KTH Electrical Engineering

Coexistence and Competition in Unlicensed Spectrum

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Doctoral Thesis
Stockholm, Sweden 2005

TRITA-S3-RST-0518
ISSN 1400-9137
ISRN KTH/RST/R–05/18–SE

KTH Signals Sensors and Systems
SE-164 40 Kista
SWEDEN

Akademisk avhandling som med tillstånd av Kungl Tekniska högskolan framlägges till offentlig granskning för avläggande av teknologie doktorsexamen fresdagen den 2 dec 2005 klockan 14.00 i C1, Electrum, Kungl Tekniska högskolan, Isafjordsgatan 22, Kista.

Tryck: Universitetsservice US AB

Abstract

Spectrum regulation is tricky and until recently the methods used for almost a century has sufficed. But as wireless communication has increased the demands on spectrum has increased. The regulators have responded by relaxing the current regulatory framework as well as opening up more bands for license exempt or unlicensed operation.

In unlicensed spectrum users can be expected to act greedily and possibly also break etiquette rules. Using game theory we find that in most cases a user benefits form acting greedily and this decrease total system capacity. It is possible to deter a user from cheating by applying punishment to the user. This function should preferably be incorporated in the access network.

We also study the case of networks competing in unlicensed spectrum and find that the most successful network is the one with lowest quality guarantees and with the most dense access network. In the case studied here the greedy behavior of the networks increases the spectrum utilization.

We also evaluate a number of cases where two networks that cooperate in unlicensed spectrum. Isolation between the networks is the key factor to achieve better performance than splitting the spectrum.

The evaluations are carried out using numerical experiments and game theory. Game theory ia a powerful tool for modelling coexistence problems in unlicensed spectrum, but the systems are too complex to allow a fully analytical treatment.

Acknowledgements

No thesis is ever written in a complete void, there are always people who has in some way or other contributed and deserves thanks.

Friends and colleagues at the radio communication systems group have been a great source of help and inspiration. I'd especially like to thank Ben Slimane who has always helped me explaining the intricacies of coding and modulation, Magnus Lindström who always had time for a chat and Lise-Lotte Wahlberg for help on all administrative matters.

A special friend and colleague is of course my advisor Prof. Jens Zander who besides guiding me on the winding path to a Ph.D. thesis also have provided encouragement and who has never lost faith in me.

My co-software-author Magnus Almgren also deserves thanks for helping me keep in touch with the real world out there.

Although doing research and discovering new things may be a reward of its own a researcher has to eat as well. The funding of most of this research work has been provided by PCC. For this I'm most grateful and I hope that the millions you spent on this book was well invested money. I'd also like to thank the PCC director Johan M. Karlsson for urging me forward in my research.

PCC has not only provided money, but has also given me the opportunity to get to know and work together with other brilliant people. I'd like to thank you all for fruitful collaborations and wild discussions over a beer in the late hours. I'd specially like to mention Maxime Flament, Matthias Unbehaun, Rickard Stridh, Jiang Wu and Aurelian Bria.

Writing a thesis is a demanding task and this thesis could not have been written without the support and understanding of my family. Karin, Eskil, Ellen and Ester, I love you.

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Chapter 1

Introduction

When Marconi invented radio over hundred years ago he could probably not imagine the effects that his invention would have on society. The technology has evolved from something that was only used by a select few in special situations to something that everyone has access to. Today owning a mobile phone is almost part of human rights.

To use a radio we need spectrum. Spectrum is a resource that cannot be seen, cannot be touched and one that cannot be depleted. Yet it is not infinite and the increased use of mobile communications has created an increasing need for spectrum.

Spectrum regulation is about ensuring efficient use of the spectrum. Until recently the methods invented for spectrum management almost a century ago have sufficed, but the last decade with increased use of wireless communications and increased demand for spectrum has forced regulators to make modifications to the methods used. One such possibility is to release spectrum for unlicensed use and this has become quite popular.

However, unlicensed spectrum creates new issues. The general problem is to ensure that the radio spectrum is used in an efficient way even though the spectrum is “free” and thus there is no incentive to the individual user to be careful with how much radio resources are used. In this thesis we analyze a few cases of operations in unlicensed spectrum and find ways to ensure efficient use of the spectrum as well as check some of the available tools for analyzing the problems at hand.

1.1 Spectrum scarcity?

There is a large body of research based on the assumption that spectrum is a scarce resource. Indeed that has been the prevalent paradigm of the last 100 years in radio resource management. But with the advent of modern radio design and new components the spectrum scarcity may be an artificial limitation. The question whether spectrum really is scarce or not remains open and the definitive answer will not be given in this thesis. However, there are some arguments that support the spectrum scarcity:

- Even though the radio spectrum is infinite, there are practical limitations to what is achievable. There is a limit to frequencies that can be handled by low-cost RF components.

- The propagation characteristics of different wavelengths put a limit to available spectrum suitable for mobile communications[1].

- More available spectrum generally reduces the amount of fixed infrastructure needed. Thus, more available spectrum translates into less infrastructure and thus lower cost. Using this argument is will always be necessary to utilize the spectrum efficiently[2].
- The spectrum prices for 3G licenses would suggest that there is indeed a shortage. In a market with infinite supply the price goes to zero and since the spectrum price is nonzero (actually far from)[3][4] the supply cannot be infinite.

The reasoning around spectrum as an unlimited resource usually follows these lines:

- Measurements suggest that only a few percent of the spectrum is actually in use at any moment[5][6][7]. Thus, there is room for at least an order of magnitude increase in spectrum usage. This can be viewed as an almost unlimited amount of extra spectrum.
- There may be models for infrastructure deployment that makes the access points ubiquitous, for example, one access point in every lamp. In this scenario the key bottleneck will not be spectrum availability.
- In areas where spectrum is scare there is likely to be many users. But this may not be a problem since we can let all users act as relays and thereby increase the available capacity. Thus, the greater the need the more available capacity[8].

Despite the arguments for the spectrum as an unlimited resource the current view is that there is indeed a shortage. The cause for this is that the spectrum has already been split into bands and there are exclusive licenses awarded to various users. These licenses have been awarded for a long time and thus it is difficult to find spectrum for launching new services. In addition what the spectrum can be used for is regulated international treaties make changes in the spectrum plan quite slow. Which also makes changes to how spectrum is used slow.

Obviously to determine if there really is a spectrum shortage is not an easy task. In this thesis we assume that spectrum is a scarce resource and use that as a motivation for studying the problem of users or operators competing for that scarce resource.

1.2 Regulators

Since the radio spectrum is perceived to be a scarce resource the regulators have been given the task to ensure efficient use of that resource. For example, the regulator in Sweden should ensure efficient utilization of the radio spectrum and ensure a functioning market for communication services[9]. They should also ensure that the communications are reasonably free from interference[10]. The rules for equipment should be also clear[11]. The task for regulators in other countries tend to be similar. The aim of the regulator is to ensure that the radio spectrum is used to benefit society as much as possible.

The regulatory framework in place today can be traced back to the earliest days of radio. In the beginning of the previous century when radio communication started to become popular interference among transmitters became a problem. In 1906 the first International Radiotelegraph Conference was held and the first version of the radio regulations was signed. CCIR (International Radio Consultative Committee) was created in 1927 and the same year the first frequency plan was made. CCIR merged with CCIT (International Telegraph Consultative Committee) in 1932 to form ITU (International Telecommunication Union). In 1947 ITU was made a specialized agency of the United Nations[12].

Today on the international level the use of spectrum is governed by the Radio Regulations (RR), which is under the control of ITU. The main purpose of RR is to ensure that the use of spectrum in one country does not cause harmful interference in another country[13]. On the regional and national scale there are similar agreements and rules. The overall aim is to ensure that interference can be avoided.

The general rule is that a license is required to operate a radio transmitter. The license may specify a number of things, e.g., the location of the transmitter, the output power, what the transmitter is going to be used for, what time the transmitter is going to be used and so on. The licence also specifies the for how long the license is valid [14] if and how payments for the license are to be made and so on. The license is issued by the (national) regulator. The idea is to give the regulator the tool to ensure efficient use of the radio spectrum. By being careful when issuing the licenses it is possible to avoid harmful interference.

The current spectrum allocation mechanisms are made for very simple transmitters and the planning is done to ensure that the one who has the rights to spectrum is not disturbed by anyone even in worst case scenarios. Thus, there must be a large amount of safety margins, which results in a lot of mostly unused spectrum.

Another problem with the current spectrum management regime is the slow changes in the regulatory framework. Since changes in spectrum allocation are decided by consensus the process of changing allocations are time-consuming to say the least. In addition licenses have been awarded for long time periods since deploying infrastructure is a long term project that needs some stability in the spectrum allocation. Also the use of spectrum has been strictly controlled to simplify interference predictions.

There seems to be a common understanding in the spectrum management community that technological developments have made the current framework for spectrum management cumbersome and a bit outdated[15]. There are initiatives on the way to adapt spectrum management to the current requirements.

1.3 Unlicensed spectrum

One trend in changing the regulatory framework is to make spectrum available to anyone as long as they follow some basic rules[16]. These license exempt bands have attracted new types of applications where the communication distance is short and the devices are numerous. The most successful examples may be WiFi and Bluetooth devices. Their success has generated an interest in opening more bands for unlicensed operation. Other examples of popular unlicensed applications are PMR 446 and 27 MHz (CB) voice communication radios.

Usually a license is needed to use a transmitter, but there are exceptions. The frequency bands where it is possible to transmit without a license are commonly known as unlicensed, free or perhaps more correctly license exempt bands. Even though no license is required the transmitters must still follow specific rules.

In some sense a GSM phone is an unlicensed transmitter since the owner of the phone does not have to obtain a permit. Instead it is the telecom operators that are given a license to operate the access network. The previous example may not be what first come to mind when unlicensed bands are discussed. Rather it is the ISM (Industrial Scientific and Medical) bands that comes to mind. The ISM bands was originally created to have pieces of spectrum to place devices that cause harmful interference. Examples are this kind of devices are radio frequency heaters used for welding, medical heating devices and so on. Even though these bands from the beginning was designated as “garbage” bands they have also been used successfully for communication purposes. The typical example of a license exempt band is the 2.4 GHz band. There are few rules that must be followed when operating a transmitter at these frequencies. Both infrastructure types of transmitters and mobile transmitters can use this band. Almost any service and any technology can be used. There are only rules on the maximum transmitted power and the out of band emissions to protect services in adjacent bands[17].

One of the major benefits of unlicensed spectrum is that it allows anyone to quickly deploy services. For the operator there is no need to obtain a (possibly expensive) license. For the equipment manufacturer the potentially very long standardization procedure in the ITU can be avoided. New markets are also opened up since private persons can purchase and operate radio equipment directly from the manufacturer. Of course when studying the issues closer there are other factors as well that comes into play. For example, standards serve a purpose since they allow devices to interoperate and they facilitate competition. Type approval can be expensive and thus creates entry barriers for new manufacturers. However, the success of WiFi illustrates some of the possibilities of unlicensed spectrum.

One drawback is that a band which has been released for unlicensed operation is difficult to reclaim for licensed use again. Since there is no control of who owns transmitters, it is difficult to know when the band is not used anymore. One way to assess this is to look at when equipment anymore and add some reasonable lifetime of the equipment.

When the regulator release a piece of spectrum and set the etiquette rules it is difficult for the operator to control the spectrum any more. The only control the operator has over the spectrum is the etiquette rules and thus it is important to get these right. Relaxed rules are good since they allow using new technological advances. Users are not locked into a specific standard and it is possible for the market forces to find the best solution. However, the good thing with strict rules is that they give the regulator more control and the possibility to forbid unwanted behavior.

1.4 Unlicensed spectrum research issues

One fundamental difference with unlicensed spectrum compared to licensed spectrum is that users do not necessarily share the same objective. Each user may be purely egoistic and want to communicate as much as possible to receive as much satisfaction without considering the other users that use the same piece of spectrum. This is fundamentally different from a piece of licensed spectrum where the license holder has one objective which he tries to achieve.

In addition to the objectives of the individual users there is the wish of the regulator to ensure efficient use of the spectrum resource. The objectives of the actors do not (always) coincide and there is a tension between the actors that creates a number of interesting research issues.

For a single user the relevant research issue is to determine what actions a users should take to best achieve his objectives. Examples of decisions that need to be made are when to transmit, what power to use as well as selecting waveforms, frequency etc. These actions may or may not be influenced by the actions of the other users in the same frequency band.

Although the objective of the regulator is reasonably clear it it difficult to measure since the definition of efficient spectrum usage varies widely. The definitions range from pure technical measures to something that benefits society the most.

The tool that the regulator has for ensuring efficient spectrum usage is the rules that users must follow. The rules should ensure that a system does not interfere with other systems and also make it less susceptible to external interference[18].There is a tradeoff between the complexity of the rules and the performance that can be achieved. Complex rules can result in high (technical) spectrum efficiency, but may limit innovation and increase the cost of the devices. Few rules on the other hand may result in poor spectrum efficiency.

Another issue is related to breaking the rules. If the possible gains that can be obtained for an individual user that breaks the rules are high it is more tempting to break the rules than if the gains are low. Thus, the "rewards" for breaking the rules are interesting to study. The regulator may have to take countermeasures to ensure that the rules are followed. To do this can be complicated and in this thesis we limit our studies to determining if there are any gains that can be obtained by not playing by the rules.

Another interesting aspect of using unlicensed spectrum is the fairness. The regulator typically has an interest in ensuring that there is a degree of fairness when using spectrum. In this thesis however, we do not consider fairness, mainly because there are many definitions of fairness and the results heavily depend on which fairness measure is chosen. In addition it is not certain that the fairness is the main objective of the regulator.

Finally, there is an interesting research issue in determining what kind of tools are suitable for analyzing the issues presented here. The current toolbox of the radio engineer is focused on creating high performance in licensed spectrum and the tools may not be appropriate to investigate the issues in unlicensed spectrum.

1.5 Game theory a tool for modelling conflicts

One mathematical tool used for modelling conflicts is game theory. It was originally invented by von Neumann and Morgenstern[19] for solving business related problems. It has since been applied to wide range of areas from politics and military conflicts to evolution and auctions[20].

Three central concepts in a game theory are:

- The players, i.e., the actors that make decisions and possible have confliction interests.
- A number of actions that a player can take when he has to do something.
- A preference relation that describes which results of the game a player prefers over other.

The actions selected by each of the players result in a specific outcome or result of the game. One way to use the preference relation is to assign a numerical value (payoff) to each outcome. In some cases an action is associated with a cost. A utility function usually takes this into account and deducts the cost from the payoff.

In this thesis we make use of game theory to model the inherent conflict in using unlicensed spectrum.

1.6 Previous work

Most of the literature on radio resource management assumes that there is only one single objective that has to be met. It can be to minimize blocking in voice systems or to maximize throughput or fairness in data communication systems. This is reasonable since a lot of research has been made on how to actually make systems work and how to make them more efficient. The research has been driven by the traditional telecom industry with access to licensed spectrum.

Some research has been on operations in unlicensed spectrum. One of the main questions have been how to coordinate devices that do not share a common control point. Typically the research is done during the standardization work to ensure that equipment built in compliance with the standard will actually work. These studies usually only take into account one system at a time. But are some papers on how different popular systems will coexist in the same spectrum and how well popular systems cope with external interference.

There is another group of papers that study coexistence in a more general context. This type of research is typically done before a piece of spectrum is released for unlicensed operation. A common question is how system behavior is affected by etiquette rules.

In some papers game theory has been used for solving radio resource management issues. This can either be to solve a resource management problem or to model an actual conflict among the users. The problems studies includes power control, the ALOHA scheme and the widely popular CSMA/CA multiple access scheme. Although not directly radio related there is also a fairly large body of research on resource competition in fixed data networks.

Power Control Games

Game theory has been applied to power control systems. In the trivial case when there are no limits on the power that can be used the user using the most power wins. However, the available power is not unlimited and thus each user has to determine the power he should use to achieve his goals. The utility of a user can be data rate, error probability or battery lifetime for portable devices.

In a CDMA system the users all share the same channel and thus interference with each other. Since each user can select output power the problem can be modelled as a game where the players select the output power i.e., the output power is the strategy. The utility function is assumed to be a function of SIR and transmission power[21]. The user wants to maximize SIR while not spending a lot of energy. The good property is that this utility function has a maximum which simplifies mathematical treatment. However, there are drawbacks to this approach as well. The tradeoff between power and datarate that a user makes is difficult since it involves such different characteristics. For example, is double datarate worth half the battery life of the terminal? At the timescale that a battery generally lasts the datarate may vary quite a lot for a users since he moves around, the interference from users vary etc. In some cases the user is probably willing to trade, but not in others cases [1] even if the value of the utility is the same. An additional issue is that on the downlink the access point supplies the power, but the benefit of the data is at the receiver.

The problem is that the suggested utility function implicitly assumes that the value of all energy is constant. But considering the battery life of a typical terminal a user will probably place little value in the top 50% of the energy in the battery. It is only when the battery energy becomes scarce that a user is likely to place any value in the remaining capacity. Since the discharging of a battery is a slow process the suggested utility function is likely to be relevant only in a fraction of the cases.

For the suggested utility function it is possible to show that there is a unique Nash equilibrium where the received power for each user is equal. However, this equilibrium is not Pareto efficient. A payment mechanism can be introduced where a fee, either actual money or some virtual control value, is paid for the used power[22]. By introducing this fee it is possible to force the system to a Pareto efficient operating point. If the aim is to find an algorithm that finds an efficient operating point for the system in a distributed way this may be fine. But to analyze the behavior of selfish users in the system this assumption may be unreasonable.

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[1] Actually it is the device that makes the decision on behalf of the user. But we can assume that the user has the possibility to inform the device about his preferences.

One of the problems with the previously mentioned studies concerns the price that a user has to pay for transmission power. In a practical setting this requires the use of a function in the network that keeps track of payments etc.

The key to prevent users from misbehaving is to impose a punishment for misbehaving. In the previous example misbehaving, i.e., using a lot of power, is punished by making the user pay a fee. Another way to punish the misbehaving user is by modelling the process as a repeated game[23]. In this paper the authors explore two different settings. One is a refereed game where the access point scrambles bits for the misbehaving users. Another method to implement the punishment is to let the other users increase their transmission power. The net result is a larger error probability for the misbehaving user. The result is that the performance of both suggested schemes is the same. Also the scheme performs better than the previously mentioned scheme with a pricing mechanism.

ALOHA

Aloha is a distributed access scheme that has been widely studied. The basic idea with ALOHA is that users transmit packets at a random point in time. Then the user waits for an acknowledgement. If no acknowledgement is received the packet is assumed to be lost and retransmitted after an additional random wait period[24].

The focus of research in ALOHA has been to stabilize the protocol and to take capture effects into consideration. But there is also some research done on users misbehaving in an ALOHA system. Obviously it is possible for an individual user to cheat by selecting random numbers with a lower average than the other users in the system. This can be modelled as a game where the strategies of the users are to select the random wait time before transmission. Since the game is asynchronous in nature, modelling the game as a strategic or a repeated game is difficult. MacKenzie and Wicker have modelled this as an extensive game where users arrive and depart and the actions a user makes is dependent on the number of users in the system[25].

The utility for a user is based on a reward for successfully transmitted packets and an associated cost for transmission. Thus, the focus is on throughput and not on delay, i.e., the utility for a user is the same regardless of how late the packet is received. The results indicate that the throughput is less than in a centrally controlled system but the performance is of the same order. Although for specific values of cost per transmission the performance is the same.

This model has further been extended to include the more general class of multi packet reception ALOHA[26]. In this paper the authors show that the results previously obtained are applicable for the more general class.

CSMA/CA problem

Another (quite popular) random access method is the CSMA/CA scheme. In this scheme a users listens to the channel to ensure that it is free before transmitting. To prevent all users colliding as soon as the channel becomes free the user waits a random time before transmitting. It is obvious that it is possible to cheat in the same way as in ALOHA systems by consistently choosing small wait times. One of the most popular standards employing CSMA/CA is the 802.11 suite of standards.

Usually punishing a cheating user can deter him from greedy behavior and make all participants in the game reach a higher total reward. One proposed system for detecting cheating users in IEEE 802.11 networks is called DOMINO[27]. To implement this system requires no changes in the standard and thus no changes in the user devices. The detection functionality is implemented in the access point, which is assumed to be honest. The authors classify the different possibilities for cheating in the MAC layer. Cheating can be accomplished by intentionally jamming frames or by manipulating the protocol parameters. The DOMINO systems relies a number of tests that each check for a specific kind of misbehavior. The most difficult cheating technique to detect seems to be manipulation of the backoff period and three of the tests address this kind of misbehavior. The results in the paper are based on both numerical experiments and on an actual implementation using readily available hardware. The results show that cheating indeed results in better performance, but the worse users misbehave the easier they are to detect. The results also show that users cheating by a small amount are difficult to detect.

Kyasanur and Vaidya have studied detection and punishment of nodes in an IEEE 802.11 network[28]. The main assumption in their paper is that one node, the access point, in the network can be trusted and thus the policing can be assigned to that node. They introduce a slight modification to the protocol that essentially let the receiver, i.e., the access point, assign (deterministic) backoff values to the nodes and thus detecting misbehavior becomes more efficient. When a cheating node is detected it is punished by assigning a higher backoff value in the next round. The results that it is difficult to detect nodes that cheat slightly, but on the other hand the gain for nodes that do so is limited. For nodes that cheat a lot the throughput is increased up to twice of the throughput of well behaved nodes. However, they are detected with almost 100% certainty. It should be noted that the proposed scheme limits the gains a cheating node can have compared to the standard protocol. The authors continue by arguing that more punishment should be inflicted by higher protocol layers, e.g., by refusing to route the packets further. Although this study considers cheating in the MAC layer of a network it does not use game theory to model the system.

In the paper by Kyasanur and Vaidya the assumption is that the receiver can be trusted to select truly random backoff values for the transmitters. However, that may not always be the case. One way to avoid the problem is to use a protocol that ensures a true random backoff period as long as either the transmitter or receiver is honest[29]. The essence of the protocol is to use one way functions to let the receiver provide a seed to the transmitter so that the transmitter can generate a random backoff period. However, the transmitter has previously published a scrambled version of the random number generator so that he cannot manipulate the random number generation process. The good property is that the scrambled version of the random number generator cannot be used by the receiver to predict the outcome, this makes it impossible for the receiver to manipulate the random number generated by the transmitter. Once the receiver has provided the seed the transmitter publishes the non-scrambled version of the random number generator so that everybody can check that the backoff period was indeed properly generated. It is of course possible for the transmitter to cheat anyway, but it cannot go undetected (and unpunished). This protocol guards against one cheating node. However, if both the transmitter and receiver collude it is possible for them to cheat and still not be detected. The authors add yet another test that can be used to detect backoff manipulation, but the results are similar to the ones obtained by DOMINO.

The previously mentioned papers has focused on detecting cheating users, but none of them has actually used game theory to analyze the case where the users try to achieve as high throughput as possible. In a report by Cagalj et al. a CSMA/CA network is analyzed using game theory[30]. Each user can manipulate the backoff window and it is shown that the equilibrium for this game is when all users starts to transmit immediately. This results in a collapse of the network. However, the authors also show that by jamming the transmissions of the cheaters it is possible to achieve maximum total throughput in the network and equal throughput for all the users. Detecting a cheater is done by measuring the throughput of each user. If a user is acieves more throughput than his fair share he is punished. Finally, the authors demonstrate a distributed algorithm that implements the detection and punishment scheme.

Cognitive radios

A cognitive radio is a radio that employs model based reasoning to achieve its goals[31]. Essentially the radio is able to observe its environment adapt to it. When the cognitive radio wants to communicate it either rents a piece of spectrum from the owner of the spectrum or just picks an empty space and starts transmitting.

Since each radio has its own objective that it tries to meet game theory is an excellent tool for modelling the interactions between them. In[32] Neel, Reed and Gilles highlights some of the important issues when applying game theory to cognitive radios. The important aspects are the steady states of the algorithms. The issues include how to find the steady states and if they are desired. In addition they also note that some restrictions need to be applied to the algorithms in order to ensure convergence. Finally, the authors give a short introduction to the relevant parts of game theory.

Genetic algorithms have also been used to make cognitive radios able to adapt to changing interference and channel conditions[33]. In the described testbed the radio had the ability to modify, transmit power, modulation scheme, forward error correcting scheme, timeslot ratio and center frequency. The genetic algorithm apply random changes to these parameters and keep the best combinations which are then randomly changed again and so on. In the described testbed the radios were able to adapt both to unknown channels and the presence of interferers.

Operators competing

The work of Mangold[34] show similarities to the case with competing operators investigated here in this work. Mangold has evaluated access points operating in unlicensed spectrum and each access point wish to maintain a specific QoS for its users. The evaluation is carried out using game theoretic tools. The difference is that the individual access points do not coordinate the actions among them. Thus, it is not really relevant to discuss competing operators in this context.

In general, there are few things written on the case where two or many operators compete. There are some studies made in the context of ensuring competition on a telecommunication market, but they focus on economic issues rather than issues related to competition for radio resources.

Game theory concepts in fixed networks

Game theory has also used when analyzing fixed networks. The problem of allocating bandwith has been studied[35]. Game theory has also been applied to routing problems in fixed networks[36] and pricing in the networks[37].

The main difference with wired and a wireless link is that the bandwidth to be distributed in the context of a fixed connection is fixed and thus the gain of one user is the loss of another. In a wireless link the capacity of that link is influenced by the actions of the other active users which adds an extra level of complexity when analyzing the system.

Coexistence

Unlicensed spectrum has been popular to use for some time and operations in unlicensed spectrum has been quite extensively studied. In parts of this thesis we focus on area covering systems that should cover the same area and use the same spectrum. This kind of problem is not encountered as often i literature though.

DECT (Digital European Cordless Telecommunications) is a system designed to provide short-range voice communication. Typically a DECT system is deployed in an office environment or at home with one access point and a few handsets[38]. DECT is designed to be able to operate without the intervention of licensing bodies. There is a specific band allocated for DECT systems, no other systems are allowed to use that particular band. However, there is no need to obtain a license to operate a DECT system. This makes DECT a license exempt system. In order to solve the frequency allocation problem DECT uses a dynamic channel allocation.

The performance of DECT and the DCA algorithms has been studied. The focus is to study the quality of service for a given traffic load. The traffic is assumed to be voice traffic and the quality of service is measured as blocking probability and signal quality for ongoing calls. The traffic is assumed to be voice traffic. However, only one system is studied, i.e., there is no interference from other systems and a user can connect to all access points. Various algorithms for the dynamic frequency allocation have been tried. For example autonomous reuse partitioning (ARP) where a call is assigned to the first available channel that passes certain quality tests. Another algorithm is the least interfered channel algorithm (LIC) where the channel with the highest SIR is assigned to a call. The LIC algorithm provides higher quality of service i.e., SIR, but the ARP algorithm can support higher traffic loads[39][40]. Personal Handy Phone (PHS) and Personal Access Communication System (PACS) are two systems that are similar to the DECT system. The envisioned usage is voice communication and as the technical solutions are similar to DECT[41]. These systems also rely on some form of dynamic channel assignment to avoid interference and the need to plan. When searching the literature it is possible to find performance studies similar to those for DECT. But there seems to be no studies where interference from other systems is considered.

HIPERLAN-2 is a standard for wireless LANs. It is intended for indoor or short-range communications with data rates up to 54 Mbit/s[42]. It operates in the license exempt band around 5.2 GHz. To avoid interference an adaptive channel allocation algorithm is used. There have been a number of investigations of the performance of HIPERLAN-2[43][44]. The focus is to find the throughput for individual users and for an entire HIPERLAN-2 system. However, these studies only take into account one system. How well two systems perform together is not considered. Part of the band allocated for HIPERLAN-2 is also allocated for radars of various kinds. How these different systems coexist has been studied. The results indicate that HIPERLAN-2 does not suffer any major performance degradation because of radar interference[45]. The radar community is worried that HIPERLAN-2 systems will create disturbances to the radars. Studies have been performed to see how the HIPERLAN-2 standard should be changed to detect and avoid interfering with radars[46].

Bluetooth is a system for short-range radio communication with data rates up to 3 Mbit/s in the enhanced version[47]. The usage is mainly intended for connecting a few devices together in an ad-hoc fashion. These devices may for example be a mobile phone, a laptop or wireless headphones. These devices are connected together in something called a piconet. Piconets are physically small and consists mainly of personal devices. Bluetooth operates in the unlicensed 2.4 GHz band. Frequency hopping is used in combination with a 2/3-rate block code and/or selective retransmissions to combat interference. The performance of Bluetooth networks that interfere with each other have been studied[48][49]. Here the throughput in the piconets has been studied for two different traffic cases, fully loaded piconets and for WWW traffic. The scenario is a room where there are a number of piconets scattered. The conclusion is that the performance is not affected until there are a high number piconets in the room. The results may be explained by the way the devices in a piconet are located compared with the location of the piconets. Generally the distance between the transmitter and receiver is much smaller than the distance to an interferer.

IEEE 802.11 is a standard for wireless LANs, or to be exact a family of standards. Currently the most popular is 802.11b, but the 802.11g offering higher datarates is becoming increasingly popular. These devices operate in the 2.4 GHz unlicensed band. To combat interference DS-CDMA is used. Although there have been a plethora of studies of the performance of IEEE 802.11 networks, e.g., [50][51][52], there has been few studies where there are more than one network operating in the same geographical area. The implicit assumption is that all the access points in a geographical area belong to the same network or at least that all users can connect to all access points. In the paper by Armour et. al.[53] there is an investigation of how one WLAN access point is affected by an interfering access point. The conclusion is that the coverage of the interfered WLAN is drastically reduced.

Both some of the 802.11 versions and Bluetooth operates in the 2.4 GHz ISM band. These devices can interfere with each other and there has been a large interest in how well they will operate together. Arumugam has studied the link level effect of 802.11g on Bluetooth and vice versa[54]. The effect of Bluetooth on 802.11g is considerable, although some improvements can be achieved if the interfered OFDM carriers are erased. On the system level there when a number of piconets coexist with a WLAN the Bluetooth devices loose some performance, but the largest loss in the WLAN which can be seen as reduced datarate[55] or coverage[56]. Due to the quick hopping sequence of Bluetooth these devices seem to be more robust against interference[57]. To mitigate the interference problems the WLAN receiver can be improved to cancel out the Bluetooth interference[58] or the Bluetooth transmitter can listen to the channels and avoid transmitting on the WLAN channels[59]. These schemes can of course be combined and seem to be quite efficient. Since laptop computers, mobile phones and so on are likely to implement both standards there has also been an interest in determining how well they will interoperate if they are put in the same device[60]. Again the impact of Bluetooth on the 802.11b device is quite severe while the Bluetooth device does not suffer as large performance loss. Since the devices are colocated it is possible to intelligently schedule transmissions and achieve acceptable performance.

In recent years there has a been a large interest in ultra wideband technology. Ultra wideband refers to the characteristic that the carrier bandwidth is on the same order as the center frequency. The output power of an UWB device is small and since the output power is low the signal is well below the noise floor. Datarates discussed are 100 Mbit/s and the range of such a device would be 10 meters or so. How well a number of UWB systems work if placed in the same geographical area has not been studied in great detail, but is seems reasonable that the capacity would be sufficent for practical device densities. Since the spectrum of UWB overlap so many other applications there has been great concern for the effects of UWB on other systems. When a 802.11a and an UWB device should coexist in the same spectrum there is almost no influcence on the 802.11a device[61]. The performance of the UWB device on the other hand is severely degraded[62][63].

