetry of interference does not have a large impact on the channel selection in the simulated scenario. Nevertheless, the asymmetry of information affects the dynamic selection of the local reuse and, for this reason, it can be beneficial to have symmetric interference information. As a remark, theoretically the symmetry of information guarantees the convergence. This can be another reason to motivate the usage of symmetric interference information. The information from the opposite link direction can be used as an approximation. Notwithstanding, this may not be possible due to practical reasons such as reduced uplink power and unpaired CC allocation.

Chapter 5

Game-based Resource Allocation in a Competitive Environment

5.1 Introduction

Game theoretic analysis takes a particular model for granted, and then the model is used for mathematical derivations which can show important features of the underlying problem. That was the approach taken in section 3.4 in order to gain enough insight into the DSA problem in a femtocell scenario. This chapter also focuses on GT. However, the opposite approach is taken: an engineering approach. The game ”model” is designed to achieve the desired goals. This designed approach was named Game-based Resource Allocation in a Competitive Environment (GRACE).

One key aspect, while modeling a problem as a game, is the definition of the utility function. In game theory, the decision makers greedily optimize their utility functions. Recaptulating, the decision makers in this thesis are the femtocells. The major design challenge here is to make the local greedy optimization within a femtocell lead to an acceptably good global performance. Therefore, a central question can be raised: what should be the utility function of a femtocell in order to achieve such a goal?

The goal is to maximize the capacity of each femtocell. Thus, the natural candidate for utility function is the cell capacity. The analysis of section 3.4 showed that the most natural state, in this case, is a reuse 1 configuration. At some game instances, a reuse 1 configuration is a desirable goal. This is especially true when the interference coupling is low. However, a reuse 1 configuration can also be an unbearable solution (section 3.7). In fact, it is not particularly enticing that distributed adaptations to maximize capacity would lead to a state that: (1) It could be reached without adaptations, (2) it leads to unfair distribution of the capacity, and (3) it can completely disrupt some networks. Is it possible to design *another* utility function such that the capacity is maximized? This is the core idea of this chapter.

In the examples of Figure 3.4, one of the possibilities for a two player game was a Prisoner's Dilemma. It is well known that if such game is repeated, it is possible to achieve player cooperation to choose the more efficient and fair strategy profile. While the players in a spectrum sharing game may have the incentive to use more efficient solutions, they may not have the knowledge. Assuming a model of implicit coordination, how can a player know whether it is facing a Prisoner's Dilemma or some other type of game? Simply measuring the incoming interference does not give a full picture of what other players are experiencing.

In addition to that, strictly adhering to a local optimization of capacity is not necessarily the most desirable solution. As previously shown in the example of Figure 3.10, in some cases it can be beneficial to reduce the utility of a player in order to have a large surplus for other players. Since the goal of a player is maximize his own utility, a little self sacrifice is not part of the GT framework. For this reason, the design of an alternative utility function is needed in order to achieve the goals established for this thesis.

The efficiency of the traditional cellular networks relies on one basic principle: the spatial frequency reuse is planned to be as tight as possible, without excessively degrading the SINR. Hence, when a dynamic spectrum allocation is introduced, the same principle shall drive the design of the utility function. On top of that, the spectrum which is not used in one femtocell has to be made available to its neighbors. I advocate that each femtocell needs to strive at the same time for:

- High bandwidth utilization.
- Avoiding transmission over heavily interfered channels.

- High spectral efficiency on the used channels.

Clearly, there is a trade-off between the first two objectives, while the third one is connected to both of them. One major contribution in this chapter is to define a utility function that can jointly handle these different aspects. This relation is further discussed later in the next section. Then a formal model of this framework as a game is introduced in section 5.3. Simulation results are presented and discussed in section 5.4 while some conclusions are drawn in section 3.8.

5.2 Utility Function

A key learning from the GT analysis in section 3.4 is that capacity maximizers nearly always want to add more channels. This proves to be a naive action, since the interference effect can lead to mutual destruction. Myopia is one term often used in GT to describe such type of strategy which is apparently good at the time being, but actually it proves to be poor on the long run. Myopic players fail to see the big picture, either because they only look at immediate gains or because they are uninformed that a better solution is possible. In their narrow-minded attempt to selfishly maximize their own goals a society of myopic players get stuck in suboptimal strategy profiles.

From the previous GT analysis (section 3.4), the erroneous addition of extra channels seems to be a key issue for a poor collective decision. Essentially, more interference can generate a snowball effect, but the players do not fear that effect enough. For this reason, the utility function proposed in this framework was designed to take into account the marginal gain, i.e., the gain of adding one extra channel. The marginal utility function is defined as:

$$\Pi = C\left(\frac{\tilde{S}}{\tilde{I}+N}\right) - w\left(\frac{k}{K}\right)C\left(\frac{\tilde{I}}{N}\right) \tag{5.1}$$

$\tilde{S}$ is the average received signal power measured at the receiver, $\tilde{I}$ is the aggregated sensed interference on channel k, C is a capacity function, $w(k/K)$ is a weighting function, and N is the noise power per channel. Note that $\tilde{I}$ corresponds to a previous game iteration, while the new $\tilde{S}$ can be estimated after power control calculation. The total utility is simply the sum of utility provided by each selected channel. Notice that all the values in equation (5.1) can be locally measured.

The utility function defined in equation (5.1) can be seen as the extra capacity provided by the additional channel discounted by a tax function. The tax function takes into account the spectrum congestion ($\tilde{I}/N$) and the number of channels already allocated ($w(k/K)$), leaving the possibility of a progressive taxation. In this way, GRACE trades off the capacity of different cells and provides fairness. In the spectrum decision, GRACE allocates the channels which provide a positive utility.

Next it is shown that the designed utility and the corresponding weighting function naturally arise on a simplified, but still relevant, topology. The framework is extended for generalized topologies simply by allowing different weighting functions.

It is intuitive that in the case of fierce interference and mutual interaction the femtocells should use a solution where the channels are orthogonal, such as Frequency Division Multiplexing (FDM). If the interference is low enough, each of the femtocells should be able to reuse the whole spectrum. Consider a situation where the interference among m femtocells is symmetric, i.e., each femtocell affects the other $m-1$ in exactly the same way. Essentially this scenario corresponds to a clique of size m, as discussed in section 3.6. Formalizing the concept, an m-clique interference game is a situation where there are m femtocells with symmetric pairwise interference coupling. Externalities are not considered here, i.e., femtocells not belonging to the clique do not produce relevant interference to the femtocells on the clique. Such a game can be considered as the basic building block of more complex topologies. The question posed here is, in a m-clique interference game, when an FDM solution can be considered superior to the shared channel one. In order to identify such a situation, one needs to analyze under which circumstances the channel capacity of a single interference-free channel becomes greater than the capacity of m interfered channels.

The concept is formalized by comparing the summed Shannon capacity in both cases. Whenever the following inequality holds, an FDM solution would surely be preferred over the full reuse:

$$B\ log_2\left(1+\frac{\tilde{S}}{N}\right) > m\ B\ log_2\left(1+\frac{\tilde{S}}{\tilde{I}+N}\right) \tag{5.2}$$

Where B is the bandwidth, $\tilde{S}$ is the average received power, $\tilde{I}$ is the average interference and N is the noise power in B. All these quantities are relative to a single channel. Note that on the left side of inequality (5.2) no interference is present (FDM solution), while on the right side interference is present (shared channels solution). By eliminating B, equation (5.2) can be rewritten as:

$$log_2\left(1+\frac{\tilde{S}}{N}\right) > (m-1+1)log_2\left(1+\frac{\tilde{S}}{\tilde{I}+N}\right) \tag{5.3}$$

And the terms can be rearranged to:

$$\begin{aligned} log_2\left(1+\frac{\tilde{S}}{N}\right) - log_2\left(1+\frac{\tilde{S}}{\tilde{I}+N}\right) > \\ (m-1)log_2\left(1+\frac{\tilde{S}}{\tilde{I}+N}\right) \end{aligned} \tag{5.4}$$

By using the properties of the logarithmic function, the terms on the left can be written as:

$$\begin{aligned} log_2\left(1+\frac{\tilde{S}}{N}\right) - log_2\left(1+\frac{\tilde{S}}{\tilde{I}+N}\right) = \\ log_2\left(\frac{\tilde{S}+N}{N}\right) - log_2\left(\frac{\tilde{S}+\tilde{I}+N}{\tilde{I}+N}\right) = \\ log_2\left(\tilde{S}+N\right) - log2\left(N\right) - log_2\left(\tilde{S}+\tilde{I}+N\right) + log_2\left(\tilde{I}+N\right) = \\ log_2\left(\frac{\tilde{I}+N}{N}\right) - log_2\left(\frac{\tilde{S}+\tilde{I}+N}{\tilde{S}+N}\right) \end{aligned} \tag{5.5}$$

By substituting equation (5.5) back into equation (5.4) one obtains:

$$\begin{aligned} log_2\left(\frac{\tilde{I}+N}{N}\right) - log_2\left(\frac{\tilde{S}+\tilde{I}+N}{\tilde{S}+N}\right) > \\ (m-1)log_2\left(1+\frac{\tilde{S}}{\tilde{I}+N}\right) \Leftrightarrow \\ (m-1)log_2\left(1+\frac{\tilde{S}}{\tilde{I}+N}\right) - log_2\left(1+\frac{\tilde{I}}{N}\right) < \\ -log_2\left(\frac{\tilde{S}+\tilde{I}+N}{\tilde{S}+N}\right) \end{aligned} \tag{5.6}$$

Now, note that the right side of the equation is always lower than zero:

$$-log_2\left(\frac{\tilde{S}+\tilde{I}+N}{\tilde{S}+N}\right) = log_2\left(\frac{\tilde{S}+N}{\tilde{S}+\tilde{I}+N}\right) \leq log_2(1) \equiv 0 \tag{5.7}$$

Substituting (5.7) in (5.6) and dividing by $m-1$ leads to this simple decision rule:

$$log_2\left(1+\frac{\tilde{S}}{\tilde{I}+N}\right)-\frac{1}{(m-1)}log_2\left(1+\frac{\tilde{I}}{N}\right)\leq 0 \tag{5.8}$$

Whenever the relaxed condition (for simplicity) shown in equation (5.8) holds, a femtocell can safely determine that it prefers an FDM allocation over a full sharing one in an m-clique interference game. One may ask how tight is the bound, since the inequality of equation (5.7) was used to arrive at equation (5.8). Note that the term on equation (5.7) is a function of $I/(S+N)$. At high SNR condition, which is common for femtocells, the omitted term tends to be dominated by the remaining ones because then $I/(S+N)\approx I/S << I/N$. Thus the bound can be quite tight in this case.

Here it is assumed that there are K channels in total, and in order to implement a channel reuse m, the femtocell allocates n_i channels. Being $m=K/n_i$:

$$\begin{aligned}\frac{1}{m-1}=\frac{1}{(K/n_i-1)}=\frac{1}{(K-n_i)/n_i}=\\ \frac{n_i}{(K-n_i)}=\frac{n_i/K}{(1-n_i/K)}\end{aligned} \tag{5.9}$$

The weighting function is defined as:

$$w(n_i/K)=\frac{n_i/K}{(1-n_i/K)} \tag{5.10}$$

Where n_i/K is the proportion of used channels. In order to simplify the notation one can further define:

$$C\left(x\right)=log_2\left(1+x\right) \tag{5.11}$$

Substituting equations (5.10) and (5.11) in equation (5.8) leads to:

$$C\left(\frac{\tilde{S}}{\tilde{I}+N}\right)-w\left(\frac{n_i}{K}\right)C\left(\frac{\tilde{I}}{N}\right)\leq 0 \tag{5.12}$$

The starting point in equation (5.2) was the comparison of two different situations: interfered and interference-free transmission. Therefore, equation (5.12) locally identifies an undesirable situation: all the nodes transmit in all channels even though they could achieve a better performance by coordinating their transmissions. It would be much more beneficial for the whole network if this condition was never reached or, at least, a recovery from this state would be possible. Hence, consider the situation where each of the femtocells starts from an empty allocation and all of them are allowed to allocate one more channel in a round robin fashion until all K channels are allocated. If each femtocell evaluates equation (5.12) before adding a new channel, the undesired condition will never be reached. Therefore, the femtocells can iteratively increase the percentage of used channels (n_i/K) and *dynamically* find a proper FDM solution *to any* m-clique interference game.

This result, derived for a basic topology, motivates the definition of a general utility function that can be used also on more complex topologies. Also, as previously illustrated by the example of Figure 3.10, due to the interference asymmetries, the best spectrum sharing solution may be quite different than just dividing the resources by m. For this reason, the utility function can be defined with an alternative set of weights than equation (5.12):

$$\Pi_i = \sum_{k_i=1}^{K} s_i^{(k_i)} [C_i^{(k_i)} - w\left(\frac{k_i}{K}\right) \psi_i^{(k_i)}] \tag{5.13}$$

Where:

- k_i is a sorting of the channels in terms of increasing interference.
- $s_i^{(k_i)} = 1$ if the femtocell transmits on channel k_i and $s_i^{(k_i)} = 0$ if there is no transmission.
- $C_i^{(k_i)}$ is the channel capacity of channel k_i, and it represents the link level performance of the system.
- $\psi_i^{(k_i)}$ is a measure of spectrum congestion based on the relation between interference and noise in channel k_i. Equation (5.12) suggests that the same function used to map SINR into $C_i^{(k_i)}$ should be used to map I/N into $\psi_i^{(k_i)}$
- $w(k_i/K)$ is a weighting function. This function is a design parameter and it should be a non-decreasing function of k_i/K. Equation (5.10) gives one possible definition.

The function $\psi_i^{(k_i)}$ has an interesting interpretation: when transmitting over an interfered channel, part of the transmit power is spent on overcoming interference instead of being used to transmit useful data rate. The function $\psi_i^{(k_i)}$ measures this quantity as the extra capacity that could be achieved on another (clean) channel.

The utility function defined in equation (5.13) can be maximized without analyzing all possible channel allocations, thanks to the channel sorting and

Algorithm 3 Game-based Resource Allocation in a Competitive Environment (GRACE)
Parameter - Vector of weigths **w**, maximum reduction of channels Δn_{MAX}

```
# Some constants are assumed to be given.
# $K$ is the total number of channels (e.g. 12).
# $\epsilon$ is the status quo review probability.
$n \leftarrow K$                    # n is the current number of channels.
Select all channels                 # Other initialization is possible.
for each radio frame do
    $v \leftarrow U(0,1)$           # Sample a random number between [0,1].
    # With probability $\epsilon$
    if $v < \epsilon$ then
        Update SINR and INR measurements per channel.
        Order the channels in terms of increasing interference (INR).
        $n_{MIN} \leftarrow n - \Delta n_{MAX}$
        $n \leftarrow 1$
        channel selection $= \emptyset$
        Add channel indexed by $k_i = 1$ to the channel selection.
        for $k_i = 2$ to $K$ do
            $\frac{\Delta\Pi_i}{\Delta k_i} \leftarrow C_i^{(k_i)} - w\left(\frac{k_i}{K}\right)\psi_i^{(k_i)}$
            if $n < n_{MIN}$ or $\frac{\Delta\Pi_i}{\Delta k_i} > 0$ then
                Add channel indexed by $k_i$ to the channel selection.
                $n \leftarrow n + 1$
            else
                Leave inner for loop                                   #
                Optional statement.
            end if
        end for
    end if
end for
```

the separability of the utility function per channel. In order to develop such a result, let the marginal utility be defined as the extra utility provided by the addition of a single channel, i.e. setting $s_i^{(k_i)} = 1$ instead of $s_i^{(k_i)} = 0$:

$$\frac{\Delta\Pi_i}{\Delta k_i} = C_i^{(k_i)} - w\left(\frac{k_i}{K}\right)\psi_i^{(k_i)} \tag{5.14}$$

Maximizing the utility in equation (5.13) is equivalent to choosing all the channels that provide positive marginal utility according to equation (5.14). Using this optimization, GRACE is summarized in algorithm 3. The parameter Δn_{MAX} will be motivated and explained in section 5.3.3.

An analysis of equations (5.13) and (5.14) shows that the following properties can be achieved by a proper choice of $w(k_i/K)$:

- *High Bandwidth Utilization*: If the interference is low enough, the utility function approximates the channel capacity. This means that each femtocell will eagerly add more bandwidth if the interference is sufficiently low. Furthermore, each femtocell will opportunistically use the channels which are not allocated by its neighbors. Therefore, a high bandwidth utilization can be achieved.
- *Avoidance of heavily interfered channels*: The marginal utility provided by a highly interfered channel is negative. Thus, a femtocell maximizing Π_i will not allocate highly interfered channels, otherwise this would reduce Π_i.
- *High spectral efficiency*: Selecting channels with a positive marginal utility, given by equation (5.14), is the same as comparing the spectral efficiency to a dynamic threshold. The higher the interference, the higher the threshold (will be). Therefore, only the channels with a high spectral efficiency are chosen.

This utility function framework is very flexible, and a suitable definition is essential for the efficiency of GRACE. In order to provide the best performance, the weighting function has to be adjusted for the desired deployment topology. Figure 5.1 shows an example of a weighting function. In general, the idea is to choose the weights in such a way that the femtocells with a low number of channels will disregard the existence of interference, and they will add more channels anyway, because the weight for $\psi_i^{(k_i)}$ will be close to zero. Moreover, the femtocells with a high number of channels will only add more if the interference is extremely low, since the weight for $\psi_i^{(k_i)}$ will be close to one. These two features enhance the capability of GRACE on attaining both minimal outage performance and fairness. Naturally, it is also an option that $w(k_i/K)$ can be dynamically learned for a given topology.

5.3 Game Theoretical Model and Analysis

In this Section the inter-cell spectrum sharing problem is analyzed in light of Game Theory (GT). The game model is introduced in 5.3.1 while the existence of the equilibria and the general game behavior are analyzed in Section 5.3.2. The dynamics and the strategy learning process are finally described in section 5.3.3.

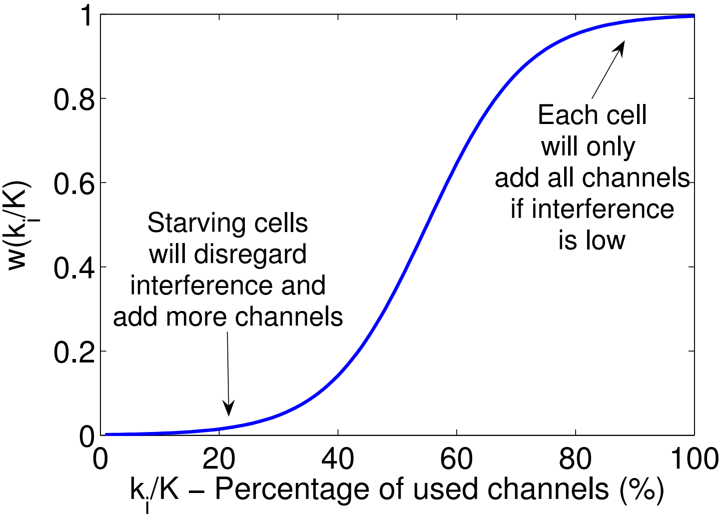


Fig. 5.1: Example of weighting function which leads to a redistribution of average capacity in GRACE framework.

5.3.1 Game Model

This section extends the game model of section 3.4 in order to include the utility function used by GRACE. It is assumed that each player is capable of reducing all relevant sensing information[1] to two values per channel: $I_i^{(k)}$ and $S_i^{(k)}$. A simple implementation of such a reduction is the use of the sensing information about the link with the worst SINR.

While k is the global channel index, common to all players, the utility function is defined by using a player–specific ordering k_i based on the increasing level of interference:

$$\begin{aligned} q_i(k) > q_i(k^*) \Leftrightarrow I_i^{(k)} > I_i^{(k^*)} \\ k_i = q_i(k), k_i \in \mathscr{K} \end{aligned} \tag{5.15}$$

The quantity q_i is defined as a bijective function from $\mathscr{K}$ to $\mathscr{K}$, corresponding to a channel sorting according to the increased level of the worst interference case.

---

[1] Although it is out of scope of this work to investigate handover procedures, once a handover is initiated, a special treatment is needed to determine whether the corresponding UE measurements should be used or not on the spectrum analysis. Otherwise, the spectrum allocation generated by GRACE could be biased to protect a UE that will soon not be served by that cell.

Since this is a bijective function, the global channel indexing can be obtained through the inverse function $k = q_i^{-1}(k_i)$. Hereafter, this conversion is implicitly considered where needed. For example:

$$S_i^{(k_i)} \equiv S_i^{(q_i^{-1}(k_i))} \tag{5.16}$$

Therefore, the utility function from equation (5.13) can be explicited in terms of $S_i^{(k_i)}$ and $I_i^{(k_i)}$:

$$\Pi_i = \sum_{k_i=1}^{K} s_i^{(k_i)} [C \left(\frac{S_i^{(k_i)}}{I_i^{(k_i)} + N_i^{(k_i)}} \right) - w \left(\frac{k_i}{K} \right) C \left(\frac{I_i^{(k_i)}}{N_i^{(k_i)}} \right)] \tag{5.17}$$

Where, $N_i^{(k_i)}$ is the noise power, and $C(x)$ is the link level mapping from SINR to throughput. A GRACE spectrum sharing game Γ is defined as the tuple $(\mathscr{I}, \mathscr{K}, (\Sigma_i)_{i\in\mathscr{I}}, I_{ji}^{(k)}, S_i^{(k)}, (\Pi_i)_{i\in\mathscr{I}})$ where,
$(\Sigma_i)_{i\in\mathscr{I}}$ is the set of strategy spaces corresponding to all possible combinations of channel allocations,
$I_{ji}^{(k)}$ is the interference coupling on channel k for the ordered pair of players i,j,
$S_i^{(k)}$ is the signal received by player i on channel k,
Π_i is the utility function given by equation (5.17).

This game formulation can be constrasted to the one in section 3.4. Figure 5.2 repeats two examples from Figure 3.4 and how they are modified by GRACE using the weights as $w(1/2) = 0$ and $w(1/1) = 1$, i.e., the first channel is not taxed, but the access to the second channel is taxed. One can see that players calculating the utility as defined in equation (5.17) make the right decision both in the case where interference is destructive (Prisoners´ Dilemma) and in the case where reuse one is a desirable output. The behavior in the intermediate cases depends heavily on the choice of weights.

5.3.2 Game Statics

The best reply correspondence b_i of player i is a mapping from the opponents' strategies to a optimal strategy for player i. A best reply selection is a particular single valued implementation of the best reply correspondence. In GRACE game, the best reply selection can be implemented by selecting all the channels with a positive marginal utility, as given by equation (5.14).

From a particular player's point of view, a GRACE spectrum sharing game with more than two players has the same structure of a two-player game. Player i utility depends only on the summed incoming interference, as given by equation

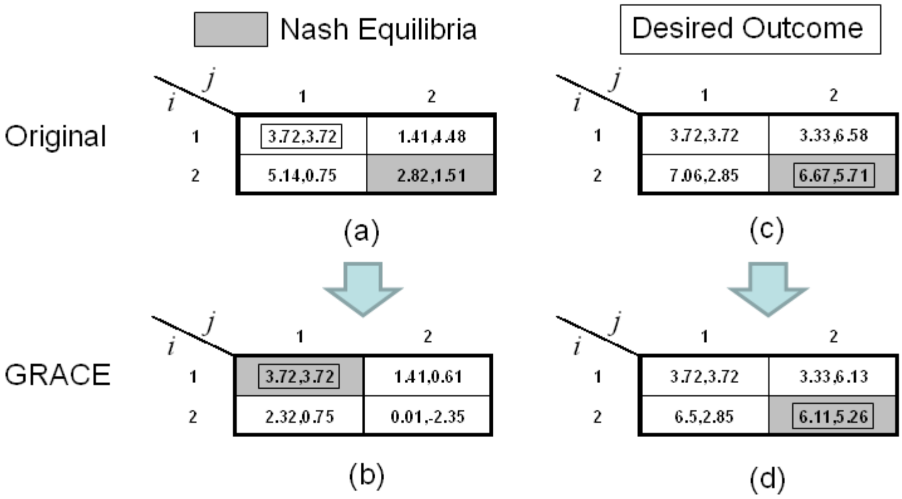


Fig. 5.2: GRACE modifies the utility function in order to overcome the mismatch between desired and expected outcome (NE). The prisoner's dilemma in (a) becomes the modified game in (b), whose NE is the desired outcome (cooperation). The game in (c) is slightly modified to the game in (d), and the best strategy profile is still correctly chosen.

(3.4), and not on which player is generating the interference. Therefore, from the player i point of view, replying to a single opponent or to several ones is exactly the same thing.

In a two player GRACE game, a best reply selection can be determined directly by the number of allocated channels, n_1 and n_2, since the two players will minimize the allocation overlap to each other. An example, with $K = 125$ channels, is illustrated in Figure 5.3. Note that in this example the function $b_1(n_2)$ has the independent variable n_2 on the y-axis while the dependent variable b_1 is on the x-axis. The NE is explicitly marked, and it corresponds to a strategy profile in which the joint best reply selection of both the players reaches a fixed point. Furthermore, the best reply $b_2(n_1)$ is downward slopping. For example, if player 1 does not have much traffic and allocates only 10 channels, the best reply for player 2 is to allocate the remaining 115 channels. If player 2 starts increasing the number of allocated channels, player 1 will be motivated to reduce its own allocation. This is a characteristic of the *submodular games* [22]. The analysis, presented later on in this section, shows that a GRACE game is indeed a submodular game under some conditions.

Another interesting characteristic of the GRACE utility function is that it creates a plateau on the best reply selection. This is an important stability result: for a large portion of the strategy profiles one player is indifferent to the strategic changes of the other player. The plateau level depends on the level of the perceived interference. If the interference coupling is very strong, several Pure Strategy Nash Equilibria (PSNE) may exist. Intuitively, the symmetric one is preferred. This is further discussed in section 5.3.3.

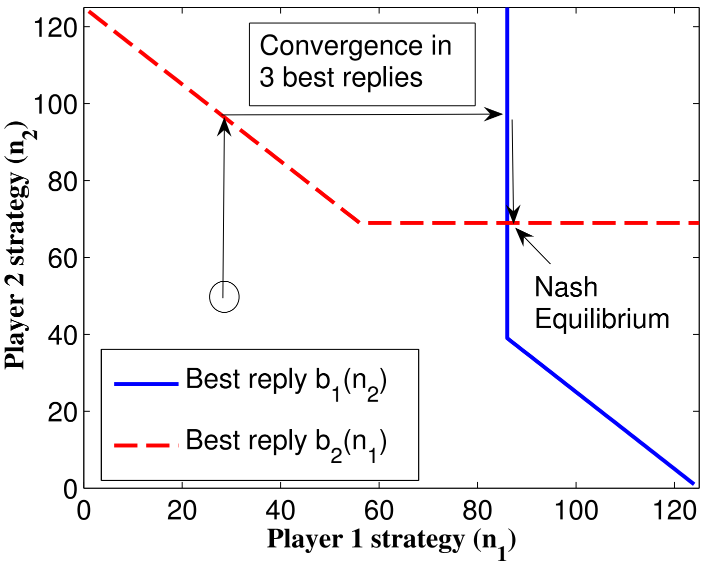


Fig. 5.3: The best reply correspondence in a two player GRACE game with fixed power per channel. Note that for $b_1(n_2)$ the independent variable is on the y-axis, and the dependent variable is on the x-axis. From any initial point the convergence to a NE can be achieved with at most three best replies.

Before formalizing the concept of a submodular game, a few additional definitions will be useful. Let x and y be k-dimensional vectors belonging to $\mathbb{R}^k$. The *meet*, $x \wedge y$, and the *join*, $x \vee y$, operators are defined as:

$$x \wedge y \equiv \{min(x_1, y_1), ..., min(x_k, y_k)\} \tag{5.18}$$

$$x \vee y \equiv \{max(x_1, y_1), ..., max(x_k, y_k)\} \tag{5.19}$$

Moreover, Σ is a *sublattice* of $\mathbb{R}^m$ if $x \in \Sigma$ and $y \in \Sigma$ imply that $x \wedge y \in \Sigma$ and $x \vee y \in \Sigma$. A real valued multi-variable function $\Pi(x)$ is *supermodular* if:

$$\Pi(x \wedge y) + \Pi(x \vee y) \geq \Pi(x) + \Pi(y) \tag{5.20}$$

The utility Π_i has *decreasing differences* in (s_i, s_{-i}) if:

$$\Pi_i(s_i, s_{-i}) - \Pi_i(\tilde{s}_i, s_{-i}) \leq \Pi_i(s_i, \tilde{s}_{-i}) - \Pi_i(\tilde{s}_i, \tilde{s}_{-i}) \tag{5.21}$$

when $s_i \geq \tilde{s}_i$ and $s_{-i} \geq \tilde{s}_{-i}$. Here, $x \geq y$ means that $x_k \geq y_k, \forall k$. If $x_k > y_k$ for some index k but $x_l < y_l$ for some other index l, then the vectors x and y are not comparable.

The Equation (5.21) can be interpreted as follows: when the externality s_{-i} is increased, the marginal profit is reduced or maintained. In other words, an increase in s_{-i} cannot make player i become more attracted to increase s_i.

A *submodular game* is a game where the following conditions stand for each player i:

- Σ_i is a sublattice of $\mathbb{R}^{m_i}$. Note that the dimension m_i of Σ_i can be player specific.
- Π_i has decreasing differences in (s_i, s_{-i}).
- Π_i is supermodular in s_i.

Proposition 1 *Σ_i is a sublattice of $\mathbb{R}^K$.*

PROOF. A strategy is defined in equation (3.3) as a binary vector $s_i \in \mathbb{R}^K$. The meet operation defined in equation (5.18) can be implemented for a binary vector as a bitwise logical AND. Similarly, the join operation is equivalent to a bitwise logical OR. Therefore, it follows that if $s_i \in \Sigma_i$ and $\tilde{s}_i \in \Sigma_i$, then $(s_i \wedge \tilde{s}_i) \in \Sigma_i$ and $(s_i \vee \tilde{s}_i) \in \Sigma_i$ since $(s_i \text{ AND } \tilde{s}_i) \in \Sigma_i$ and $(s_i \text{ OR } \tilde{s}_i) \in \Sigma_i$. Consequently, Σ_i satisfies the definition of sublattice of $\mathbb{R}^K$.

Proposition 2 *Π_i is supermodular in s_i.*

PROOF. From the definition in Equation (5.20), this condition requires that:

$$\Pi_i(s_i \wedge \tilde{s}_i) + \Pi_i(s_i \vee \tilde{s}_i) \geq \Pi_i(s_i) + \Pi_i(\tilde{s}_i) \tag{5.22}$$

for any pair of strategies $\tilde{s}_i$ and s_i. As noted in proposition 1, this is equivalent to:

$$\Pi_i(s_i \text{ AND } \tilde{s}_i) + \Pi_i(s_i \text{ OR } \tilde{s}_i) \geq \Pi_i(s_i) + \Pi_i(\tilde{s}_i) \tag{5.23}$$

Using equations (5.13) and (5.14), the right side of equation (5.23) can be written as:

$$\Pi_i(s_i) + \Pi_i(\tilde{s}_i) = \sum_{k_i=1}^{K} s_i^{(k_i)} \frac{\Delta \Pi_i}{\Delta k_i} + \sum_{k_i=1}^{K} \tilde{s}_i^{(k_i)} \frac{\Delta \Pi_i}{\Delta k_i} \tag{5.24}$$

The terms of the first sum for which $s_i^{(k_i)} = 1$ but $\tilde{s}_i^{(k_i)} = 0$ can be moved to the second sum and set $s_i^{(k_i)} = 0$ in the first sum. After this change, the positive terms in the first sum will consist of the positive terms in both $\tilde{s}_i$ and s_i, while the second sum will consist of the positive terms which are $\tilde{s}_i$, s_i or both of them. Then, by definition:

$$\Pi_i(s_i) + \Pi_i(\tilde{s}_i) = \Pi_i(s_i \text{ AND } \tilde{s}_i) + \Pi_i(s_i \text{ OR } \tilde{s}_i) \tag{5.25}$$

Proposition 3 *The quantity Π_i, as defined in GRACE, has decreasing differences in (s_i, s_{-i}).*

Proof. Equation (5.21) compares the quantity $\Pi_i(s_i, t) - \Pi_i(\tilde{s}_i, t)$ for $t = s_{-i}, \tilde{s}_{-i}$. Using equations (5.13) and (5.14), this quantity can be written as:

$$\Pi_i(s_i,t) - \Pi_i(\tilde{s}_i,t) = \sum_{k_i=1}^{K} s_i^{(k_i)} \frac{\Delta\Pi_i}{\Delta k_i}(s_i,t) - \sum_{k_i=1}^{K} \tilde{s}_i^{(k_i)} \frac{\Delta\Pi_i}{\Delta k_i}(\tilde{s}_i,t) \tag{5.26}$$

Recall that the strategies are binary vectors of size K. Therefore, $s_i \geq \tilde{s}_i$ implies that $s_i^{(k)} = 1$, whenever $\tilde{s}_i^{(k)} = 1$. Otherwise the vectors would not be comparable. In other words, the allocation $\tilde{s}_i$ is necessarily contained in s_i. Therefore, all the terms appear in both sums in equation (5.26), except the channels which are in s_i but not in $\tilde{s}_i$. Let κ represent such a set, with reference to the index k_i.

Then, equation (5.26) can be rewritten as:

$$\Pi_i(s_i,t) - \Pi_i(\tilde{s}_i,t) = \sum_{k_i \in \kappa} s_i^{(k_i)} \frac{\Delta\Pi_i}{\Delta k_i}(s_i,t) \tag{5.27}$$

Similarly, the condition $s_{-i} \geq \tilde{s}_{-i}$ only holds if $s_{-i}^{(k)} = 1$, whenever $\tilde{s}_{-i}^{(k)} = 1$. This last condition implies $I_i^{(k)}(s_{-i}^{(k)}) = I_i^{(k)}(\tilde{s}_{-i}^{(k)})$ if $s_j^{(k)} = \tilde{s}_j^{(k)}$, for all players $j \neq i$ and $I_i^{(k)}(s_{-i}^{(k)}) > I_i^{(k)}(\tilde{s}_{-i}^{(k)})$ if $s_j^{(k)} \neq \tilde{s}_j^{(k)}$, for any player $j \neq i$. These relations can be seen from equation (3.4). Therefore, the interference to player i can only increase or be maintained when the opponents move from $\tilde{s}_{-i}$ to s_{-i}.