There are a number of papers that deal with the usage of unlicensed spectrum without focusing on a specific standard. For example, the etiquette rule listen before talk is studied in the paper “An evaluation of Traffic throughput in the Asynchronous UPCS band”[64]. Both voice and data traffic is studied. The results indicate that it is hard to guarantee the quality of voice connections, but moderate data rates can be achieved. Another example is the paper “On the feasibility of a CDMA Overlay for Personal communication Networks”[65]. Here the authors study if a cellular CDMA system can coexist with microwave links in the frequency band around 2 GHz. The authors find that coexistence is indeed feasible. Yet another paper studies quality of service i.e., blocking probability in a cellular system where four operators coexist[66]. The mechanism for avoiding interference is dynamic channel allocation. The results show that the capacity of the system is approximately the same for the case when there is only one operator and four operators. Although in the 4-operator case four times as many access points are used.

There is also research that has been performed in a different context. Regulators make decisions on how spectrum should be allocated. Although there may be many interests the regulator has to consider at least there are interests and they do not overlap with the interests of other actors on the scene. To be able to make well-informed decisions there are studies performed with the interest of the regulators in focus. These studies try to determine if unlicensed operation is feasible or they try to determine how the etiquette rules should be designed. A survey of some of the issues facing a policy maker is the paper “Spectrum Management Policy Options”[15]. One problem that has been identified in unlicensed operation is the problem the “tragedy of the commons”. In short this is the problem that greed benefits a single user. If one user is greedy and for example, uses higher transmitter power or keeps a channel even if there is no communication that user will benefit at the expense of other users in the system. But if all users behave in the same manner everybody looses. In the papers by Sapathy and Peha[67][68] the authors discuss this problem and also proposes various solutions. Again the solutions are based on some kind of penalty or cost for using the spectrum, for example, a device must wait a certain time after transmitting before it can transmit again, this waiting period increases when a device transmits longer time. The conclusion is that a penalty function can discourage users to be greedy, but there is some performance loss.

1.7 Thesis focus

In this thesis we study two problems that are of relevance when designing rules, equipment or algorithms for unlicensed spectrum.

The first problem is to find the behavior which will maximize the performance of an individual user under different circumstances and under different rules. In other words, given a set of rules, how will the user act? If we assume that all users act rationally and we know what the behavior of the users are, it is possible to determine the overall performance of a system since the actions of one user becomes part of the circumstances for another user. Thus, we are interested in individual performance and overall system performance under a specific set of rules.

The second problem has to do with the interplay of rules and the actions of the users and ultimately the efficiency of spectrum usage. If we know the circumstances and how the users will act we can also find out how efficiently spectrum is utilized. We want to compare this achieved efficiency with what is possible when the objective is efficient use of the spectrum. Since the efficiency measure is elusive and may include economic and societal aspects as well, this thesis will not provide the complete answer. Rather the results shown here are one factor to consider when designing rules for unlicensed spectrum.

In this thesis we make use of game theory as a tool both for understanding the problems and to model them. At the end we summarize the experiences about the suitability of game theory as a tool for solving problems in unlicensed spectrum.

1.8 Contributions and thesis outline

Parts of the material presented in this thesis has previously been published. In this section we give a short introduction to each of the chapters in the thesis along with a listing of where the material the chapters are based on has been published.

Chapter 2 - Scope and Limitations

In this chapter start from a broad perspective and look at various options for spectrum management. We give an introduction to the problems and choices the regulators face when they are trying to ensure efficient spectrum utilization. This topic is not only a matter of technology problems, but involves economy, politics and juridical matters.

It is difficult to exactly trace all the origins of the material presented here. However, the author of this thesis has participated in two research projects that has provided most of the material. The first is a scenario study of the telecom world in 2010[69]. The study was made in 1998 and pointed out unlicensed operation as one of the interesting areas for further research. The other project was done in 2003 and 2004 and the project focused on dynamic spectrum access as a means to stimulate small and medium size firms in the telecom sector[13].

Chapter 3 - Timeslot game

In this chapter we present one example of a game where the users in the communication system select time to transmit and the transmission power while subject to an energy constraint. Parts of the contents has been presented in a conference paper[70]. In the paper the solution to a strategic game with a few timeslots and users are presented. However, in the thesis the results have been extended with numerical experiments to cover more complex systems. In addition the analysis for repeated games has also been added. This chapter represents an analytical approach to understanding the competition that occurs in unlicensed spectrum.

Chapter 4 - CSMA/CA in a radio environment

This chapter is about more practical systems than those presented in the previous chapter. Here we study the CSMA/CA protocol as an example of rules to follow in unlicensed spectrum. The numerical results of the outdoor scenario was first presented in 2004[71] and extended in 2005[72]. The results for a single cell repeated game was presented in 2005[73]. In addition the work has been extended with the indoor scenario, which is first presented in this thesis.

Chapter 5 - Competing operators

This chapter adds further complexity to the problem by letting operators compete with each other. Here we limit the studies to only two operators competing.

The material in chapter is mainly based on the licenciate thesis of the author[74]. However, the parts about competition using the admission policy for playing games is based on the publication[75]. Finally, the material has been extended with a proper game formulation and additional numerical results which are presented here.

Chapter 6 - Co-existing networks

One of the large questions about unlicensed spectrum has been how to allow networks to coexist. In this chapter the main issue is not competition. Instead we focus on the performance that can be achieved if systems cooperate. We outline design choices that are suitable and design choices which should be avoided.

In this chapter we look at five different cases and the first three have already been reported in[74]. The fourth case has been reported in a master thesis[76]. The last case started out as a student project[77]. In this thesis new experiments have been done and the material extended in general. Those results have not been presented previously.

Chapter 7 - Conclusions

This chapter contains the conclusions of the thesis.

Chapter 2

Scope and Limitations

One of the intended readers of this thesis is the regulator. Although we cannot provide the ultimate answer to how spectrum management should be done we can provide a decent understanding of unlicensed spectrum. In this chapter we outline the some of the options for spectrum management and present a classification of spectrum management regimes. Then we focus on one regime, which is unlicensed spectrum, and make a classification of different modes of operations in unlicensed spectrum. We also present the tools selected for our analysis.

The material presented in this chapter provides the background and motivation for selecting the problems mentioned in the introduction. In the interest of keeping the introduction short this material has been put in this chapter instead. Parts of this chapter are based on the results of projects the thesis author has been involved in.

2.1 Spectrum regulation options

In a study of possible characteristics of the telecommunications world in 2010 the increasing need for radio communications as well as an increasing need for spectrum was identified[69]. The study generated three scenarios, which all capture some possibilities of the future telecom world. A short recap of the study as well as an overview of scenario methodology in general can be found in appendix A. The increased need for spectrum puts new requirements on the regulators, who ultimately control spectrum use.

The spectrum regulator has the complex task of ensuring efficient use of the spectrum. The regulator cannot only focus on measures in the technology domain, but must also consider efficiency from an economist perspective. Since there are many options to consider there are also many suggestions for how spectrum management should be done. The traditional spectrum management regime where an exclusive license to a piece of spectrum is awarded for years and decades is now changing.

In[13] the authors make an exhaustive search of the many possibilites a regulator has. The method used is adapted from scenario making. In the report we identify five characteristics of a spectrum management regime. These five characteristics, or dimensions, span a five-dimensional space. The three most important[1] can be used to span a three-dimensional space, which is outlined in figure 2.1. Interestingly all spectrum management regimes commonly in use today can be found together with some new interesting concepts. The characteristics identified in the report are:

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[1] The importance of the characteristics has not been analytically calculated. Instead we picked the three dimensions that we believe has the greatest impact on the qualities of the spectrum management regime.

Transferability (Transferable - non transferable) of the rights to transmit. The right to operate a transmitter can either be traded or rented for some time, or the rights are exclusively given out by the regulator.

Exclusivity (Exclusive - shared - commons) of the rights to a piece of spectrum. The alternatives considered here are: *Exclusive* where only one entity, e.g. operator, has the rights to a pieace of spectrum. *Shared* where a few entities has the rights to spectrum and finally, *commons* where anybody can use the spectrum.

Rulebook size (Strict Rules - Etiquette). This characteristic ranges from a few simple rules that a transmitter must obey to a complex set of rules, for example, a full air interface standard such as GSM or HIPERLAN-2.

Lifetime (Milliseconds - Decades) of the rights. This dimension denotes how long someone has the right to use spectrum.

Implementation (Centralized - Decentralized) of the system that use the spectrum. For example, is it centralized or distributed mechanisms that coordinate carrier frequency, output power, waveform etc.

It turns out that the last two characteristics do not influence or only make a small difference in the qualities of the spectrum management in most cases. Note that the difference is seen from the regulators point of view. For example, in the unlicensed operation cases the difference for the regulator is small between a system that implements a centralized and one that uses decentralized power control. There are also combinations of characteristics that do not make sense at all. For example, handing out traditional licenses on a millisecond basis makes little sense.

In a few cases the last two characteristics actually make a difference. For example, trading spectrum can be done on a long term scale (months, weeks or days) or on short term basis (milliseconds) and the timescale the trading is done on have a strong influence on the actual implementation of the market and the control functions of the regulator. For long term trading it may be sufficient with manual interaction, but trading on a short term basis requires an automated solution.

The traditional spectrum management method can be found in this model in the lower left corner (no. 16-19). A license is awarded exclusively to an operator for an extended period of time and the spectrum may only be used for, for example, providing 3G services using UMTS. There is no easy way the operator can transfer the license to someone else.

One trend in spectrum management is to allow trading of spectrum[78]. In our model these options are found in the upper half plane (no. 0-15). The reasoning behind the trend is that once trading is allowed the market forces will ensure that spectrum is available to the ones who values it most. The idea is to make spectrum a valuable resource. Thus, for a license holder who does not use a piece of spectrum there is an incentive in selling or renting it. This will hopefully result in a more efficient use of spectrum as well as allowing new actors to easily acquire spectrum for new applications. The debate is ongoing on how to implement trading in practice and how the transition from traditional licensing should be done. It is also not clear that trading of spectrum will be a suitable tool for spectrum management. In this thesis we do not not consider spectrum trading because there are a lot of techno-economic problems in this inherently cross disciplinary field.

Unlicensed spectrum, which is the focus of this thesis, can also be found in this model. It is in the “License exempt” and “Unlicensed operation” (no. 32-39) that we find this management regime. Note that trading of unlicensed spectrum makes no sense.

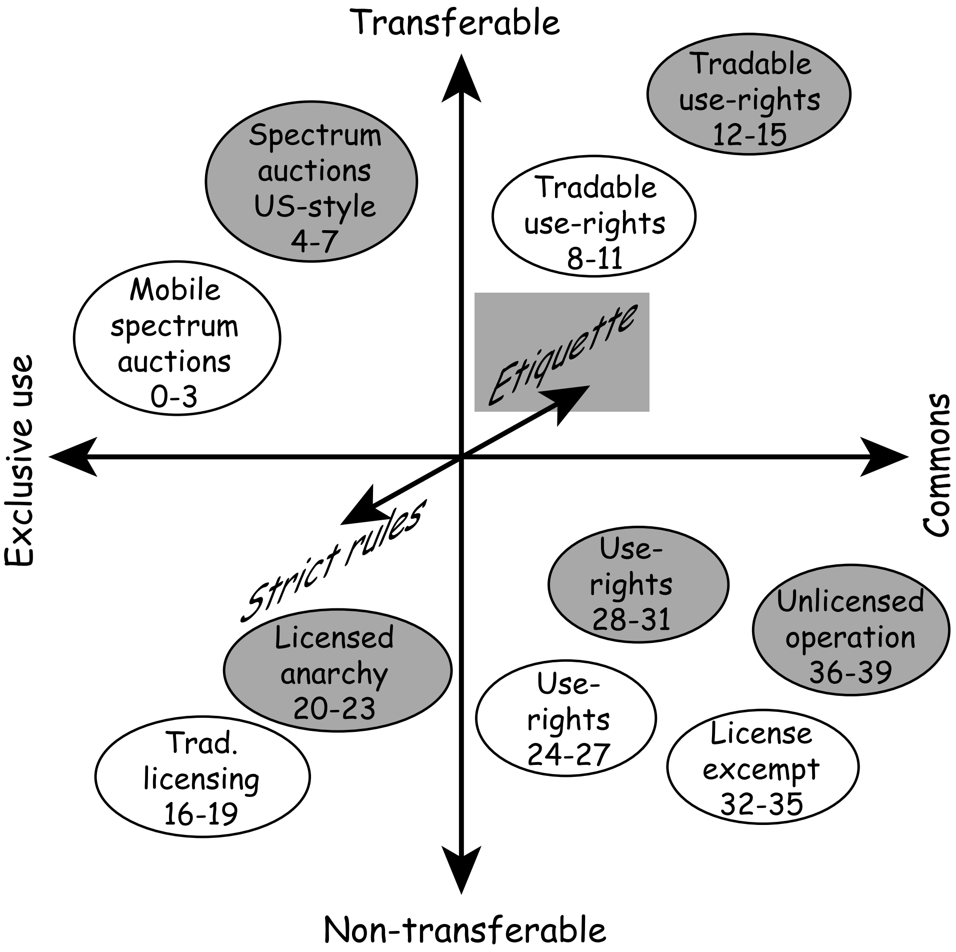

Figure 2.1: Classification of different operation cases in unlicensed spectrum. The gray and white color denotes the third characteristic. The number refers to the numbers given to each management regime and further detailed in[13].

There have been relaxations in the current framework as well. One example is the increased use of block assignments. For a block assignment the license holder is given the possibility to manage their own spectrum when selecting technologies and designing their network. The license rules can be very relaxed as long as the out of band emissions are kept within a strict limit. One example of a block assignment is fixed wireless access (FWA) allocations in Sweden. In the license there are no specifications of what technology to use, the only limitations are limits on spurious emissions[79]. Block assignments corresponds to "licensed anarchy" (no. 20-23) in our model.

It is encouraging to see that the presented space encompasses all the current trends in spectrum management. The model also shows a possible management scheme with "user rights" (no. 24-31). In this management regime the regulator awards a few users the right to use the spectrum. However, the number is small so they can make agreements with each other to limit the use of the radio spectrum. Similar contemporary cases include taxi dispatching systems and remote electricity metering in Sweden[2].

Of all the possible combinations five were deemed as interesting to study further[13]. These cases are detailed more closely in appendix B. In this thesis we focus on unlicensed spectrum. The main reason is that the thesis is written in the tradition of engineering research and this area offers most technical challenges. The results can be applicable to other areas though, for example the "user rights" cases share many problems with unlicensed spectrum.

2.2 Unlicensed spectrum classifications

The main tool a regulator has to control how unlicensed spectrum is used is the spectrum rules. For licensed spectrum the operator can revoke the license, but in unlicensed spectrum that option is not available.

There are different suggestions for categorizing the rules for unlicensed spectrum. One way is to look at how strict the rules are[13][80]. There can be rules for both the technology used and the services employed and the rules for each category can have a different degree of strictness. Another categorization is to determine if transmitters can be part of an infrastructure. Finally, there are hybrid variants of rules where some parts of a system requires a license while others do not[74].

One example of a license exempt transmitter is a GSM phone. Although a license is required to operate the infrastructure the owner of the phone does not need a license to use the phone. However, the rules that the phone must follow are detailed and strict, i.e., it must fulfill the GSM specification. Another example of license exempt transmitters is devices for canine location. Here the service definition is strict but the technical rules are quite relaxed.

If we span the space using only the exclusivity and rulebook size characteristics from the previous section we get the space outlined in figure 2.2. Here we assume that spectrum cannot be traded. As a side note the issue of trading also becomes a non-issue in some cases. For example, if unlicensed spectrum is free for all there is no need for a market, since nobody would be interested in purchasing anything that can be had for free [3].

We should elaborate on the "rulebook size" a little bit. On the right side there are absolutely no rules and on the left side the rules are quite extensive and can specify things like modulation schemes, resource allocation protocols etc. In the middle there is "etiquette" where only a few rules are specified, for example, maximum duty cycle or maximum transmission power.

The number of users denote how many entities that can use the spectrum. One user can refer to one transmitter receiver pair only, but it can also refer to one operator that has an entire network, which uses the spectrum. The reason for this definition is that the operator is in full control of what goes on in "his" spectrum. Interference from other networks is nonexistent and therefore not a problem. Of course there may be interference within a system if there are many transmitter receiver pairs, but these problems have already been extensively studied. Actually these are the kind of problems studied in traditional radio resource management.

In figure 2.2 the "traditional" license regime is found in the upper left corner. The traditional license gives the holder the exclusive rights to use the spectrum for a specific

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[2] The frequencies are actually license exempt, but the service requirements are strict so there is in practice only a few actors that can use the frequencies[17]

[3] It is possible that operators use unlicensed spectrum to provide services which users are interested in paying for. Wi-Fi hotspots is one example.

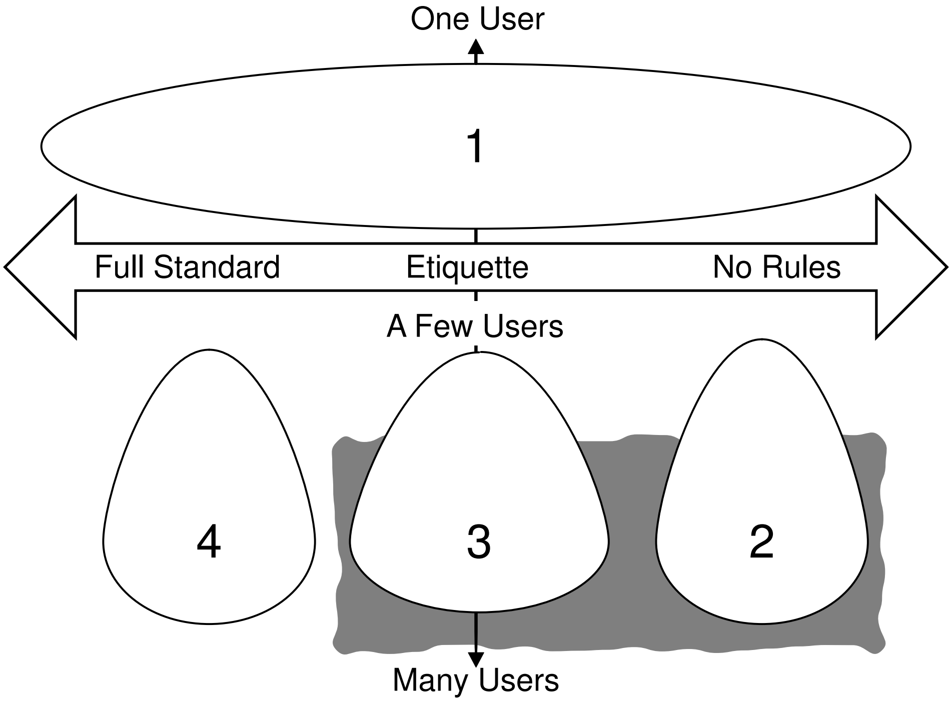

Figure 2.2: Classification of different operation cases in unlicensed spectrum using the exclusivity and rulebook size dimensions. The gray area shows the focus of the thesis.

purpose and using a specific technology. Lately there have been relaxations of the traditional licensing scheme and block allocations have become increasingly popular. This means that the regulator relaxes the conditions on how the spectrum should be used and what technology should be used. This would correspond to a shift to the right in figure 2.2.

In region (1) there is only one user of the spectrum. This region is not studied in this thesis.

Case (2) is the wild west of the spectrum management. There are no rules to follow except the physical limitations of the individual users. Obviously rule design is not a problem for the regulator, since there are no rules to design. However, the spectrum usage efficiency that can be achieved is interesting to study. If good spectrum efficiency can be achieved without rules the task of the regulator becomes much more simple.

For case (3) there are rules to follow and thus the available actions for the users are more limited than in the previous case. The rules make it simpler for the regulator to ensure a specific behavior, but it also opens up the possibility for the individual user to break the rules.

In case (4) the freedom of the users is severely limited. In essence the rules here state exactly how a user should behave. To set the rules is “merely” a matter of designing good distributed algorithms that perform well according to some given criteria. A single user may benefit from breaking the rules though. Ensuring that the users behave the way they are supposed to s a problem that must be solved.

This thesis focus on the case (2) and (3) described above. These cases have been selected since the unlicensed spectrum is one area where there are many technology issues to study. Another reason is the increased use of unlicensed spectrum in for example WiFi and

Bluetooth applications.

Note that the selected cases cover all cases with more than one user. Although we do not elaborate on the difference in this thesis there is a qualitative difference between a small limited amount of users and many users. When there are only a few users it is possible to know who the other users of the spectrum are and thus it is possible to make agreements between them. There is also a reasonable chance to learn the behavior of the other users and thus be able to cooperate nicely.

2.3 Case studies

We have already mentioned that this thesis will not give the ultimate answer on how spectrum management is to be done. But the results we obtain can be used to determine if unlicensed operations is suitable for certain cases. What we would like to know is if that way of managing spectrum is efficient.

Defining efficient spectrum usage is in itself a difficult task. On one end of the range there is the degree to which spectrum is given to the ones who value it the most[81]. On the other end of the scale there is the number of bits that can be transmitted per second per hertz per site[82][83][84]. In this thesis the focus is on the technology centered measures of efficiency, e.g., the number of users that can use the spectrum simultaneously. The evaluations are carried out mainly using technology centered methods and thus the measures seem appropriate.

The problem at hand is quite complex and completely evaluating all possibilities is not practical. Instead we study a number of cases and draw our conclusions based on them. One common denominator for all unlicensed operations is that there are many users that do not share the same objective, they have their own goal that they want to reach. Another is that the regulator wants to ensure efficient use of the spectrum. In each case we can determine how users act and from this determine how efficiently spectrum is used. Then by comparing that to a case where the goal is as efficient use of the spectrum as possible we can determine if unlicensed operations is a good spectrum management regime.

The cases chosen are intended to span a large range of issues and are also intended to provide an insight into different environments where radio communication is used. The first case presented in chapter 3 where users should select a time and a power when transmitting leans toward the analytical approach with an idealized radio environment. Although the results may not be of direct practical importance the case gives insight into mechanisms and applicability of the tools used. The second case in chapter 4 is based on contemporary system designs and problems. The results provide valuable insights into behavior of systems operating in unlicensed spectrum as well as some insight into the applicability of the tools used. The third case presented in chapter 5 provides further insights into complex systems. In this case the users are not single users, but instead it is operators that try to reach their goals. In the cases presented in chapter 6 the main goal is to use the spectrum as efficiently as possible and these cases provide reference efficiencies.

For each specific case the choice of method is easier in the sense that each case is of the same type as most radio resource management problems. For each case the problem is to determine the performance and actions of the actors in the system. Although the multiple objectives is novel many of the same tools used in other radio resource management problems can be used. Thus, for each case the evaluation is carried out using numerical experiments and analytical calculations.

2.4 Greediness, cheating and malicious behavior

When each user has his own objectives we must define new behaviors. Greediness is “an excessive eagerness or longing for wealth or gain”[85]. In a radio system we call a user *greedy* when he tries to achieve as high throughput as possible or as high quality as possible. A common assumption about the users in a system is that they are rational and that they always try to maximize their own performance. Thus, in that sense all users in unlicensed spectrum are greedy. However, there are rules that limit what the user can actually do and that prevent users from hoarding all resources. In this thesis we define a greedy user to be a user that maximizes his benefit, but also obeys the rules.

In general, as long as there is no resource shortage, all users can be satisfied. It is only when there is a (local) resource shortage that the behavior of the users may be a problem. There are two types of problems that can arise. The first is when users do not share the available resources in a “fair” way. For example, there may be an uneven distribution of the resources or users may receive the same amount while paying different fees. Fairness is not dealt with in this thesis since there are many different kinds of fairness and it is always easy to claim that one method is more fair than another. The second type does not arise in all resource sharing but in radio systems the problem arises. In many types of resource sharing the resource to share is constant, e.g., when sharing a cake, but in the radio resources are not constant. Depending on the actions of the users there may be more or less resources available. The problem in this second case is that if a user acts greedily he may reduce the total amount of resources available. We call this behavior *selfish*[23].

A user may also take actions that are in violation of the rules. In this thesis we call this behavior *cheating*. In general, we believe that a user cheating would lower the amount of available radio resources. However, there may be cases where a cheating user may increase the available radio resources. In this case the rules should probably be changed to allow the cheating behavior.

If we look at the interests of the users and the regulators there can sometimes be conflicting objectives. There is one case where a user cannot improve his performance, not even by cheating and the overall performance is the maximum one. In this case the objectives of the regulator and the users coincide and there is no conflict of interest. Unfortunately this is very seldom the case. The regulator has set a number of rules to achieve high spectrum efficiency. The rules often allow a user to cheat and improve his performance at the cost of total performance. There is a conflict of interest here and to meet his goal the regulator can use some form of policing to ensure that the rules are followed. But some users will always try to outsmart the “police” and does everything to avoid detection which calls for better policing and so on.

Finally, a user may deliberately disrupt the communication of other users. If this is the only purpose of the user we call this behavior *malicious*. There may be hybrid cases where the user disrupts the communication of other users to create more resources for himself and in this case the behavior is greedy. Here we do not consider malicious behavior in particular. However, there are situations where this may be of prime interest, e.g., in battle situations where the one objective is to disrupt the communications of the enemy[86].

2.5 Game theory

Game theory was invented to model interactions among actors in the business area. The theory models conflicts in a fruitful manner and has since then found use in such diverse areas as evolutionary biology and political sciences. In unlicensed spectrum there is also

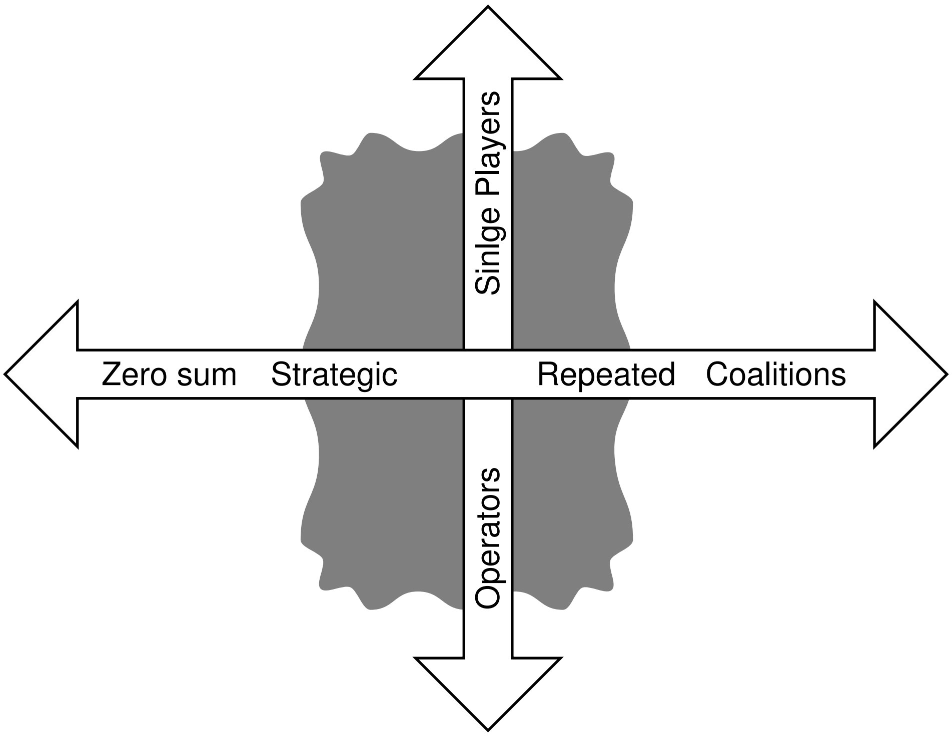

Figure 2.3: A conceptual classification of the game theoretic concepts focused on in this thesis. The horizontal axis denotes the complexity of the game model and the vertical axis denotes the complexity of the actors.

conflicting interests among the actors and this makes game theory a suitable tool for modelling the behaviors of the users.

The theory makes distinctions depending on the number of users that are involved, what kind of results are achievable and the actions that the users can take. The simplest as well as most fully understood is the two-player zero sum game. In this case the win of one player is the losses of the other player. One example of this kind of game is chess. If one player wins the other looses. A slightly more complicated game to analyze is the strategic game. In this case the win of one player is not necessarily the losses of another player. This is typically the case in radio environments where users may interfere with each other and nobody can communicate or they manage to share the radio resource and all of them are able to communicate. In the examples so far the game has conceptually been played once. The players make a decision on what action to take before the game and stick to that. If users are able to learn from past experience the analysis becomes more complex and there are the possibilities for the players to punish each other for misbehaving. If the users are allowed to agree on forming groups there are further complications added. Now there are issues to consider within the groups, e.g., who has the power to benefit the most, as well as inter group issues, e.g., how one groups should act to win over the other groups.

In figure 2.3 we give an overview of the relevant parts of game theory used in this thesis. Other ways of describing the concepts are of course possible, but this figure gives a classification that is easy to understand. The horizontal axis denotes the features included when modelling the interactions between the users as a game. In general, problems in the radio domain cannot be modelled as a zero sum game. The amount of radio resources is not constant. Some solutions to the resource sharing problem give good throughput or capacity for the users and other solutions give less. Radio problems usually cannot be modelled as a strategic game since a user has the ability to react on the results of previous actions and modify his behavior. However, in some cases there is just one opportunity to select a strategy. It is possible to imagine that users in a radio system decide to cooperate and thus form coalitions that act as one actor.

The vertical axis denotes the complexity of a user in a game. A single user has a limited knowledge of his environment and he has limited possibilities when selecting actions. An operator with centralized control has extensive knowledge of the environment and has many possibilities when selecting actions. An operator with decentralized control is somewhere in between.

Game theory is most elaborated and has the most developed tools in the upper left corner. Most of the examples of applying game theory to radio resource management problems have been done on single users in single-stage or multistage games, i.e., in the grey area.

Since game theory is commonly used to model actions and interactions of people one aspect that has to be handled is that people are assumed to be fully rational. For people this may be a pretty strong assumption. For communicating devices this may actually be true however. It is most likely an algorithm in the device that makes decisions and machines are usually rational.

Concluding remarks

There are many options available to a regulator. In this chapter we have created structures for understanding spectrum management and where the work in this thesis fits in. Unlicensed spectrum is the focus of this thesis and. the cases selected and the tools used should give results that allow us to understand some of the fundamental characteristics.

Chapter 3

Timeslot game

3.1 Introduction

Game theory provides a good framework for analyzing systems where there is more than one user with their own objective. The difficulty when applying the theory to radio systems is that a radio system is quite complex. Obviously simplifications can be made so that the problems become tractable to apply game theory to. However, there is always the risk that the problem is overly simplified and the results that are obtained do not have relevance in a practical system. Other studies that have used game theory for analysis have limited the action space to one variable, for example, backoff time[30] or output power[87][21].

In this chapter we introduce another model of a real system where the users have more freedom when choosing a strategy. At the same time this model also makes some simplifications that may ease analysis but at the same time the results may not be directly applicable to practical systems. One important aspect of the model though is that it does capture the energy limitation experienced by portable devices.

We analyze a strategic game, i.e., all users have to decide their actions beforehand and this cannot be changed during the course of a game.

3.2 System model

The system we study in this chapter consists of M transmitter receiver pairs. The channels between the transmitters and receivers are modelled as a constant propagation loss with gaussian noise. I.e., the propagation loss between transmitter i and receiver j is G_{ij} and the receiver noise of receiver j is η_j.

To analyze the system we divide the time into (synchronized) timeslots of length T. We group K timeslots into a strategic game. In timeslot k user i transmits using power P_{ik}. The strategy consists of the selections of transmit powers in each timeslot a user makes.

All users have limited energy E_{max} to spend in a game. In a game user i uses energy E_i. For notational simplicity this can be reformulated as:

$$E_i = \sum_{k=1}^{K} P_{ik} T \leq E_{max} = P_M T \tag{3.1}$$

This allows us to use the slightly simplified energy limitations in further calculations.

$$\sum_{k=1}^{K} P_{ik} \leq P_M \tag{3.2}$$

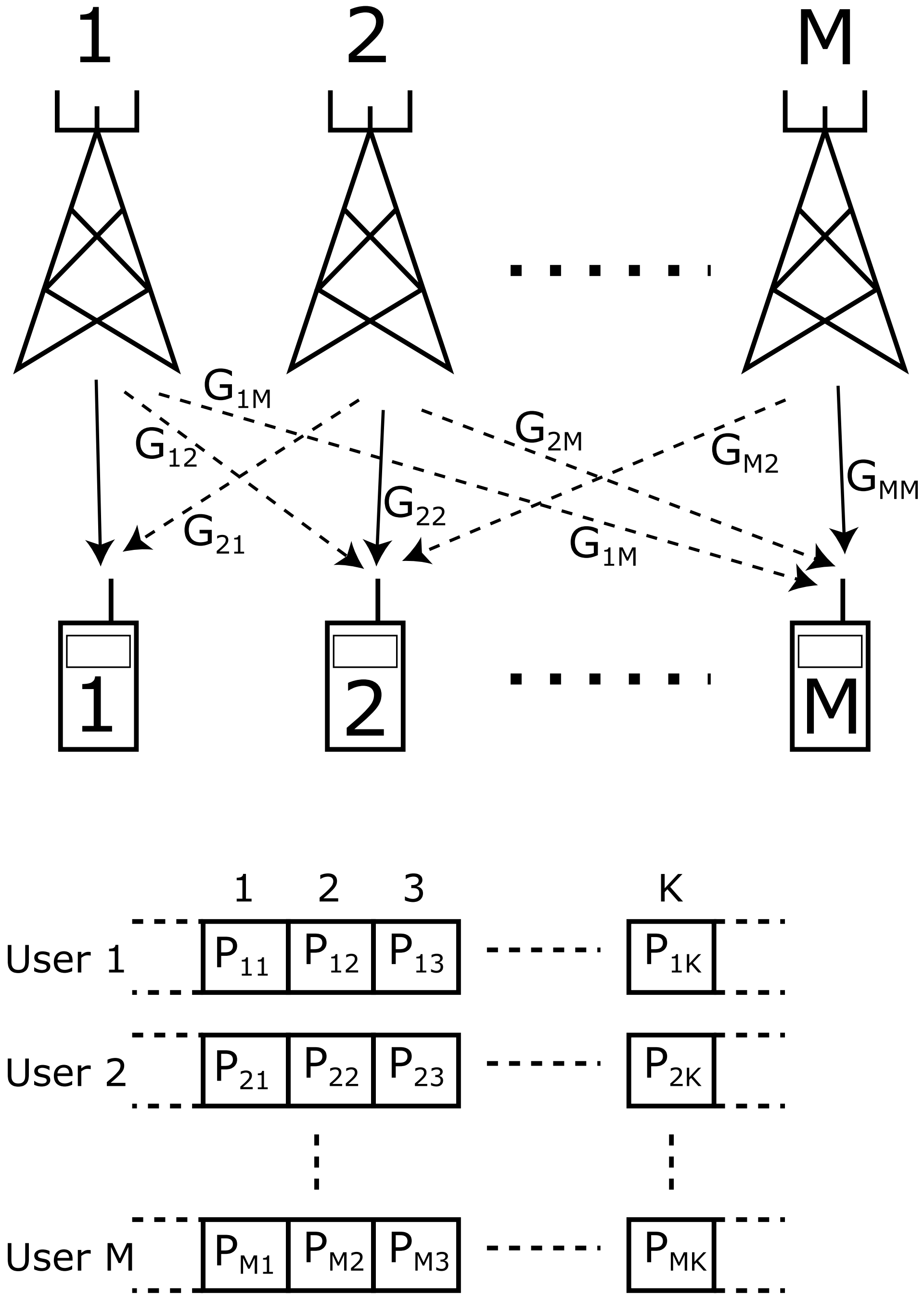

Figure 3.1: Schematic overview of the game structure and the relevant variables. The system consists of M transmitter receiver pairs. The pathloss from transmitter i to receiver j is G_{ij}. A strategic game consists of K timeslots. In timeslot k user i transmits with power P_{ik}.

The signal to noise ratio for user i in slot k becomes:

$$\Gamma_{ik} = \frac{P_{ik}G_{ii}}{\sum_{i \neq j} P_{jk}G_{ji} + \eta_i} \tag{3.3}$$

We base the payoff in the games on the number of bits that a user can transmit. The data rate that a user can achieve in a practical system depends the channel coding, modulation scheme, interference conditions and received power and a number of other factors. Here we use a simple model where the rate a user can achieve in each timeslot is modelled by the equation 3.4. Here Γ_{ik} is the experienced signal to interference in the timeslot and C is a system dependent constant. Contemporary coding and modulation makes this a realistic model. The total payoff for user i in a game U_i then becomes the sum of the achieved rates in all K timeslots.

$$R_{ik} = C\log(1 + \Gamma_{ik}) \tag{3.4}$$

$$U_i = \sum_{k=1}^{K} R_{ik} = \sum_{k=1}^{K} C\log\left(1 + \frac{P_{ik}G_{ii}}{\sum_{i \neq j} P_{jk}G_{ji} + \eta_i}\right) \tag{3.5}$$

Interference scenarios

Throughout this chapter we will distinguish between four different interference scenarios. The reason is that the qualitative aspects of the outcomes of the games are different for the different interference cases. We do not strictly define the cases since they serve mostly as a tool for explaining the results and the cases are not a strict dichotomy of the problem, rather a loose way of defining different problem classes. The first case is the normal interference or normal case. Here the signal is stronger than the interference at the receiver for the users. An example could be two users connected to two access points that are separated by a large distance. In the strong interference case the reverse it true. The interference is stronger than the signal at the receiver. Think of two users connected to two access points again, but where the users are connected to the most distant access point. In the uplink case there are a number of users connected to a single access point and the users transmit to the access point. In the downlink case there are also a number of users connected to the access point, but here the access point transmits to the users.

3.3 Strategic game

We first start by finding the Nash equilibria of the game. We rely on the technique of finding the best response function. A best response function for a user is a function that finds the actions that maximizes the payoff for that user given the actions of all the other users. The best response functions of all the users give a set of equations that can be solved to obtain Nash equilibrium points. To find the best response function for user i we must solve the optimization problem:

$$\begin{aligned} \max U_i = \sum_{k=1}^{K} R_{ik} &= \sum_{k=1}^{K} C\log\left(1 + \frac{P_{ik}G_{ii}}{\sum_{i \neq j} P_{jk}G_{ji} + \eta_i}\right) && (3.6) \\ &\text{s.t.} \\ P_M &= \sum_{k=1}^{K} P_{ik} && (3.7) \end{aligned}$$

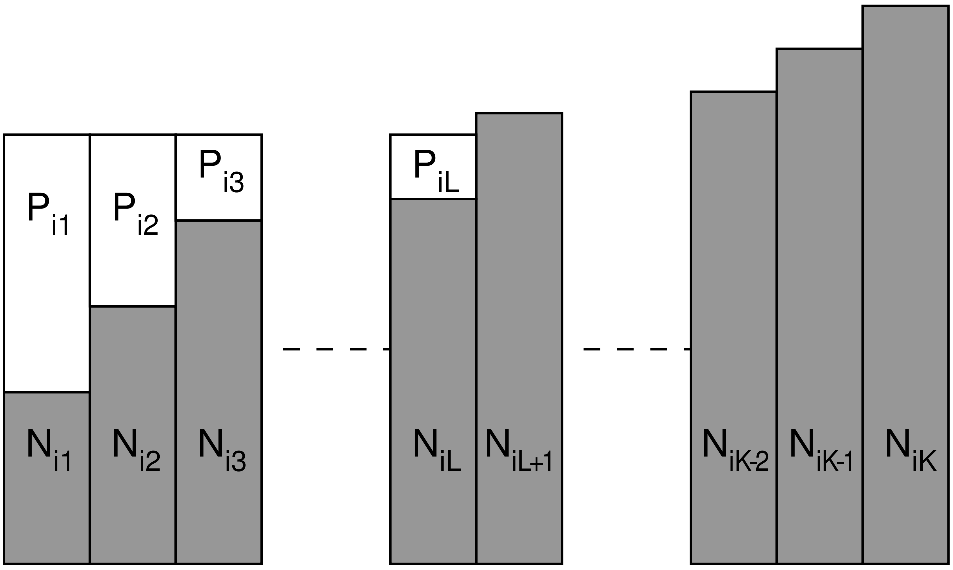

Figure 3.2: Illustration of water filling where the energy is allocated over the available timeslots so that the sum of the signal and interference is constant in the timeslots. Note this is a schematic picture. In the full equations the pathgain is also included.

This optimization problem can be solved using lagrangian multipliers and the result is commonly known as water filling[88]. We define the noise for user i in timeslot k as:

$$N_{ik} = \sum_{i \neq j} P_{jk} G_{ji} + \eta_i \tag{3.8}$$

For mathematical convenience we let the noise for user i be increasing over the timeslots, i.e., $N_{i1} \leq N_{i2} \leq \ldots \leq N_{iK}$. Notice that this is not the general case and we need to be careful when applying the results. A schematic overview of the situation is goven in figure 3.3. For all slots where power is allocated the sum of transmit power and noise is the same. To find L we calculate how much power is required to fill the first L slots as much as possible without spilling into the $L+1$ slot. We then compare this with the available power. For user i we get the conditions 3.9 and 3.10 for L. When L=K condition 3.10 is not defined and should be ignored.

$$(L-1)N_{iL} - \sum_{k=1}^{L-1} N_{ik} < P_M G_{ii} \tag{3.9}$$

$$L N_{iL+1} - \sum_{k=1}^{L} N_{ik} \geq P_M G_{ii} \tag{3.10}$$

$$P_{ik} = \frac{P_M + \frac{1}{G_{ii}} \sum_{k=1}^{L} N_{ik}}{L} - \frac{N_{ik}}{G_{ii}} \quad \text{for} \quad k \leq L \tag{3.11}$$

$$P_{ik} = 0 \quad \text{for} \quad k > L \tag{3.12}$$

Example 2 timeslots and 2 users

We start with the simple case of two users and two timeslots. Although the case has little practical use it still illustrates some interesting aspects of this problem. In order to simplify the analysis we assume that user 2 transmits more power in timeslot 2 than in timeslot 1, i.e., $P_{21} \leq P_{22}$. The best response function of user 1 can be divided into two cases. In the first case user 1 only allocates power to one timeslot and in this case the power allocation is trivial: $P_{11} = P_M$ and $P_{12} = 0$. In the other case the best response is to allocate power to two timeslots, i.e., $P_{12} > 0$. We determine the requirement that user 1 allocates power to only one timeslot. Thus, user 1 allocates power to only the first timeslot if:

$$P_{21} < \frac{P_M}{2}(\frac{G_{21} - G_{11}}{G_{21}}) \tag{3.13}$$

If condition 3.13 is not met, user 1 will allocate power to 2 slots according to:

$$P_{11} = P_M \frac{G_{11} + G_{21}}{2G_{11}} - P_{21}\frac{G_{21}}{G_{11}} \tag{3.14}$$

$$P_{12} = P_M \frac{G_{11} - G_{21}}{2G_{11}} + P_{21}\frac{G_{21}}{G_{11}} \tag{3.15}$$

When $P_{21} \geq P_{22}$ the problem can be solved in a similar manner. Actually it is mostly a matter of changing indices. We can now plot the best response of user 1 as a function of the actions of user 2. In figure 3.3 we plot the power selected by user 1 in slot 1 (P_{11}) as a function of the power selected by user 2 in slot 1 (P_{21}). There are a few things worth noting. If $G_{11} > G_{21}$, user 1 will allocate power to both timeslots regardless of the actions of user 2. This corresponds to the situation where the interference is weaker than the signal. In the case of heavy interference, i.e., when the best response is to allocate power to one or two timeslots depending on the power allocation of user 2. Of course most power should be to allocated to the slot which is least interfered.

Since there are only two decision variables in this game we can easily plot the best response functions of both users in figure 3.4. The plot can then be used as a guide to finding the Nash equilibria. A Nash equilibrium is found where the best response of one user to the best response of the other user intersect. Notice that there are 3 equilibrium points in the example shown: both users allocate half power to both timeslots and two equilibrium points when each user allocates full power to one timeslot each. However, the pathgain between the interferer and the intended receiver is larger than between the transmitter and the receiver, i.e., $G_{21} > G_{11}$ and $G_{12} > G_{22}$. In most practical cases, i.e., when $G_{11} > G_{21}$ and $G_{22} > G_{12}$ there is only one equilibrium point where both users allocate half of the available power to each timeslot.

When $G_{11} = G_{21}$ and $G_{22} = G_{12}$ as is the case in the downlink the best response of both users coinside. [1] The result is infinitely many equilibrium points. Also when $G_{11} = G_{12}$ and $G_{21} = G_{22}$ as is the case in the uplink there will be parts of the best response functions that overlap and infinitely many equilibrium points are generated. In the heavy interference case, i.e., when $G_{11} < G_{21}$ and $G_{22} < G_{12}$ there are three equilibrium points.

However, for practical cases, in the normal interference case, we can expect $G_{11} > G_{21}$ and $G_{22} > G_{12}$, i.e., the pathloss to the transmitter is lower than to the interferer. In this case there is only one equilibrium point where both users allocate half power to each timeslot.

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[1] There are some additional cases when the columns or rows in the matrix contain the same value, typically when the system layout is symmetric. However, these are uncommon cases and the results in this section still holds, even though the classification of the interference case may not be correct.

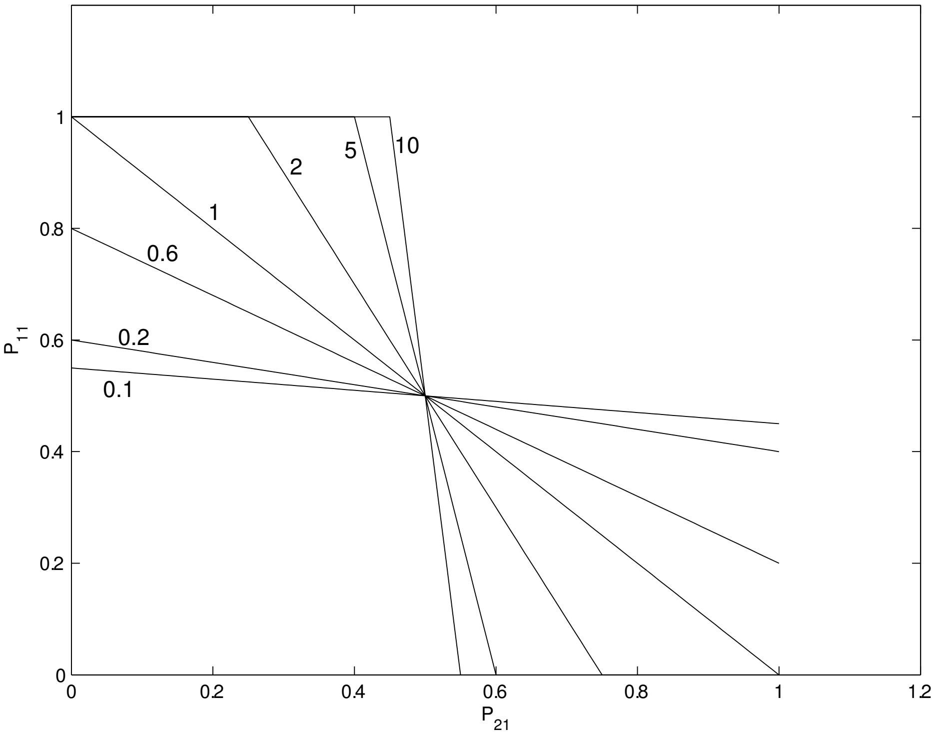

Figure 3.3: The best response function for User 1 as a function of the actions of User 2 for various gain relations. Curves shown for: $\frac{G_{11}}{G_{21}} = 0.1, 0.2, 0.6, 1, 2, 5$ and 10.

The Nash equilibria only indicates the stable points of the game. However, there may be other power allocations that give better performance for both users. For the normal interference case we can plot the payoffs for both users for all possible strategies, see figure 3.5. (Note that in the plots we have discretized the actions into 501 possibilities.) In this game there is only one Nash equilibrium located at the square. First we can note that the Nash equilibrium is not Pareto efficient, but that there are a number of Pareto efficient points shown by the solid line. A Pareto efficient outcome has the property that no user can improve his throughput without any degradation for the other user. The case where both users use one timeslot, denoted by a star, can be noted to maximize the total throughput in the system. From the figure we can also see that when both use full power in the same timeslot, shown by a triangle, gives the worst performance.

In figure 3.6 we show the payoff combinations that can be obtained when user 2 varies his strategy while user 1 keeps his strategy fixed. In the point when the maximum system throughput is reached both users allocate full power to each timeslot. But we can also see that it is possible for user 2 to obtain a slightly higher throughput at the expense of user 1. The gain by user 2 is less than the loss experienced by user 1. But we can also see that user 1 can regain some of this loss by shifting some of his power allocation. I.e., push the curve down. But if both users do this they end up in the Nash equilibrium, the square point.

For the downlink case the maximum system throughput (for reasonable noise levels) is always obtained when each user uses full power in one timeslot each. This point is also

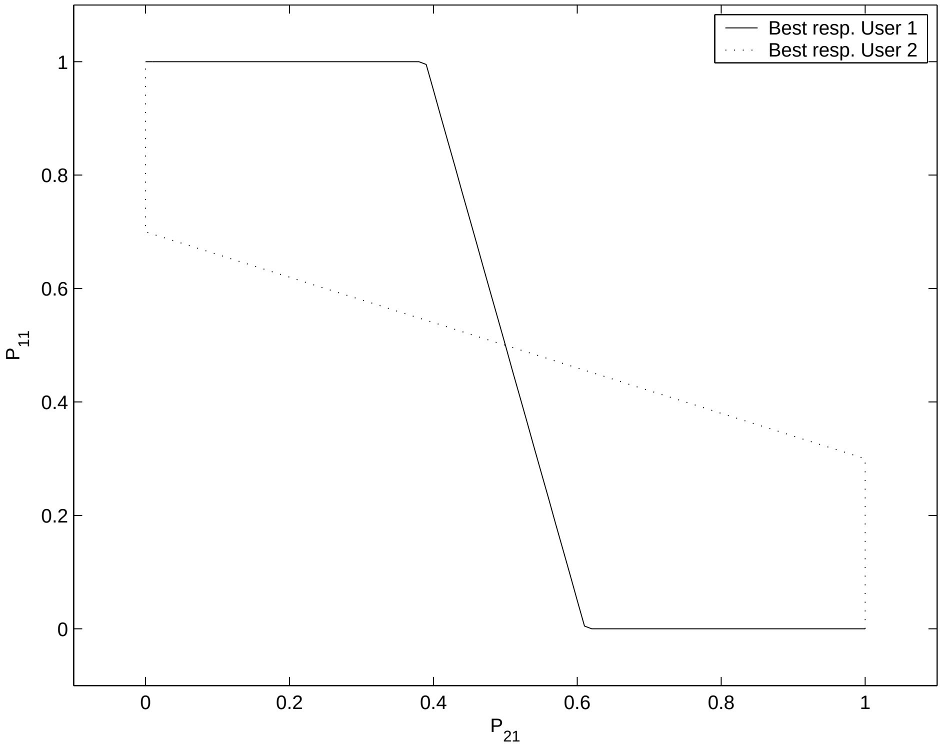

Figure 3.4: Best response functions for User 1 and 2 in the same plot. The Nash equilibria are located at the intersections. $G_{11} = 0.2, G_{12} = 1 G_{21} = 0.9$ and $G_{22} = 0.4$.

Pareto efficient. This is however only one of the Nash equilibrium points. For the uplink case the Nash equilibrium is not Pareto efficient. For the heavy interference case there are two Nash equilibria when both users use one timeslot each and these are Pareto efficient. There is also the Nash equilibrium where both users allocate half power to each timeslot and that equilibrium point is not Pareto efficient.

Example 3 timeslots 2 users

In the next example we increase the number of timeslots with one to obtain a game with two users and three timeslots to allocate the power over. We first focus on the best response function of user 1. The best response function of user 2 can easily be determined from that by exchanging the appropriate variables. We assume, without loss of generality, that $P_{21} \leq P_{22} \leq P_{23}$. There are 5 other possible combinations, but by permuting the appropriate variables the solution for these 5 combinations can easily be obtained.

Each user can allocate a maximum power of P_M. In a strategic game there is no point in using less than the allocated energy. Thus, the transmit power in slot 3 is a function of the power in the first two slots, $P_{23} = P_M - P_{21} - P_{22}$. The powers in the first two slots P_{21} and P_{22} span a two-dimensional space. We divide this space into three regions. In each of these regions we can define the best response function of user 1. The best response function allocates power for user 1 to 1,2, or 3 slots respectively to maximize the throughput for user

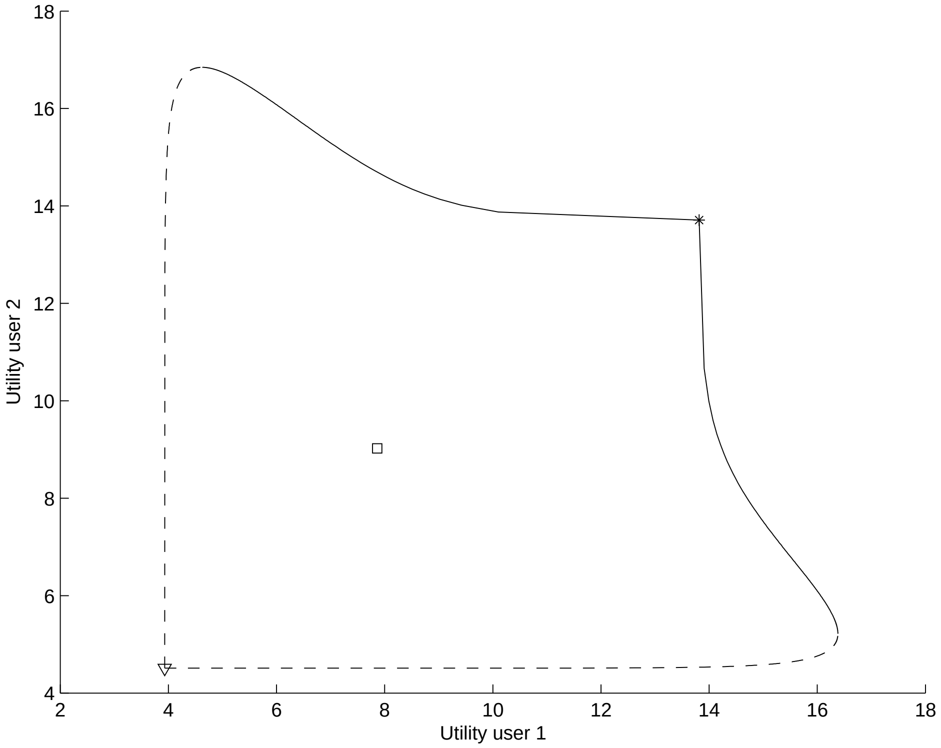

Figure 3.5: Overview of the obtainable utilities for a game with two users connected to two different access points (normal interference case). The Pareto efficient points are along the solid line. All combinations of utilities inside the solid and dotted line are possible to obtain in the game. The star denotes the case where both players select one timeslot each. The triangle denotes the obtained utilities when both users select the same timeslot. Finally, the square denotes the Nash equilibrium where both users allocate half of the power to each timeslot. $G_{11} = 1 G_{22} = 0.9 G_{21} = 0.01$ and $G_{12} = 0.02$

1.

We start with the case of user 1 allocating to only one timeslot. This will occur if this condition is met:

$$N_{11} + P_M G_{11} \leq N_{12} \tag{3.16}$$

Which can be rewritten as:

$$P_{22} \geq \frac{P_M G_{11}}{G_{21}} + P_{21} \tag{3.17}$$

In this case the best response is trivial.

$$\begin{aligned} P_{11} &= P_M & (3.18) \\ P_{12} &= 0 & (3.19) \\ P_{13} &= 0 & (3.20) \end{aligned}$$

User 1 allocates power to 2 timeslots if the following condition is met:

$$N_{12} + P_{11} G_{11} \leq N_{13} \tag{3.21}$$

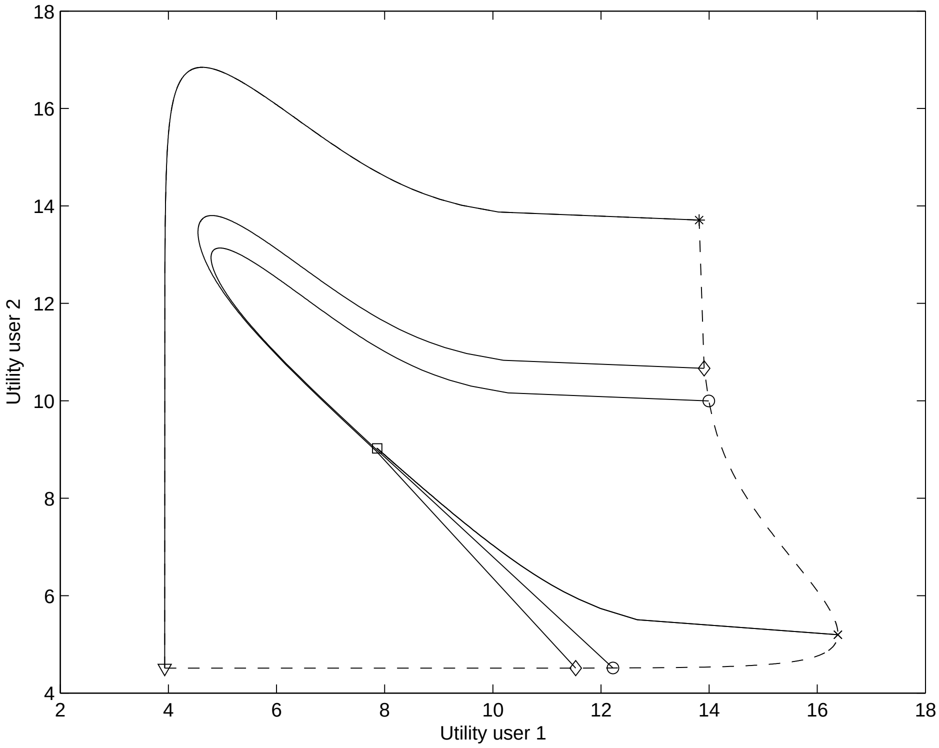

Figure 3.6: The utilities obtainable for user 2 for various fixed strategies of user 1. Diamond user 1 allocates 0.2% of the power to slot 2. For the circle the corresponding number is 0.4%. The x indicates half of the power is allocated to each slot for user 1. The other items are as in figure 3.5.

If we rewrite and substitute with $P_{23} = P_M - P_{21} - P_{22}$ and P_{11} with the expression 3.23 we get this boundary condition:

$$P_{22} \leq \frac{P_M}{3}\left(\frac{2G_{21} - G_{11}}{G_{21}}\right) - P_{21} \tag{3.22}$$

The best response is given by the following expressions:

$$\begin{aligned} G_{11}P_{11} &= \frac{P_M G_{11}}{2} - \frac{G_{21}P_{21}}{2} + \frac{G_{21}P_{22}}{2} && (3.23)\\ G_{11}P_{12} &= \frac{P_M G_{11}}{2} + \frac{G_{21}P_{21}}{2} - \frac{G_{21}P_{22}}{2} && (3.24)\\ P_{13} &= 0 && (3.25) \end{aligned}$$

If none of the conditions above are fulfilled user 1 allocates power to all 3 timeslots. The best response then becomes:

$$\begin{aligned} G_{11}P_{11} &= \frac{P_M}{3}(G_{11} + G_{21}) - G_{21}P_{21} && (3.26)\\ G_{11}P_{12} &= \frac{P_M}{3}(G_{11} + G_{21}) - G_{21}P_{22} && (3.27) \end{aligned}$$

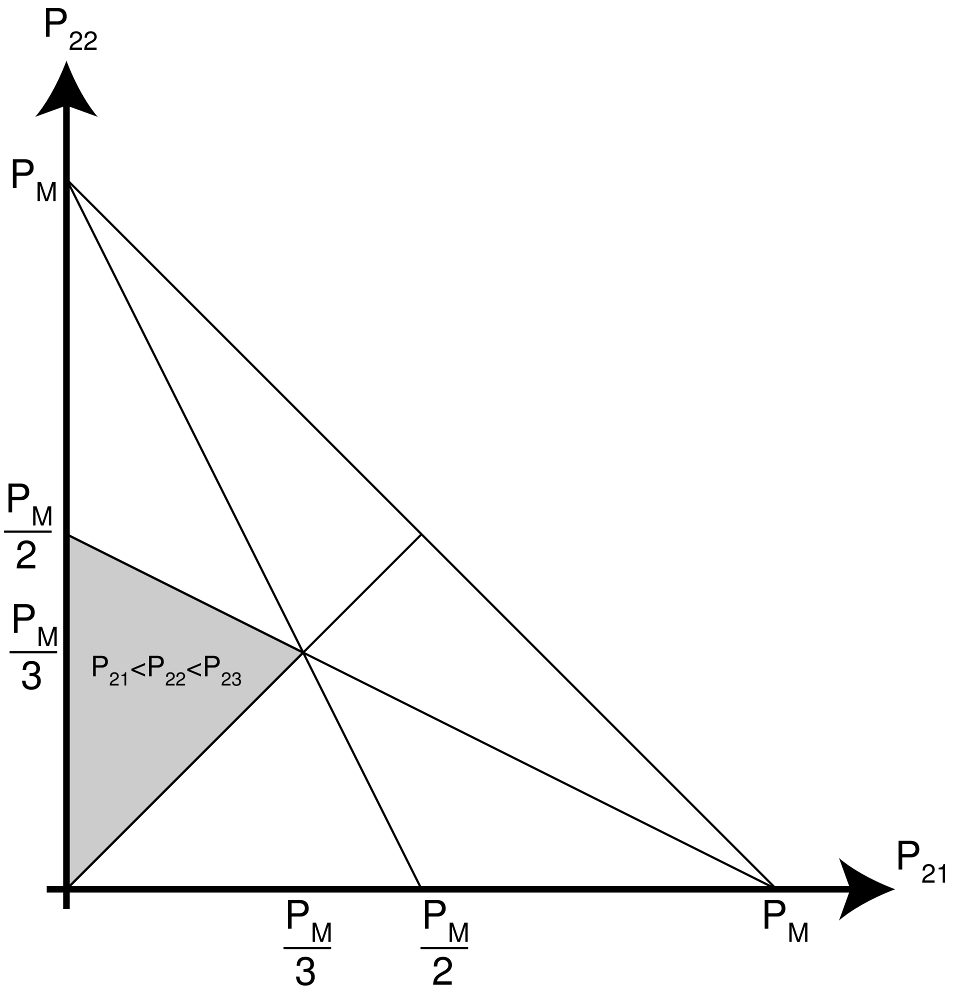

Figure 3.7: Schematic outline of the cases and regions analyzed in the game with 3 timeslots and 2 players. User two allocates power P_{21} to the first timeslot and P_{22} to the second, P_M is the total available power. P_{23} can easily be calculated using the expression $P_M - P_{21} - P_{22}$. Six regions can be constructed with the property that the relative ordering of P_{21},P_{22} and P_{23} is fixed. For example, in the gray region $P_{21} < P_{22} < P_{23}$.

$$G_{11}P_{13} = \frac{P_M}{3}(G_{11} - 2G_{21}) + G_{21}P_{21} + G_{21}P_{22} \tag{3.28}$$

We can easily find the crossing point among the three areas. It is given by these expressions:

$$P_{21} = \frac{P_M}{3}\left(1 - \frac{2G_{11}}{G_{21}}\right) \tag{3.29}$$

$$P_{22} = \frac{P_M}{3}\left(1 + \frac{G_{11}}{G_{21}}\right) \tag{3.30}$$

The equations above give the mapping from the power allocation of user 2 to the best power allocation for user 1. The best response of user 2 as a response to the power allocation of user 1 has the same form and can be easily be obtained by simple substitutions. We then get a system of equations that we can solve to find the Nash equilibria. The system of equations that should be solved has the form:

$$(P_{11}, P_{12}, P_{13}) = f_1(P_{21}, P_{22}, P_{23})$$
$$(P_{21}, P_{22}, P_{23}) = f_1(P_{11}, P_{12}, P_{13})$$

Unfortunately the equations are nonlinear, but they are linear in a region where the number of allocated slots are the same. To solve the problem we divide the area into the 9 possible combinations of slot allocations and solve the linear equations inside that region.