Note that the indexing k_i may be different in the two situations compared in equation (5.21), since the interference affects the ranking according to equation (5.15). Let us denote $k_i = q_i(k)$ as the indexing when the opponents strategy profile is s_{-i} and $\tilde{k}_i = \tilde{q}_i(k)$ when their strategy is given by $\tilde{s}_{-i}$. Furthermore, let $\tilde{\kappa}$ represent the set of channels s_i but not in $\tilde{s}_i$, with reference to the index $\tilde{k}_i$. According to equation (5.26), κ and $\tilde{\kappa}$ have the same number of elements in the sum. Because of that, the n-th element of κ will have an indexing k_i which is no smaller than the index $\tilde{k}_i$ of n-th element $\tilde{\kappa}$. This is relevant because the elements of κ and $\tilde{\kappa}$ can be paired such that the weighting function relation can be written as $w(k_i/K) \geq w(\tilde{k}_i/K)$ for $k_i \in \kappa$ and $\tilde{k}_i \in \tilde{\kappa}$. Summarizing, it is possible to pair the elements of κ and $\tilde{\kappa}$ such that the following conditions hold for all of them:

- $k_i \geq \tilde{k}_i$
- $w(k_i/K) \geq w(\tilde{k}_i/K)$
- $I_i^{(k_i)}(s_{-i}^{(k_i)}) \geq I_i^{(\tilde{k}_i)}(\tilde{s}_{-i}^{(\tilde{k}_i)})$
- $\psi_i^{(k_i)} \geq \psi_i^{(\tilde{k}_i)}$

If it is further imposed, $C_i^{(k_i)} \leq C_i^{(\tilde{k}_i)}$, then the following condition necessarily holds for the marginal utilities, given by equation (5.14):

$$\frac{\Delta \Pi_i}{\Delta k_i}(s_i, s_{-i}) \leq \frac{\Delta \Pi_i}{\Delta \tilde{k}_i}(s_i, \tilde{s}_{-i}) \tag{5.28}$$

Then, substituting (5.28) into equation (5.27):

$$\Pi_i(s_i, s_{-i}) - \Pi_i(\tilde{s}_i, s_{-i}) =$$
$$\sum_{k_i \in \kappa} s_i^{(k_i)} \frac{\Delta \Pi_i}{\Delta k_i}(s_i, s_{-i}) \leq \sum_{\tilde{k}_i \in \tilde{\kappa}} s_i^{(\tilde{k}_i)} \frac{\Delta \Pi_i}{\Delta \tilde{k}_i}(s_i, \tilde{s}_{-i}) \tag{5.29}$$

Then, the equation (5.27) can be used at the right side of equation (5.29) to establish the condition of equation (5.21) which is the definition of decreasing differences:

$$\Pi_i(s_i, s_{-i}) - \Pi_i(\tilde{s}_i, s_{-i}) \leq \Pi_i(s_i, \tilde{s}_{-i}) - \Pi_i(\tilde{s}_i, \tilde{s}_{-i}) \tag{5.30}$$

Theorem 1 *A GRACE spectrum sharing game is a submodular game.*

PROOF. It follows directly from the definition of a submodular game, Proposition 2 and Proposition 3.

Corollary 5.1 *A PSNE always exists in a two-player GRACE spectrum sharing game.*

Proof. A *supermodular game* can be defined along the same lines as a submodular game, by replacing decreasing differences with increasing differences [73], i.e., if Equation (5.21) is true when the inequality signal is reversed.
A two-player submodular game can be turned into a supermodular game by reversing the action vector of one of the players [77]. In the case of a GRACE spectrum sharing game this modification can be done as follows: one of the players decides which channels to allocate, and the other decides which channels *not* to allocate.
Supermodular games always have at least one PSNE. Therefore, a two-player GRACE spectrum sharing game always has a PSNE.

It is still an open issue in the game theory literature what are the most general conditions that can guarantee the PSNE existence in submodular games with more than two players. Refer to [78] and references therein for the latest advances in the topic.

5.3.3 Game Dynamics

The game dynamics can be seen as a learning process, in which the players attempt to discover how to play a NE after a few game repetitions. In the particular case of a GRACE spectrum sharing game, the players are interested in learning, through the past sensed information, the equilibrium for the spectrum allocation.

Figure 5.3 shows one example where the convergence to PSNE can be achieved in a two-player game with only three steps using the best-reply dynamics, i.e. if the players iteratively play the best responses.

Despite the nomenclature, there are several situations where the *Better-Reply Dynamics (BRD)* are preferred over best-reply dynamics [75]. The BRD is a random process in which, at each stage of a repeated game, one player $i \in \mathscr{I}$ is selected to revise its current strategy (the status-quo strategy). The selected player will sample other strategies. The sampled strategy will be adopted if and only if it is a *better-reply*, i.e. if its utility is higher than the one provided by the status-quo strategy. Otherwise, the status-quo strategy is kept for the next stage.

Supermodular games have the *weak Finite Improvement Property* (weak-FIP), which guarantees the convergence of the game to a PSNE. Therefore, any two-player GRACE spectrum sharing game will converge under BRD, because it is a supermodular game (see Corollary 5.1) as well. Whenever the BRD converges, the convergence point is a PSNE [75]. Therefore, the convergence to a PSNE can be empirically verified by using the BRD.

Here, two modifications to the BRD are proposed:

1. Each player decides autonomously to revise its status-quo strategy with probability ϵ, equal for all players. This modification, which is also used in [50], avoids any coordination amongst the players, enhancing the scalability of the algorithm.

2. A femtocell can only change its allocation by a maximum of Δn_{MAX} channels at a time. This modification smooths the changes in the spectrum allocation, and it serves a number of purposes. First, the sensing information becomes more stable because the spectrum allocation varies less often. Secondly, the other processes, such as the RRM and the Admission Control, can more easily adapt to small changes in the spectrum allocation rather than large ones. Furthermore, a femtocell will wait for the adaptation of the other femtocells before making drastic changes in its own allocation. This is very important for the presence of multiple PSNE, where the convergence towards a symmetric equilibrium is preferred. Last, but not least, this modification should provide smoother transitions in the transmission data rate provided to the upper layers. Naturally, this modification comes at the price of a reduced spectrum agility. Some of the agility can be recovered by setting high values of the status-quo revision probability (ϵ).

This modified BRD will also converge in games with weak-FIP property, since there is a positive probability that the players will follow exactly the same improvement path as in BRD.

One implementation note: from Equation (5.14) it is possible to state that the better replies can be formed from the current allocation by adding the channels which have a positive marginal utility while removing those which have a negative marginal utility. Therefore, the modified better-reply dynamics can have a simple implementation, where only a few channels have to be evaluated at a time instead of analyzing all possible channel allocations.

5.4 Simulation Results

5.4.1 Convergence Study

Because of the lack of stronger theoretical convergence results, the convergence of the GRACE algorithm is empirically studied at this section. The size of the scenario was varied. The target is to evaluate the scalability of the algorithm when the size of the problem is increased, i.e. scenarios with more femtocells. The convergence has been addressed for four setups:

- Two femtocells, forming a 2x1 grid of houses.
- Four femtocells, forming a 2x2 grid of houses.
- 16 femtocells, forming a 4x4 grid of houses.
- 64 femtocells, forming a 8x8 grid of houses.

For each of these setups the convergence results were averaged over 640 samples from randomly generated scenarios. They are presented in the form of an *allocation error*, defined as the difference between the number of channels currently allocated and the number of channels allocated in the NE. Therefore, the allocation error is a metric that measures how far a particular femtocell is on the equilibrium allocation.

Figure 5.4 shows the evolution of the worst allocation error. It is possible to observe that there is some dependency of the worst case of the convergence behavior from the number of femtocells, but the time required for converging does not grow as fast as the problem size. In the worst case scenario with 64 femtocells, the PSNE is only achieved after 58 iterations, but even in this case, most of the convergences are achieved within 30 iterations.

Figure 5.5 shows the evolution of the average allocation error. The average convergence behavior is very interesting. In the simulated scenarios, the average convergence time for the 64 femtocells scenarios is the same as for the 4 femtocells scenarios. Therefore, GRACE scales very well with the problem size, and it is suitable as a spectrum sharing solution in massive uncoordinated deployments.

As a remark, the convergence behavior is a consequence of the limitation of the maximum allowed allocation change (Section 5.3.3). Depending on the scenario, the convergence can be made faster if no limitations are imposed on

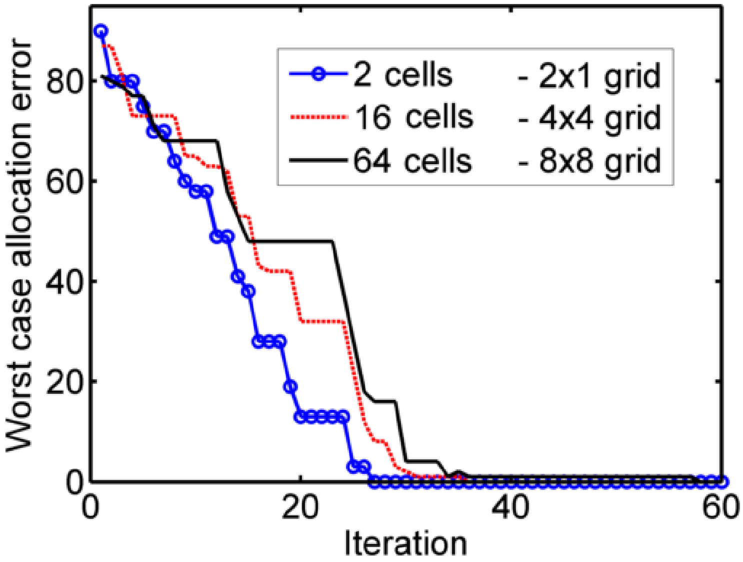


Fig. 5.4: Evolution of worst case allocation error, among 640 femtocells. This is indicative of the worst-case convergence behavior of GRACE.

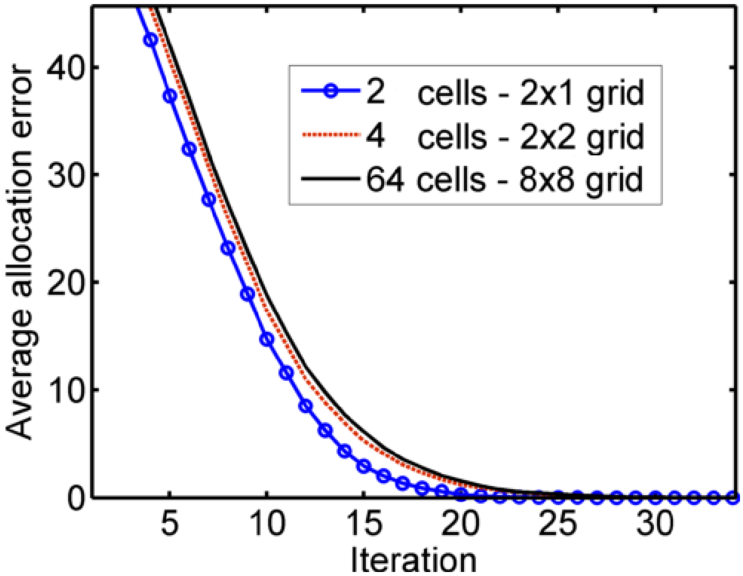


Fig. 5.5: Evolution of the average allocation error, amongst 640 femtocells. This is indicative of the average convergence behavior of GRACE.

how fast the femtocells can adapt. However, that can lead to different equilibria. Furthermore, as discussed in section 5.3.3, the convergence results of this section imply that the PSNE exists for all the studied scenarios, because the convergence point of the BRD must be a PSNE.

5.4.2 Comparison with Baseline Methods

In the following GRACE simulations, the parameter Δn_{MAX} was set to 1. The simulation scenario is the one described in section 3.5. The number of channels available in the band is $K = 12$. All the throughput results are normalized by dividing the throughput by the maximum theoretical capacity of the system. Hence, a *normalized throughput* of 100% means that the theoretical capacity is achieved (transmission over the whole bandwidth at the maximum spectral efficiency of the system).

The GRACE framework is rather flexible. If the set of weights on equation (5.13) is varied, one can end up with very different final allocations. For example, if all weights are set to zero, then each player is a capacity maximizer, and the reuse one NE is expected to be achieved. On the other hand, if the weights are set very high each player will strive for a low utilization of resources. Preliminary results were generated for more than 1000 weighting function settings. From these, three cases were selected to illustrate the performance of GRACE corresponding to the cases with best average performance in a dense network (100% deployment ratio), best outage performance in the same conditions, and the best balance between the two KPIs. These 3 weighting cases are plotted in Figure 5.6 and they correspond to:

- **Case 1**: a progressive taxation case.
- **Case 2**: For the first five channels $w\left(\frac{k_i}{K}\right) = 0$. For the remaining channels $w\left(\frac{k_i}{K}\right) = 1$.
- **Case 3**: For the first three channels $w\left(\frac{k_i}{K}\right) = 0$. For the remaining channels $w\left(\frac{k_i}{K}\right) = 1$.

Note that in all 3 cases, the weighting of the first 3 channels is zero. Such a type of weighting tends to make most cells allocate at least 3 channels. Notice, however, that cells which see zero throughput when adding one more channel can still allocate fewer than 3 channels. Furthermore, the weights of the last 3 channels is set to 1 (which was empirically found to be quite restrictive). These 2 settings are selected in order to get the behavior previously described conceptually on Figure 5.1: avoid starvation of any cell. Recall also that at least one channel is always allocated.

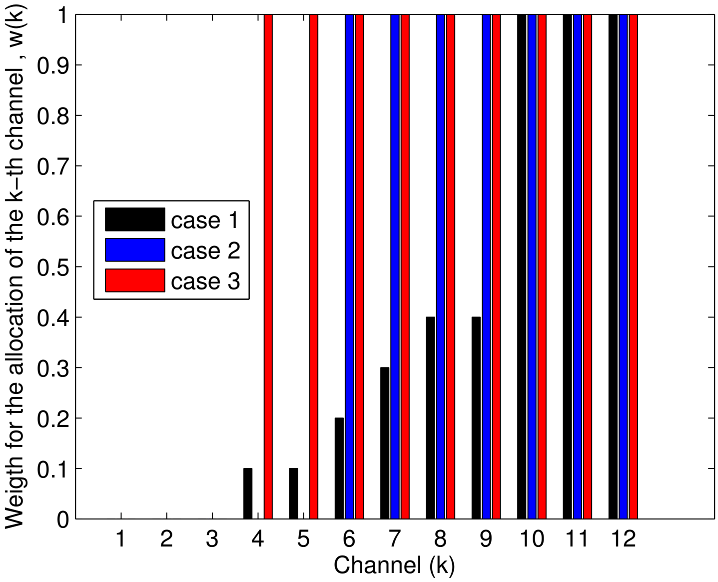


Fig. 5.6: Three simulated GRACE cases, corresponding to different settings of the weighting function $w(k)$.

Figure 5.7 shows the comparison of GRACE and the statically allocated reuses 1 and 2. One can see that GRACE(case 1), can provide average throughput comparable to reuse 1, while substantially increasing the 5$^{\text{th}}$ percentile of throughput. It is important to notice that at higher deployment ratios, GRACE(case 1) average performance is superior to that of reuse 1. As compared to reuse 2, GRACE(case 1) always provides better performance in terms of both metrics. Such type of progressive taxation setting provides a balanced trade-off between average and outage throughput and a high degree of adaptability to different deployment ratios.

The other two simulated GRACE cases can achieve better outage performance than case 1. The cost comes in terms of average throughput loss compared to GRACE(case 1), as it can be seen from Figure 5.7a. As shown in Figure 5.7b GRACE(case 2) outperforms GRACE(case 3) in terms of the 5$^{\text{th}}$ percentile of throughput, for low deployment ratios. However, on higher deployment ratios GRACE(case 2) underperforms GRACE(case 3). The reason for this different behavior is the shift in the distribution of maximal clique sizes, as previously illustrated in Figure 3.9. At higher deployment ratios GRACE(case 2) cannot cope adequately with cliques of size 3 or 4.

GRACE and D-ICIC are compared in Figure 5.8. For a similar performance in terms of 5$^{\text{th}}$ percentile of throughput, GRACE can achieve much higher average throughputs. This behavior extends even to a 100% deployment ratio for GRACE(case 1) and GRACE(case 2). From this comparison, one can conclude that GRACE outage performance can be made quite strong when the weigths are sharply defined (case 2 and 3). It can be noted, for example, how closely D-ICIC(r=4) and GRACE(case 3) performs in terms of 5$^{\text{th}}$ percentile of throughput. Essentially, because a weight $w\left(\frac{k_i}{K}\right) = 1$ is quite demanding in terms of SINR, GRACE(case 3) is quite similar to a dynamic reuse 4 in higher deployment ratios. Nevertheless, by using a progressive taxation (case 1), with many weigths with less restrictive settings $w\left(\frac{k_i}{K}\right) < 1$, GRACE can have much higher average throughputs.

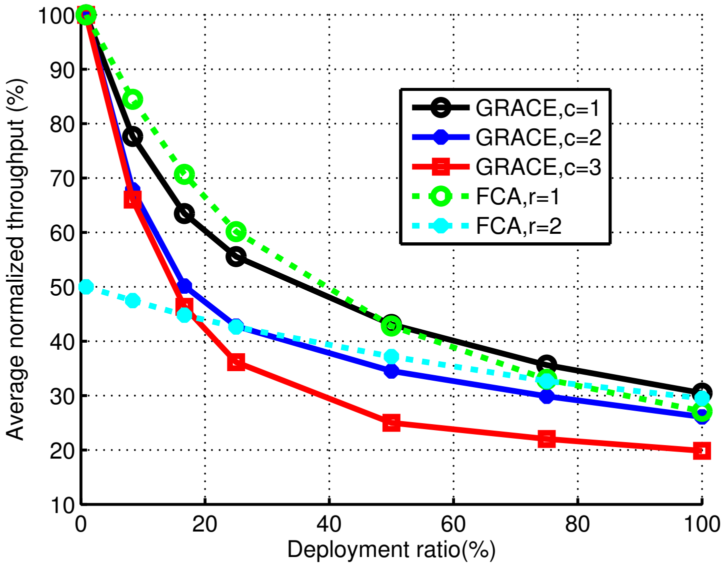
5.5 Conclusions

In this chapter a solution based on Game Theory (GT) was proposed. The overall complexity of Game-based Resource Allocation in a Competitive Environment (GRACE) algorithm is low since no inter-cell signaling is required. The utility function was used as a design parameter, and the design targets of such an utility function were set to be: high bandwidth utilization, avoiding transmission over heavily interfered channels and high spectral efficiency on the selected channels.