To aid in further development we state the equations for user 2 as well. Note that in the region of interest that we study the nature of waterfilling gives us the following ordering of the powers $P_{11} \geq P_{12} \geq P_{13}$. We also make use of the relation $P_{13} = P_M - P_{11} - P_{12}$ when rewriting the equations for user 2.

User 2 allocates power to only 1 slot if:

$$P_{12} \geq \frac{P_M}{2}\left(\frac{G_{22} + G_{12}}{G_{12}}\right) - \frac{P_{11}}{2} \tag{3.31}$$

Again the best response is trivial:

$$P_{21} = 0 \tag{3.32}$$

$$P_{22} = 0 \tag{3.33}$$

$$P_{23} = P_M \tag{3.34}$$

User 2 allocates power to 2 slots if the condition above is not true and:

$$P_{11} \geq \frac{P_M}{3}\left(\frac{G_{22} + G_{12}}{G_{12}}\right) \tag{3.35}$$

The power allocation in this case becomes:

$$P_{21} = 0 \tag{3.36}$$

$$G_{22}P_{22} = \frac{P_M}{2}(G_{22} + G_{12}) - \frac{G_{12}P_{11}}{2} - G_{12}P_{12} \tag{3.37}$$

$$G_{22}P_{23} = \frac{P_M}{2}(G_{22} - G_{12}) + \frac{G_{12}P_{11}}{2} + G_{12}P_{12} \tag{3.38}$$

Finally, user 2 allocates power to 3 timeslots if none of the conditions above are met. The best response in this case becomes:

$$G_{22}P_{21} = \frac{P_M}{3}(G_{22}+G_{12}) - G_{12}P_{11} \tag{3.39}$$

$$G_{22}P_{22} = \frac{P_M}{3}(G_{22}+G_{12}) - G_{12}P_{12} \tag{3.40}$$

$$G_{22}P_{23} = \frac{P_M}{3}(G_{22}-2G_{12}) + G_{12}P_{11} + G_{12}P_{12} \tag{3.41}$$

Now we are ready to determine the locations of the Nash equilibria. First we investigate the case where both users allocate power to 1 slot. The power allocation for user 1 and 2 are:

$$P_{11} = P_M \tag{3.42}$$

$$P_{12} = 0 \tag{3.43}$$

$$P_{13} = 0 \tag{3.44}$$

$$P_{21} = 0 \tag{3.45}$$

$$P_{22} = 0 \tag{3.46}$$

$$P_{13} = P_M \tag{3.47}$$

However, there is no one-slot solution for user 2 since condition 3.31 must be satisfied:

$$P_{12} \geq \frac{P_M}{2}\left(\frac{G_{22}+G_{12}}{G_{12}}\right) - \frac{P_{11}}{2} = \frac{P_M}{2}\left(\frac{G_{22}}{G_{12}}\right) \tag{3.48}$$

By substituting P_{12} with 3.43 we obtain:

$$\frac{P_M}{2}\left(\frac{G_{22}}{G_{12}}\right) \leq 0 \tag{3.49}$$

This condition is obviously not satisfied since both G_{22} and G_{12} are both positive and finite.

If user 1 allocates power to one slot and user 2 allocates power to 2 slots we can find the power allocation by solving this equation system.

$$P_{11} = P_M \tag{3.50}$$

$$P_{12} = 0 \tag{3.51}$$

$$P_{21} = 0 \tag{3.52}$$

$$G_{22}P_{22} = \frac{P_M}{2}(G_{22}+G_{12}) - \frac{G_{12}P_{11}}{2} - G_{12}P_{12} \tag{3.53}$$

The solution is trivial:

$$P_{22} = \frac{P_M}{2} \tag{3.54}$$

This is a valid solution if user 1 actually selects only one timeslot. I.e., condition 3.17 must be met.

$$\frac{P_M}{2} \geq \frac{P_M G_{11}}{G_{21}} \tag{3.55}$$

This gives us the requirement that:

$$\frac{G_{11}}{G_{21}} \leq \frac{1}{2} \tag{3.56}$$

We have already seen that 3.31 is not met, which is necessary if user 2 should allocate power to 2 slots. However, another requirements is that condition 3.35 is satisfied:

$$P_{11} = P_M \geq \frac{P_M}{3}\left(\frac{G_{22}+G_{12}}{G_{12}}\right) \tag{3.57}$$

This condition is satisified if:

$$\frac{G_{12}}{G_{22}} \geq \frac{1}{2} \tag{3.58}$$

Thus, there may be a Nash equilibrium for some values of the gains.

We move on to the case where user 1 allocates power to one slot and user 2 allocates power to 3 slots. The power allocation is given by:

$$\begin{aligned}
P_{11} &= P_M && (3.59)\\
P_{12} &= 0 && (3.60)\\
G_{22}P_{21} &= \frac{P_M}{3}(G_{22}+G_{12}) - G_{12}P_{11} && (3.61)\\
G_{22}P_{22} &= \frac{P_M}{3}(G_{22}+G_{12}) - G_{12}P_{12} && (3.62)\\
& && (3.63)
\end{aligned}$$

Which has the solution:

$$\begin{aligned}
P_{21} &= \frac{P_M}{3G_{22}}(G_{22}-2G_{12}) && (3.64)\\
P_{22} &= \frac{P_M}{3G_{22}}(G_{22}+G_{12}) && (3.65)
\end{aligned}$$

For this to be a Nash equilibrium expression 3.17 must be satisfied:

$$\frac{P_M}{3}(G_{22}+G_{12}) \geq \frac{P_M G_{11} G_{22}}{G_{21}} + \frac{P_M}{3}(G_{22}-2G_{12}) \tag{3.66}$$

Which gives the following condition:

$$\frac{G_{12}}{G_{22}} \geq \frac{G_{11}}{G_{21}} \tag{3.67}$$

In addition 3.31 should not be satisfied. Since the allocation of power for user 1 has not changed this is still not true. Finally 3.35 should not be met. Which gives us the requirement:

$$\frac{G_{12}}{G_{22}} < \frac{1}{2} \tag{3.68}$$

The case where user 2 allocates power to 1 timeslot and user 1 allocates power to 2 or 3 timeslots can be analyzed in the same manner, but symmetry makes it simply a matter of swapping variables.

The next case we analyze is when both user 1 and user 2 allocates power to 2 timeslots. To find the power allocation we must solve the equation system:

$$\begin{aligned}
G_{11}P_{11} &= \frac{P_M G_{11}}{2} - \frac{G_{21}P_{21}}{2} + \frac{G_{21}P_{22}}{2} && (3.69)\\
G_{11}P_{12} &= \frac{P_M G_{11}}{2} + \frac{G_{21}P_{21}}{2} - \frac{G_{21}P_{22}}{2} && (3.70)\\
P_{21} &= 0 && (3.71)\\
G_{22}P_{22} &= \frac{P_M}{2}(G_{22}+G_{12}) - \frac{G_{12}P_{11}}{2} - G_{12}P_{12} && (3.72)
\end{aligned}$$

This system of equations has the solution:

$$
\begin{aligned}
P_{11} &= P_M\left(\frac{2G_{22}G_{11}-G_{12}G_{21}+G_{21}G_{22}}{4G_{22}G_{11}-G_{12}G_{21}}\right) && (3.73)\\
P_{12} &= P_M\left(\frac{2G_{22}G_{11}-G_{21}G_{22}}{4G_{22}G_{11}-G_{12}G_{21}}\right) && (3.74)\\
P_{21} &= 0 && (3.75)\\
P_{22} &= \frac{P_M G_{11}(2G_{22}-G_{12})}{4G_{22}G_{11}-G_{12}G_{21}} && (3.76)
\end{aligned}
$$

To make sure that this is a valid Nash equilibrium we must ensure that condition 3.17 and 3.31 are not satisfied and condition 3.22 and 3.35 are satisfied. We start with 3.17:

$$\frac{P_M G_{11}(2G_{22}-G_{12})}{4G_{22}G_{11}-G_{12}G_{21}} < \frac{P_M G_{11}}{G_{21}} \tag{3.77}$$

Which gives the condition:

$$\frac{G_{11}}{G_{21}} > \frac{1}{2} \tag{3.78}$$

Also 3.22 should be satisfied:

$$\frac{P_M G_{11}(2G_{22}-G_{12})}{4G_{22}G_{11}-G_{12}G_{21}} \leq \frac{P_M}{3}\left(\frac{2G_{21}-G_{11}}{G_{21}}\right) \tag{3.79}$$

This expression simplifies to:

$$(2G_{11}-G_{21})(G_{12}G_{21}-G_{22}G_{11}) \geq 0 \tag{3.80}$$

The first part of the expression is positive since condition 3.78 must be satisfied. This gives us the additional condition:

$$\frac{G_{12}}{G_{22}} \geq \frac{G_{11}}{G_{21}} \tag{3.81}$$

We proceed with 3.31, which should not be satisfied:

$$P_M\left(\frac{2G_{22}G_{11}-G_{21}G_{22}}{4G_{22}G_{11}-G_{12}G_{21}}\right) < \frac{P_M}{2}\left(\frac{G_{22}+G_{12}}{G_{12}}\right) - \frac{P_M}{2}\left(\frac{2G_{22}G_{11}-G_{12}G_{21}+G_{21}G_{22}}{4G_{22}G_{11}-G_{12}G_{21}}\right) \tag{3.82}$$

After some simplification we end up with:

$$\frac{G_{12}}{G_{22}} < 2 \tag{3.83}$$

Finally, 3.35 should be satisfied:

$$P_M\left(\frac{2G_{22}G_{11}-G_{12}G_{21}+G_{21}G_{22}}{4G_{22}G_{11}-G_{12}G_{21}}\right) \geq \frac{P_M}{3}\left(\frac{G_{22}+G_{12}}{G_{12}}\right) \tag{3.84}$$

After some rearranging we get:

$$(G_{12}G_{21}-G_{11}G_{22})(2G_{22}-G_{12}) \geq 0 \tag{3.85}$$

This condition is satisfied since we already have the conditions 3.81 and 3.83. Thus, there is a Nash equilibrium where both users allocate power to 2 timeslots.

The next step is to analyse the case with 2 slots for user 1 and 3 slots for user 2. The system of equations to solve is:

$$G_{11}P_{11} = \frac{P_M G_{11}}{2} - \frac{G_{21}P_{21}}{2} + \frac{G_{21}P_{22}}{2} \tag{3.86}$$

$$G_{11}P_{12} = \frac{P_M G_{11}}{2} + \frac{G_{21}P_{21}}{2} - \frac{G_{21}P_{22}}{2} \tag{3.87}$$

$$G_{22}P_{21} = \frac{P_M}{3}\left(G_{22} + G_{12}\right) - G_{12}P_{11} \tag{3.88}$$

$$G_{22}P_{22} = \frac{P_M}{3}\left(G_{22} + G_{12}\right) - G_{12}P_{12} \tag{3.89}$$

This has the solution:

$$P_{11} = \frac{P_M}{2} \tag{3.90}$$

$$P_{12} = \frac{P_M}{2} \tag{3.91}$$

$$P_{21} = \frac{P_M}{6}\left(\frac{2G_{22} - G_{12}}{G_{22}}\right) \tag{3.92}$$

$$P_{22} = \frac{P_M}{6}\left(\frac{2G_{22} - G_{12}}{G_{22}}\right) \tag{3.93}$$

We then check for the validity of the solution, i.e., that the best response for user 1 is to allocate power to 2 slots and that user 2 allocates power to 3 slots. After some simplifications condition 3.17, which should not be satisfied, becomes.:

$$\frac{P_M G_{11}}{G_{21}} > 0 \tag{3.94}$$

Equation 3.22 becomes:

$$\frac{P_M}{6}\left(\frac{2G_{22} - G_{12}}{G_{22}}\right) \leq \frac{P_M}{3}\left(\frac{2G_{21} - G_{11}}{G_{21}}\right) - \frac{P_M}{6}\left(\frac{2G_{22} - G_{12}}{G_{22}}\right) \tag{3.95}$$

Thus, a condition is that:

$$\frac{G_{12}}{G_{22}} \geq \frac{G_{11}}{G_{21}} \tag{3.96}$$

Neither 3.31 nor 3.35 should be satisfied. Both conditions give us the following requirement:

$$\frac{G_{12}}{G_{22}} < 2 \tag{3.97}$$

Thus, there is a Nash equilibrium for some values of the gain matrix.

Finally, we study the case where both users allocate power to all 3 timeslots. The equations to solve are:

$$G_{11}P_{11} = \frac{P_M}{3}(G_{11} + G_{21}) - G_{21}P_{21} \tag{3.98}$$

$$G_{11}P_{12} = \frac{P_M}{3}(G_{11} + G_{21}) - G_{21}P_{22} \tag{3.99}$$

$$G_{22}P_{21} = \frac{P_M}{3}\left(G_{22} + G_{12}\right) - G_{12}P_{11} \tag{3.100}$$

$$G_{22}P_{22} = \frac{P_M}{3}\left(G_{22} + G_{12}\right) - G_{12}P_{12} \tag{3.101}$$

Table 3.1: Requirements to have a Nash equilibrium of various types in the 2 users, 3 timeslots game.

	User 1 - 1 Slot	User 1 - 2 Slot	User 1 - 3 Slot
User 2 - 1 Slot	Never	$\frac{G_{11}}{G_{21}} \leq 2 \quad \frac{G_{12}}{G_{22}} \geq 2$	$\frac{G_{12}}{G_{22}} \geq \frac{G_{11}}{G_{21}} > 2$
User 2 - 2 Slot	$\frac{G_{11}}{G_{21}} \leq \frac{1}{2} \quad \frac{G_{12}}{G_{22}} \geq \frac{1}{2}$	$\frac{1}{2} < \frac{G_{11}}{G_{21}} \leq \frac{G_{12}}{G_{22}} < 2$	$\frac{1}{2} < \frac{G_{11}}{G_{21}} \leq \frac{G_{12}}{G_{22}}$
User 2 - 3 Slot	$\frac{G_{11}}{G_{21}} \leq \frac{G_{12}}{G_{22}} < \frac{1}{2}$	$\frac{G_{11}}{G_{21}} \leq \frac{G_{12}}{G_{22}} < 2$	Always

The solution to this system of equations is:

$$P_{11} = P_{12} = P_{21} = P_{22} = \frac{P_M}{3} \tag{3.102}$$

Condition 3.17 as well as 3.22 becomes:

$$\frac{G_{11}}{G_{21}} > 0 \tag{3.103}$$

We should note that this is always the case. In the same manner 3.31 as well as 3.35 are also always true. Thus, regardless of the values of the gain matrix there is always a Nash equilibrium where both users allocate an equal amount of power to all three slots.

In the various interference cases we can see that for the normal interference case, i.e., when $G_{11} > 2G_{21}$ and $G_{22} > 2G_{12}$, there is only one Nash equilibrium when both users allocate power to all three slots. For the case with heavy interference, i.e., when $G_{11} < 2G_{21}$ and $G_{22} < G_{12}$ there are two additional equilibrium points where one user allocates power to one slot and the other allocates power to two slots. For the downlink case there are a number of equilibrium points where the user allocate power to two or three slots respectively. In the uplink case there are also a number of equilibrium points and depending on the relation between the pathgains, the users allocate power to one, two or three slots.

More users and timeslots

As we can see the used method quickly becomes cumbersome as the degrees of freedom increase, i.e., as the number of users and timeslots in the system increase. To find the Nash equilibrium points for larger systems we resort to numerical methods.

Since the best response of the users in general are non-linerar it makes solving the equations cumbersome and not well suited for computer assisted equation solvers. In addition the number of possible combinations quickly becomes too large for a complete search of combinations to be feasible. We can expect to find multiple Nash equilibria since the previous cases had multiple Nash equilibria. This is also a complicating factor for solving the system of equations. To find the equilibrium points we use a Monte-Carlo style simulator.

In the beginning of each experiment we let the users select a random power allocation for the timeslots. In each round we let each user make the power allocation that is the best response to the actions of all the other users. The order the users update their power is randomized each round. Finding the best response is easily done using waterfilling.

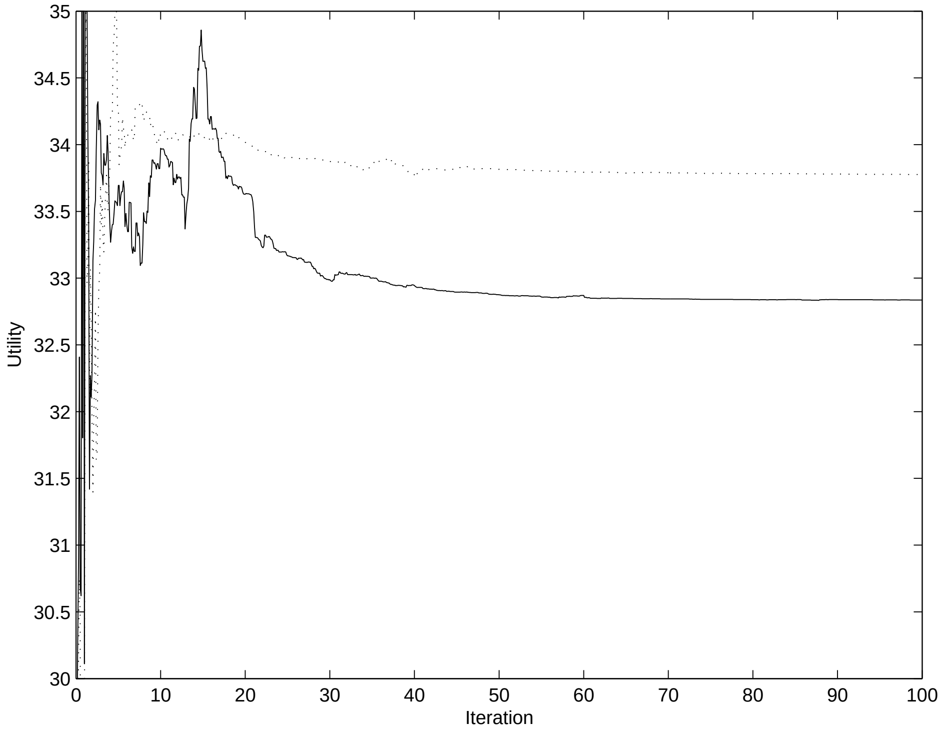

Figure 3.8: Example convergence of the numerical algorithm for two different initial power allocations and two different equilibrium points. The convergence time is around 50 iterations. Experiments performed in environment 1.

We terminate the experiment when we a Nash equilibrium is found. If all users have kept their power allocation in the round we assume that the Nash equilibrium has been found. Typically the algorithm converges approximately within 50 rounds. In figure 3.8 the total utility in the system is plotted as the algorithm converges. The example obviously shows the algorithm converging to two different equilibrium points. However, if the algorithm has not converged within 1000 rounds the algorithm is stopped and the results discarded.

To distinguish Nash equilibria from each other we compare the total utility obtained in the experiment. If the sum of the utilities of all users is equivalent we assume that we have found the same equilibrium point. It is possible that by using this method we would wrongly assume that two different equilibria are the same. However, since the gain matrix is randomly generated the probability that we will make this error is negligible. Manual inspection of a couple of results has also shown that the power allocations for one equilibrium point are indeed the permutations of each other.

Note that we consider permutations of the power allocation to be equivalent. For example, in the two timeslot case say that user 1 and 2 allocates full power to one timeslot each. We consider this to be the same point regardless if it is user 1 or 2 that transmit in the first slot. Thus, when we find one equilibrium when there are 10 timeslots there are actually up to $10! = 3628800$ equilibrium points.

We consider three main cases. The first is “the scattered pairs”. The service area is square (1x1) where the transmitters are randomly distributed over area with a uniform probability

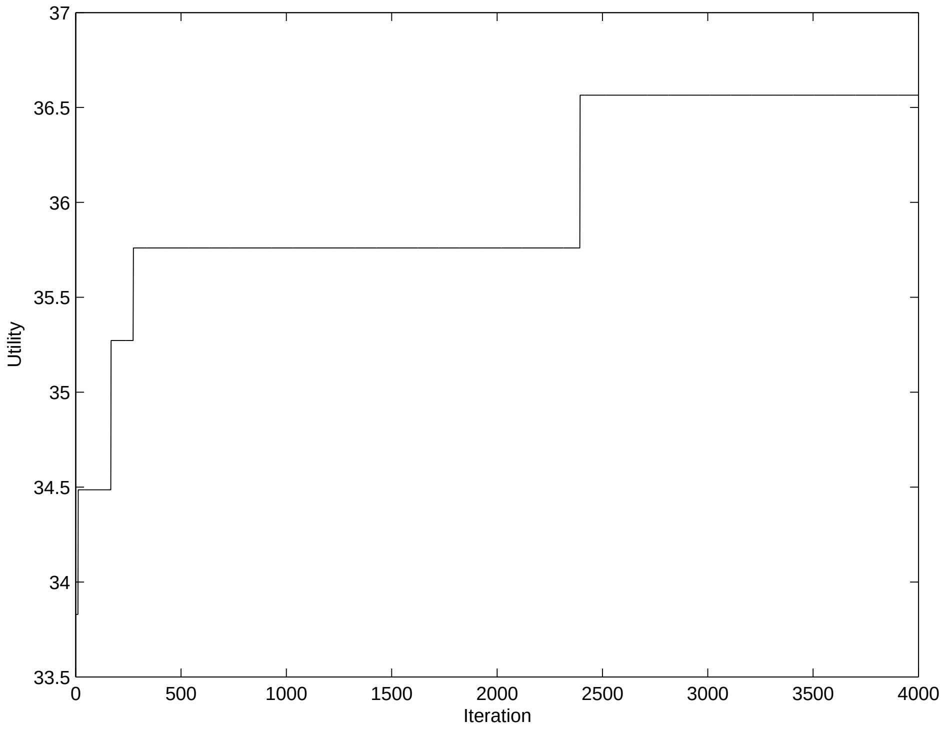

Figure 3.9: Example of (sorted) utilities obtained in one environment of the scattered pairs scenario (environment 1, 7 users, 10 timeslots). Here we have found 5 Nash equilibria.

distribution. The receivers are located at a distance of 0.3 (first three environments) or 0.1 (fourth environment) from the transmitters in a uniformly distributed random direction. We use four different realizations of this environment. The second and third cases are the uplink and downlink of a single circular cell with radius 1. Users are randomly distributed within the cell using uniform distribution. Pictures of the environments can be found in appendif C.

The gain matrix is calculated using free space propagation, i.e., $G = \frac{1}{d^2}$. The noise level is set to 10^{-6} and P_M is 1.

In each of the three main cases we look at: more users than timeslots (10 users 7 timeslots), more timeslots than users (7 users 10 timeslots) and the same number of users and timeslots (10 of each). For each of the anvironments we run 4000 experiments.

The results are summarized in table 3.2. “Many” denotes that the algorithm essentially found one equilibrium point for each experiment. One example where many Nash equilibria were found is outlined in figure 3.10. Here we can see that the algorithm did find a large number of equilibrium points since there are no steps in the curve. Detailed analysis of the behavior also shows that the equilibrium point is reached immediately indicating that all possible power allocations schemes are Nash equilibria. An example of results when the algorithm converges nicely is found in figure 3.9. Here we clearly see 5 distinct levels which corresponds so the utility obtained in the five equilibrium points. In the scattered pairs scenario the equilibrium points showed little regularity. Some users allocated full power to one slot and others spread the power more evenly over the timeslots.

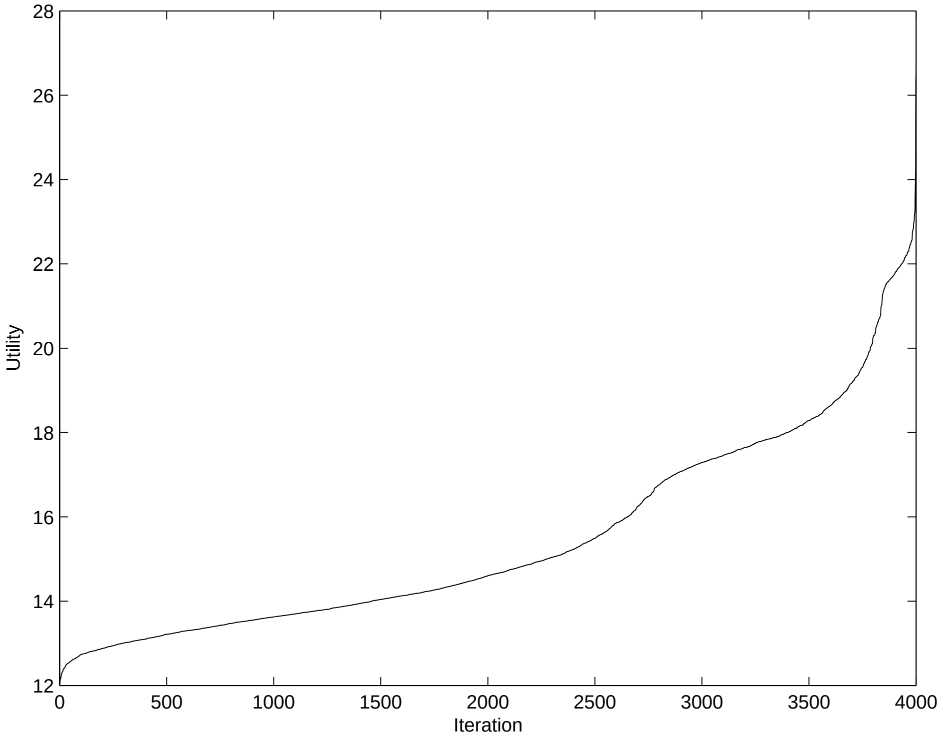

Figure 3.10: Example of (sorted) utilities obtained in the uplink scenario (10 users, 10 timeslots). Here we have found 4000 Nash equilibria.

The “Data points” heading denotes how many times the algorithm converged. In some of the scattered pairs environments (particularily environment 2) the algorithm does not converge for certain start values of the power allocation. A plot of the obtained utilities in each iteration is shown in figure 3.11. It seems that the algorithm oscillates around in a number of states and the graph shows no sign of ever converging and little regularity. Even if the order users update their power allocation in a deterministic manner there are few signs of convergence or regularity. We ran the algorithm for some randomly selected starting points and the sequence of utilities obtained showed no sign of any significant autocorrelation properties. Even when the users update their power in deterministic order can we find any significant autocorrelation.

We can compare the results to the “obvious” cases. In the 10 users and 10 or 7 timeslots cases we can compare the equilibrium points to the pure TDMA solution. It turns out that the utility obtained in the equilibrium points is almost always lower than the TDMA solution. The only exception is in environment 4 with 7 users. In this case only 7 timeslots are used and this cases the odd result.

Another case to compare to is when all users allocate the same power to all timeslots. All equilibrium points found have higher utility than the pure spreading solution. Note that this power allocation is a Nash equilibrium. If the interference is equal in all slots the best thing to do is to allocate even power to all timeslots. This action causes the interference to increase equally for all timeslots. Note that the algorithm never converges to this point.

Table 3.2: Number of Nash equilibria found for various numbers of users and timeslots. “Many” denotes that the search algorithm converged at a different point for each start value. Data points denote how many times the algorithm terminated. Note that in some uplink downlink cases we only ran 100 experiments.

	10 users 7 timeslots	10 users 10 timeslots	7 users 10 timeslots
Scattered Pairs Env 1			
Equilibrium points	1	2	5
Data points	4000	4000	4000
Utilities obtained	22.46	32.83 - 33.77	33.83 - 36.56
Utility spread power	19.29	27.53	20.15
Utility TDMA	N.A	70.14	49.10
Scattered Pairs Env 2			
Equilibrium points	0	1	23
Data points	0	255	4000
Utilities obtained	-	32.55	33.27 - 34.60
Utility spread power	16.53	23.58	19.68
Utility TDMA	N.A	70.14	49.10
Scattered Pairs Env 3			
Equilibrium points	3	12	132
Data points	3964	3827	4000
Utilities obtained	19.55 - 19.89	27.30 - 28.12	25.85 - 29.48
Utility spread power	11.90	16.99	16.99
Utility TDMA	N.A	70.14	49.10
Scattered Pairs Env 4			
Equilibrium points	1	1	1
Data points	4000	4000	4000
Utilities obtained	62.36	89.05	82.77
Utility spread power	62.36	89.05	82.77
Utility TDMA	N.A	92.10	64.47
Uplink			
Equilibrium points	Many	Many	Many
Data points	100	4000	100
Utilities obtained	8.37 - 13.87	12.04 - 26.66	13.38 - 26.81
Utility spread power	7.75	11.06	11.86
Utility TDMA	N.A	57.28	40.14
Downlink			
Equilibrium points	Many	Many	Many
Data points	100	100	100
Utilities obtained	7.79 - 8.76	11.70 - 17.26	12.22 - 19.47
Utility spread power	7.35	10.49	10.72
Utility TDMA	N.A	57.28	40.14

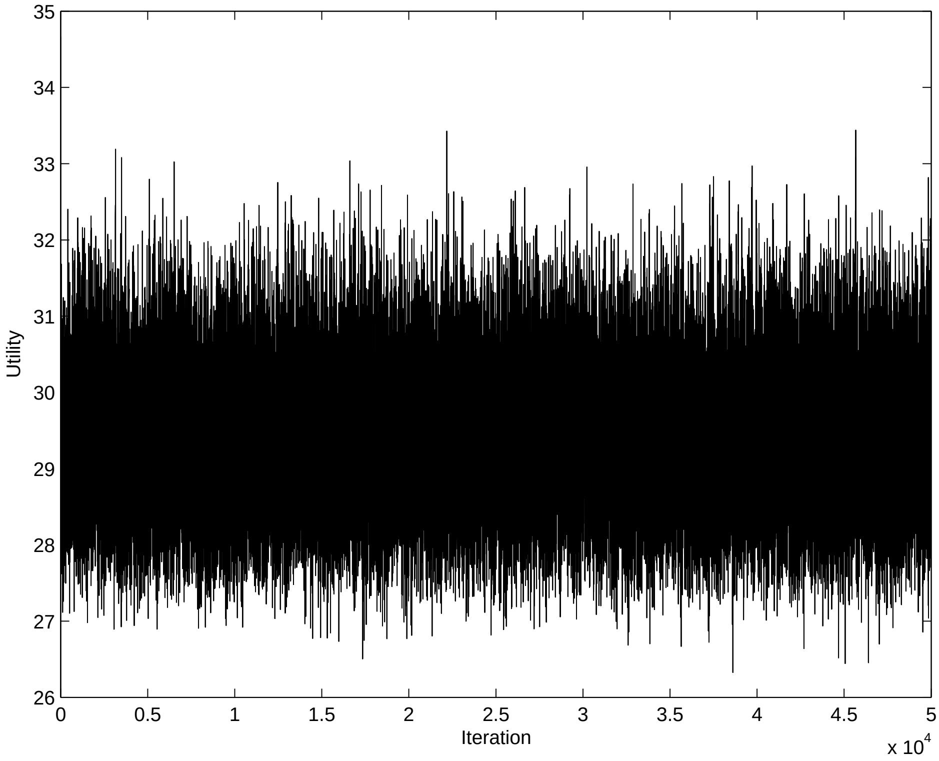

Figure 3.11: For certain initial power allocations and environments the algorithm does not converge. The figure shows the utility obtained in the first 50000 iterations. The environment shown is no. 2 with 10 users and 10 timeslots.

For the interference cases the results obtained for many users are similar to the results obtained for fewer users. For the uplink and downlink the there seem to be infinitely many Nash equilibria. The first three scattered pairs environments roughly correspond to the heavy interference cases and there are multiple Nash equilibria in these cases. The scattered pairs environment 4 corresponds to the normal interference case, i.e. the interference is weaker than the signal. In this case we only find one equilibrium when all users spread their power evenly.

For the scattered pairs case there are more equilibrium points when there are more slots available per user. This seems intuitive since more timeslots per user would correspond to more degrees of freedom for the user.

3.4 Concluding notes

The class of games presented here all have some common properties. For the uplink and downlink we find that there are many Nash equilibria caused by the fact that the best response of the users coincide.

For the heavy interference case there are multiple Nash equilibria. The utilities obtained in these is lower than the pure TDMA case. It is only in rare cases that the pure TDMA case is a Nash equilibrium. The requirement for this is that the pathgain to all other users are higher than the gain for the signal path and that rarely happens in practice.

For the normal interference case, i.e., the signal is stronger than the interference, there is only one Nash equilibrium where all users divide their power evenly over the timeslots. We also note that this equilibrium point is always present in all games.

The theory only predicts the existence of Nash equilibria. It does not describe how to find it and how to make all users agree on a specific point. Thus, in a game with multiple equilibria a user cannot decide which actions to take before the start of the game. We have also shown that iterative approaches for converging to the equilibrium is not always successful. For the normal interference case there is only one equilibrium and the outcome of the game is easy to predict.

There are power allocations that provide higher total utility than the equilibrium allocations. We note that in this game when users act greedily they cause the total system performance to degrade. If we model this game as a repeated game the users can learn from past experience and also punish each other for acting greedily. Depending on the assumptions made it is possible to obtain higher total utility than in the Nash equilibrium in the strategic game.

From a method point of view it seems like game theory provides a suitable framework for attacking this kind of resource sharing problems. However, the complete analytical solution quickly becomes cumbersome as the number of parameters to choose from increase. Thus, for larger size problems we have to resort to numerical experiments. The interesting point here is that in some practical systems we can expect to have only a few users competing and thus it is actually possible to solve the problem analytically. Another observation is that it is difficult to tell beforehand which problem and which simplifications that will yield a tractable problem or not. Some of the previously mentioned studies are able to model quite complex systems with ease, while this chapter illustrates the opposite situation.

Chapter 4

CSMA/CA in a radio environment

4.1 Introduction

To apply game theory successfully a lot of simplifications and assumptions about the system usually has to be done. In practical systems the issues are more complex and there are also more possible actions available to the individual users. This complicates analysis of and makes it difficult to understand what happens. It also makes it difficult to understand how a good overall performance can be achieved. However, two central concepts in the design and analysis of any system is punishment and the ability to detect misbehavior[32].

In this chapter we study one specific case of a radio system where some users misbehave. The general flavor of the case is an infrastructure based system where individual users try to cheat. The infrastructure approach was selected since most systems in use today have an infrastructure component. The multiple access method in the system we study is CSMA/CA, which is one of the most used methods today, partly because of the popular WiFi systems. Similar approaches have been reported in the literature, which makes comparison of our results with these studies possible. Previous studies have made simplified assumptions about the radio environment however. Using a less simplified radio model is the main contribution of this chapter.

When studying cellular systems and misbehaving users there are a number of issues that should be considered. It is clear that the access point plays a central role. In general, a user usually communicates with the access point. In fact many practical systems do not allow for communication directly between users.

The direction of communication is also of interest. Many studies assume that most of the traffic will be from the access point to the users. The application envisioned behind this has typically been web browsing or downloading of content, e.g., e-mail, files, music, video etc. However, with the widespread use of file sharing and peer to peer networks the balance between uplink and downlink may be more even. Also increased use of various kinds of wireless sensors, e.g., cameras and audio devices may tip the balance to make the uplink the most used path.

Another question is who can be expected to cheat and who can be expected to be honest, i.e., follow the rules at all times. The access points and the users in one network may be expected to act differently. In many cases the access point is owned and operated by an operator. In these cases it is not likely that the access point will cheat, simply because cheating can reduce total throughput and, possibly to a lesser extent, make the provided services unfair. Whether fairness is an important characteristic and if fairness can be experienced by the individual user is an interesting matter to investigate, but the question is far out of scope for this thesis. The end user can be expected to cheat at all times.

In the case where there are more than one operator active in the same area there may be a possibility that the access points also cheat. In this case we can imagine that it is the operator who is trying to cheat the other operators to achieve better performance for his users. In this scenario it is the access points that are most likely to cheat. If the operators have some control over the user devices as well, e.g., when the user buys or rents his device from the operator, the user devices can be expected to cheat as well. We can also assume that an access point is not likely to cheat for only one user, rather if the access point misbehaves it does so when sending traffic to all users.

To discourage users from cheating there are two key components: detection and punishment. The first problem is to determine whether it is actually possible to punish a cheating user. There are various ways of doing this. One possibility is for the fellow users to deliberately jam the transmissions of the cheating user. This punishment scheme has been suggested as an efficient method to handle punishment in a distributed way[30]. The advantage with this method is that there is no central control necessary to implement the punishment mechanism and thus this scheme may be especially suited for scenarios where entire networks compete against each other. The drawback with this method is that it is not always possible to punish a cheating user. There are cases when the signal from the user is sufficiently stronger to be captured despite the efforts of the other users to jam the transmissions. Another way of implementing punishment is of course to let the access point block the cheating user's traffic. This form of punishment is especially effective if the access points within the network exchanges information about cheating users so that the cheating user is effectively banned from the network. Although the problem is not addressed here a further possibility is that the cheating user takes one access point as hostage by locating himself close to the access point and deliberately jam all transmissions until he is provided services again. In this part of the thesis we evaluate to what extent a distributed punishing scheme is successful and effective.

The other vital part in designing a punishment scheme is the ability to detect cheating users. The detection schemes can be divided into two classes. Schemes in the first class are based on an information exchange between the transmitter and receiver where both transmitter and receiver must agree on how much radio resources to use. If one of the parties is cheating that can be detected by the other party and possibly by the bystanders as well. This type of detection schemes works well if either the transmitter or receiver is honest. On the other hand if they collude, i.e., decide to cooperate to cheat and avoid detection, the detection scheme is not able to function.

The detection schemes in the other class are based on passive observation of the user. If the user does not follow the agreed protocol he is assumed to cheat. Correct detection of a cheater is complicated by several factors. The first is that some protocols have elements of randomness built in. The CSMA/CA protocol may be the most well known example. In this case it is necessary to observe a user for a prolonged timespan to see if the user cheats by violating the protocol in the average sense. The typical example is that a users consistently selects small backoff values in the CSMA/CA protocol. The other problem in a radio environment is that due to propagation conditions it may not be possible to observe a user over long time periods due to fading, user mobility and so on. In addition the interference situation at the observer may not be the same as the transmitter and receiver experiences. In this chapter we find some of the constraints that detection algorithms will have to perform under in practical systems

4.2 Models and assumptions

We can expect the results to be dependent on the models selected to a large extent. For example, finding a cheating user that does not move in a “nice” radio environment is much easier than detecting a cheating user that quickly moves around in an environment with heavy shadowing. In this chapter we have picked two representative environments where communication systems are used. The two models we have picked are quite different and gives the results a broad span.

The first environment is an outdoor scenario with the users moving at vehicular speeds. This environment is intended to model users travelling by car in a city. The main characteristics of this is the frequent handoffs that occur since the users travel fairly quickly in a dense network with many access points. The radio propagation is fairly nice without any large variations and rapid changes.

The second environment is an indoor scenario with users moving at pedestrian speeds. In this particular case we model an one floor office, but this environment is similar to the ones typically found in airports, shopping malls and other kinds of public spaces. This kind of environment is characterized by rapid changes of the propagation conditions. For example, a user turning a corner may experience a rapid drop in signal strength. On the other hand users remain stationary for longer times and thus handoffs are not as frequent as in the outdoor scenario.

Outdoor environment

The outdoor scenario is one with mobiles moving at pedestrian and vehicular speeds. The propagation is modelled here using the “traditional” Okumura-Hata propagation model, i.e., the pathloss between an access point and a user can be described using the following equation:

$$L = L_0 + 35log(d) + X \tag{4.1}$$

Where L_0 is the propagation loss at 1 meter (28 dB) from the access point. This value corresponds to dipole antennas for the transmitter and receiver with a carrier frequency of 900 MHz. Lognormal shadow fading is modelled by X which is a normal distributed variable with standard deviation of 8 dB[89]. The lognormal fading is correlated in space with a correlation distance of 110 meters. I.e., the correlation of two samples of the fading made at 110 meters distance is $1/e$. The random component is implemented in such a way that the same position will always exhibit the same fading for a user.

The access points are located in a hexagonal pattern with a cell radius of 1000 meter. The cells are omnidirectional. The reuse factor is set to 3 corresponding to the reuse typically seen for IEEE 802.11b networks. For this environment we use a wraparound technique where all cells are located on a torus. That way border effects in are avoided.

Indoor environment

The second system is an indoor office scenario with users moving at walking speeds or remaining stationary. We model a typical office floor with offices around closest to the outer walls of the building. In the middle of the building there are conference rooms or other forms of common rooms and there is also a slightly larger open space. In figure 4.1 we can see the exact layout of the office we model.

The pathloss between a user and an access point or between users can be described using the following equation[90]:

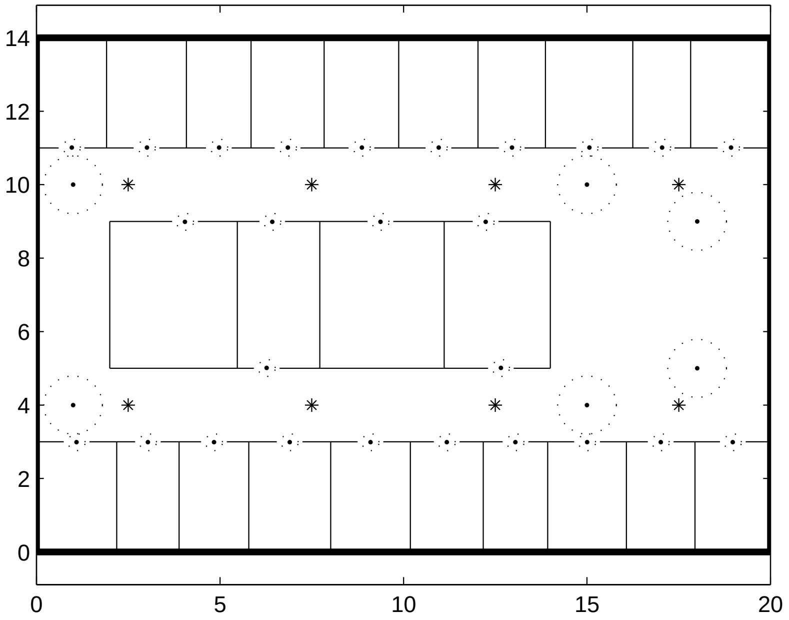

Figure 4.1: Schematic overview of the indoor environment. The access point location are denoted by stars and the waypoints used for user mobility are indicated by dots. The diameter of the mobility points is also shown.

$$L = L_0 + 20log(d) + L_{wi}k^{\frac{k+1.5}{k+1}-b} + X \tag{4.2}$$

L_0 is a constant to account for antenna parameters etc. Here we have set L_0 to 48 dB which corresponds to isotropic antennas with a carrier frequency of 5.8 GHz.

The second part of the expression models the excess loss due to walls and other obstacles. L_{wi} is a parameter to account for wall losses and has been found to be 8.4 dB at 5.8 GHz in a typical office building with a mix of wall type. k is the number of walls traversed. The parameter b is the nonlinearity parameter. It accounts for the fact that the signal is perceived to be attenuated more by the first wall than the second, which in turn attenuates more than the third and so on. The reason is that for multiple walls there may be reflections that bounce around the obstacle and they contribute proportionally more to the signal than the direct path as the direct path experiences more shadowing. Empirical measurements has shown b to be 0.5. Finally, X is normal distributed variable with standard deviation 4 dB[91]. The lognormal component is modelled with a correlation distance of 2 meters.

The location of the access points is shown in figure 4.1. Each access point operates on a separate channel and there is no cochannel interference. This is reasonable since there are at least 8 channels available in the 802.11a bands.

User mobility - outdoor

There are many models for modelling user mobility. A good overview is given in[92]. In the paper the authors note that the mobility model influences the performance results of ad-hoc networks protocols significantly. It is reasonable to expect that there will also be an influence on the performance of detection and punishment schemes for competing users. There are two general classes of mobility models where the users act as individuals or as groups. We model the users as individuals since we do not expect group behavior to be a large component in this kind of networks.

For the outdoor scenario the users have a velocity vector that they move according to. This velocity is affected by a random acceleration. This way of modelling the movements of the users makes their moves smoother than a completely random walk and resembles the movements of vehicles better[89]. This model bears a strong resemblance with the Gauss-Markov model described in[93]. The average acceleration is $2m/s^2$ and the average speed is $15m/s$.

User mobility - indoor

For the outdoor scenario the mobility model is fairly straight forward and even though there is a plethora of available models only a few are commonly used. If the environment contains obstacles of some kind there is no commonly used model. In the indoor setting there are doors, walls and other obstacles that limit the possibilities for users to move. Some models take this kind of obstacles into account. One example is the ant mobility model. The idea is that users tend to follow each other. In an ant colony the ants mark the path they walk by a pheromone that can be found by the other ants. Over time the pheromone decays and if the path is not travelled by more ants the path disappears. The same method can be mimicked and used for generating mobility of nodes in an ad-hoc network[94]. Although developed for a downtown area the street unit mobility model described in[95] lets the users move along streets in a Manhattan style environment. Indoor mobility has been modelled using random waypoint models where the waypoints form an Markov chain[96]. I.e, a user moves to one waypoint and can then choose a number of new destinations, but the possible new destinations are only a subset of all the available destinations. For example, a user in a room must move through the door before he can move into the corridor. The drawback of the Markov chain model is that some users may move back an forth between two waypoints, where in reality users usually move longer distances without changing direction. Some models also model the three dimensional nature of buildings by allowing the user to move between floors using the elevator[97].

The model used here is based on the model proposed by Jardosh et al.[98]. The model described in the paper is used to describe the behavior of users moving around on a campus area. At the core of the model there is an assumption that users randomly select a destination and move there. When they have reached the destination they wait for some time and then select a new destination. The interesting part of this model is how a user selects the path to the destination. In an environment with obstacles a number of points between obstacles (e.g., buildings) and corners are calculated using Voronoi graphs. These points tend to lie halfway between things, i.e., in the middle of paths, on the middle of walls and so on. A user selects one of the points as a destination and moves there from point to point using the shortest path. This model captures the idea that people usually walk in between things and possibly also takes shortcuts through buildings.

In our adaptation of this model we rely on the same principle. However, there are some differences in our implementation. We do not calculate the points a user must move through. Instead they are defined beforehand using an adhoc approach where the points are located approximately in between “things”, in the middle of door openings, in the middle of the corridor etc. The users select any position in the office as the destination. To get there the user must move from point to point using the shortest path. We take walls into account so users cannot walk through walls. To each point along the path the user travels we add a random offset to model the behavior that users do not walk in exactly the same paths in a corridor etc. When a user starts walking he selects a random velocity uniformly on the interval 1 to 3 m/s. Once he reaches the destination he waits for a random time. The wait time is exponentially distributed with an average 30 seconds. The exponential distribution is truncated to 240 seconds.

Traffic

The user density is important. When there is only one user within a cell it does not matter[1] if that user cheats or not since he does not have to share the capacity with anyone anyway. When more users enter the cell there is an incentive for cheating. If punishment is carried out by the users themselves by jamming, with only a few users in each cell the possibility to punish a cheating user is limited. When the number of users in a cell increase the ability to punish someone is increasing since the probability to find a user sufficiently close to an access point to carry out the punishment increases. In the numerical experiments here we have three users per access point on average.

We use the full traffic load case, i.e., a user always has a packet to send. This way we can measure capacity and it is in the high load cases that greediness will be most noticeable. There may be other measures that are of interest as well, for example, delay, delay jitter and throughput variations over time. These factors may also influence the experienced quality of the services and may have an impact on the behavior of higher layer protocols. The reason that we have omitted them here is that we are mainly interested in capacity of the system and thus how well spectrum can be utilized. Another reason is that cheating is most relevant when resources are scarce. When there is enough capacity available to all users there is little point in trying to obtain more resources than can be successfully used.

Although we no not know the ratio of uplink to downlink traffic we assume that there is only uplink traffic. The reason is that it is in the uplink that a user has the most obvious ways to cheat. Focusing on the uplink will give us results that are easier to interpret.

The transmit power is set to 30 dBm for all users in all scenarios. The noise floor is set to -118 dBm. For the outdoor scenario these are typical values for a mobile communication system. For the indoor scenario these values are somewhat exaggerated. However, in the indoor scenario there is no co-channel interferers and the effect of these settings will essentially be to eliminate the problem with hidden terminals. The hidden terminals problem is not expected to be severe in the indoor scenario anyway since the network has quite small cells.

We assume that users are connected to the strongest access point. However, when making the handoff decision we apply a 3 dB hysteresis. Also handoffs are not made when a user is transmitting a packet.

In the numerical experiments we use a slot based simulator. Each packet is broken down into 10 timeslots that are transmitted in sequence. To be correctly received the SIR in a slot has to be above 10 dB for all slots in the packet. There is no retransmission scheme, so if one slot is below the threshold the entire packet is lost. We use different slot lengths for the outdoor and indoor system. The timeslot in the outdoor system is 20 ms and in the

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[1] Always selecting small backoff values actually gives a slight performance increase for a lone user.

indoor system the duration of a timeslot is 2 ms. In all numerical experiment we let the system run for 400 seconds.

4.3 Strategies

When we study the effects of cheating in a complete system we consider three different strategies that users can follow. This selection is in no way an exhaustive set, but instead the purpose it to illustrate some of the concepts and to achieve insight into the problem. Strategies are randomly assigned to the users. No user switches strategies during the numerical experiments.

Strategy A is the greedy strategy. The user starts to transmit a packet as soon as he has finished the previous packet. If the other users are timid and listens before speaking, this strategy will essentially give the greedy user the full access to the bandwidth. However, if all users implement the greedy strategy this is obviously not a good strategy since all users will interfere with each other.

Strategy B is to use the CSMA/CA protocol and follow the rules strictly, this is the timid strategy. The protocol implemented by these users is very similar to the protocol used by devices implementing IEEE 802.11[99]. Whenever a user has finished transmitting a packet he draws a random number on the interval [0,FW]. The user then waits for this number of empty slots before transmitting the next packet. An slot is considered empty if the received signal strength is less than 5 db above the noise floor. If there is someone else transmitting on the channel the counting down is suspended. If the packet is lost on the way the FW variable is doubled. If the packet is successfully transmitted the FW is reset to the initial value. The minimum FW value is set to 8 and the maximum is 256.

Strategy C is to follow the timid strategy (strategy B) initially. However, if a user detects that another user is behaving in a greedy fashion he can punish that user. Detecting that a user is cheating is non-trivial. In the paper written by Cagalj et. al.[30] it is suggested that each user measure the throughput of all the other users and deem a user to be cheating when that user achieves a higher throughput than the rest of the users. Here we use a slightly simpler algorithm. The user that transmits 5 packets in a row without releasing the channel is considered to be greedy. Punishing a user is done by deliberately jamming a packet sent by the user. The user is punished for 5 packet times. We assume that this can be done since the packet header contains the address of the sender and thus it is possible to quickly determine which packets are sent by a specific user. If a user moves into another cell the punishment is stopped immediately. We also assume no communication between the cells thus it is not possible to punish a user if he is on another channel or in another cell.

4.4 Results

Punishment possibility

If punishment of users is to be carried out in a distributed way it is necessary to determine how often it is actually possible to punish a misbehaving user. The purpose of jamming is to make sure that the cheating user does not reach the necessary C/I for his transmissions. In figure 4.2 we plot the probability that a user cannot be punished by the other users in the cell in the outdoor case. For the indoor scenario the results are shown in figure 4.3. The plots show the system with 3 and 10 users per cell on average. The dotted line denotes the probability that a user is alone in a cell. The solid line shows the probability that the

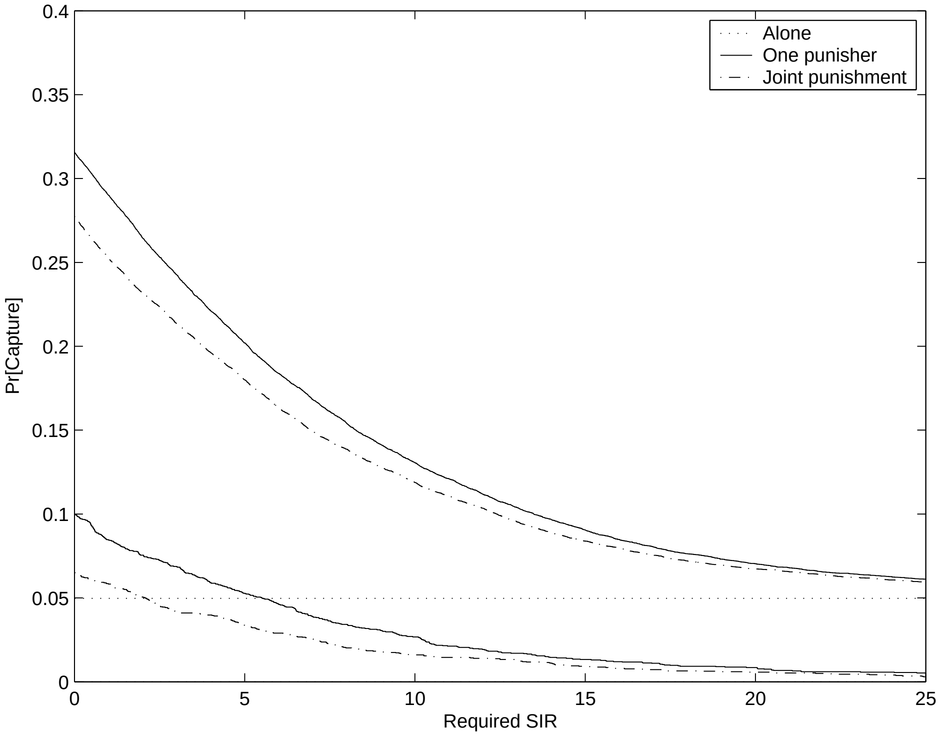

Figure 4.2: Probability that a user in a cell cannot be punished since no other user in the cell is able to jam with sufficient energy. The solid line only takes into account one punisher, while the dashed considers the case when all users in the cell jointly jam the transmission. The dashed line indicates the probability that a user is alone in the cell. Outdoor scenario with 3 users per cell for the upper set of curves, 10 users per cell for the lower set of curves.

cheater cannot be punished if only one user tries to jam the transmissions, while dashed line shows the probability if all the other users in the cell cooperate.

When the number of users in the cell increases the probability that a user cannot have his transmissions jammed decreases. Also the higher C/I requirement a user has the larger the possibility to jam his transmissions. We note that for three users on average and a C/I requirement of 10 dB there is a 10% chance that a cheater is “untouchable” This is excluding the case when a user is alone in a cell, which happens around 5% of the time. Thus, in this particular case there is a significant part of the time that a user can cheat without being punished. On the other hand when there are 10 users per cell on average the probability that a users cannot be punished is only a few percent and the probability that a user is alone in a cell is almost zero. Obviously the more users the better the chance of carrying out the punishment. It should be noted that when the access point can participate in punishment of a cheating user it is always possible to punish the user by blocking his traffic.

For a limited number of users and reasonable C/I requirements there is a non-negligible probability that a user cannot be punished. Thus, it seems like the distributed policing scheme should be complemented by other punishment methods e.g., by incorporating the policing functions in the access points.

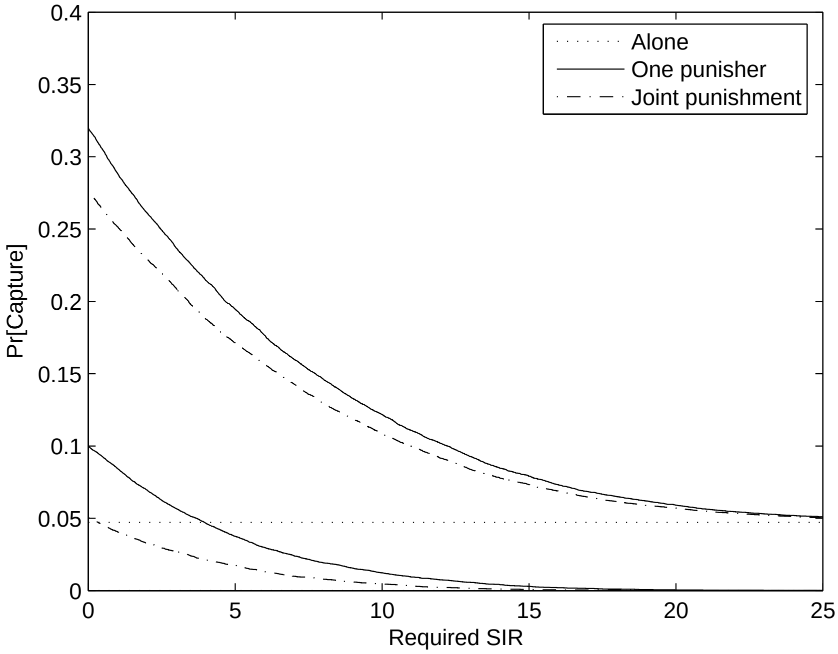

Figure 4.3: Probability that a user in a cell cannot be punished since no other user in the cell is able to jam with sufficient energy. The solid line only takes into account one punisher, while the dashed considers the case when all users in the cell jointly jam the transmission. The dashed line indicates the probability that a user is alone in the cell. Indoor scenario with 3 for the upper set of curves, 10 users per cell for the lower set of curves.

As a side note we can discuss what a suitable punishment is. Blocking traffic is obviously an efficient way of reducing the user satisfaction provided that the aim of the user is communication, but if the intention of the user is to deliberately disrupt communication, possibly as part of a blackmail scheme, blocking traffic may have little effect.

Detection limitations

Detecting that a user is cheating is necessary before he can be punished. Since CSMA/CA has a random element it is necessary for a passive observer to gather data that can be used for statistical analysis of the behavior of a user. Of relevance is for how long data has to be gathered in order to make a correct detection of a cheater. In this section we look at the reverse problem we study much time that is actually available for detecting the cheater. In the case of active detection schemes this is not an issue since a user who breaks the rules is immediately detected by a trusted observer.

In figure 4.4 the time a user stays within a cell is plotted as well as the time that users spend together in a cell, i.e., the "joint time". The time a user spend in a cell is the relevant measure if it is the access point that makes the detection. If the detection is made in a distributed way it is the time users spend together in a cell which is of relevance. We can see that in the rapidly changing outdoor scenario the time that a cheater can be detected

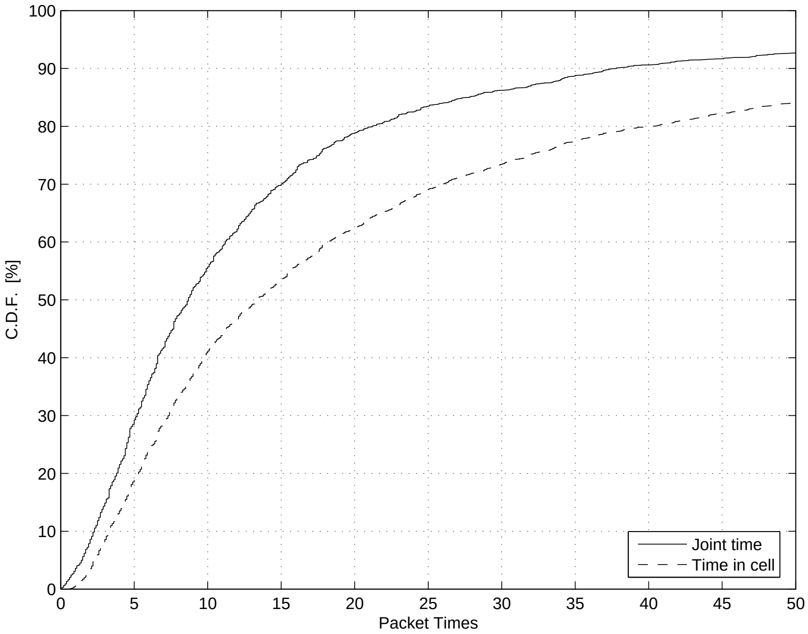

Figure 4.4: Time spent in a cell and the time users spend together in a cell, i.e., joint time for the outdoor scenario. For reference the packet duration is 10 slots.

by a fellow user is fairly short, either because the cheater moves out of the cell or the user moves out of the cell. If the access points monitor cheaters as well the time a detection scheme can observe the cheater is longer and detection is presumably easier. Finally, in the case the access points can use the backbone to communicate the observation time of a user extends to the entire duration of the stay in the network.

The detection method used and the exact way in which the cheater breaks the rules influences the time to detection. The detection scheme employed in the numerical experiments here is quite rapid and can detect a cheater after approximately 5 packet durations. On the other hand the cheaters in these experiments are quite easy to find since they never release the channel, i.e., they never back off. In other studies with more elaborate traffic models and more advanced detection schemes the time to detection is longer. In the paper by Raya, Hubbaux and Aad[27] the proposed scheme identifies the severe cheaters with almost 100% certainty after on the order of 10000 packets. Note that in the mentioned study there are no explicit results of the time to detection.

From the experiments we can note that the time available if we should detect at least 50% of the cheaters is the range from 10 packet durations for the outdoor case to approximately 200 packet times in the indoor scenario. These values is heavily influenced by the mobility of the users. In both the indoor and outdoor models the users do not stay in any specific spot for very long times. In a quiet office where people only go for lunch once a day the time that detection can take place is on the order of hours. The duration of the packets has a large impact on how many packets that can be observed during the stay of a user in one cell.