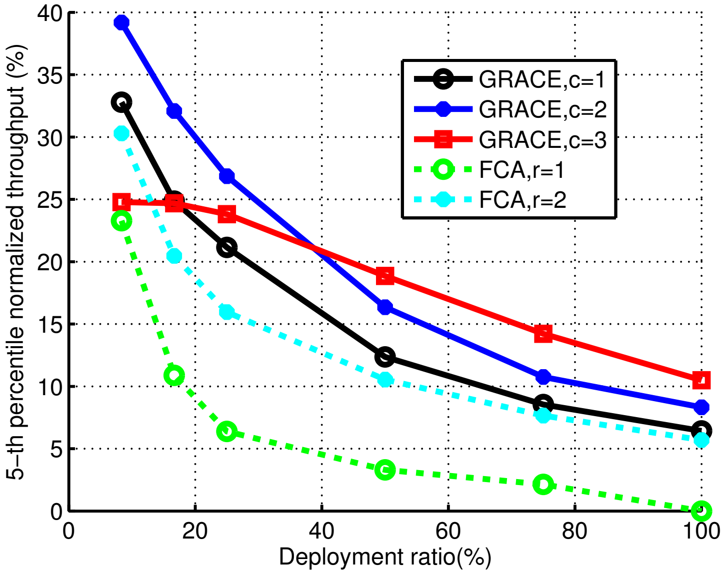
Since capacity maximizers tend to underestimate the effects of interference, the designed utility function reinforces the interference effect using a non-linear taxation term which depends on the INR. In order to enhance fairness, the taxation utilizes a progressive scheme which prevents the cells from allocating too few or an excessive number of channels.

Game theoretic analysis showed that the GRACE framework can be classified as a submodular game under certain assumptions. Such type of game is an active area of research in GT. NE existence and convergence are only known for some subclasses of submodular games and cases with two players. For this reason, the convergence was also studied through system level simulations.

The proof-of-concept simulation results highlight the main strength of GRACE: to adapt efficiently and dynamically in a fully distributed manner. The convergence of such a procedure shows little dependence on the number of femtocells, a high average throughput is achieved, and a minimum outage is

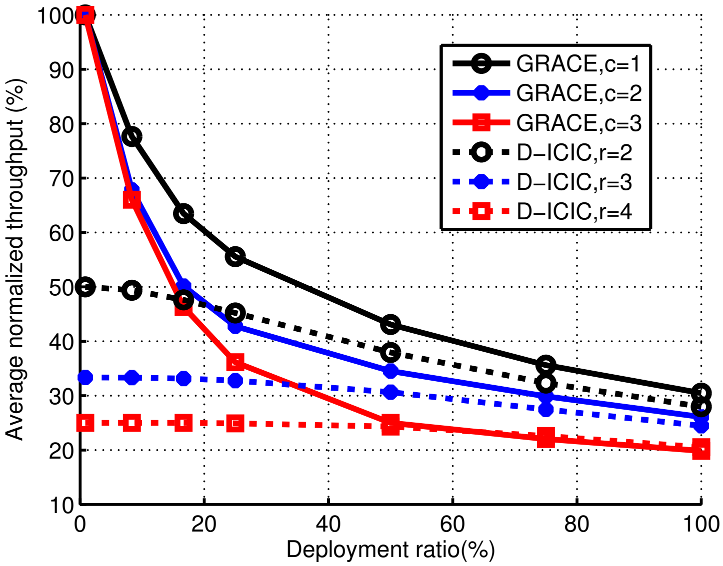


(a) Average throughput.

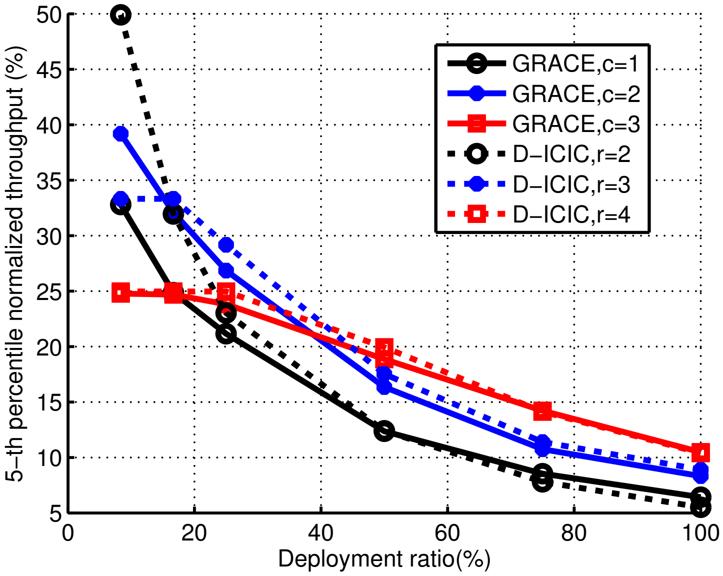


(b) 5^{th} percentile of throughput.

Fig. 5.7: Comparison of GRACE and FCA schemes. The GRACE cases correspond to the weight sets shown in Figure 5.6.



(a) Average throughput.



(b) 5^{th} percentile of throughput.

Fig. 5.8: Comparision of GRACE and D-ICIC. The GRACE cases correspond to the weight sets shown in Figure 5.6.

attained. These are the main characteristics of any DSA solutions which aim at an efficient and fair spectrum sharing in fully uncoordinated deployment scenarios.

Chapter 6

Self-Organizing Coalitions for Conflict Evaluation and Resolution

6.1 Introduction

When different cells can communicate to each other it is possible to perform explicit coordination of the spectrum access. In this case, femtocells can exchange measurements and negotiate the channel allocation. However, extra communication implies in extra overhead and system complexity. Thus, in light of the goals established for this thesis, i.e., high capacity, low complexity, fairness and stability, the cell-to-cell communication should be kept to a bare minimum.

The framework proposed in this chapter, namely Self-Organizing Coalitions for Conflict Evaluation and Resolution (SOCCER)[1] is based upon a few principles. First, the femtocells exchange measurements which characterize the interference coupling between two cells. Then, based on such measurements the femtocells are capable of evaluating whether there is a potential conflict or not. Finally,

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[1] SOCCER was designed together with Luis Guilherme Uzeda Garcia (with 50/50 share of contributions), and for that reason it also appears in his thesis [79].

the femtocells exchange messages needed to decide the allocation and coordinate the access to the spectrum.

This chapter is organized as follows. Section 6.2 discusses the system model and the proposed framework overview. The details of specific building blocks are presented in sections 6.3, 6.4 and 6.5. Then, section 6.6 introduces a game theoretic modeling. The method is evaluated in section 6.7 and conclusions are summarized in section 6.8.

6.2 The Proposed Framework and System Model

Figure 6.1 illustrates the framework. Two FAPs with relevant interference coupling needs to share the band. As long as the total demand for channels can be met, there is no conflict between the FAPs. For example, if one of the FAPs of Figure 6.1 needs only two channels and the other can satisfy the demand with one channel there is no reason for special actions. Nevertheless, when a conflict of interest arises, due to congestion, it is highly desirable to ensure that the set of resources is utilized in an efficient and fair manner. This task can be accomplished by explicit coordination.

The FAPs can establish cooperative sets via bi- or multilateral agreements. Once established, a cooperative set dictates how its members shall share resources targeting resource orthogonalization. As such, a FAP may be part of none, one or several cooperative sets at the same time[2]. Within a femtocell the partitioned resources are imposed as a restriction to the packet scheduler which can assign the available resources to the different users. The participation in a cooperative set is assumed to be binding. Once agreed the participating FAPs must respect the agreement, and their packet schedulers shall abide to the imposed restrictions.

The process of formation of cooperative sets is assumed to take place due to changes in topology or traffic, because those are the times when new conflicts can arise. For example, every time a new FAP is deployed or turned on corresponds to a change in current network topology, changing the potential interference footprint. When the user makes new requests the transmissions will de facto take place, increasing the interference to other cells. As such, those events are the natural points for conflict evaluation. The performance during the most

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[2] Originally, the term *coalition* was used instead of cooperative set. However, the term was avoided here in order to prevent confusion with the usual definition of coalition in GT, which typically only allows each player to be member of a single coalition.[21]

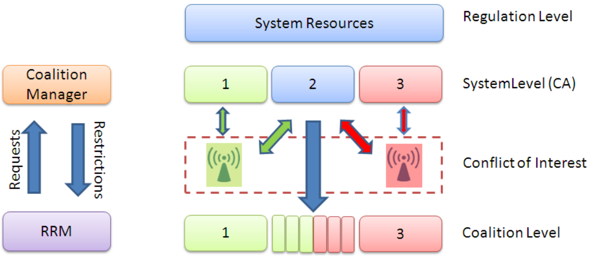

Fig. 6.1: Proposed framework.

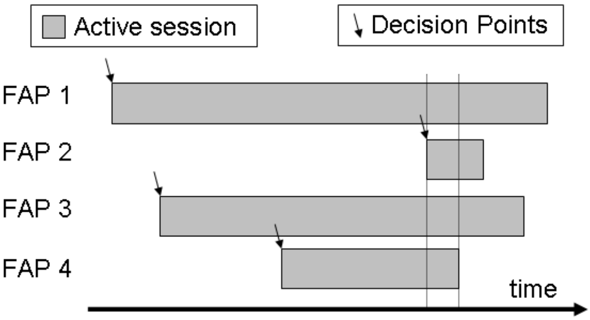

Fig. 6.2: New sessions arrive randomly, and due to the surge on traffic demand new conflicts arise. Those are the natural decision points to form new cooperative sets. The most congested time is illustrated by the vertical bars.

congested times is of particular interest, because during congestion the capacity can be severely constrained by interference. The decision points and the most congested time are illustrated in Fig. 6.2. Note that no particular time scale is specified for this model. The time granularity is ultimately restricted by the cell to cell and FAP to UE signaling capabilities. If the signaling can be done fast, then new spectrum decisions can be updated for every new traffic session. More conservatively decisions could be done on FAP power on and updated from time to time.

The framework developed in SOCCER is composed of these parts:

1. Measurements Acquisition and Exchange (section 6.3).
2. Conflict evaluation at the critical decision points, as illustrated in Figure 6.2 (section 6.4).
3. The rules which guide the conflict resolution and channel redistribution

(section 6.5).

Each of these building blocks are detailed in the following sections.

6.3 Measurements Acquisition and Exchange

A simple way to characterize the interference coupling of a pair of cells is using Background Interference Matrices (BIMs). Such a concept of pairwise characterization of incoming and outgoing interference is also the basis for other DSA proposals for LTE-A [15, 65] and a very advanced DCA technique in Global System for Mobile Communications (GSM) networks [80, 81].

Essentially, a BIM entry is a measurement of SINR for a single interferer[3]. For example, for a pair of cells, i and j, the incoming downlink BIM of i is denoted $\mathrm{DL}_{\{i\}\leftarrow\{j\}}$ and it is a representative value of the SINR experienced by UEs at femtocell i if the FAP at cell j is the only interferer. Conversely, the outgoing downlink BIM of i towards j is the SINR measured by UEs at femtocell j, when i is the only interferer. The outgoing BIM is denoted as $\mathrm{DL}_{\{i\}\rightarrow\{j\}}$. Naturally, for a pair of cells the incoming BIM of a cell is the outgoing BIM of the other, i.e., $\mathrm{DL}_{\{i\}\leftarrow\{j\}} \equiv \mathrm{DL}_{\{j\}\rightarrow\{i\}}$, by definition.

Figure 6.3 shows the BIM concept. The FAP A is serving UEs 1 and 2 and FAP B serves UEs 3 and 4. Each UE measures the Reference Signal Received Power (RSRP) [82] from both its serving cell and neighboring FAPs, just as in handover measurements. The RSRP values are reported to its serving FAP. In turn, the corresponding FAP gathers this information and calculates differences of RSRP values (in dB). For example, FAP A receives from UE 2 both the RSRP measured over FAP A Reference Signals (RSs) and the one measured over FAP B RSs. The difference (in dB) of these two values characterizes the potential downlink incoming SIR of UE 2 in case the same channel is reused by the neighboring cell. If the noise level is signaled to the FAP or a typical value can be assumed, then the SINR can be estimated similarly to the SIR. The same SINR calculation is done for each UE. Clearly, there are many possible manners to utilize this knowledge, but in the context of femtocells the lowest SINR reported towards a given neighbor can be taken as representative of the downlink incoming interference coupling between the pair of cells. In case of Figure 6.3 the links $(A, 2)$ and $(B, 2)$ would characterize $\mathrm{DL}_{\{A\}\leftarrow\{B\}}$ whereas the links $(B, 3)$ and $(A, 3)$ yield $\mathrm{DL}_{\{B\}\leftarrow\{A\}}$. Naturally, if the femtocell serves more

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[3] In other references the BIM is often defined as the SIR for a single interferer. Defining it based on SINR simplifies the treatment here. In case of interference limited situations then one can assume $SIR \approx SINR$.

than a single UE, the lowest SINR value for different neighbors can come from different UEs. In such a way, interference coupling among cells is quantified on a pair-wise basis, i.e. not considering the total effectively received interference power.

After each femtocell acquires the incoming BIM information, the femtocell needs to inform the relevant sources of interference about their outgoing BIMs. In that way, those cells can mind their allocations in order not to create harmful interference. Altogether, the BIM information essentially "teaches" each cell about its mutual interference coupling with neighboring cells, which makes them capable of estimating the impact of any new allocation on surrounding cells, both as victims and sources of interference.

A beneficial aspect of the BIM concept is that it reduces the characterization of interference among two cells i and j to two values: $\mathrm{DL}_{\{i\}\to\{j\}}$ and $\mathrm{DL}_{\{j\}\to\{i\}}$. Such characteristic makes the exchange of measurements rather lightweight. Another advantage is that the BIMs can be calculated based on measurements standardized for other purposes (in the example, RSRP) [82]. One point to be stressed is that BIMs do not need to be exchanged from all femtocells to all femtocells, but only to neighbors. If a particular cell detects a high value of incoming BIM, say 35 dB, it does not have to inform the other cell. The interference at this low level have little effect. This can be seen, for example, in Figure 3.2. For all the reasons described above, altogether the overhead of exchanging BIMs is kept low.

Depending on the implementation of the method, one may also need to signal the typical SNR each cell achieves in case of interference-free transmissions. In case of multiple UEs the reported SNR should be consistent with the reported BIM value.

6.4 Conflict Evaluation

The graph theoretic analysis 3.6 showed that the pairwise characterization of SINR, i.e. the BIM values, can be used to characterize the conflicts among femtocells. The intensity of interference coupling (low BIM values), number of conflicts and direction are all important, but such analysis showed that the intensity is the most important factor. This motivates to characterize the strength of the interference coupling between a pair of femtocells.

Such characterization leads to the definition of *strong bonding*. Conceptually, the presence of a strong bonding between two FAPs implies that mutual

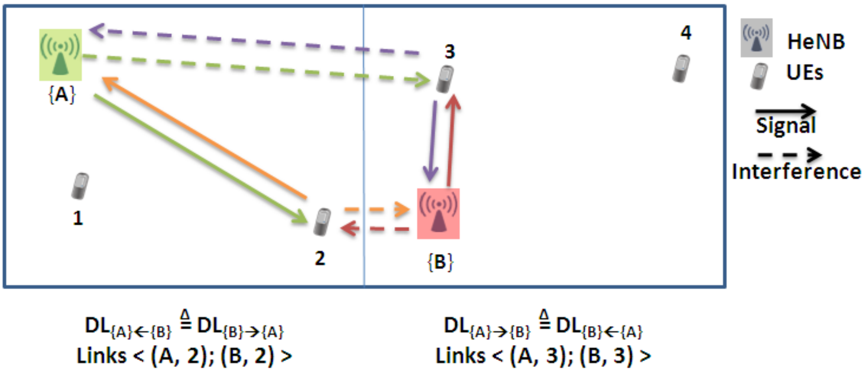


Fig. 6.3: Simplified scenario illustrating how the BIM is estimated. In the context of femtocells the lowest SINR reported towards a given neighbor is taken as representative of the interference coupling between a pair of cells.

cooperation by means of an orthogonal allocation is deemed beneficial. Conversely, in the absence of strong bonding, competition is fruitful and no restrictions are enforced, i.e. the reuse of resources can be sought.

Different alternative definitions for strong bonding have been devised in order to cope with different optimization targets:

- *Max-sum* strong bonding: the two FAPs deem cooperation beneficial if by doing so they can increase their sum capacity. The target of this evaluation is to maximize the average throughput.
- *Max-min* strong bonding: the FAPs agree on cooperation if such behavior will benefit at least one of them. The target of such evaluation is to maximize the outage throughput.
- *Selfish* strong bonding: two FAPs cooperate only if they expect a win-win situation from such agreement. This rule was devised to evaluate the usual expected behavior considered in GT.

Now, let two neighbor femtocells be denoted by i and j. Mathematically, a max-sum strong bonding occurs whenever (6.1) is satisfied,

$$\frac{1}{2}C(\mathrm{SNR}_i) + \frac{1}{2}C(\mathrm{SNR}_j) > C(\mathrm{DL}_{\{i\}\leftarrow\{j\}}) + C(\mathrm{DL}_{\{j\}\leftarrow\{i\}}) \tag{6.1}$$

where SNR_i and SNR_j are representative values of SNR for transmissions free of interference. C is a capacity function, for example as given by equation (3.1).

Essentially, equation (6.1) compares the sum throughput in two situations. In the left hand side the femtocells coordinate transmissions, achieving interference free allocation, but each femtocell only has access to half of the channels. In the right hand side the two FAPs reuse all channels, but then they interfere in each other transmissions.

In a similar way, the max-min strong bonding is defined as:

$$\frac{1}{2}C\left(min(\mathrm{SNR}_i, \mathrm{SNR}_j)\right) > C\left(min(\mathrm{DL}_{\{i\}\leftarrow\{j\}}, \mathrm{DL}_{\{j\}\leftarrow\{i\}})\right) \tag{6.2}$$

Equation (6.2) defines a conflict in case at least one of the cells could have higher capacity in case they coordinate the access to the spectrum channels. As previously illustrated in Figure 3.2, for the particular link-level model used for evaluation, such a condition is equivalent to having at least one of the cells with SINR below 12.5 dB in case of shared use of spectrum. Naturally, such value will vary for different link-level models, but equation (6.2) is always applicable.