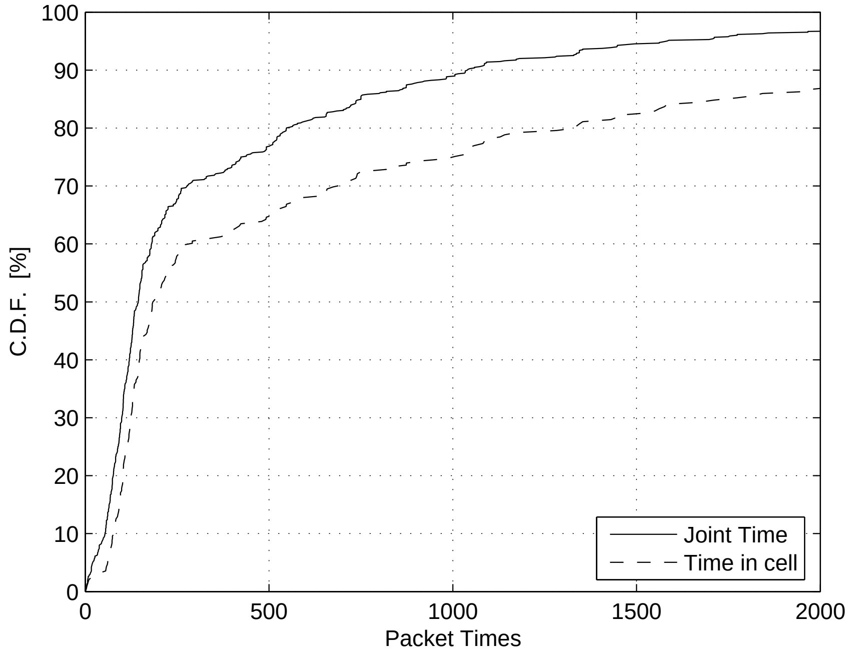

Figure 4.5: Time spent in a cell and the time users spend together in a cell, i.e., joint time for the indoor scenario. For reference the packet duration is 10 slots

We also note that detection is also complicated by packet collisions in this type of systems. Since it may not be possible to determine from which users the packets that collided came, the gathering of the actual backoff times for users will be inconclusive. The traffic situation can also lead to erroneous conclusions. For example, a user with a low datarate application that generates packets with large timespace in between will be difficult to detect. If he cheats by reducing the backoff window the pattern will be the same as for a user, with a high datarate application, who adheres to the protocol.

We can see that the time to detection is an important aspect of the detection scheme and that it will have an influence on the performance of a policing scheme.

Overall throughput

In this section we present the results of the complete system. The throughput per user is measured as the fraction of slots that a user sends useful data. In an ideal situation with only timid users they would achieve a throughput of roughly 33% each. In our experiments it less. Handoffs, hidden terminals and contention times all reduce the throughput. The in addition the length of the packets are fairly short compared to the contention times and thus a lot of the time is spent in contention for the channel.

It has been established in previous studies[27][28] that cheating has a positive effect on performance of the cheating users. This result is confirmed by our experiments. In figure 4.6 10% of the users cheat (follow strategy A) and the other 90% of the users are timid (use strategy B) in the outdoor environment. The results for the same user behavior

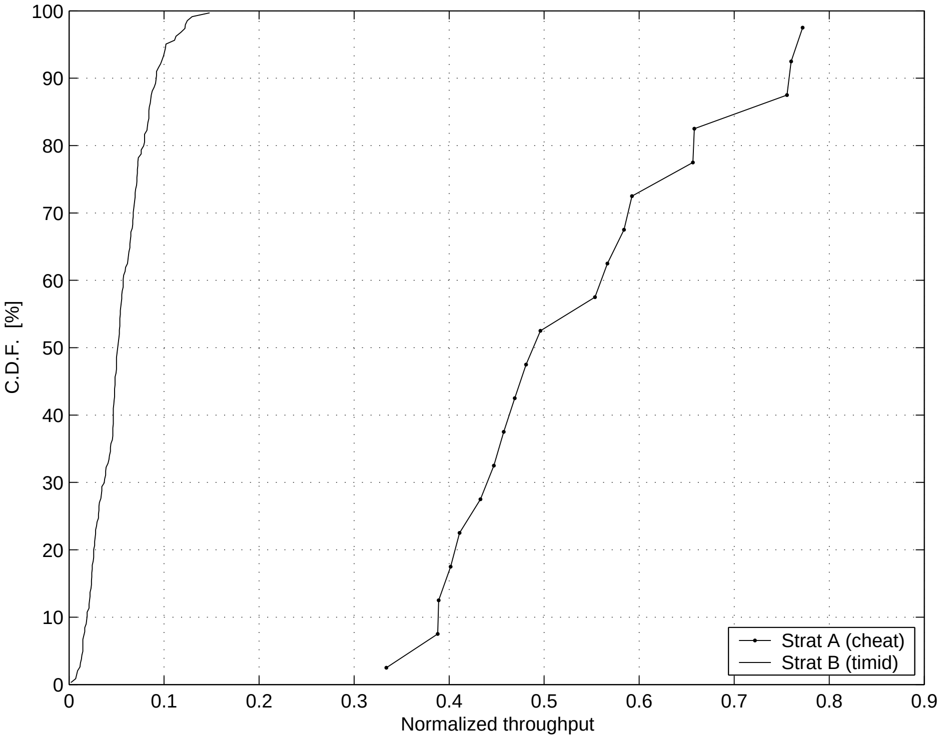

Figure 4.6: In a system with only timid users (solid line) and only a few cheating users the performance improvement for the greedy users (dotted line) is substantial. Outdoor environment.

in the indoor scenario is shown in figure 4.7. The reward for cheating is substantial and the timid users loose throughput. Note that even though the users following strategy B can be expected to have no throughput at all there are cases when there are only timid users in a cell and occasionally a packet is captured as well for the timid users, which give the timid users a throughput slightly larger than 0. We can also note some of the differences between the indoor and outdoor scenarios. The throughput in the indoor case is generally slightly higher. The main reason for this is that there is no co-channel interference and no hidden terminal problem. If the number of cheating users is increased the throughput for all users would drop since the transmissions mostly collide.

If we introduce users that have the ability to punish misbehaving users the results look slightly different, but it is still beneficial to cheat. In figure 4.8 we have 10% cheating users and 30% of the users have ability to punish the misbehaving users. The punishment mechanism that strategy C users have available results in some performance loss for the cheating users, but it is obvious that strategy A still pays off. We also note that the performance of the users following strategy B and C are the same. The reason is that strategy C users are timid in the sense that they follow the protocol for sending their data. In a more elaborate system the cheating users would notice that they are punished and thus be more careful which in turn would let the punishers achieve higher performance. Punishment could also be carried out by actually transmitting useful data and then strategy C users would achieve higher throughputs since their packets would be captured sometimes.

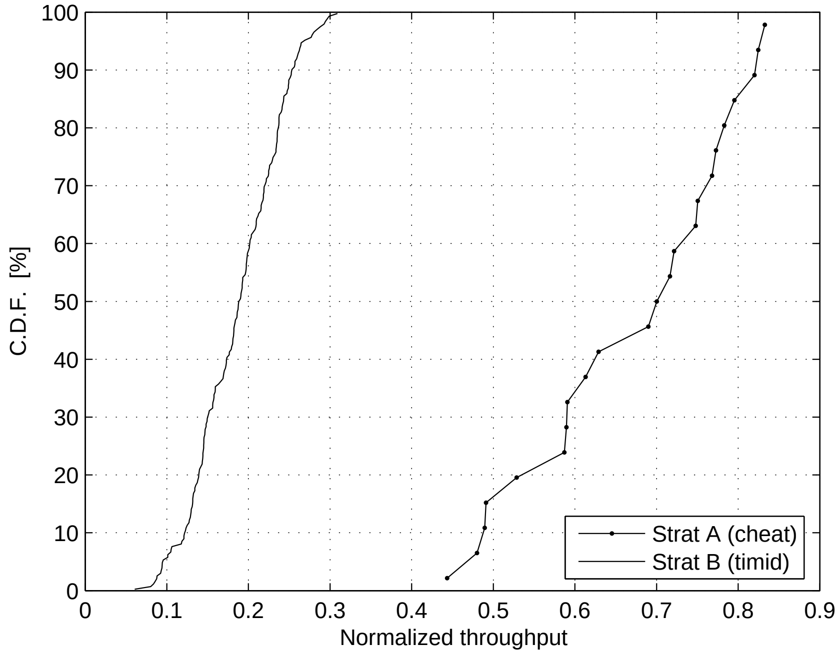

Figure 4.7: In the indoor system it pays off to cheat. However, due to more pronounced capture effects and no co-channel interference the timid users experience a slight improvement compared to the outdoor case.

As more users punish the cheating users the rewards for cheating is reduced. In figure 4.10 and figure 4.11 we plot the throughput of the cheating users for various amounts of punishment. We can see that the throughput for the cheating users drops when there are 30% and 90% users that punish. However, the drop is not substantial. We also introduce the “perfect” punishment scheme where a cheater is immediately detected and punished infinitely by the other users in the cell. In this case we can actually see a large drop in throughput. In the figures we also plot the performance of a system without greedy users (reference).

There is a difference between the indoor and outdoor scenario. In the indoor case the users stay longer and thus, they are easier to detect and punish. The effect can be seen because the reduction in throughput for the cheaters is larger in the indoor case.

Exactly how effective punishment and the expected gains are depends on location of users, how many users there are in each cell and so on. Thus, it is difficult to draw conclusions that always are valid for all users. If we look at the median user we see that the degradation for a user that is beeing perfectly punished is small compared to the gains of cheating undetected. In the outdoor case the gain is on the order of ten times the loss when punished. If we assume that it is the total throughput of a user that is of interest a user must be punished 10 times longer than he was able to cheat undetected before the losses equals the gains. This is when the best thing to do is to refrain from cheating. This implies that the detection scheme must be able to detect a cheating user during the first tenth of a

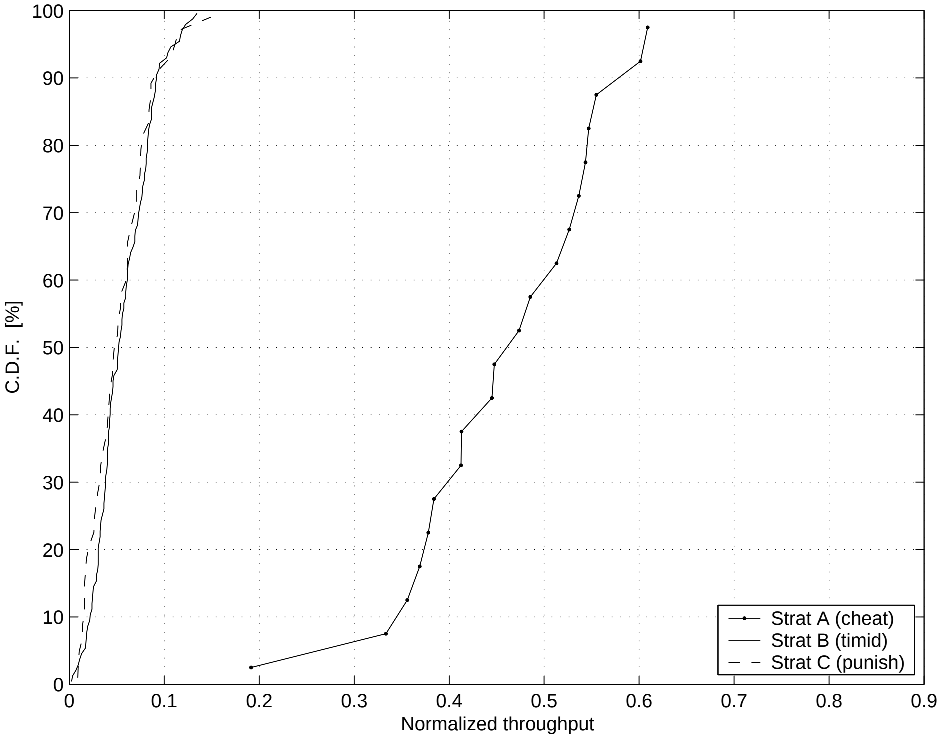

Figure 4.8: In a system with a few cheating (10%) users and the rest of the users following strategy C there is some performance loss, but the performance loss for the cheating users is not substantial.

users stay in a cell and then punish him for the rest of his stay do make cheating not worth it. In the indoor scenario the requirements are not stringent since the ratio between gains from cheating and losses from punishment is not as large.

In these experiments the packet length is fairly short compared to the contention windows. This makes the reference throughput in a system without cheating fairly small. In systems with larger throughput, i.e., with longer packets, the ratio between gain from cheating and loss from punishment is not as large and the detection scheme does not have to be as quick. We should also note that in this system with distributed punishment there is always the capture effect for users close to their access point. For specific users that don't move and are located close to an access point there is no incentive to be nice.

With more users there is a possibility of having more efficient punishment since there are less capture effects. At the same time the gain from cheating, e.g., acquiring the whole channel, is larger since the per user throughput is smaller. In addition detection of a cheater should require more traffic since there are many sources of the traffic. This makes the time to detection longer.

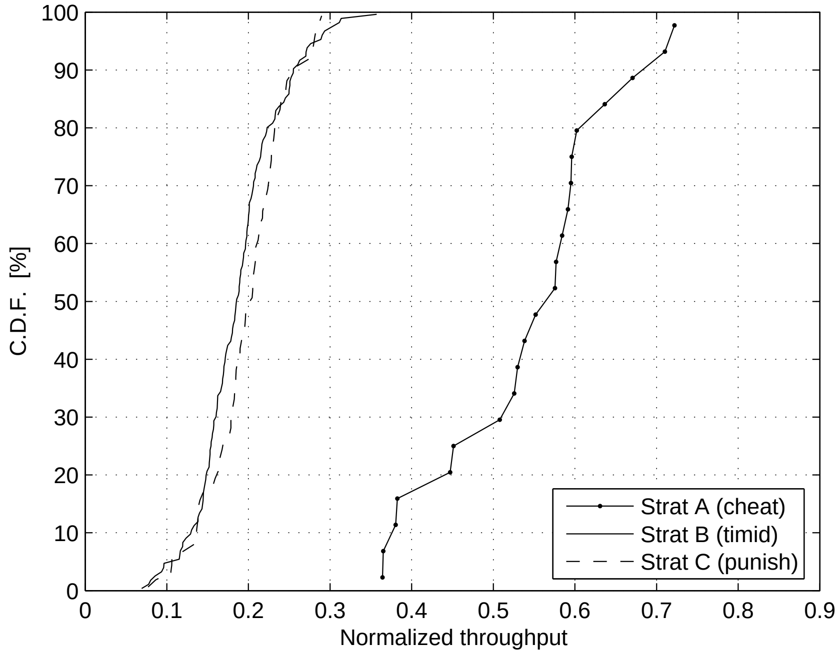

Figure 4.9: In a system with a few cheating (10%) users and 30% of the users following strategy C there is some performance loss, but the performance loss for the cheating users is not substantial. The indoor propagation conditions also make punishment more difficult and the performance loss for the cheaters is even smaller than in the outdoor case.

4.5 Concluding comments

The distributed punishment mechanism does not perform well mainly since detection is difficult and since it is not always possible to punish the misbehaving user. To remedy the problem with capture and so on it is necessary to allow the access point to participate in the punishment scheme. Since the access point simply can refrain from forwarding traffic on behalf of the user punishment can be made efficient. We have seen that the detection scheme must be rapid if the users should be punished enough before they leave the cell. The remedy for this is to let the access points communicate via the backbone network and forward information about a user that has been deemed as a cheater so that he can be immediately punished when connected to the next access point.

The strategies implemented here are quite rudimentary and thus fairly easy to detect. More elaborate cheating mechanisms may be implemented that cheats only occasionally or only when the user has important traffic so that the perceived reward for cheating is higher. A user may cheat only when leaving the system to be out of reach for punishment. The possibilities are endless. More complicated cheating mechanisms are obviously more difficult to detect and requires longer time to spot the cheater. This requires better detection algorithms and better "intelligence" gathering by the entire network. Another way to handle cheating is to make the protocols more robust and implement means for easier detection of cheating in the protocol.

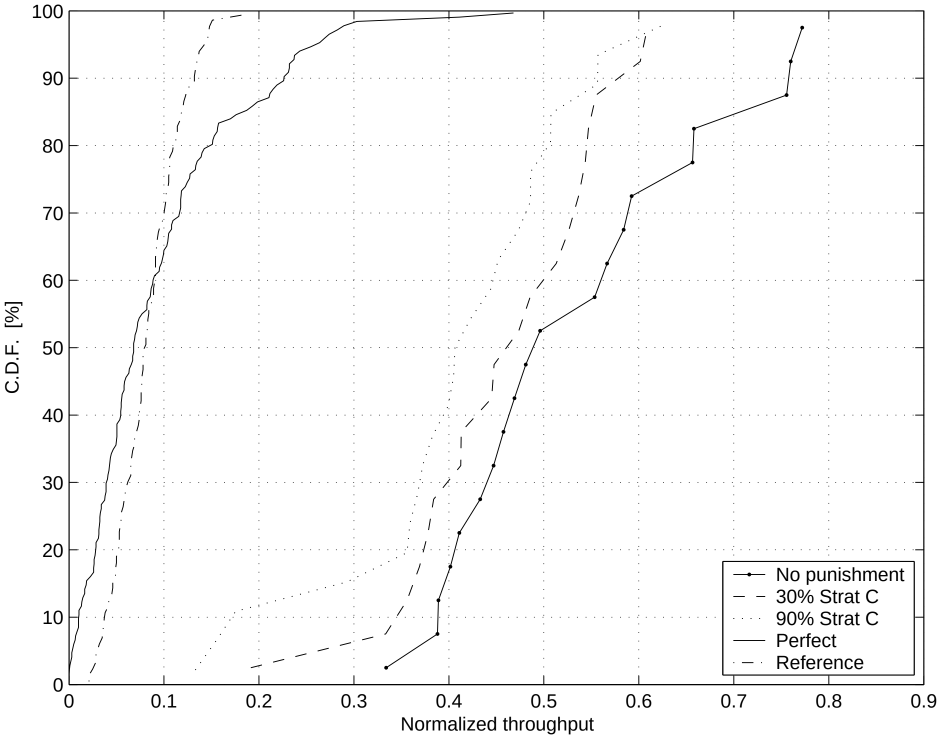

Figure 4.10: Throughput for cheating users (10%) when 0%, 30% and 90% of the users in the system has the ability to punish. In the perfect punishment scheme a cheater is immediately detected and his transmissions jammed until he leaves the cell. The reference case is a system without cheaters. Outdoor scenario.

When a few users cheat the total system performance is not affected a lot, actually there are cases when cheating actually improve total performance[73]. The distribution of throughput is drastically changed by the cheaters and if all users act greedily the system performance drops. We should also note that for the users close to the access point the short radio link is a big advantage since it allows them to cheat without punishment.

From a methodology point of view we can see that the concepts from game theory are quite useful tools for understanding the problem.

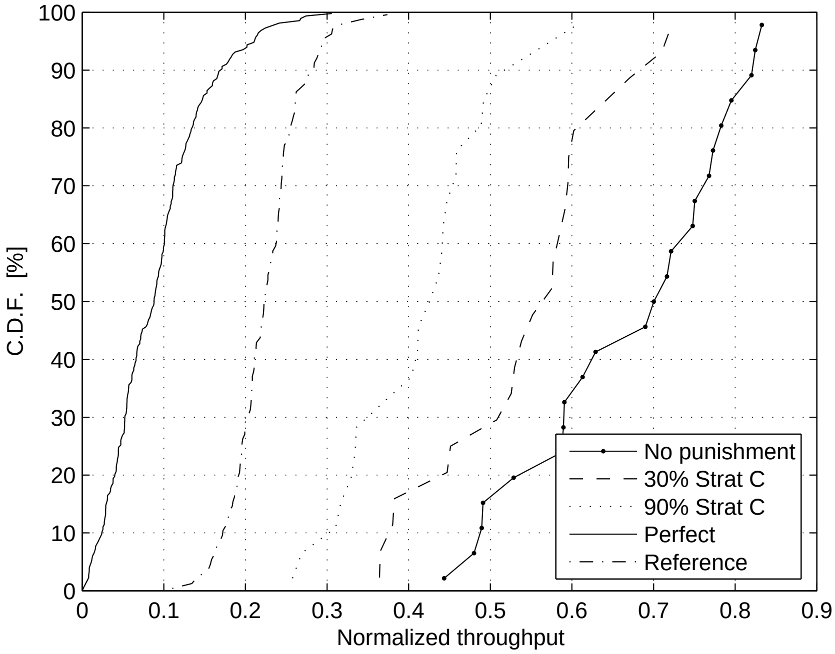

Figure 4.11: Throughput for cheating users (10%) when 0%, 30% and 90% of the users in the system has the ability to punish in the indoor environment. The reference case is a system without cheaters. Note the larger impact of punishment compared to the outdoor case, since a user stays longer in a cell in the indoor scenario.

Chapter 5

Competing operators

5.1 Introduction

In most cases when operators want to provide service they rely on licensed spectrum. The current trend though is that operators either have to share the spectrum with others or that an operator uses unlicensed spectrum for providing services. Public hotspots using WiFi technology is one example of this trend. In this chapter the competitors we study are not individual users, rather it is the operators that compete for the radio resources to ultimately maximize their revenue.

When the actors are not individual users but instead operators there are many more possible actions when designing a strategy. The fundamental difference is the geographical spread of the users and that there is more than one user that should be served. This gives a lot of new possibilities when designing a strategy. The operator has the possibility to select which users to serve and how to do that. Since the propagation and interference conditions varies from user to user and over time as well, selecting only the users that are easy to serve may be a successful strategy. Another possibility that an operator has is to coordinate activities across a geographically spread infrastructure. One example may be to hand users off from a busy area to a less active one.

Another complicating factor when studying this type of games is to define the utility of the operators. Ultimately, an operator wants to maximize revenue, but there are many things to consider when doing that. Maximizing revenue does not correspond directly to maximizing total throughput in the system[100]. For example, users may be willing to pay more for a small amount of throughput than for an increase in an already large throughput. Another thing an operator may want to consider when determining utility is the experienced service quality of the users. A bad (experienced) service quality can cause the user to select another operator, which results in losses in revenue in the long perspective. Thus, determining the utility for an operator is a complex issue and may influence the design of the strategies.

Investigating all possibilities for creating strategies is obviously not practical. Instead, we present a case study in this chapter. The focus is which users to serve and how many users to serve. In general, serving more users gives lower quality for the users.

Although not evaluated in this thesis an operator may use his network to gather information about the other operators. Since the access points generally have some possibilities to monitor the radio environment it is possible to gather information about the traffic situation for the other operators, where the other users are located, etc. This information can be sent to a central point to get a complete picture of what is going on in the other networks. It is also possible to determine what kind of actions the other operator makes to specific situations, i.e., determine the strategies of the other operators, either by passive monitoring or by actually generating fake traffic. There are probably many other kinds of information that can be obtained and used in various ways. This kind of “intelligence gathering” may both increase the total throughput and the throughput in the operators own network. The information can also be used to intentionally disturb the performance of the other networks if that for some reason is desired, e.g., for being able to offer a better service than the competition.

5.2 Game formulation

In this chapter we formulate the game with two operators that compete. We only look at a strategic game. I.e., the operators select a strategy initially and then stick to the strategy for the entire duration of the game.

The assumption is that the users want a certain minimum quality of the service. If the operator cannot provide the required quality the user is removed from the system to avoid creating unnecessary interference to the others in the system. The strategy of the operator is then simply the quality threshold at which users are thrown out of the system.

In the first game we assume that the operators have the same number of access points in the network, but in the next game we let the operators have different density of their networks. Operator 2 has 4 times more access points. The number of access points can be viewed as one additional parameter when creating the strategy.

The utility for the operator is measured as the fraction of users served and the total system throughput. The underlying assumption is that users have some kind of usage based fee and thus the revenue is dependent on the amount of data actually transmitted. At the same time users should not experience the service as unreliable and thus the operator wants to serve as many users as possible.

The best strategy may be different under different loads and thus we need to vary the traffic load to determine the equilibrium strategy under each load condition.

5.3 Models and assumptions

The results in this chapter of the thesis relies on the results obtained in[74]. Here we have investigated the capacity that can be obtained from two networks in the same geographic area using various multiple access techniques. The models are made for narrowband voice-type or data cellular networks. Even though the focus in the mentioned thesis is capacity it is possible to use the results to understand how two operators would act in a competition situation.

Propagation and environment

To be able to study the behavior of the competing systems we use numerical experiments to model two competing networks. The layout chosen is the traditional hexagonal pattern with an access point with an omnidirectional antenna in the middle of each cell. Previous studies[101] have shown that the worst case is when the two networks have their access points shifted one cell radius relative to each other. The measure of interest in the previously mentioned study was capacity. Capacity was defined as the maximum number of users that can be served while providing a large fraction (95%) above a specified quality threshold. Since we will let the utility obtained by the operators be the available capacity and resource

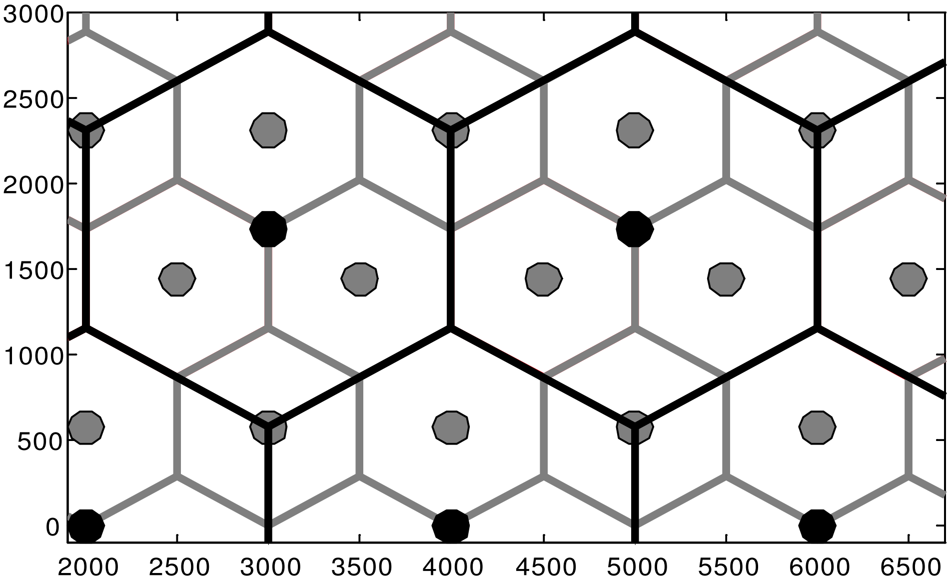

Figure 5.1: Part of the system layout in the case with different network densities. The cell radius for operator 1 (black) is 1000 m and the cell radius for operator 2 (gray) is 500 m. Operator 2 has 4 times as many access points as operator 1.

competition will be most interesting when the resources are scarce it seems reasonable to assume that the previously used cell layout will be a worst case from a game theoretic point of view as well.

The cell radius used is 1000m. We model 16 cells for each operator when they have the same access point density. A part of the equal density environment is shown in figure 6.1. When operator 2 has a denser network we model 16 cells for operator 1 and 64 cells for operator 2. A part of these networks is shown in figure 5.1. We use a wraparound technique which projects the system onto a torus. That way we can avoid border effects.

The propagation loss is modelled using the Okumura-Hata model described in[89]. The model includes three components. The pathloss (in dB) can be found using the following expression:

$$L = 21 + 35log(r) + 8X \tag{5.1}$$

Where r is the distance between the user and the access point in meters and X is a normal distributed random variable with variance 1. The 21 dB is a constant to account for antennas etc. It should be noted that the described model also includes spatial correlation of the random shadow fading component. However, since the users are stationary in the experiments the spatial correlation is of little relevance.

The output power of a transmitter is 30 dBm and the receiver noise is set to -118 dBm, which corresponds to a decent narrowband receiver. The influence of receiver noise is small since the system essentially becomes interference limited.

Traffic

The traffic used here is web traffic with moderate datarates. We model the downlink only since that is generally assumed to be the limiting factor. The traffic model used here has

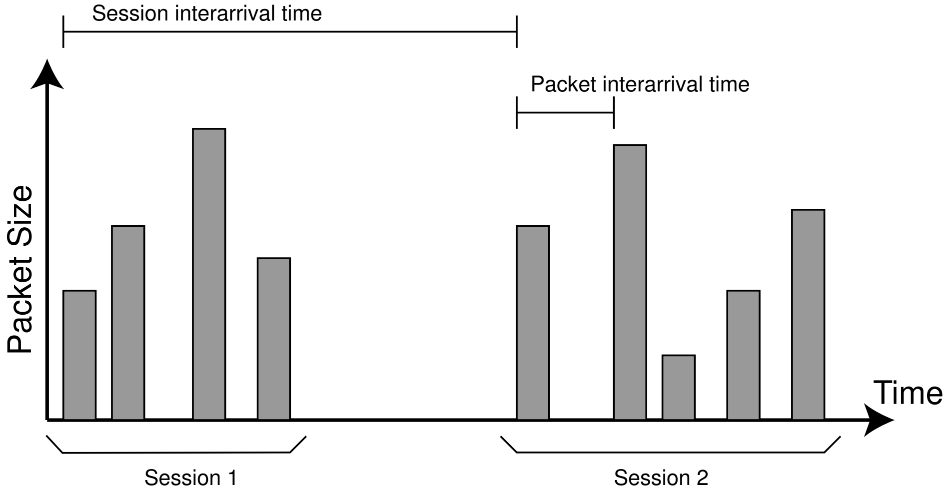

Figure 5.2: The traffic is modelled as a number of sessions with a exponentially distributed interarrival time. The packet size is normal distributed, the number of packets in a session are binomially distributed and the interarrival time is Pareto distributed.

been used to model traffic in Bluetooth networks[48], in wireless LANs[102] and in cellular systems with moderate dataratesb[103].

The traffic model is slightly complicated and the reason for using this model was originally to correctly capture delay performance in the networks. Traffic on ethernet networks has been shown to exhibit a self similar property[104]. Usually there are trunking gains when aggregating traffic streams with a poisson characteristic. However, this gain is not seen when the traffic has a self similar property and thus the delays experienced are larger than they would be when the traffic streams exhibit a poisson distribution. We do not study delay in this chapter, but since the implementation of the model was readily available it was used.

The traffic of one user is modelled in the following way: The communication of each user arrives in sessions. In each session the user transmits a number of packets of a random length with a random time between each packet. This is illustrated in figure 5.2. The number of packets in a session is geometrically distributed with mean 10 packets. The packet inter-arrival time is considered to have a truncated Pareto distribution with shape parameter $\alpha = 1.2$. The minimum is 0.84 s and maximum 333.3 s. The packet length is lognormally distributed with mean 5 Kbytes and variance (σ) of 15 Kbytes. The session inter-arrival time is modelled as an exponential distribution, which makes the number of sessions that arrive in a specific time interval Poisson distributed. The arrival rate is the same for all users and this is the only parameter used to control the load of the system.

In each cell there are on average 50 users. Since the system saturates at significantly less than 50 active users in each cell we avoid problems with modelling traffic correctly when the user is active all the time. The users are assumed to be stationary for the duration of the numerical experiments.

Multiple access method

The multiple access method in these experiments is frequency hopping. This access method has shown good resistance to the near far problem, which is often the limiting factor in this type of settings, further details are given in chapter 6.

There are 100 channels available to the systems. The hopping sequence is random. That is, each user selects one channel out of all the available with an equal probability in each hop. The exception to the rule is that users connected to the same access point do not select the same channel.

We assume that the channels are completely orthogonal, i.e., there is no adjacent channel interference. This may be a somewhat optimistic assumption. However, the adjacent interference is most pronounced between two channels next to each other in frequency. If the frequency difference is larger the adjacent channel interference is not as pronounced. If the number of channels is large and the number of users is small the probability that two users end up at frequencies next to each other is reasonably small. Thus, this assumption is not overly optimistic.

The packets generated are split into blocks of 2 kbit each. To be correctly received the C/I must be above 11 dB for the block. Erroneous blocks are retransmitted until they are correctly received. The assumption is that the feedback is instantaneous and error free. If the retransmission fails 10 times for a block the packet is dropped. We assume that all access points are synchronized and that blocks are padded to completely fill one slot. This simplifies the numerical experiments.

The slot time is 0.2 s which gives a maximum datarate of 10 kbit/s. The achieved datarate is measured as the number of bits transmitted divided by the time the user actually has something to transmit, i.e when there is at least one packet in the queue or one packet being transmitted.

The satisfaction of a single user is measured by comparing the achieved datarate with a threshold, which is the quality level the operator has decided to offer. If the user achieves a higher throughput than the minimum guaranteed datarate he is assumed to be satisfied. It is this minimum guarantee that is the strategy variable we study here.

Admission and removal scheme

In the case of more traffic than the system can handle some users are removed if they cannot be provided with the minimum guaranteed quality. Each operator removes users one by one and checks if the guaranteed quality is achieved for the remaining users. If that is not the case another user is removed, the quality is checked and so on until all remaining users reach their quality target. When deciding which user to remove the user with the lowest throughput is selected.

The interesting aspect of this particular system is that the quality for one operator depends on the actions of the other operator. Thus, it is actually possible that if one operator removes a user to improve the quality for the rest of his users the reduction in interference can actually be used by the other operator to admit more users.

Admission control in frequency hopping systems have been based on a load factor or average load factor[105][106]. These measures capture the interference in the system or the vicinity of a user that wants to be admitted to the system. If the interference or load is deemed to be low enough the user is admitted.

Since there is a resource shortage in the studied load situations some of the users cannot be served. To find out which users that can be served under specific quality requirements we start by allowing all users to be active and then remove them one after another until the quality targets are met for the rest of the users. Since the traffic in this case is data instead of voice calls we use a different approach to determine when more users can be admitted. The interference is judged by measuring the throughput of the user with the lowest throughput. If that is higher than the minimum guaranteed quality level plus 5% there is room for admitting users and the user that was last thrown out is put back into the system. This admission policy is probably somewhat conservative, but the general system behavior can still be seen.

This use of the admission and removal scheme is slightly different than in traditional voice type networks. Here we use the scheme to support as many users as possible while still maintaining the quality requirements set by each operator. No new users arrive during the execution of the scheme. In a voice type network the admission scheme is used to determine if a newly arrived user can get service or not. Over time this may give preference to users located in favorable locations. We should also note that the solution found by the described scheme is heuristic and it might be possible to serve a few more users. The allocation of users between the operators may also be different even if the same number are served.

In figure 5.3 we show the behavior of the algorithm. The load in the figure is equal for both operators and the quality requirement for operator 1 is 50% and 75% for operator 2.

Since both operators have users that do not meet the requirement both operators remove users. After some iterations operator 1 has fulfilled the quality requirements for the remaining users. However, operator 2 has a higher quality guarantee and must remove more users to be able to fulfill the requirements of the remaining users. The interesting thing to note is that as operator 2 removes more users and frees up radio resources there is actually some “room” for operator 1 to readmit some of the users that was previously thrown out.

This can be seen as a packing problem where operator 2 has larger pieces that must be fitted in than operator 1. Thus, for small space the only possible pieces that can fit are the smaller pieces of operator 1.

5.4 Results

Equal access point density

Competition for the radio resources is only relevant in the case of an actual resource shortage. To be able to understand the context the games are played in this chapter we first determine the load cases where there is an actual resource shortage. In figure 5.4 we plot the capacity regions for various quality requirements. Within the capacity region 95% of the users are satisfied. For example, below the 50% curve the average throughput for 95% of the users the throughput is above 50% of the raw channel bitrate.

In this experiment we focus on two specific load combinations. The first is equal load for both operators, i.e., the session arrival rate is the same for all users in the system. In the second case the session arrival rate for the users belonging to operator 1 is 4 times as high as for the users belonging to operator 2. Both load combinations are marked in the figure by a star. We note that both these points are outside of the 50% capacity region. There is a resource shortage in these load combinations, but the load is still reasonable, i.e., the systems are not completely overloaded.

Once the load cases have been selected it is straight forward (although cputime consuming) to determine the number of blocked users and average throughput for each of the load cases and for each of the strategies (quality targets) for both operators. The fraction of removed users and the average throughput per access point is given for the equal load case in table 5.1. The corresponding results for the unequal load case is given in table 5.2.

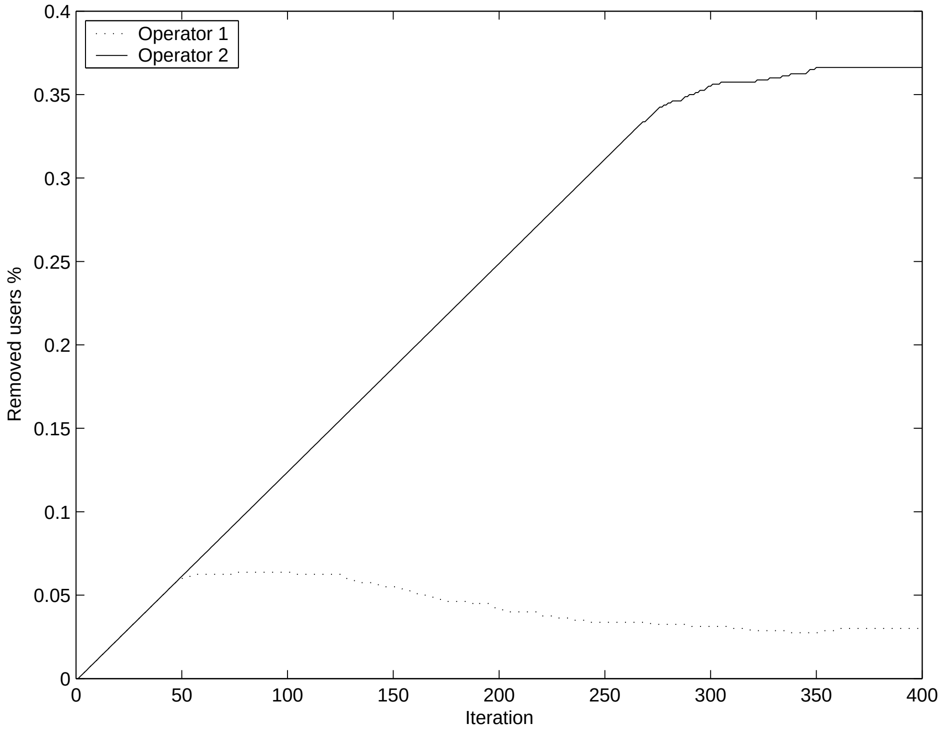

Figure 5.3: The fraction of removed users as a function of the iteration of the admission and removal algorithm. The load is equal for both operators and the operators has 16 access points each. The quality requirement for operator 1 is 50% of the maximum bitrate and 75% for operator 2.

We can note a few things from the results. In the case with symmetrical load the results should also be symmetrical. There are some variations due to the random properties of the numerical experiments. The general trends are clear however. In all cases the operator with the highest quality requirements removes most users, which is what can be expected.

The main problem for the operators is to keep the quality guarantees of the users. We would expect the throughput to degrade at some point when there is a lot of interference from the other operator. The only sign we can see of this is in the asymmetric load case when operator 1 has a 25% quality requirement. (Look at the first row in table 5.2 and the throughput figures for operator 1 which is the first number in the lower parenthesis.) In this case (almost) no users are removed thus the throughput figures are mainly a result of the interference from the other operator. The load is also high which makes the access points fairly loaded. Here we can actually see the throughput increase as operator 2 removes users, i.e., decreases the interference.

The Nash equilibrium in this game is easy to determine. It is when both operators select the 25% quality target. It is also this point which achieves the highest total throughput in the system. There may be a degradation of system throughput when there are more active users and higher interference levels, but in the chosen load cases the main influence on system throughput is the removal of users.

It is best to allow as many users as possible to be active. It makes sense since the

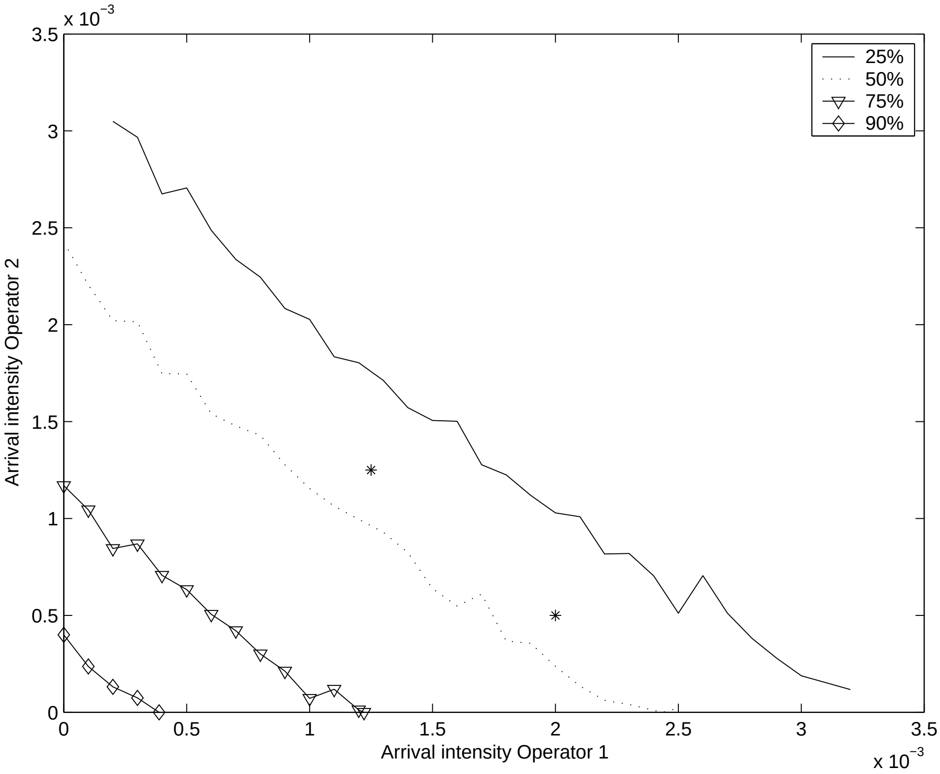

Figure 5.4: The capacity regions available for two operators when the fraction of served users is 95% and there are no removals. Figure shown for throughput requirements of 25, 50, 75, 90 % of the raw link throughput. The stars denote the load cases we evaluate the game in.

Table 5.1: Fraction of removed users (first row) and total average throughput per access point in kbps. Results shown for the equal traffic load for both operators 0.00125 sessions arrivals per slot and user and access point. Both operators have 16 access points.

Operator 2	25%	50%	75%	90%
Operator 1 25%	(0.1,0.1) (42.3,40.1)	(0,10.5) (41.4,36.7)	(0,42) (41.1,24.7)	(0,73.4) (40.5,11.7)
50%	(8.1,0) (37.5,40.8)	(7.6,6.4) (37.4,39)	(3,35) (40.7,26.7)	(0.6,68.4) (41.7,12.5)
75%	(42.1,0) (23.4,40.2)	(38,3.4) (25.3,39.6)	(28.6,29.9) (29.2,29.3)	(22.1,68.1) (31.5,12.6)
90%	(75.5,0) (9.9,42)	(70,0.5) (12.6,41.3)	(65.5,23) (14.5,31)	(56,54.1) (18.7,19.1)

Table 5.2: Fraction of removed users (first row) and total average throughput per access point in kbps. Traffic load for operator 1 is 0.002 session arrivals per slot and user and access point and 0.0005 for operator 2. Both operators have 16 access points.

Operator 2	25%	50%	75%	90%
Operator 1 25%	(0.1,0.4) (64.3,16.3)	(0,21.9) (66.5,13.1)	(0,63.8) (67,6.1)	(0,84.8) (67,2.8)
50%	(7.9,0) (59.3,16.1)	(4.9,12.5) (63.2,14.7)	(4.9,56) (61.9,7.3)	(3.8,81) (62,3.3)
75%	(29.1.1,0) (47.9,15.8)	(27.6,2.9) (46.9,16.2)	(26.4,41.6) (49.1,9.8)	(24.1,80.9) (49.5,3.2)
90%	(59.9,0) (27.9,16.4)	(56.8,0) (28.5,16.9)	(55.5,27.1) (29.5,12.1)	(50.2,74.0) (32.8,4.3)

interference expected by one operator cannot be influenced to a large degree. The main interference source is the other operator and only a small part is intrasystem interference. Thus, adding more users is not likely to cause a lot of extra interference within the system and all users will eventually get some bits through.

Unequal access point density

We can repeat the experiments when the operators have different access point densities. In this section operator 1 has 16 access points and operator 2 has 64. We first plot the overview of the load cases in figure 5.5. Note the rapid drop in the curves when operator 1 adds a little bit of traffic. The reason is that operator 2, who has a dense network, has to remove a lot of the users in the network to avoid interfering too much with the users in network 1. The users in network 1 have long radio links, which are susceptible to interference.

We pick two load cases between the 50% line and 25% lines to make the experiments in high load cases. The symmetric load case is 0.0009 session arrivals for both operators. In the asymmetric load case we use the same loads as in the previous section. The results of the experiments are given in table 5.3 and table 5.3.

The results in this section are similar to the results in the previous section. The Nash equilibrium is in the same place, i.e. minimum quality requirements. Lowering the quality requirements also increases total system throughput.

One point worth noting is that the denser network of operator 2 allows him to provide higher quality guarantees while keeping the blocking probability at the same level as the competitor. For example, if in the equal load case (table 5.3) operator 1 sets the quality target at 25% operator 2 can set the quality target at 50% and still keep a lower blocking probability than operator 1.

5.5 Concluding comments

It is difficult to provide any quality of service guarantees in this system scenario. The problem is that the option of removing some users to keep the other users in the system happy is not available since any attempt to free up radio resources by one operator only results in more available resources for the other operators.

The winning strategy is to accept users regardless of the quality that they can be provided by. This may not be that surprising. What is disturbing though is that if an operator wants to provide more higher service guarantees he will have less capacity compared to the

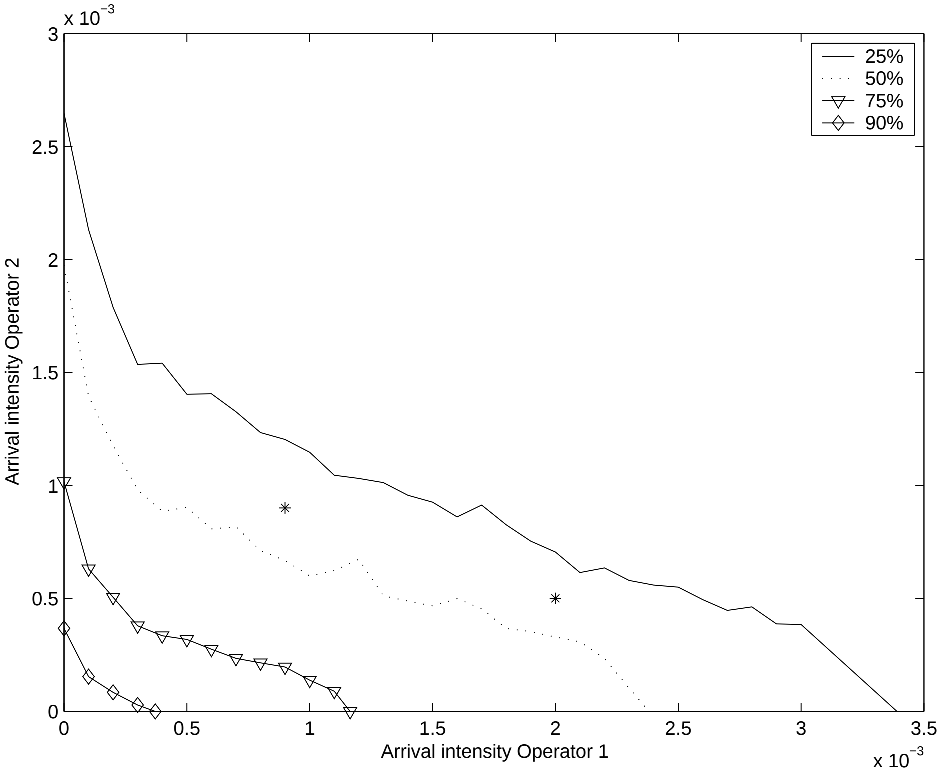

Figure 5.5: The capacity regions available for two operators when the fraction of served users is 95% and there are no removals. Figure shown for throughput requirements of 25, 50, 75, 90 % of the raw link throughput. Operator 2 has a 4 times more dense network. The stars denote the load cases we evaluate the game in

Table 5.3: Fraction of removed users (first row) and total average throughput per access point in kbps. Results shown for the equal traffic load for both operators. Operator 2 has a 4 times more dense network.

Operator 2	25%	50%	75%	90%
Operator 1 25%	(9,0) (26.2,30)	(8.4,0.4) (27.3,29.6)	(5.8,10.9) (27.4,26.9)	(2.1,31.3) (28.4,20.8)
50%	(38.9,0) (18.2,30)	(30.5,0.4) (20.8,29.8)	(29.2,8.9) (21.1,27)	(22.3,31.3) (23.3,20.6)
75%	(69.3,0) (9,29.5)	(65.8,0.2) (10.1,30.3)	(65.4,10.3) (10.6,27.2)	(58.5,31.3) (12.7,20.3)
90%	(89.4,0) (3.3,29.3)	(89.3,0) (3.4,30.1)	(90.5,9.1) (3.2,27.1)	(85.9,31.2) (4.3,20.3)

Table 5.4: Fraction of removed users (first row) and total average throughput per access point in kbps. Results shown for 4 times more load for operator 1. Operator 2 has a 4 times more dense network.

Operator 2	25%	50%	75%	90%
Operator 1 25%	(5.6,0) (61.8,16.6)	(5.8,1.1) (61.1,16.8)	(2.8,25.2) (63.6,12.4)	(1.5,31.3) (64.5,11.6)
50%	(22.3,0) (51.4,16.6)	(22.8,0) (50.5,16.6)	(20.1,16.3) (52.6,13.6)	(15.9,31.3) (55.5,11.3)
75%	(53.4,0) (30.2,16.8)	(53.8,0) (30.4,16.6)	(48.3,10.6) (33.8,14.7)	(44.5,31.3) (37.8,11.2)
90%	(78.6,0) (14.4,16.9)	(79.6,0) (13.9,16.7)	(79.4,6.2) (13.3,15.4)	(75.5,31.2) (16.8,11.3)

case where both operators select the same quality target. We have found that the operator with the lowest quality target always win.

Although not discussed here there are other aspects of the payoff an operator receives. Providing low service quality sometimes may make the users less willing to pay for the services and thus make each bit less worth. On the other hand it is only in situations with a resource shortage that the users will suffer. They may appreciate some communication more than none at all. It may be better for them to have some kind of communication with the low quality operator than be blocked by the high quality operator.

In this particular case we have also seen that the outcome of the game when operators are selfish is also the outcome that has the highest total throughput.

Chapter 6

Co-existing networks

The previous chapters have focused on what we can expect from users in shared spectrum and how efficiently we can expect the spectrum to be used. In this chapter we instead look at what options there are when sharing a piece of spectrum and how efficiently we can use it.

The rest of the chapter is organized as follows: We start with a discussion on various possibilities for sharing spectrum. Then we present a five cases where users share the spectrum. We introduce the common models and assumptions for all cases first and then present the specific assumptions and results for each case. Finally we sum up the results.

6.1 Sharing spectrum

In the entire chapter the assumption is that there is a radio access infrastructure connected to a wired network. There are mobile users that use the spectrum to communicate with the infrastructure and the wired network. In one case we also introduce the possibility for users to relay traffic for other users to reach the fixed infrastructure. Infrastructure communications has been selected since that it is expected that most users want to access the fixed network. The infrastructure networks is also the prevailing paradigm in the wireless industry.

There are three fundamental ways of dividing a piece of spectrum between users: It can be split, it can be shared or the users can build a common infrastructure and share that.

Splitting spectrum corresponds to traditional licensing. The network operators get one piece each and are then assured to be alone in that piece of spectrum. The advantage is simplified planning and possibilities to control service quality since the system does not have to consider external interference. The drawback is that splitting the spectrum in half also halves the capacity[1][2].

The spectrum can also be shared by the operators. We assume that users can only connect to the one operator's access points. The disadvantage with spectrum sharing is that operators interfere with each other. The added interference reduces capacity compared to the situation where the operator is alone in the spectrum. The main advantage of spectrum sharing is when an operator is alone in the spectrum. For example, the other operators

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[1] For an operator it is possible to support the same number of users by doubling the investment in infrastructure. What we mean here is that the capacity/cost is halved. There are also many other effects that should be taken into consideration. For example, trunking losses may reduce the capacity even further, it may not be necessary to duplicate the entire infrastructure, capacity may not be the main problem for the operator it may be coverage, the equipment may not handle a larger bandwidth, etc.

may not have any active users for some period, they many not have any infrastructure in a specific geographic area, etc. In this case the operator has access to the full spectrum which is more than he would have had in the case of splitting the spectrum.

The third way to share spectrum is to build a common infrastructure and let the operators rent capacity instead. The advantage with this option is that it combines interference free operation with access to the entire spectrum. For various reasons this is impractical and shared spectrum or other solutions are preferred. It is difficult for the operators using the infrastructure to offer different service qualities or the licenses may specify that the infrastructure cannot be shared.

The three discussed spectrum sharing methods can be combined in various ways to form a number of hybrid methods.

A very simplified example can be used to illustrate the concepts. Assume there are two operators that owns one access point each and two pieces of spectrum. Each access point can support one user for each piece of spectrum that is available. In the split spectrum case each operator gets one piece of spectrum and can then support one user each for a total of two. In the case where the operators build a common infrastructure each access points can support two users each which gives a total of four. In the shared spectrum case one operator can support two users with his access point if he is alone in the spectrum. When the other operator starts using his access point the networks will interfere with each other and the access point cannot support two users anymore. Depending on the assumptions we make the two access points may be able to support one, two or maybe three users in total.

This is the issue we focus on in this chapter. We determine how much the capacity of the networks is reduced when they interfere with each other. The achieved capacity is then compared to the case when spectrum is split.

So far we have discussed sharing spectrum among equals. The regulators have also introduced the concept of primary and secondary users of spectrum[14]. The secondary users may use the spectrum if they do not cause any interference to the primary users. One example is the shared spectrum is the band between 5250 and 5255 MHz[107]. It is shared by earth exploration satellites and WLAN. The satellite service is the primary user and the WLAN is secondary user. The WLAN users can use the band as long as they do not cause any interference to the satellite service. In addition the WLAN must tolerate interference from the satellites.

6.2 Common models and assumptions

In the entire chapter there are implicit assumptions. The first assumption is that there are operators that want to provide service in a service area. The operators have deployed an infrastructure to be able to serve its users. The aim of the operator is to provide some full area coverage with at least some guaranteed quality for it's users. This is very similar to the way cellular systems are described in a lot of the radio resource management literature. The important difference here is that the operators share the same spectrum.

It is of course possible to imagine other uses of unlicensed spectrum. One example is the way WLAN is used today. Each WLAN only covers a fairly small area and there are rarely overlapping service areas. The typical case is an office or a hotspot in an airport or café. This is changing as WLAN technology is used to cover larger areas and more actors are starting to provide services. There are also user deployed access points that need radio resources, e.g., WLAN access points placed in homes. It is obvious that when the WLAN is relatively isolated spectrum sharing works well. When the demand and requirements of the users increase it is likely that full coverage in the presence of many operators is something that becomes valuable.

The assumption that there is an operator that provides the services can be discussed. It is possible that networks are built in a community fashion where the actors all share a common interest and by joint efforts are able to create a communication network. One example of a large non-operator based network is the amateur packet radio network which had 100000 users in 1992[108]. The technical problems faced by this kind of network is similar to the problems an operator faces. Access to the network must be coordinated and it is possible that more than one network is deployed in the same area that competes for the radio resources.

There are also networks that do not incorporate any wired infrastructure. Communication networks designed for emergency and battlefield situations are examples of this kind of networks.

The fact that unlicensed spectrum can successfully be used to provide services in small areas is well established. The situation for operators that want to provide services over larger areas is more unclear. In addition some of the problems relevant for these operators are also relevant for other types of systems in unlicensed spectrum. Thus, it seems reasonable to study operators that coexist.

System layout

In the coexistence problem we can see that most problem occurs when the interference is strong compared to the desired signal. When studying the downlink this happens when a user is far from its own access point and close to another operator's access point. Studies have shown that the worst-case scenario is when the access points are located as far apart as possible[101]. In these studies we have used hexagonal cell layouts for each operator. The cell patterns for each operator are shifted one cell radius to get access points as far apart as possible. A part of the system used for numerical experiments is depicted in figure 6.1.

The path loss model used is the commonly used Okumura-Hata model. The pathloss between an access point and is determined using the expression:

$$L = C + 35log(d) + X \tag{6.1}$$

Where C is a constant to account for antennas, the frequency used etc (28dB), d is the distance between the transmitter and receiver. Finally, X is a normal distributed variable with mean 0 and 8 dB variance[89]. The antennas are omnidirectional.

The receiver noise is set to -118 dBm which corresponds to a decent narrowband receiver and the transmit power is 30 dBm unless power control is used and then the maximum transmit power is 30 dBm. The cell radius is 1000 m, which makes the systems mostly interference limited.

The networks of each operator consists of 25 access points. We project the system onto a torus which creates a system without borders. That way border effects are eliminated.

Capacity region

In this chapter we study the capacity of two networks that coexist in the same geographic area. With capacity we understand the number of users that each access point in the system is able to serve while providing satisfactory quality for the users. In general, there is a tradeoff between the individual user quality requirements and the number of users that can be served by the infrastructure. The lower the requirements of a user is the more users can be fitted into the system.

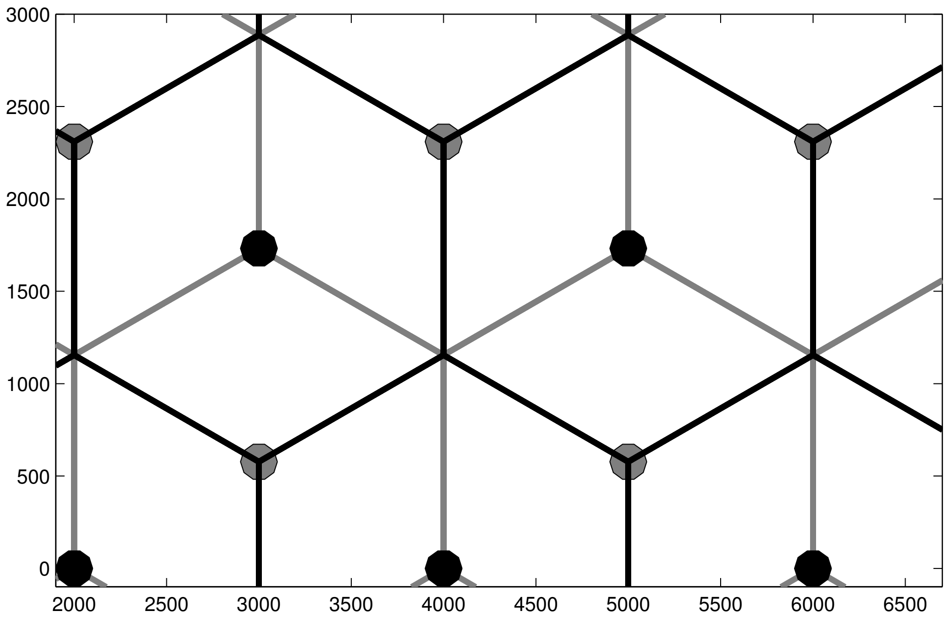

Figure 6.1: In the numerical experiments two overlaid hexagonal cell layouts are used. The systems are shifted one cell radius relative to each other to obtain the worst case for sharing spectrum. The gray network belongs to one operator and the black network to the other.

Since the number of users one network is able to support depends on the number of users in the other network we plot all combinations of loads that the networks are able to support. In figure 6.2 we show a schematic overview of such a plot. The load on the axes in the cases we present is the amount of traffic each user generates. For each combination of loads we can run a numerical experiment and determine the fraction of satisfied users. If the fraction of satisfied users is above 95% the load combination is inside the capacity region.

From the capacity region we can determine determine total capacity of the available spectrum by summing the loads of the individual networks. The capacity of a single (uninterfered) network can easily be determined by looking at the axis. If the sum of the loads is larger than that of a single network, spectrum sharing is performs better than splitting the spectrum. The capacity of a shared infrastructure can be approximated by doubling the capacity of a single network.

All users in our evaluations transmit data in the downlink except the multihopping case where they transmit data in the uplink. The exact criterion for user satisfaction varies in the presented cases. It is either based on the achieved throughput or the average delay of the packets. Empirical experience suggest that the the systems studied have a fairly abrupt transition region between a well working system and a completely overloaded one. This makes the exact criterion for a user to be satisfied a minor issue.

We have selected the requirement that at least 95% of the users must be satisfied instead of 100%. The reason is that there is almost always at least one user in a really bad position, with a lot of interference or high pathloss or both. If it was necessary to satisfy all users the capacity would be low. Another problem is that the system capacity becomes very hard to

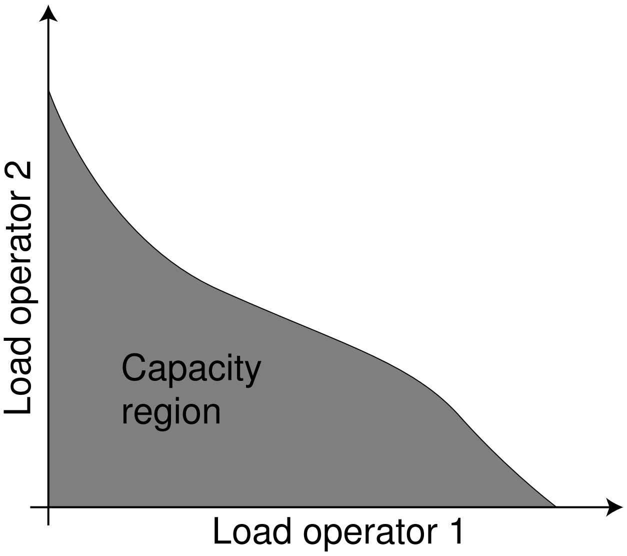

Figure 6.2: The capacity region describes all load combinations in network 1 and 2 where it is possible to achieve at least 95% user satisfaction.

measure. Since the location of a user is stochastic and the system reaches capacity when one single user is located in an unfavorable position it is easy to realize that the system capacity becomes dependent on one single event. If we rely on numerical experiments to find the capacity we need a lot of experiments to average over.

One could argue that we should study how well more than two networks are able to coexist. One difficulty is that performing the numerical experiments with two networks is quite time consuming and with more than two networks the numerical experiments would become impractical. Also the results for two networks are easy to visualize since 2D plots can be used. In addition the results obtained for two networks are expected to be valid for any number of networks and thus the additional insight gained by studying more than two networks is expected to be small.

6.3 DS-CDMA

Direct sequence CDMA is a technique that has been used to suppress interference in both military (stealth) and civilian applications, e.g., W-CDMA and IEEE 802.11b wireless LANs.

The interference from one user to another user depends on the cross correlation between the codes used. It also depends on the time difference, the multipath propagation conditions and the design of receivers. Here we use a simplification: Interference is suppressed by the processing gain for users that are not connected to the same access point. The users that are connected to the same access point are assumed to have perfectly orthogonal codes and thus not interfere with each other.

Since the channels in a DS-CDMA system are not orthogonal a power control scheme is usually employed to ensure that all users experience approximately the same amount of interference. In this system we use a SIR balancing algorithm known as DCPC[109].