Finally, the selfish strong bonding definition defines a conflict occurring only if these equations are simultaneously satisfied:

$$\begin{aligned} \frac{C(SNR_i)}{2} &> C(\mathrm{DL}_{\{i\}\leftarrow\{j\}}) \\ \frac{C(SNR_j)}{2} &> C(\mathrm{DL}_{\{j\}\leftarrow\{i\}}) \end{aligned} \tag{6.3}$$

All these strong bonding definitions allow us to evaluate the conflict between a pair of cells, and they can be used to construct a *conflict graph* which is a graph without weights defining whether there is a conflict between two cells or not. One example of such construction was previously shown in Figures 3.6 and 3.7.

One implementation note: In order to avoid signaling SNR_i and is SNR_j one option is to assume $C(\mathrm{SNR}_i) = C(\mathrm{SNR}_j) = C_{FREE}$ where C_{FREE} is the maximum capacity of channel free of interference, as it was defined in equation (3.2). In this case, one is simply assuming that SNR is high as it is often the case in femtocells.

6.5 Cooperative Set Formation

The formation of cooperative sets needs to take into account three aspects:

1. Which control messages FAPs exchange to negotiate agreements.

2. Which femtocells should be part of the same cooperation set.
3. How a cooperation set should allocate the resources.

The rules described in this section were designed to solve these three issues in a simple and efficient way. The process can be understood as follows. The FAPs are activated one by one as illustrated in Figure 6.2. In each step, the femtocell being activated is named the new entrant of that step. The new entrant needs to determine which neighboring FAPs should be considered as candidates for cooperation. Each candidate FAP should fulfill two conditions: it has an active session and it shares a strong interference bonding with the new entrant, as defined in section 6.4. If there are no candidates for cooperation, the solution is trivial: the new entrant FAP can reuse all channels.

If candidates are found the new entrant communicates with them with a simple protocol for the formation of a cooperative set:

1. The new entrant sends a Coordinated Transmissions Request (CTR) message to each candidate, which contains a list of all potential participants on the new cooperative set.
2. Each candidate answers with a Coordinated Transmissions Reply (CTY) which indicates channel allocation restrictions implied by existing cooperative sets. In addition to that, the message indicates whether any of the candidates already form a cooperative set among themselves.
3. The new entrant collects all the information from CTY messages. Then it can calculate the new allocation which is included in a Coordinated Transmissions Acknowledgment (CTA) message sent back to the candidates. This latter message confirms the formation of the cooperative set which then is completely formed. The new allocation can then take effect.

In order to reduce the complexity of the method, the rules described here were designed to cope with cases where the new entrant sends the CTR for at most two cooperation candidates. This choice can be justified by the prevalence of cliques up to cardinality three as illustrated in Figure 3.9. In the case of an isolated clique of size 4, these rules will still solve all conflicts but one. Another reason to restrict the maximum size is to avoid excessive subdivision of the resources, as previously explained in the example of Figure 3.10.

Given these assumptions SOCCER can be implemented using six simple formation rules, depending on two aspects:

- Whether there is one or two candidates for cooperation.
- Whether the candidates are already involved or not in previously formed cooperative sets.

The formation rules are summarized in the following sections.

6.5.1 Only one cooperation candidate

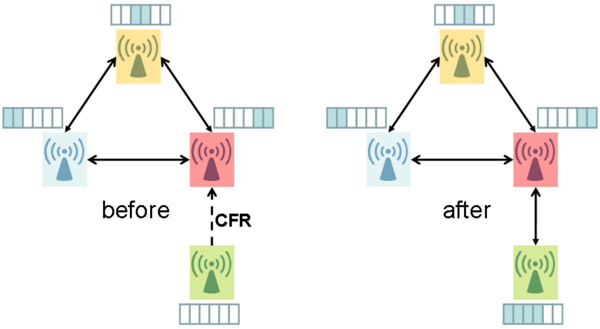
There are two sub-cases:

- If the cooperation candidate has no restrictions to allocation, the resources shall be equally divided. Therefore, both the new entrant and the cooperation candidate will have different halves of the channel set, precisely as in Fig. 6.1. This is called an augmentation rule, since the cooperative set grows from size 1 to size 2.
- If the cooperation candidate is already involved in other cooperation sets, the new allocation has to abide the existing restrictions. In this case, the new entrant can use all the sub-resources which are not already allocated by the cooperation candidate. Note that in this case the new entrant may have even more than half of resources, characterizing a “free rider” situation, illustrated in Fig. 6.4a. If the cooperation candidate has more than or exactly half the resources, then each of the parts shall allocate half of the channels as in the previous rule.

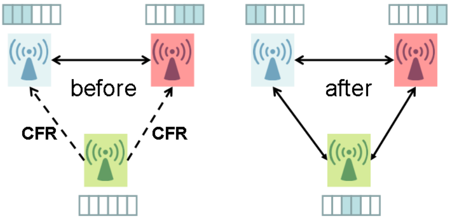
6.5.2 Two cooperation candidates

Here, there are four sub-cases:

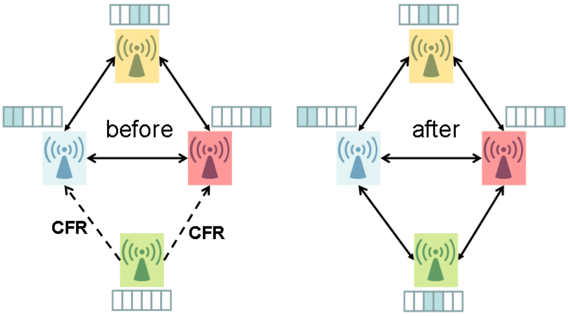
- The two cooperation candidates already cooperate between the two of them with no third party involved in this cooperation. In this case, the resources shall be divided equally amongst the three FAPs, augmenting the size of the cooperative set from 2 to 3 as shown in Fig. 6.4b.
- The two cooperation candidates are part of one or more cooperative sets with third party FAPs. In this case, the new entrant has to allocate exactly the same resources as the third party, and no changes are made to the resource allocation of the candidates. A new cooperative set is formed



(a) “Free rider” scenario.



(b) Augmentation: from a cooperative set of size 2 to size 3.



(c) Example of “Follow suit” cooperative set.

Fig. 6.4: Before: the new entrant sends a CTR to one or more strongly bound interferers. After: the cooperation is formed the resources are divided accordingly.

amongst the three involved parts, as exemplified in Fig. 6.4c. Because the new entrant simply copies the allocation of the third party, this rule has been named “Follow suit”.

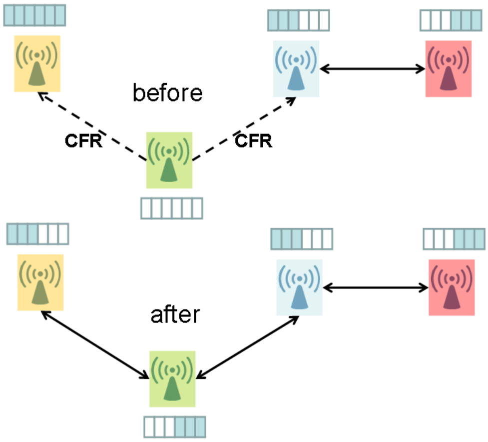
- The candidates do not cooperate yet and their allocations can be made compatible with the new entrant allocating half of the resources. In this case, the new entrant will form one cooperative set with each of them and will allocate half of the resources on the most efficient fashion. One example is illustrated in Fig. 6.5a.
- The candidates do not cooperate yet but their allocations can *not* be made compatible with the new entrant allocating half of the resources, due to restrictions imposed by other cooperations previously formed. In this case, the new entrant will form one cooperative set with each of them, but the channel set will be divided in the same way as if there was cooperation among all of them, i.e., in three equal parts, as shown in Fig. 6.5b.

6.5.3 Cooperative Set Formation Summary

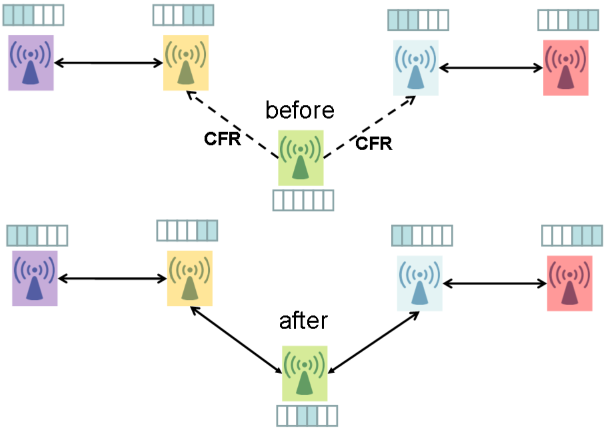
These six rules have been designed considering resource fairness, efficiency and solving all conflicts locally, i.e., up to the first tier of neighbors. This choice was made to reduce the need for signaling and the complexity of the underlying inter-FAP communication protocol, as well as avoiding reconfiguration storms. The main reason being that there is no straightforward way for a FAP to know how far it is from the edge of the network. If further communication is considered, e.g. with the second tier of neighbors, refinements are possible at the cost of increased complexity, e.g. the left- and rightmost FAPs in Fig. 6.5b could become free-riders.

Inspection of the SOCCER rules introduced in this section shows that:

- The channel allocation respects the mutual agreements among femtocells.
- All conflicts are solved locally, enforcing stability, i.e., only “neighbor” players may lose channels when a new player is activated.
- Any FAP which forms a cooperative set with the new entrant on will end-up with a subset of the channels from its previous allocation.
- The following invariant is kept: the new entrant and the candidates will reuse the whole spectrum. This invariant can be kept for all FAPs if the second tier of players can become free-riders.



(a) Two new cooperative sets which allow a compatible allocation.



(b) Two new cooperative sets. The allocation is restricted by previous cooperative sets and for this reason each cell needs to receive one third of spectrum instead of one half.

Fig. 6.5: Before: the new entrant sends a CTR to two strongly bound interferers. After: the cooperation set is formed the resources are divided accordingly.

- If possible, each femtocell in a clique receives the same share of channels.

Analysis of these rules can also show that the number of channels a particular cell will receive is one of the following: all K channels (if in no cooperative set), $K/2$, $K/3$ or $2K/3$ (in case of free rider). As a summary of the rules and a guide for practical implementation, SOCCER is summarized in algorithm 4.

6.6 Game Theoretic Modeling

The SOCCER algorithm was initially developed without resorting to game theoretic modeling. Notwithstanding the model introduced at this section not only formalizes the concept but also provides a generalization of the negotiation rules for the cases where the number of channels cannot be exactly divided into two or three parts.

The formation of cooperative sets is studied in coalitional GT [21]. However, the usual assumption for the most common models is that coalitions (cooperative sets) are disjoint. This is not the case in SOCCER. Also related to coalitional GT, NFG [23] model the interaction of players which can establish or sever many bi-lateral agreements. In section 6.6.1 NFG are presented. Then, section 6.6.2 discusses a sequential formation model which allows the analysis of SOCCER.

6.6.1 Network Formation Games

In *Network Games* the outcome of the game depends on a network of relationships among the players [23]. NFG deals with how such networks are formed, their efficiency and stability. If two players have a relationship they are said to have a link. Some network game models assume that mutual consent is needed to form a link. On the other hand, links can be terminated by unilateral decisions. As one may note, the nomenclature used in network games can be confusing to wireless engineers as the terms network and link have other well established meanings in our field. Hereafter the term bi-lateral agreement will be used instead of link to avoid any confusion with the wireless counterpart. In addition to that, networks will be qualified as *cooperation networks* when referring to the NFG concept of network.

A cooperation network is typically represented by a graph $g \in \Gamma$. The edges of the graph correspond to bi-lateral agreements. A value function v is a mapping $v : \Gamma \to \Re$, which is a measurement of the whole cooperation network

Algorithm 4 Self-Organizing Coalitions for Conflict Evaluation and Resolution (SOCCER)

```
# $i$ is this femtocell. Other femtocells are $j$ or $k$.
# $n_i$, $n_j$ and $n_k$ refer to the number of allocated channels.
# $K$ is the total number of channels (e.g. 12).
# $BIM_{thr}$ is the threshold in order to exchange BIMs.
for each neighbor $j$ do
    Measure $\mathrm{DL}_{\{i\}\leftarrow\{j\}}$
    if $\mathrm{DL}_{\{i\}\leftarrow\{j\}} < BIM_{thr}$ then
        Send $\mathrm{DL}_{\{i\}\leftarrow\{j\}}$ to $j$
        Request $\mathrm{DL}_{\{j\}\leftarrow\{i\}}$ from $j$
    end if
end for
for each new session do
    Select $nc$ candidates.          # See section 6.6                    .
    if $nc = 0$ then
        Allocate all $K$ channels.
    else
        Send CTR to the $nc$ candidates.
        Receive CTY from the $nc$ candidates.
        if $nc = 1$ then
            if The candidate $j$ is not part of any cooperative set then
                Allocate $K/2$ channels to $i$, and the other $K/2$ channels to $j$.
            else
                If $n_j > K/2$ remove channels from $j$ until $n_j = K/2$.
                Allocate to $i$ all channels which are not allocated to $j$.
            end if
        else if $nc = 2$ then
            if $j$ and $k$ already form a cooperative set of size $s$ then
                if $s = 2$ then
                    Reduce their allocation to $n_j = K/3$ and $n_k = K/3$
                    Allocate to $i$ all channels which are not allocated to $j$ or $k$.
                else if $s = 3$ then
                    Allocate to $i$ all channels which are not allocated to $j$ or $k$.
                end if
            else
                if Their allocations are compatible with reuse 2. then
                    $r \leftarrow 2$
                else
                    $r \leftarrow 3$
                end if
                Remove channels from $j$ and $k$ until $n_j = K/r$ and $n_k = K/r$.
                Allocate to $i$ all channels which are not allocated to $j$ or $k$.
            end if
        end if
        Send CTA with the updated allocation to the $nc$ candidates.
    end if
end for
```

productivity. The set of all possible value functions is denoted by V. The cooperation network value is divided among the players by means of an allocation rule. An allocation rule is a function $Y : \Gamma \times V \rightarrow \Re^N$ which defines a mapping from the cooperation network topology and possible values V to the final utility given to each player. Following the definition in [23], it is assumed that the allocation rule is *balanced*. This means that all the generated value v is allocated to the players, i.e., $\sum_i Y_i(g, v) = v(g)$, where Y_i is the utility allocated to player i.

So, how does the NFG framework applies to the SOCCER algorithm? Essentially, in SOCCER the players locally analyze a subgraph of the conflict graph, evaluated according to the rules explained in section 6.4. Then, using the formation rules from section 6.5 the players will attempt to resolve the conflicts as much as possible subject that at each step the new entrant will eliminate at most two conflicts. Note that the rules defined in section include the possibility of cooperative sets with more than two players. This difficulty can be overcome by defining a bi-lateral agreement if the two players are part of one or more cooperative sets. In this case, a cooperative set among three players implies a clique of size three in the cooperative network g.

A much more complicated issue is the characterization of the allocation rule. The nature of the spectrum sharing problem simply does not allow arbitrary divisions of the value v. Instead, each player shall be allocated a set of channels, and the player utility is simply given by the resulting sum capacity, as it was given in equation (3.7). While a full characterization of the allocation rule Y is difficult, each new entrant can estimate how it will affect v and consequently Y for its neighbors. This is the analysis approach taken in the following.

6.6.2 Sequential Formation

In SOCCER the formation of the cooperation network is sequential. The first FAP to be activated simply allocates all channels. At each step t, the new entrant can make agreements with the FAPs which were already activated. Let $g(t-1)$ denote the cooperation network at step $t-1$. Then $g(t)$ is formed by adding bilateral agreements between the new entrant and the players activated up to step $t-1$. Such activation of each player is naturally modeled as a dynamic game [73]. In dynamic games, there is a defined structure of decision points, named information sets. In an information set, a particular player is presented with a set of possible actions, and he must make a decision based on the information he has at hand. Dynamic games often are divided into smaller parts named *stages*. The activation of a new player starts a new game stage in this model. Each game stage can be described as follows:

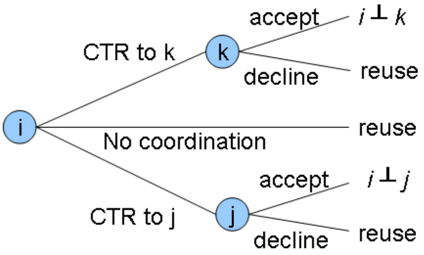


Fig. 6.6: Representation of a possible stage game. If two players agree to coordinate, then they will attain orthogonal spectrum allocation. Otherwise they reuse spectral resources.

- A player is randomly selected for activation. Using GT nomenclature this is a move made by *Nature*, i.e., a random movement the players do not have control upon.
- The new entrant can choose a subset of other players to send a CTR to.
- The existing players may accept or decline the CTR.

A game stage is exemplified in Fig. 6.6, where player i is being activated and players j and k were already active. An information set is represented by a circle marking the name of the player responsible for the decision. In this example, the new entrant i has three possible actions: send CTR to j, send CTR to k or do not coordinate transmissions, i.e., reuse the spectral resources. Upon request, player j or player k can decide whether or not to accept to form a cooperative set. In case a candidate accepts to form a cooperative set, an orthogonal allocation is established.

6.6.2.1 Strategies

In dynamic games, strategies are essentially a contingency plan of how to play the game on each possible information set [73]. Rational players are typically assumed to select their strategies on a purely selfish manner, i.e. attempting to maximize only their own utility. Under these assumptions, negotiations succeed and transactions take place only if the involved parties can achieve terms of agreement which are perceived as a win-win situation. However, there are counter examples of such selfish behavior from society [83] and nature [84]. For this reason, it was decided to investigate also different behaviors in order to understand how the femtocells perform when they attempt to increase their capacity selfishly, altruistically or balancing these targets. In the following analysis four different ways of selecting strategies are discussed, three of them directly related to the strong bonding definitions in section 6.4:

(i) *Selfish*: All players select their strategies according to the canonical GT assumptions, optimizing only their own instantaneous throughput.

(ii) *Selfless* new entrant: The new entrant intends to protect the existing players, and it is *selfless*. Other players still play selfishly.

(iii) *Max-min*: a pair of players will choose to cooperate if this is of benefit of the player with lowest incoming BIM, i.e, the existence of conflict is evaluated using equation (6.2).

(iv) *Max-sum*: A pair of players will coordinate transmissions if this decision is expected to increase their sum capacity compared to uncoordinated transmissions, guided by the evaluation of equation (6.1).

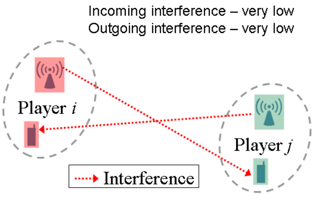
In order to provide a grasp of the implications of the way of selecting strategies, Figure 6.7 shows some example interference scenarios and the expected outcome for different player strategies.

6.6.2.2 Analysis of Selfish Strategy Selection

Henceforth, it is assumed that the players at a particular game stage t can only know about stages 1 to t. In other words, the players can not foresee if the game will have more stages or not. This seems to be a reasonable assumption since the players can not predict the arrival of new sessions in other femtocells in a non-causal way (see Figure 6.2). Therefore, selfish players making decisions at stage t will attempt to maximize their utility at stage t, regardless of future unknown implications.

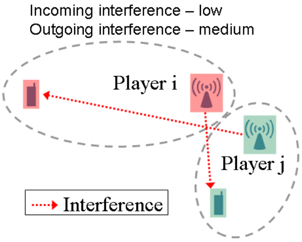
The analysis of dynamic games usually follows backward induction[73]. This essentially consists in predicting the behavior of the players in sub-branches of the game and then reducing the game. For example, in the game of Figure 6.6, one can analyze the expected behavior of players j and k and later analyze the expected behavior from i.

So, the first question is how active players are expected to behave when they receive a CTR from a new entrant? "To coordinate or not to coordinate? That is the question". Any rational player would be willing to coordinate transmissions with a new entrant, as long as this does not imply further losses in spectrum



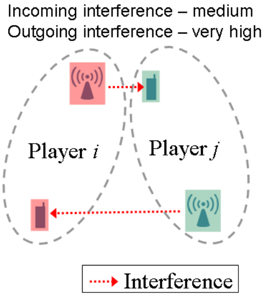
Strategy	Outcome
Selfish	Reuse
Selfless *i*	Reuse
Selfless *j*	Reuse
Max sum	Reuse
Max-min	Reuse

(a) Example Scenario 1 - Two players have little interference coupling. Regardless of the cooperation network formation strategy the players will reuse the resources.



Strategy	Outcome
Selfish	Reuse
Selfless *i*	Orthogonal
Selfless *j*	Reuse
Max sum	Reuse
Max-min	Orthogonal

(b) Example Scenario 2 - Interference coupling is highly asymmetric. If the players reuse the resources, player j will be severally affected but the gains to player i may be considerable.



Strategy	Outcome
Selfish	Reuse
Selfless *i*	Orthogonal
Selfless *j*	Reuse
Max sum	Orthogonal
Max-min	Orthogonal

(c) Example Scenario 3 - Interference coupling partially asymmetric and generally strong.

Fig. 6.7: Example scenarios of the behavior of different strategies.

allocation. After all, the less incoming interference the better. So any player j satisfying this condition with coordinated transmissions will cooperate:

$$Y_j(t) = Y_j(t-1) \tag{6.4}$$

This will be always the case when j is already allocated $K/3$ resources and the new entrant forms a new cooperative set with j , because $K/3$ is the minimum allocation considered in SOCCER and then the new entrant will not add any interference to these resources.

Nevertheless, If a player had full spectrum allocation in stage $t-1$, then it will not be that easily willing to donate spectrum to the new entrant on stage t. After all, under a fair spectrum allocation rule, coordinating transmissions with the new entrant would imply losing half of the channels. Let j be the player deciding about the coordination request from i. If j has full spectrum allocation, then i may expect j to cooperate if:

$$C(\mathrm{DL}_{\{i\}\to\{j\}}) \leq \frac{C(SNR_j)}{r} \tag{6.5}$$

where C represent the SINR to throughput mapping, r is the intended reuse in a cooperation set (2 or 3) and SNR_j is the signal-to-noise ratio (interference excluded) of player j. Essentially, (6.5) says that a selfish player will be willing to coordinate transmission if the SINR gain outweigh the spectrum losses.

The other cases can be evaluated also by using equation (6.5). If j has $K/2$ of the resources, it will at most lose 1/3 of the spectrum by forming new cooperative sets. Thus, evaluation of equation (6.5) with $r = 3/2$ can determine the willingness to cooperate in that case. Similarly, if j has $2N/3$ of the resources, the potential loss can be assessed by considering equation (6.5) with $r = 2$ or $r = 4/3$.

In short, a selfish existing player is expected to accept the coordination of transmissions if that does not imply any loss of resources or if uncoordinated transmissions would imply even larger losses than cooperation.

Note that in practice, the already active players know what were the bilateral agreements they formed in the previous stages, but the new entrant does not. The only way the new entrant can learn about it is by asking the other players. Thus, acquiring such information can be a waste of signaling capacity, and it would require a more complex protocol than the one presented in section 6.5 (which was designed with the max-min and max-sum strong bonding rules in mind).

Next, the expected behavior of the new entrant is analyzed. A selfish new entrant will try to extract the maximum from the new formed bilateral agreements. A rational new entrant will not send CTR to players that will certainly decline it and he can determine that by backward induction. Furthermore, if the new entrant does not engage on coordination with any player, he will be able to reuse the whole spectrum. Therefore, a new entrant will only consider making bi-lateral agreements to players which satisfy:

$$C(\mathrm{DL}_{\{i\}\leftarrow\{j\}}) \leq \frac{C(SNR_i)}{2} \tag{6.6}$$

The new entrant can not choose inadvertently an arbitrary number of players to send the CTR. In the devised rules the number of CTRs was limited to two. Hence, the new entrant needs to prioritize the players according to his own interests, i.e., in terms of incoming BIM. In summary, the steps which the new entrant need to perform to maximize his stage utility are:

1. Create an ordered list of the existing players in terms of incoming BIM.
2. Remove players which do not satisfy (6.6).
3. Remove players which do not satisfy at least one of the two: (6.4) or (6.5).
4. Send the CTR up to two players according to the list priority.

This summarizes the expected strategy of a selfish new entrant. Note that in step 3. he may have to acquire information of existing cooperative sets prior to sending the CTR, something that would make the protocol for the formation of bi-lateral agreements more complicated.

6.6.2.3 Analysis of Selfless Strategy Selection

In the second considered strategy the new entrant is selfless, while the existing players are selfish. Then, the new entrant has only to:

1. Evaluate equation (6.5) to decide which players would benefit from coordination. As an implementation simplification the new entrant can assume $r = 2$ in equation (6.5).
2. Order those players in terms of outgoing BIM.
3. Send the CTR up to two players according to the list priority.

The chosen candidates have no incentive to decline offers of cooperative set formation, since the new entrant selects them on their best interests.

One may ask why even to consider selfless strategy in a communication system. This a design present in practical systems. Listen before talk, used e.g. in CSMA/CA systems, is actually a selfless strategy. The assumed behavior is that a listen before talk system will defer transmission until the channel becomes free. Thus, a listen before talk system relies on the varying nature of traffic such that a deferring transmitter will ever have a transmission opportunity. On the contrary, the selfless strategy here is less radical and it can be seen as: the new entrant needs to transmit and he will transmit anyway. However he will attempt to choose the channel allocation in order to minimize losses to other players.

6.6.2.4 Analysis of Max-min Strategy Selection

Whenever a new entrant needs to access the spectrum, he will add more interference on the channels it chooses for transmission. Thus, the arrival of a new entrant can represent the addition of new edges in the conflict graph according to equation (6.2). Essentially, what the max-min strategy does is solving the strongest conflicts, regardless of their direction. By doing so, the players are effectively trying to maximize the minimum (*max-min*) throughput subject to these constraints:

- No player is allocated less than $K/3$ channels.
- At each step a maximum of two conflicts are eliminated.
- Making only local changes to the allocation.

The feasible candidates set is formed by selecting players which will satisfy the conflict condition expressed in equation (6.2) and sorting them accordingly, i.e. using the metric $min\left\{\mathrm{DL}_{\{i\}\leftarrow\{j\}}, \mathrm{DL}_{\{i\}\rightarrow\{j\}}\right\}$. If all players behave according to max-min policy, then the relation is symmetric and the existing players will reach the same conclusions as the new entrant. Therefore, the decisions made by the new entrant are also deemed sensible by the other players.

6.6.2.5 Analysis of Max-sum Strategy Selection

Maximizing the sum-throughput of a cellular network is no easy feat, especially using a distributed algorithm that has to cope with a random arrival of new sessions like SOCCER. Nonetheless, when the players are using the SOCCER rules with a max-sum strategy, they are attempting to accomplish exactly that: maximizing the value of the cooperation network. The analysis of an extreme case can provide some insight why such approach tends to rise the value of the cooperation network as long as SINR in each channel is kept high.

Consider the case where SNR is high such that if all conflicts are solved the capacity of the allocated channels is C_{FREE}. In addition to that suppose that the ordering of the players is such that no new entrant will ever face more than two conflicts, as evaluated by equation (6.1). Under these conditions all conflicts will be solved and the utility of a player j is given by:

$$Y_j(t) = C_{FREE} N_j(t) \tag{6.7}$$

Where $N_j(t)$ is the number of channels allocated for player j at the end of stage t. Then, in this case, the allocation rule from the NFG formulation matches the distributed channel allocation rules, and the value (at stage t) of the cooperation network $v(t)$ is given by:

$$v(t) = C_{FREE} \sum_{i=1}^{|\mathscr{I}|} N_i(t) \tag{6.8}$$

One can analyze the formation rules described in section 6.5 to understand how those rules affect the total number of allocated channels, and, consequently, the value of the cooperation network:

- When there are no conflicts, the new entrant will simply allocate all K resources, largely increasing the value of the network.
- Free rider and follow suit rules will add more channels to the new entrant without reducing the number of channels for the candidates. Thus, also when these cases happen $v(t)$ is expected to be greater than $v(t-1)$.
- In the two augmentation rules, the number of channels reduced from the candidates is at most , i.e., just the sharing of resources is changed from K to $K/2$ or $K/2$ to $K/3$. Consequently, augmentation will not change the value v.
- In the bridge cases, the candidates may have to abdicate more channels than the new entrant can allocate (but not necessarily).

Table 6.1: Summary of new entrant i behavior for different strategies.

Strategy	Prioritization to send a CTR	Equivalent Utility
Selfish	$C(\mathrm{DL}_{\{i\}\leftarrow\{j\}})$	C_i
Selfless	$C(\mathrm{DL}_{\{i\}\rightarrow\{j\}})$	$min(C_j), j \neq i$
Max-min	$min\left\{\mathrm{DL}_{\{i\}\leftarrow\{j\}}, \mathrm{DL}_{\{i\}\rightarrow\{j\}}\right\}$	$min(C_k), \forall k$
Max Sum	$\frac{C(SNR_i)+C(SNR_j)}{C(\mathrm{DL}_{\{i\}\rightarrow\{j\}})+C(\mathrm{DL}_{\{i\}\leftarrow\{j\}})}$	$\sum_k C_k$

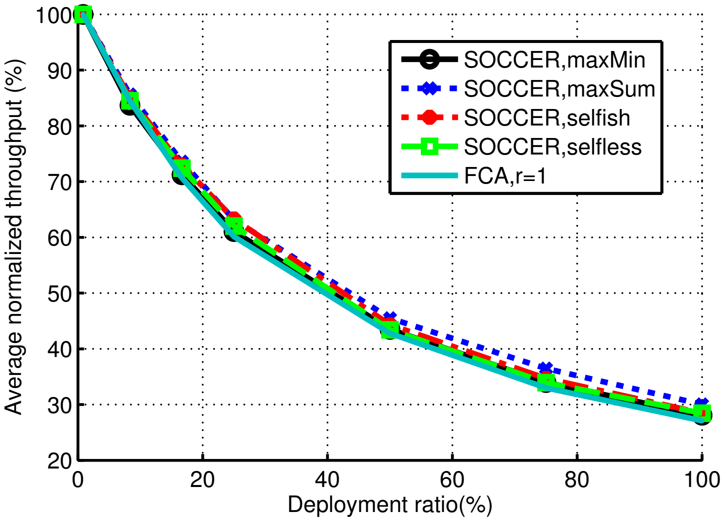
The latter case is more evident if two femtocells have K channels allocated and the new entrant has a conflict with each of them. For each channel allocated to the new entrant, two channels have to be removed from the candidates, i.e. one from each candidate. Thus, in such case it is simply a impossibility to have any channel allocated to the new entrant without reducing the value of the network. However it can be also the case that a bridge condition will not lead to a reduced value. For example, if the two candidates have allocated the same half of the channels, the new entrant can form a bridge by allocating the other half of the channel set.

So, in summary, the max-sum strong bonding rule will have a strong tendency to maximize the value of the cooperation network stage after stage, especially if there is a clear cut division of very strong interferers and weak interferers. Fortunately, this can be quite often the case.

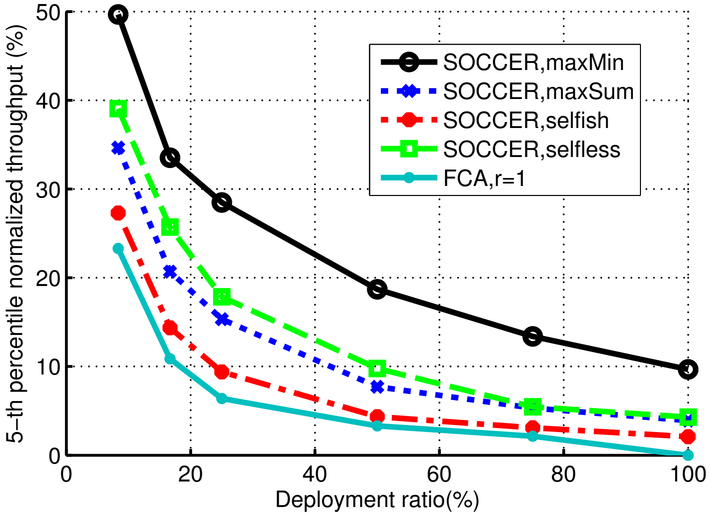
As in the max-min case, the max-sum strong bonding is a symmetric relation, and therefore the candidates are expected to always accept the decision done by the new entrant.

6.6.2.6 Summary and Equivalent Utility

In a similar way that was done in section 5.2, one can define new utility functions as a way to design a distributed optimization, even though the original optimization target was different. Such interpretation allows to describe the aforementioned strategies as equivalent utility functions. Table 6.1 summarizes the considered strategies and formalizes them by expressing an equivalent utility function. In Table 6.1 j is an already active player. k represents any player including i. C_k represents the capacity of player k, whereas $|\mathscr{I}|$ is the total number of players.



(a) Average throughput.



(b) 5^{th} percentile of throughput.

Fig. 6.8: SOCCER performance with different strategies/strong bonding rules.

6.7 Results

The performance evaluation scenario and main simulation parameters were previously described in section 3.5. The specific results shown here intend to:

- Evaluate the different strategies described in section 6.6.2.
- Compare SOCCER with the baseline results first presented in section 3.7.

Figure 6.8 shows the SOCCER results for the different strategies described in section 6.6.2 and the corresponding strong bonding rules used for conflict evaluation as discussed in section 6.4. The players have been activated in a random order.

First and foremost it can be observed that the canonical GT selfish strategy provides rather marginal benefits when compared to universal reuse, which entails no complexity at all: no need for signaling and no algorithm to make decisions. Referring to Figure 6.7, one can understand this behavior. Cooperation will only take place when the interference coupling is severe and "nearly-symmetrical".

Interestingly, a selfless approach renders much higher benefits in terms of outage improvement than the selfish one. This can be explained by the fact that players which are early activated will be protected from interference. Still, the best that can be done to improve the 5^{th} percentile of throughput is to consider the adverse effects of interference in both directions as it is done in the max-min strategy.

The selfless and max-sum approaches had some similarities of performance. This may sound unnatural in a first analysis, but it can be clearly explained. Referring to Table 6.1 the prioritization to send the CTR is essentially the same if $C(SNR_j)$ is the same for all j. Thus, in this case, the two approaches only differ in the evaluation of a conflict: in the max-sum case it is given by equation (6.1) and in the selfless case the conflict exists if femtocell j was activated before i and equation (6.5) holds for $r = 2$.

In the max-min approach the collaborative sets are formed much more frequently, as cooperation will arise whenever the network topology renders one cell less fortunate. The most outstanding result in Figure 6.8 is that the max-min enables to have excellent outage performance without degrading the average performance even when the deployment is very dense. The reader may refer to the comparison in chapter 7 and section 3.7 to verify that this was not the case for any other method. The improvement over reuse 1 is very significant. At a 75% deployment ratio, SOCCER max-min provided 525% outage throughput gain over reuse 1 while attaining the same average performance.

Regarding average throughput, the max-sum strategy leads to the best performance as expected. Nevertheless, the gains compared to reuse one and all other strategies are rather modest. Even at full load max-sum gain was about 11% more average throughput than reuse 1. At 25% deployment ratio, the average throughput gain was about 5%.

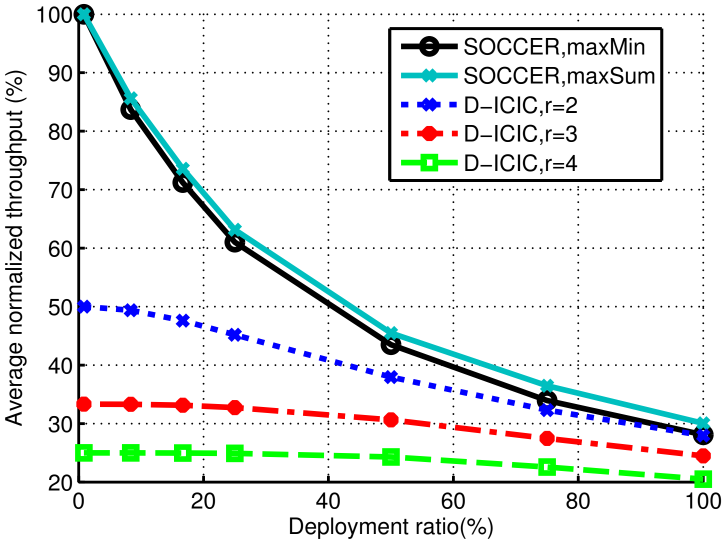
In terms of the two target KPIs, the max-sum approach Pareto dominates the selfish one for all deployment ratios. And the max-min is very close to Pareto domination of the selfless approach. For this reason, only max-sum and max-min strategies are considered hereafter.

Figure 6.9 compares the max-min SOCCER results to D-ICIC. As explained in section 3.7 the outage results of D-ICIC are consistent with the clique distribution in Figure 3.9 and for this reason the dynamic reuses 2, 3 and 4 given by D-ICIC are better for different deployment ratios. SOCCER max-min shows not only the adaptability to all deployment ratios, but it can achieve such performance without sacrificing average throughput. As one example, at a 75% deployment ratio SOCCER max-min 50% more average throughput than D-ICIC,$r = 4$ for nearly the same outage performance. Interestingly, this performance has been achieved without considering cooperative sets with 4 or more femtocells. Because SOCCER max-min will eliminate the strongest conflicts first, the results at 75% or 100% deployment ratio are closer in terms of outage to D-ICIC with reuse 4 than D-ICIC with reuse 3. The reason why becomes clear when seeing examples like the one in Figure 3.10.

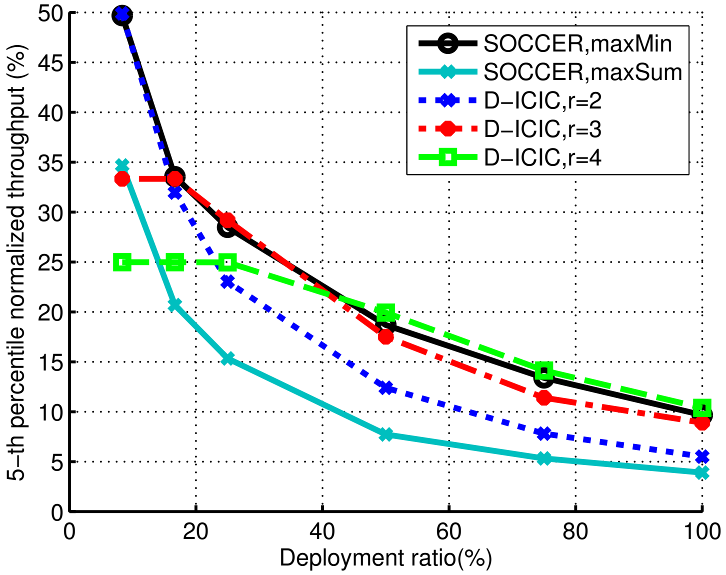
6.8 Conclusions

In this chapter a framework for the formation of cooperative sets was considered. Self-Organizing Coalitions for Conflict Evaluation and Resolution (SOCCER) is built upon some key components:

- Exchange of measurements, which characterize the interference coupling between a pair of femtocells.
- A protocol for message exchanging needed to establish coordinated transmissions.



(a) Average throughput.



(b) 5^{th} percentile of throughput.

Fig. 6.9: Comparison between SOCCER and D-ICIC.

- A set of rules on how the resources should be redistributed when some femtocell needs access to them.

With these components in place, a cooperation network can be sequentially formed, for example every time a new FAP is activated.

In order to investigate possible behaviors, different ways of categorizing conflict have been devised: selfish (win/win target), selfless (protect ongoing sessions), max-min (maximize outage throughput) and max-sum (maximizing sum throughput). If the femtocells seek to cooperate only in win/win situations, then little benefit is extracted from forming the cooperation sets. However, if each femtocell strives to maximize not only its own capacity but also minding the neighborhood then the target KPIs can be largely boosted.

While the channel allocation rules in SOCCER are remarkably simple, the achieved performance was very attractive, especially in terms of outage throughput when that is the optimization target. Interestingly, this can be accomplished without reducing average throughput. The SOCCER rules, by construction, preclude the possibility of reconfiguration storms and therefore, stability is assured. Fairness is attained whenever possible, without sacrificing efficiency. The signaling requirements are close to minimal and the exchanged information can be derived from typical standardized measurements. All these characteristics make SOCCER a strong candidate for practical implementation.

Chapter 7

Performance Comparison

7.1 Introduction

Throughout the thesis, many performance results were presented based on the simulation scenario described in section 3.5. Those results compared each specific proposed method with the baseline results established in section 3.7. The improvements over the baseline can be found in section 4.4 for TBRS, section 5.4 for GRACE and in section 6.7 for SOCCER. Naturally, the reader should be interested also on how the proposed methods perform compared to each other. This brief chapter provides such a comparison.

7.2 Comparison

The performance comparison of the proposed solutions is done in two steps. First GRACE is compared to TBRS. The best configurations of these two methods are then compared to SOCCER. The reason is that TBRS and GRACE share some similarities while SOCCER is from a completely different class of algorithm with other set of requirements.

TBRS has two parameters: the number of stages R and the SINR threshold T leading to several configuration possibilities as studied in section 4.4. As the weighting function for each channel is essentially one parameter, GRACE has a plethora of configuration possibilities. For these reasons, only three parameter configurations were selected to compare the two methods according to the following criteria:

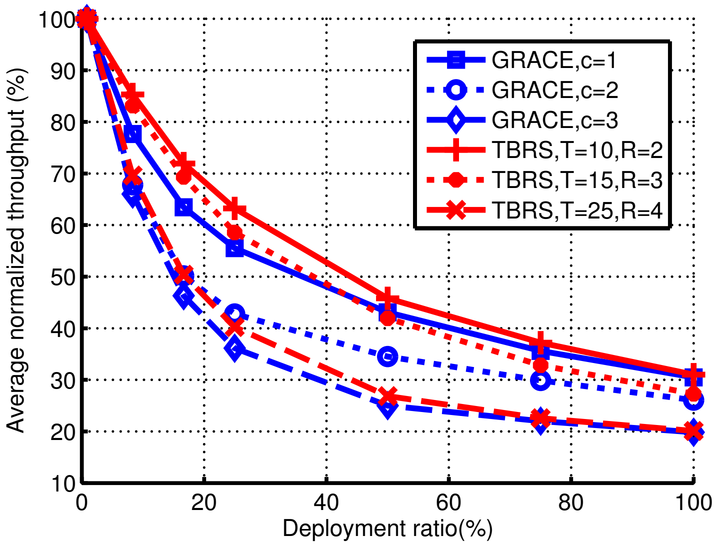
- The parameter configuration which led to the best average throughput at a 100% deployment ratio
- The set of parameters which could achieve the highest value for the 5^{th}-percentile of cell throughput, also at a 100% deployment ratio.
- One configuration which provides balanced performance of the two KPIs over all deployment ratios.

In case of TBRS these configurations correspond respectively to TBRS(2,10), TBRS(4,25) and TBRS(3,15). The three GRACE settings are the ones previously shown in Figure 5.6 and discussed in section 5.4.2. These results are compared in Figure 7.1.

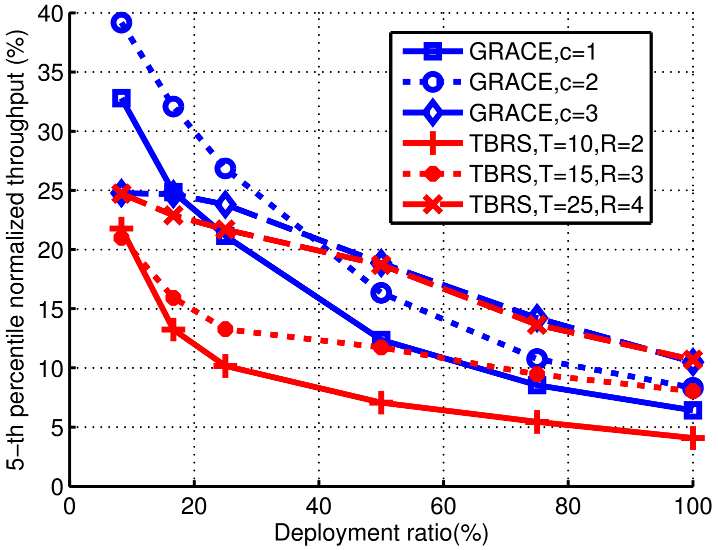
It can be seen that TBRS(2,10) achieves significantly higher average throughput than the other cases, at the cost of having the lowest outage performance. GRACE(case 3) and TBRS(4,25) are twin configurations with TBRS having a little advantage on average performance, and GRACE having the front edge on the 5^{th}-percentile. The similar performance of these two cases is not by chance. They both could be summarized as: at every frame allocate the best $N/4$ channels. Only allocate more channels if the quality is excellent.

The analysis of the remaining cases is not that straightforward, and for this reason a different perspective is taken in Figure 7.2 which highlights the trade-offs being made. Figure 7.2 was generated in the following way. Among these 6 configurations and for each deployment ratio the best performing case in a particular KPI was assigned a score of 1. The performances of the remaining cases were then normalized by dividing the KPI by the best performing case. In this way, one can have a grasp of the adaptivity of the methods for different deployment ratios and how well each case is performing compared to each other.

Now, analyzing Figure 7.2 it becomes clear that when GRACE(case 3) and TBRS(4,25) are compared to the other possibilities they are still excessively sacrificing average performance in order to obtain a high outage performance (even though they do better than D-ICIC in that regard, see sections 4.4 and



(a) Average throughput.



(b) 5^{th} percentile of throughput.

Fig. 7.1: Comparison between TBRS and GRACE for different configurations.

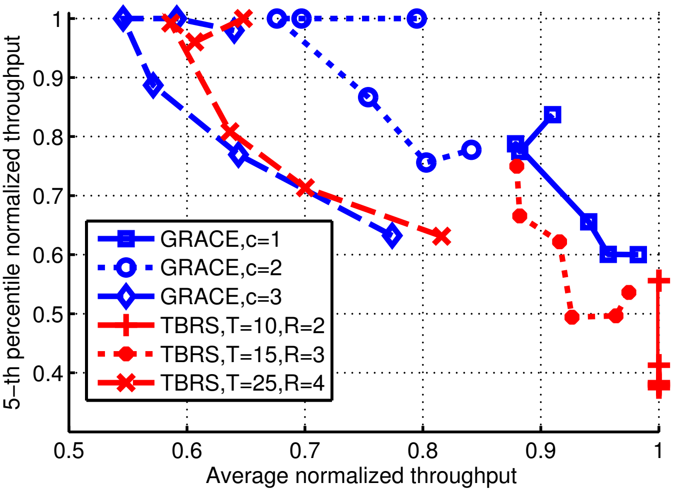


Fig. 7.2: Plot showing the trade-off of 5^{th}-percentile and average throughput for selected TBRS and GRACE configurations (normalized within this population for each deployment ratio). Up and right is the most desired performance in a CSG deployment.

5.4). Also, it can be seen in Figure 7.2 that GRACE does better on the trade-offs, while TBRS excels at finding the extremes. This behavior can be explained because of two key differences: 1) GRACE utility function, equation (5.13), does a non-linear trade-off while TBRS is based on an absolute threshold. 2) TBRS takes large steps going from one reuse to another (1,2,3 and 4) while GRACE can adjust channel by channel.

From the analysis of Figure 7.2, TBRS(2,10), GRACE(case 1) and GRACE(case 2) were selected to be compared with SOCCER. Akin to Figure 7.2, Figure 7.3 explicits the trade-off between the two KPIs, among the analyzed configurations. Figure 7.4 shows the average throughput and the 5^{th}-percentile of the distribution for these configurations.

TBRS(2,10) and SOCCER max-sum present top or close to top performance of average throughput for all deployment ratios. Actually, the difference of the two methods in this KPI should not be deemed as statistically significant given the confidence interval of the simulations. Nevertheless, for the same average throughput SOCCER max-sum can provide better outage performance at the lower deployment ratios. Thus, SOCCER max-sum gives preferable outcomes.

Comparing SOCCER max-min and GRACE(case 1) the story is pretty much the

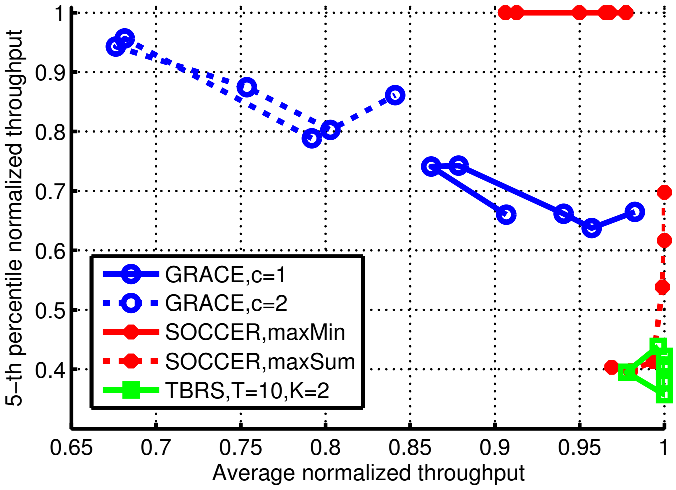
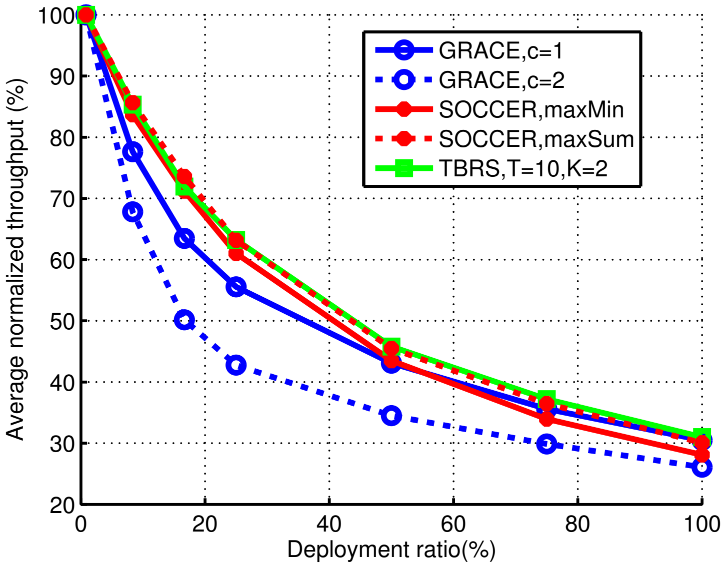


Fig. 7.3: Plot showing the trade-off of 5^{th}-percentile and average throughput for selected configurations of the 3 proposed methods (normalized within this population for each deployment ratio). Up and right is the most desired performance in a CSG deployment.

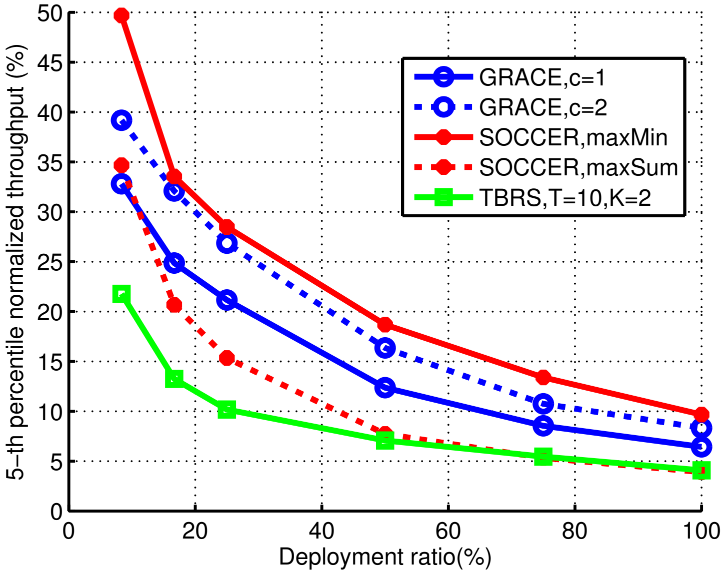
other way around. The two methods provide comparable figures in the average performance (note how the curves cross in Figure 7.4a) but SOCCER max-min can significantly extend the achievable throughput for the cells in less favorable conditions.

Since GRACE(case 1) and TBRS(2,10) were selected for their strong performance among many possibilities within the class of implicit coordination methods, then it is possible to conjecture that the extra gain from SOCCER is feasible due to the extra information available at decision. One can conclude that the case for explicit coordination is stronger if one should strive for both average and outage performance, as then SOCCER max-min shows the best trade-off of all methods investigated in this thesis.

Nevertheless, as discussed in [19] there can be some technical and non-technical aspects to prefer implicit coordination (co-existence) over explicit coordination, especially when doing spectrum sharing among different technologies. Consequently GRACE and TBRS can be more suitable in those cases. Also, the implicit coordination methods can, in principle, work in shorter time scales than the ones which use explicit coordination. This is due to the signaling latency from one cell to another.



(a) Average throughput.



(b) 5^{th} percentile of throughput.

Fig. 7.4: Comparison of one explicit coordination (SOCCER) with two methods of implicit coordination (GRACE and TBRS).

7.3 Conclusions

This chapter compared the performance of the three proposed solutions: TBRS, GRACE and SOCCER. The two implicit coordination methods, TBRS and GRACE can achieve high outage throughput by using settings which aggressively mitigate the interference. Nevertheless, such settings sacrifice average throughput excessively. When TBRS parameter settings are tweaked targeting more average throughput, the method reaches the other end of the possibilities. The average throughput is indeed boosted, but the outage performance is not so attractive anymore. GRACE can reach better intermediate trade-offs, but among the tried configurations none could provide the same average performance as TBRS.

SOCCER is from a different class of algorithms, with explicit coordination. Since SOCCER uses more information than TBRS and GRACE, a higher performance was expected. This was confirmed in the comparison. In particular, SOCCER max-min could deliver about 40% more outage throughput than GRACE(case 1) for similar levels of average performance. From all the methods and cases simulated in this thesis SOCCER max-min provided the best trade-off of the two target KPIs. Therefore, SOCCER max-min was the one best fulfilling the goals previously established in section 1.4.

Chapter 8

Conclusions and Future Work

8.1 Summary and Conclusions

Local area network deployment is expected to become increasingly important to provide mobile broadband because of the imminent spectrum scarcity. Reducing the cell size is one of the key tried and proved techniques to increase the area spectral efficiency. The importance of reduced cell sizes can even grow in the near future (section 1.3). Since femtocells are a relatively new frontier in cell granularity, the propagation and interference conditions can differ very much from larger cells. These facts motivates femtocell specific studies. The investigations in this thesis contribute to the emerging views on future femtocells.

Typically, in the initial femtocell deployments, intra-tier interference management is not a must due to the sparsity. Nevertheless, as the deployment density will increase smart channel allocation will be needed to guarantee a minimum quality for each femtocell (sections 1.3 and 3.7), especially due to unfavorable topologies created by CSG deployment.

Because of the massive number of cells to be deployed, and the ad-hoc (potentially end-user) installation, the traditional approach to frequency planning and optimization will fail to be cost effective or even possible.

Instead, self-organization of the channel allocation should be achieved with distributed Dynamic Spectrum Access (DSA) algorithms. These algorithms should dynamically select a set of channels for the operation of each femtocell striving to maximize the throughput of each cell.

In this thesis the focus is on the design of DSA solutions where each femtocell can make autonomous decisions. On the one hand, autonomous decisions minimize complexity and maximize the scalability to a very large number of cells. On the other hand, this decision structure place significant burden on how to achieve high capacity, fairness and stability. This work has overcome these difficulties to a greater or lesser extent these difficulties.

DSA starts to be considered essential to avoid the caveat of spectrum underutilization. Chapter 2 discussed several DSA aspects ranging from taxonomy to the latest advances, including closely related problems such as the channel assignment in cellular networks. In this context, it was discussed that to a great extent, DSA among femtocells can be seen as Dynamic Channel Allocation (DCA) with revised assumptions. While most of the DSA literature focuses on primary/secondary spectrum sharing investigate, this particular work focus on spectrum sharing among equals, which is a complementary approach. State of art approaches to the latter problem often focus on the allocation of a single channel or a fixed reuse, leading to the reduction of interference but not to a high channel utilization. Other algorithms may involve a lot of signaling among the cells, and some existing solutions lack the scalability to a large number of cells. These issues have been addressed in the proposals included in this thesis.

In chapter 3 the thorough analysis of the problem has given understanding from different angles. From a single link perspective, a link experiencing low SINR is very sensitive to quality improvements but links with high SINR have little benefit from interference reduction, especially due to MCS limitations (3.3). For this reason, a fine balance between interference avoidance and spectrum utilization needs to be found. Increasing the modulation order and MIMO order will extend the usable SINR range. Thus, such an analysis should be extended for the link level performance of the specific system.

When two or more links freely compete for spectrum access, the result is often destructive and reuse 1 can be expected from independent adaptations. When the interference between the two links is time correlated over time (a repeated game) there is incentive to achieve a better allocation. Even though the incentive exists, the different cells cannot certainly know about it without signaling among cells. One key contribution of this thesis was to define better ways of making independent decisions without the need for explicit signaling (chapters 4 and 5). The third piece of analysis shows that even though a large number of cells interact, the need of interference coordination is mostly characterized by the strength of interference and local interactions among neighbor cells. If the channel allocation is done smartly one can avoid excessively sparse reuses while solving most of the interference conflicts (sections 3.6, 3.7). In the investigated scenarios the outage performance can be enhanced by adapting among reuses 1,2,3 and 4.

Two different approaches for making decisions were considered (section 2.2): implicit coordination (chapters 4 and 5), i.e. based only on intra-cell information, and explicit coordination where femtocells can exchange measurements and negotiate the allocation (chapter 6). As expected, the latter can provide superior performance (chapter 7) at the complexity cost of introducing cell to cell control channel. For this reason, an implicit coordination method can, in principle, achieve higher spectrum agility than a explicit coordination one. Timeout Based Reuse Selection (TBRS) and Game-based Resource Allocation in a Competitive Environment (GRACE) showed very interesting performance in the class of implicit coordination methods (sections 4.4 and 5.4). They are based on iterative adaptations against the measured interference. A probabilistic approach can be used to avoid all cells changing their allocations at the same time [50]. When the femtocell decides to update the allocation, it can switch to different channels or also add and remove channels. In case of GRACE, these decisions are done in a combined way in each step by the calculation of an utility function. In TBRS most steps can only switch to different channels, selecting the least interfered channels, but when the interference is persistent a large removal of channels is performed at a single step.

It is intuitive that iterative methods should adapt to select the best channels, but it is also important to adapt how many channels are selected. In that respect TBRS and GRACE are examples that hard limits to spectrum utilization may not be needed. Instead, it is advisable to design methods which are able to adapt the total bandwidth but are conservative in face of interference, providing soft limits to spectrum utilization. Such methods can provide high outage throughput during congestion of dense networks while not excessively sacrificing the average capacity of non-congested or sparse networks.

The symmetry of interference information is usually regarded as important to provide interference avoidance using implicit coordination. At least in the simulated scenario, the symmetry of information did not prove to be essential (section 4.5). Nevertheless, symmetric interference assessment can help to improve the decisions and, in special, it makes easier to optimize the outage throughput.

GRACE is the design which is mostly rooted in Game Theory (GT) and it illustrates how GT can be used in a engineering approach as a basis for distributed optimization. Each player (the decision maker) greedily optimizes his/her own target, but the definition of this target will play a crucial role in the outcome of the adaptations. On the one hand, whenever the need for win-win perception has been imposed over the cell capacity, the gains from cooperation were rather limited (sections 3.4 and 6.7). On the other hand, it is possible to modify the utility function of each player so that the distributed decision making leads to improved global KPIs. For example, from a global point of view one may wish to maximize the throughput of each cell. However, that does not mean that the local target of each cell should be to maximize its own capacity. Instead, it has been found that each cell should seek to maximize utility functions which mind not only a single cell but also its neighborhood (sections 5.2 and 6.6.2.6).

Self-Organizing Coalitions for Conflict Evaluation and Resolution (SOCCER) is based on explicit coordination among femtocells and the method was presented in chapter 6. SOCCER is quite a different approach than GRACE and TBRS. Instead of making iterative decisions, the algorithm is applied once, e.g. whenever a new FAP is activated. As such, the provided allocation is stable for the lifetime of a session. The building blocks of such approach are: exchange of measurements which characterize the pairwise interference, evaluation of interference conflicts, exchange of messages to negotiate the formation of cooperative sets and the definition of how the channels should be allocated within a cooperative set.

In general, the proof-of-concept simulation results show that all the proposed concepts, namely GRACE, TBRS and SOCCER, can effectively be used to largely improve the 5^{th}-percentile of cell throughput over a reuse one configuration (sections 4.4, 5.4 and 6.7). For example, at 75% deployment ratio the outage performance gains over a reuse 1 configuration can exceed 500%. Fixed frequency reuses and a state of the art DCA method are also capable of providing large outage gains (section 3.7), but they pay a high price in terms of average throughput, especially at low deployment ratios. Interestingly the proposed novel solutions are capable of delivering much more average throughput than such alternatives while attaining the desired outage performance.

In the investigated simulations scenarios there seems to be little room for extra average capacity compared to a reuse one approach. A more efficient trade-off which can be accomplished is to increase the outage throughput as much as possible without sacrificing the total capacity. Such trade-off was more easily achieved by SOCCER and GRACE (chapter 7). Still, if average throughput would be the key goal, as conceivably it could be the case for OSG deployment accompanied of efficient load balancing, both SOCCER and TBRS can achieve this target (chapter 7).

8.2 Recommendations and Guidelines

SOCCER due to the simplicity, attractive performance and inherit stability is the most recommended for a practical implementation. Furthermore SOCCER has no parameters (no need for optimization) and the signaling requirements are relatively low. Nevertheless, one would need to standardize the exchanged messages for measurements and cooperative set formation as well as the behavior, i.e., pre and post-conditions after the reception of each message. If such standardization is possible, the benefits of an algorithm like SOCCER could have widespread reach. Otherwise, the algorithm is still feasible as a vendor specific solution which could be implemented for example in a private commons or as a self configurable enterprise solution. The max-min approach is suggested.

Algorithms like GRACE and TBRS are, in general, recommended when algorithms based on explicit coordination are not feasible. There can be a number of reasons for that:

- Total absence of control channel or interfaces among cells, especially in inter-operator sharing (due to trust issues).
- Gridlock on the standardization of explict coordination methods.
- Spectrum sharing among different RATs.

The standardization needs for GRACE or TBRS are less stringent. In principle several algorithms based on this principle of autonomous selection, e.g. GRACE, TBRS and D-ICIC could co-exist over the same set of channels as implementations from different vendors. The most important aspects to standardize in this case would be: time and frequency (channel) granularity and real time measurements fed back to the FAP. The latter are often available as channel information reports used for scheduling. It is highly advisable that the measurements are filtered prior to being passed to the decision algorithms. In this way allocation fluctuations can be mitigated.

In order to avoid implementations which just select all channels regardless of neighbor cells, one could also standardize policies which define the maximum number of channels that can be used given a particular measured interference profile. As discussed in section 4.6 , these should not be absolute limits. Otherwise this would unnecessarily cap the system capacity. Instead, the limits should be demanding, but based on the measured interference.

In addition to the aspects discussed above, here are a few recommendations to designers of systems and algorithms, and researchers trying to solve problems which are similar to the one in this thesis:

- **Strive for the right balance between spectrum utilization and efficiency**: on the one hand if too many channels are allocated each cell becomes interference limited and capacity is limited. One the other hand if too few channels are allocated the spectral efficiency of each transmission is high, but the system becomes bandwidth limited. Find the best trade-off.
- **Understand the interference scenario given by the topology**: if one can understand the potential gains, the relative strength of interferers and the graph aspects (e.g. cliques) one can tailor algorithms for the particular topology.
- **Use information measured at the receivers**: a channel selection method which uses measurements fed back by the receiver can make better decisions than one based only on transmitter side information. The presence of information from the communication peer is very important. Information about potential interference victims also facilitates the allocation decisions.
- **Minimize the need of information exchange**: incautious application of the previous recommendation may certainly lead to overshoot. One should never forget that the addition of more information exchange in the design quickly increases the complexity and the extra value which can be obtained from extra information will likely face diminishing returns.
- **As simple as possible, no simpler**: As a generalization of the previous two recommendations, one should keep adding complexity as long as the gains justify such addition. When additional gains are only found by disproportionate complexity increase it is likely the time to step back in the design. In practice, high complexity is hardly justified by optimality. Any algorithm or existing communication system will break in extreme scenarios.
- **Fairness and flexibility involve divisibility**: when the total number of channels in the band is small it becomes very important how the band is divided. For example, how to share 2 channels among 3 cells? Or how to share 3 channel among 2 cells? These simple and practical examples state the issue. There are two key ways out of this problem: make the number of

channels large (flexibility) or make the total number of channels divisible by common reuses (e.g. define 6 or 12 channels). The latter option could help to minimize complexity.

- **In case of iterative methods**: use probabilistic updates in order to avoid the need for communication among cells.

8.3 Future Work

8.3.1 Advanced Evaluation and Prototyping

The evaluation of communication systems is rather complex and in the concept development phase it is impossible to capture all the nuances that can arrive due to complex cross-layer interactions. For example, what is the effect of the variable bandwidth provided by DSA algorithms to Transmission Control Protocol (TCP)? What is the actual improvement of end-user experience provided by DSA? How do different packet schedulers interact with different DSA algorithms? Those are questions which were beyond the scope of this work, nonetheless they are very important questions. Future work should address them.

At the same time, it is impossible to predict all the needs and the details of implementation of a particular algorithm only with system-level simulations. For this reason, prototyping the DSA algorithms in hardware testbeds is an essential step towards the practical implementation of such frameworks. The fine details of real-time processing, shared memory access, multi-threaded implementation, etc should not be overlooked.

Also related to prototyping, it was taken for granted that measurements can be taken. When and how the measurements are performed will make a difference to the overall performance of the DSA algorithms. Reference points for measurements and standardized ways of reporting are also important to be investigated.

8.3.2 More Advanced Transmission Schemes

Among the assumptions taken in these work, in section 3.2, a important one was to assume that the interference is treated as noise. Such assumption allows us to use the AWGN model for the evaluation of capacity and as a consequence increasing interference is always deemed as detrimental. However, this does not necessarily need to be the case. When the interference signal is much stronger than the desired signal it is possible to use the information of the interference signal in order to increase the probability of decoding the desired signal. Practical implementations of such concept include advanced receivers capable of doing interference cancellation. The feasibility of implementing interference cancellation usually depends on specific conditions of signal alignment and synchronization. Notwithstanding, interference cancellation is increasingly being used in modern systems.

Future work including more advanced receiver modeling should be focused, but not limited, to:

- Comparison of advanced receiver performance as an alternative to DSA.
- Evaluation of existing DSA algorithms combined with advanced receivers.
- Design of specific DSA algorithms suitable for implementation together with advanced receivers or modifications of the existing algorithms to cope with such combination.

For example, in the design GRACE algorithm it was assumed that interference effect on capacity was negative. Then such effect was reinforced so that a femtocell would avoid transmitting in a channel which is highly interfered. Nevertheless, in case the interferer can be canceled it should be quite the opposite. The receiver should decide to reuse the strongly interfered channels if the interference can be canceled in order to boost the total spectral efficiency. Such interaction may make the convergence tricky as it could be that one of the receivers is able to decode the interference from the other but not vice-versa.

Likewise, other special transmission and reception schemes such as network MIMO [33] could be considered for future work.

8.3.3 Other Topologies

Mobile networks are increasingly incorporating some elements of other topologies than purely cellular. For example relay nodes which can be used e.g. for self-backhauling or Device-to-device (D2D) communications [85] are expected to play larger roles in the future. When such richer forms of communication are present, many of the assumptions taken for the work of this thesis have to be revised. For example, the usual approach of system-wide duplexing orthogonality may have to be abandoned. At the same time, new restrictions in channel allocation can apply as often communication nodes are not able to transmit and receive at the same time.

In a scenario with more flexible topologies, channel access method, duplexing, scheduling and interference management will interact in more subtle ways. As such, further investigation is needed in order to establish the division of responsibilities among nodes as well as suitable algorithms with sufficient scalability and manageable complexity.

List of Acronyms

1G 1^{st} Generation

2G 2^{nd} Generation

3GPP the Third Generation Partnership Project

ACI Adjacent Channel Interference

AP Access-Point

AWGN Additive White Gaussian Noise

BIM Background Interference Matrix

BRD Better-Reply Dynamics

BS Base Station

CA Carrier Aggregation

CC Component Carrier

CCI Co-channel interference

CD Code Division

CF Cognitive Femtocell

CR Cognitive Radio

CS Circuit Switched

CSG Closed Subscriber Group

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

CTA Coordinated Transmissions Acknowledgment

CTR Coordinated Transmissions Request

CTY Coordinated Transmissions Reply

D2D Device-to-device

D-ICIC Distributed Inter-cell Interference Coordination

DCA Dynamic Channel Allocation

DCF Distributed Coordination Function

DSA Dynamic Spectrum Access

FAP Femtocell Access Point

FCA Fixed Channel Allocation

FCC Federal Communications Commission

FD Frequency Division

FDD Frequency Division Duplexing

FDM Frequency Division Multiplexing

GSM Global System for Mobile Communications

GT Game Theory

GRACE Game-based Resource Allocation in a Competitive Environment

HCA Hybrid Channel Allocation

HARQ Hybrid Automatic Repeat reQuest

IA Interference Avoidance

ICIC Inter-cell Interference Coordination

IEEE Institute of Electrical and Electronics Engineers

IMT-A International Mobile Telecommunication – Advanced

INR Interference to Noise Ratio

ISM Industrial, Scientific and Medical

ITU International Telecommunications Union

KPI Key Performance Indicator

LA Link Adaptation

LTE Long Term Evolution

LTE-A LTE Advanced

MA Multiple Access

MCS Modulation and Coding Scheme

MIMO Multiple Input Multiple Output

NBS Nash Bargaining Solution

NE Nash Equilibrium

NFG Network Formation Games

OFDMA Orthogonal Frequency Division Multiple Access

OSG Open Subscriber Group

PRB Physical Resource Block

QoS Quality of Service

PS Packet Switched

PSNE Pure Strategy Nash Equilibria

RAT Radio Access Technology

RRM Radio Resource Management

RS Reference Signal

RSRP Reference Signal Received Power

SC-FDMA Single Carrier Frequency Division Multiple Access

SFR Soft Frequency Reuse

SISO Single Input Single Output

SINR Signal to Interference plus Noise Ratio

SIR Signal to Interference Ratio

SNR Signal to Noise Ratio

SOCCER Self-Organizing Coalitions for Conflict Evaluation and Resolution

SU-MIMO Single-user MIMO

TBRS Timeout Based Reuse Selection

TCP Transmission Control Protocol

TD Time Division

TDD Time Division Duplexing

TVWS Television White Spaces

UE User Equipment

U-NII Unlicensed National Information Infrastructure

UMTS Universal Mobile Telecommunications Systems

WLAN Wireless Local Area Network

WRC World Radiocommunication Conference

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