The algorithm is iterative. The transmitted power is updated according to the following function:

$$P_i = min(P_{max}, P_{i-1}\frac{\Gamma_T}{\Gamma_{i-1}}) \tag{6.2}$$

The idea is that all users should have a specified SIR (Γ_T). If a user is below that target in one iteration of the algorithm (Γ_{i-1}) the transmit power (P_i) is increased and if he is above the power is decreased. However, there is a maximum allowable transmit power (P_{max}) due to physical constraints. In this study the maximum transmit power is set to 30 dBm and the SIR target is set to 11 dB.

The DCPC algorithm is run every slot until it converges or for 20 iterations, whichever occurs first. In most cases the algorithm converges after only a few iterations.

In this case we only consider the downlink traffic. The traffic model used here is the same used in the experiments in chapter 5. This model is used to capture the behavior of a user browsing the web. The control parameter used to vary the traffic load in the system is the arrival rate of the sessions. On average there are 0.5 users per access point and “channel”. Thus, for a system with spreading factor 100 there are 50 users per access point on average. Since the network cannot support 50 simultaneously active users per cell a user is active only a fraction of the time.

Packets are split into smaller blocks that are transmitted one at a time. A block is erroneously received if the achieved SIR in the slot is below 11 dB after despreading. The blocks that fail are retransmitted. We also assume that the acknowledgements are error free and instantaneous.

There is a problem with users that transmit at maximum power, but that cannot reach the quality target. They cause a lot of interference to the other users in the system and thus they should stop transmitting. The problem is to determine when they should start transmitting again. An exponential back-off algorithm is used in various systems to control the congestion in the system. The one used here is similar to the one used in the 802.11b standard[110]. Whenever a user hits the maximum power target he waits for a number of slots until he transmits again.

The number of slots he waits is a random number os slots from 1 to 2^n. Initially n is 1. But if the user tries to transmit and fails, n is increased by one. The maximum allowed n is 8. Upon a successful transmission n is reset to 1 again. Note that no packets are ever dropped. A user in a really unfavorable spot will continue retransmitting on average every 128th slot.

Results

In figure 6.3 we can see that the performance drops dramatically when there is traffic in both networks. The reason for this is mainly the limited protection from interference that DS-CDMA offers. For a spreading factor of 100 the “adjacent channel interference” is on the order of 20 dB for all users and channels. Since the difference in pathgain is often larger than this and the power control increases the variance of the interference there will be many cases where the interference suppression offered by the spreading is not sufficient to suppress some of the interferers.

Another observation that can be made is that the performance degrades more if there is more bandwidth available. To understand this behavior we need to consider the following scenario. One user belonging to operator 1 is far from the access point of operator 1 and close to one access point belonging to operator 2. This means that operator 1 has to increase transmit power to overcome the interference. But if operator 1 increases the power that

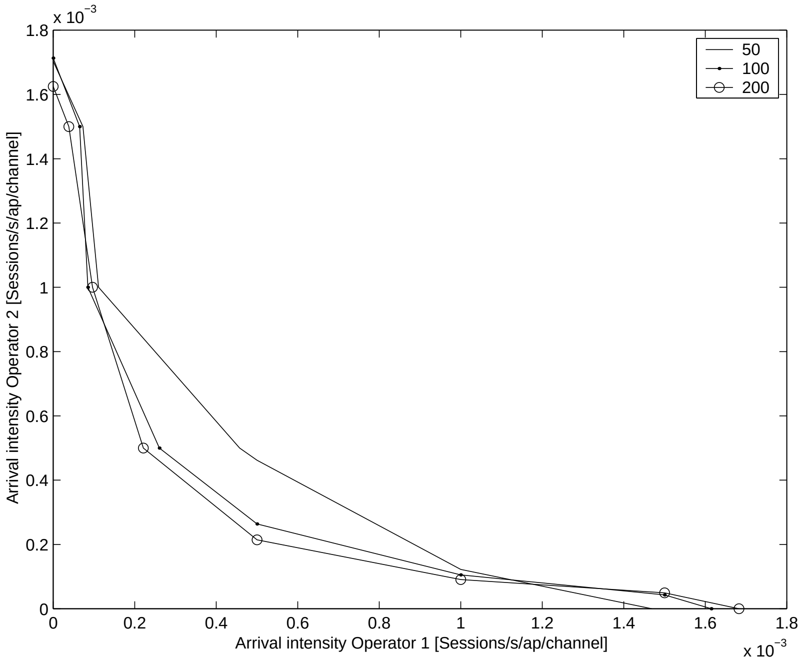

Figure 6.3: Capacity region for DS-CDMA systems for different spreading factors. The spreading factors used are 50,100 and 200

means that there is more interference created for those users belonging to operator 2. So operator 2 has to increase the power on the access points and so on. The closer a user is to the access point of the “enemy” operator the more severe this problem becomes. If the processing gain is larger that means that more users can fit in the system. This in turn means that it is more probable that there will be a user far away from the their own access point and close to the other access point of the other operator. This is what explains the degraded performance when there is traffic in both networks.

In figure 6.4 we can see that the areas where it is difficult to provide coverage for operator 1 are located close to the access points of operator 2. The access points essentially burns holes in the coverage of operator 1.

We can also note that the performance characteristics in this case is similar to hierarchical cellular systems where both the micro and macro layer use DS-CDMA[111]. The assumptions made for a hierarchical system are a little bit different, the micro layer has a much higher access point density and the power targets are different for both the micro and macro layer. The important thing to note is that in these systems we can also see a dramatic decrease in performance when there is traffic in both layers.

6.4 Frequency Hopping

Frequency hopping is a technique to spread the signal over a large spectrum to combat interference or to avoid detection. Some symbols are sent on a specific frequency and the

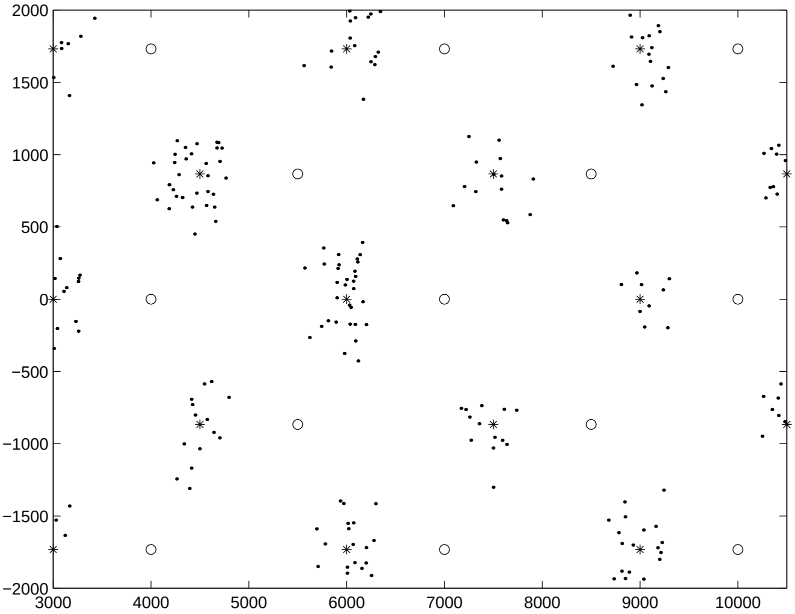

Figure 6.4: Location of users belonging to operator 1 that do not achieve the required quality requirements (dots). The circles are access points belonging to operator 1 and stars are the access points of operator 2.

transmitter is then tuned to a new frequency and some more symbols are sent and so on. Error correction is employed to ensure that the message is correctly received even if some symbols are lost because of interference or fading. Examples of widely spread systems that use frequency hopping are GSM[112] and Bluetooth networks[113].

The simulation tool used in this section is the same that was used in chapter 5 so the assumptions used are similar.

In this case two networks coexist by means of frequency hopping. The hopping sequence is random over the whole set of available channels. That is, each user selects one channel out of all the available with an equal probability in each hop. There is no coordination between access points. In this case we only study the downlink. Thus, it is reasonable to assume that the hopping sequences are orthogonal for users that are connected to the same access point. We assume that the whole system is synchronized. There is also synchronization between operators. This assumption is done since it makes implementation of numerical simulators easier.

We assume that the channels are completely orthogonal, i.e., there is no adjacent channel interference. Thus, this assumption is probably not overly optimistic. The adjacent channel interference is most pronounced between adjacent channels and for systems with many channels the probability that the interferer is on the neighbor channel is small.

The web traffic model used in the previous case is used in this case as well. There are 0.5 users per access point and channel in average. Thus, for a system with 100 channels there are 50 users per access point on average. There is one queue for each user. A packet that arrives is immediately transmitted if there are no packets in the queue. If the user is already transmitting a packet the new packet is put in the queue. The packet is split into equal sized blocks that are transmitted in each slot. Blocks that are erroneously received are retransmitted using an ARQ scheme. We assume that the acknowledgements are perfect and instantaneous. If a slot is not filled with data the slot is padded to fill the complete slot.

Because all slots are synchronized we will make a slight overestimation of the available capacity since collisions occur less frequently. Under this assumption a block either collides and is completely lost or it is received correctly. In a practical system there is a larger probability that a block collides with two blocks. Parts of these blocks are then lost. Depending on the coding and interleaving schemes used this may result in more errors.

The output power has been set to 30 dBm. The SIR will vary for each hop. Since all access points are synchronized the SIR is assumed to be constant for the entire slot. If the SIR is above 11 dB we consider the block to be correctly received and if the SIR is below the block is considered to be lost.

Results

In figure 6.5 the capacity region for two operators using frequency hopping as a method for coexistence is shown. The thing to note is that the sum of the capacities in both systems is roughly constant. This is due to the orthogonality of the channels. Even if there is an interferer close by there are always channels which are not occupied in a specific timeslot. These channels can be used for successfully transmitting a block Or put another way: Even if some slots are heavily interfered this does not affect other slots.

We cannot see any trunking gains. This is an effect of the characteristics of the traffic patterns. It has been pointed out previously that the burstiness of data traffic makes aggregated data streams bursty as well[104]. This means that there are no trunking gains to get since the same fraction of spare capacity is needed to be able to maintain the quality requirements.

In this system we have assumed no adjacent channel interference. This is an optimistic assumption and we can expect the performance to degrade when there is adjacent channel interference but the amount of adjacent channel interference is not as large in FH systems as in DS-CDMA systems. Thus we can expect a reduction in the total capacity when the networks share the load.

6.5 Dynamic channel allocation

Dynamic channel allocation has been used for automatic frequency planning as well as for avoiding interference in unlicensed systems. The frequency band is split into a number of channels and the users measure the interference to find one channel that is reasonably free from interference and thus can be used for communication. Examples of systems that use dynamic channel allocation are DECT[40] and HIPERLAN-2[114].

In this case we study the downlink of two networks that coexist by means of dynamic channel allocation. The traffic model use here is the same web traffic model used in the previous two sections. On average there are 0.5 users per access point and per channel.

The main issue when designing an dynamic channel allocation algorithm is to determine which channel to use for communication. There have been a number of suggestions on how this can be done. However, here we use a method known as minimum interference[115]. A user listens to all channels and measures the interference, i.e., signal power, on all channels.

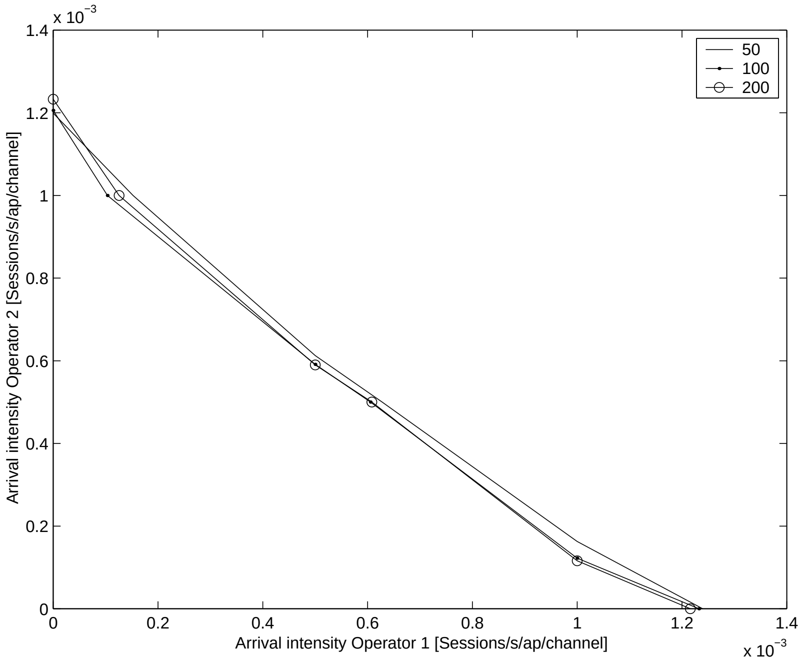

Figure 6.5: Performance of two coexisting frequency hopping networks. The total capacity is roughly constant. Graphs shown for 50, 100 and 200 available channels.

Then he selects the one with the lowest interference for communication. This channel is used until the communication quality becomes too low, i.e., the interference becomes too high. The user then repeats the channel selection process to find a new suitable channel.

In the numerical experiments presented here the transmit power is set to 30 dBm. A packet is split into smaller blocks that are transmitted one each slot. A block is correctly received if the SIR in the slot is above 11 dB. Failed blocks are retransmitted using an ARQ scheme and we assume that the feedback is instantaneous and error free. If the SIR is below 12 dB the channel quality is considered too low and channel reselection is performed. Channel reassignment is performed every slot if necessary. A user is satisfied if he achieves at least half of the physical channel throughput.

Results

In figure 6.6 we can see the performance of two coexisting DCA networks. The results show that the total available capacity is roughly constant. In general, the performance is similar to that of the frequency hopping network, however the absolute capacity is larger than in the frequency hopping system. The frequency hopping system does not coordinate frequencies between access points. On the other hand the DCA system is able to coordinate the use of the frequencies since the algorithm can listen to the interferers close by. Thus, the DCA algorithm is able to avoid the most difficult interferers.

In this system the channel reselection algorithm is quick. In systems with longer response times we can expect a performance degradation. If one network is quicker than the other

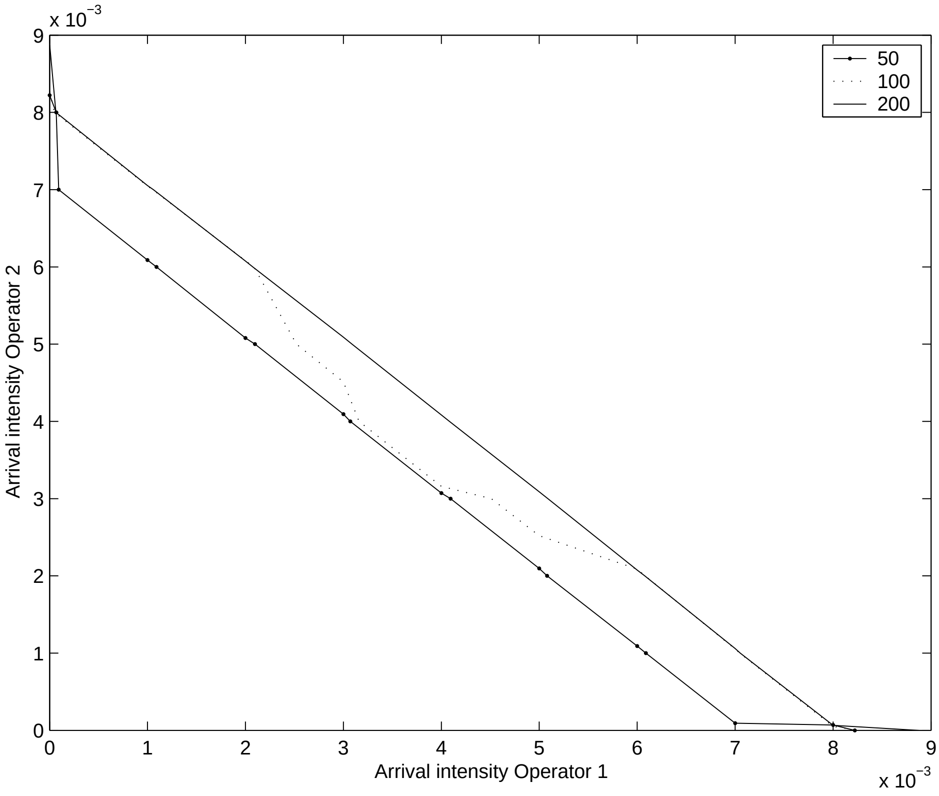

Figure 6.6: Performance of two coexisting networks using DCA. Graphs shown for 50, 100 and 200 available channels.

we can expect the slower network to loose.

6.6 Multi hopping

The work described in this chapter has been mostly been performed by the thesis author. However, the case study on multi hopping has been performed by a master student[76] under the supervision of the author. The reason the results are included here instead of in the related works section is that all results share a common ancestry with similar models and assumptions and thus all the results in this chapter are possible to compare. Together all cases give an extensive understanding of how networks share the available capacity.

As we have seen the problems when networks are coexisting are located lose to the other operators access points and to some lesser extent the users belonging to the other network. It is these coverage holes that limit the capacity. Another observation is that the links with low performance, i.e., low SNR, tend to be links where the geographic distance between the transmitter and the receiver is long. It is these long links that limit the performance of the system. If the long links could be avoided the performance of the entire system would improve. One way to do this is to employ multihopping. Traffic from the users far from their access point and close to the access point of the other operator use other users as a relay to forward their traffic to the final destination.

In multihopping systems there are two crucial issues to be addressed, namely scheduling and routing. The routing algorithm determines which paths packets are routed to reach the final destination, in this specific case it is the access point. Since users are not able to transmit and receive at the same time and since users interfere with each other a schedule must be designed to determine who transmits when.

In this specific case all traffic is assumed to be destined for the access point, i.e., we focus on the uplink. The routing algorithm used here is known as minimum energy routing[116]. The implementation is similar to the algorithm described in the original paper and the implementation by Lungaro[117]. However, the objective here is to minimize the interference, i.e., transmitted radio energy, and thus energy spent by the receiver and by processing is ignored.

The routing is performed in two steps. In the first step the neighbors of each node are found. The neighbors of a node are all those nodes where where a direct transmission consumes less energy than a transmission where the message is relayed by another node. Since this step is computationally intensive the problem is first partitioned into one problem for each access point. Users select the access point where the direct path has the lowest path loss. This partitioning may cause the algorithm to make erroneous decisions for some users close to the border of a cell. These errors are believed to be relatively rare.

In the second step of the algorithm the shortest route is found for each user to the access point. Since each route has an associated energy use, i.e., cost, applying Djikstra's shortest path algorithm[118] is straight forward.

Once the routes have been established the transmissions are scheduled to ensure that no users transmit and receive at the same time. The scheduling algorithm also ensures that the SIR requirements are satisfied. The scheduling algorithm used here is the Grönkvist algorithm[119]. The algorithm takes into account the traffic load on each link so that links with a lot of traffic are given more timeslots. The algorithm also takes into account the required SIR of the link in order to be able to schedule links simultaneously. The required SIR is 11 dB and the target SIR is set 3 dB higher in order to allow some interference from the other operator's network.

If the schedule is of the same length for both networks there will be some slots where the transmissions on two links from both networks always collide. To avoid this the schedule is randomly permuted each frame to spread the effect of the interference.

We note that there are only a few nodes that limit the performance of the network and an adaptive algorithm has been developed to enhance the performance of the critical nodes. The algorithm uses two queue length thresholds to adapt the schedule. When the queue length exceeds the low threshold the node is given an extra slot in the schedule each frame. This process is repeated as long as the queue length exceeds the low threshold. However, if the queue length exceeds the high threshold this process is stopped since the node probably is "beyond salvation". The extra slots are not revoked to give the node a last chance to recover. If the queue length length falls below the low threshold the extra slots are removed from the node in the schedule unless other nodes with a queue length above the low threshold are scheduled in the slot. In general, if an extra slot is added to the frame the slot can be used to help many nodes and it is not removed until all nodes have been "rescued". The low threshold in the experiments was 90 packets and the high threshold 300 packets.

The propagation model is the same propagation model used in the other cases in this chapter. The model was originally developed for cellular telephony. The model does not fit perfectly for propagation between mobile nodes. Since the model generally underestimates the propagation gain between mobile nodes the results will be pessimistic since the interferers are attenuated more in a practical system than in the simulated environment.

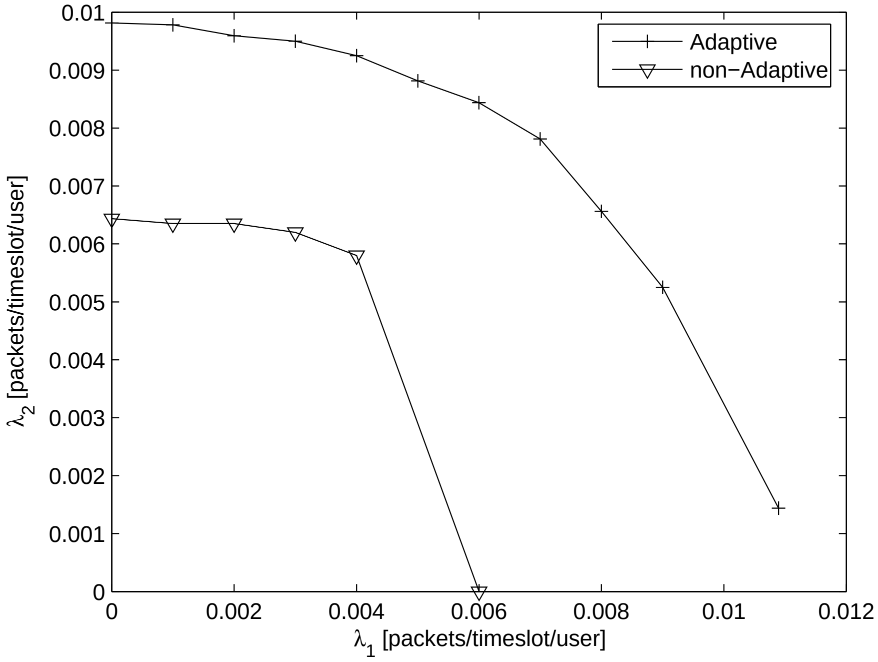

Figure 6.7: Performance of two coexisting networks using multihopping to avoid interfering with each other. Results shown for adapative and non-adaptive scheduling[76]

The network of each operator consists of 16 access points. On average there are 10 users associated with each access point. The users are spread around the area using a 2D Poisson process. The users generate packets with an exponentially distributed interarrival time. There is a slight modification in the arrival process where there cannot be more than one arrival in a slot. However, since the arrival rates are small this closely approximates an Poisson process. The arrival rate is the same for all users in one network.

A user is assumed to be satisfied if the delay is bounded. This is estimated by measuring the packets in transit at the end of a simulation run of 10000 frames. If the number of packets in transit, i.e., generated packets that has not arrived at the access point, exceeds 100 packets the user is assumed to have a non-bounded delay and is thus dissatisfied. If the number of dissatisfied users exceed 5% the system has reached capacity. It can be argued that the measurement criteria is somewhat ad-hoc. However, empirical observations show that the number of packets in transit is either small or very large and the exact threshold has little influence.

Results

In figure 6.7 we can see the performance of both networks. The main thing to note is that the total capacity when there is traffic in both networks is actually larger than the capacity when there is only traffic in one network. Thus, the strategy to avoid the long fragile links seems to be successful. This can also be interpreted as the multihopping is able to isolate the networks from each other.

Another thing to note is the improved performance from the adaptivity of the algorithm. Obviously the possibility to adapt to statistical variations in the traffic gives a performance increase.

6.7 Directional antennas

Directional antennas with steerable beams have been used to improve capacity in various types of networks. In this study we determine if directional antennas are able to provide good coexistence properties.

Again we focus on the downlink. In this case we rely on snapshot simulations. The load in the system is measured as the average number of users per access point. A thing to note is that a given load figure corresponds to an exact number of users in the system. The users are located according to a uniform random distribution in the service area. The transmit power is set to 30 dBm and the reuse factor is 1.

We use a simplified antenna model with a main lobe that is 30 degrees wide and has a 10 dB gain. The antenna also provides two steerable nulls that attenuates 10 dB. The nulls can be placed anywhere except in the main lobe. The rest of the antenna is assumed to have 0 dB gain. Both the access points and the terminals are equipped with this kind of antenna.

Determining the direction of the antennas is a non-trivial task. Here we have used a simple straight forward approach. The main beam of the access point is pointed directly at the terminal and the main beam of the terminal is pointed directly at the access point. The access point locates the nulls in the direction of the closest users, actually of the users with the lowest pathloss, and the users direct their nulls in the direction of the strongest access points. Since the nulls cannot be placed in the main beam the users or access points located in these directions are ignored when placing the nulls.

One of the main problem occurs when two terminals are located in the same direction from the access point. In this case both users will experience low signal quality. In order to improve the performance of the system the user with the lowest SIR is removed. Users are removed one by one until all users have achieved the required SIR, which in this experiment is 7 dB. When 5% of the users have been removed the system has reached capacity.

It could be argued that the antennas should be redirected after each removal. However, since the main reason for removing users is that they are in the same direction from the access point there is little to be gained from redirecting the beams when one of the users is removed.

Results

In figure 6.8 the results are outlined. The main thing to note is that the curve bends "outwards", i.e., the sum of capacities when there is traffic in both networks is larger than the capacity of a single network. This is a desirable property since this allows one network to utilize the spectrum as if it was alone, even if it is not. It seems like the directional antennas are able to provide some isolation of the networks.

6.8 Concluding remarks

All the previous cases have focused on networks with the same interference mitigation techniques. But it is possible to imagine that networks use different techniques and the question is how well they coexist.

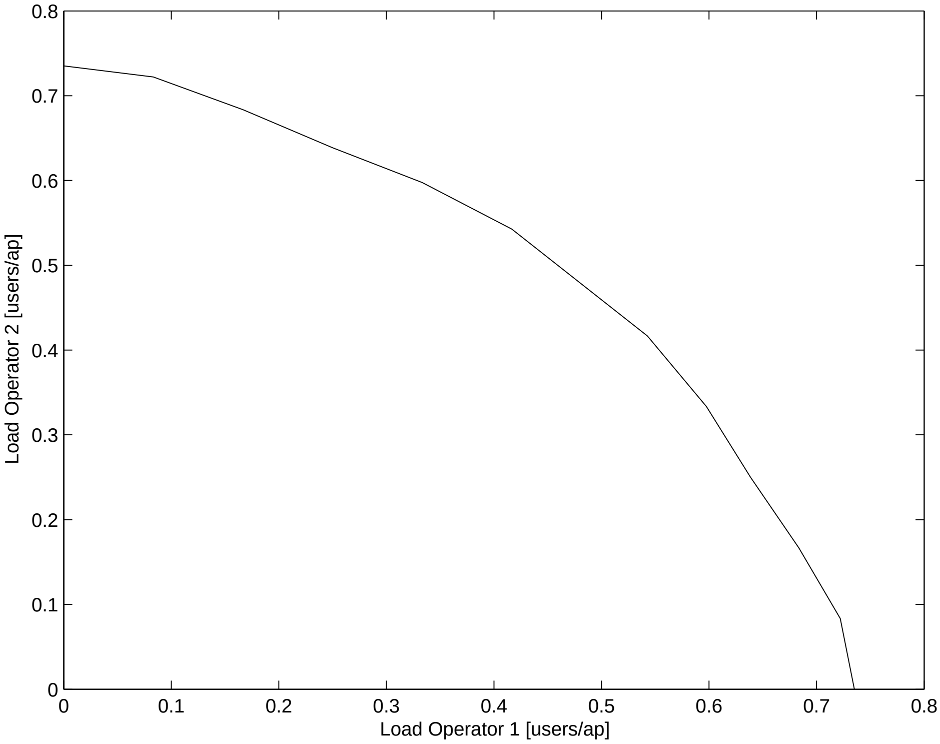

Figure 6.8: Performance of two coexisting networks using directional antennas

In the literature there are studies on how well 802.11b/g WLAN coexist with Bluetooth networks[54][57]. The Bluetooth network is more robust against interference and one of the reasons is the high hopping rate. The widebande WLAN receiver is also more susceptible to interference than the more narrowband Bluetooth receiver.

Research has also been done on the coexistence of UWB and 802.11a[62]. Here the UWB system is more affected than the 802.11a system. This is not strange since UWB uses less power and wider carrier frequency than 802.11a.

In general, it seems like systems that use orthogonal signals fare better than those that do not. Thus, frequency hopping and DCA networks have an advantage over DS-CDMA systems. Note that time multiplexing can be a method of achieving orthogonality.

In the beginning of the chapter we wanted to determine if sharing spectrum was better than splitting it. In the cases we have investigated we have found instances when sharing spectrum is better. These cases are characterized by isolation of the networks from each other. Isolation can be achieved by using adaptive antennas or multihopping.

We find that if operators cooperate the spectrum usage efficiency can be better for the shared spectrum case than splitting the spectrum.

Chapter 7

Conclusions

In this thesis we have studied a few cases of operations in unlicensed spectrum ranging from simple cases with two users to entire networks operating in the same piece of spectrum.

We have seen that individual users are likely to act greedily in most of the cases. Exactly how be greedy depends on the exact system design and for the evaluated methods there is a reward for cheating. Another factor that increases the reward for an individual user is to be close to the access point, i.e., have a short radio path. A short radio path both increase raw link performance and makes the user more difficult to punish.

We have identified two factors that increases the reward for an operator. The first is to have a dense network, i.e., have short radio paths. The other advantage is for operators to provide a low service quality. This makes it difficult for an operator to provide service quality guarantees in unlicensed spectrum because a competitor with lower guarantees will have an advantage.

We find that the greedy users reduce the total capacity of the spectrum.

A key to efficient spectrum use is to punish greedy users. A punishment scheme is difficult for the users themselves to implement. This makes the fixed part of the network a candidate for enforcing punishment. Detection is also a key issue. It is difficult to detect cheaters in the case of networks with a lot of mobility, but again the fixed networks should be utilized for better performance. Cheating can also be done in system using licensed spectrum so watching out for cheaters is probably a good idea in licensed spectrum as well.

The capacity of shared spectrum is in most cases the approximately the same as split spectrum. When the capacity is larger for shared spectrum the key factor is isolation between the networks. This can be achieved through adaptive antennas. Another way is local geographical isolation, i.e preferring the short links and avoid those links which are close to users or access points from the other networks. This can be done using multihopping. Note again the importance of short links.

We also note that in the case of operators competing the requirement for short links is beneficial. We have seen that the operator with the densest network has an advantage. Thus, there is an incentive for building a dense network.

In general, using unlicensed spectrum has disadvantages compared to similar services in licensed spectrum. For example, lower spectrum efficiency, difficulties in guaranteeing quality of service etc. The advantages with unlicensed spectrum is not seen in a radio resource study, rather its main strengths may be the ease with it can be used for short distances and the ease of introducing new services.

Game theory can be used as tool for analyzing competitive scenarios in a radio environment. A complete mathematical treatment is often quite cumbersome or out of reach for most practical purposes. Thus, there is a need to supplement the solution with numerical experiments. However, the game theoretic framework and the methods used for formulating the problems are very useful.

Appendix A

Scenario work

To be able to identify key research questions that would likely have a large impact in the future telecom world a number of possible futures were created as a start of the research process[69]. Increasing need for spectrum and more actors in the telecom market was two of the identified trends. In this appendix we give a short account of the scenario work performed.

A.1 Scenarios - not a prediction of the future

Predicting the future has always been something that people have wanted to do. The methods have varied from looking at the stars to the remains in a coffee cup. However, after the Second World War people started to attack the problem in more organized ways. One of the ways to envision the future was pioneered by Royal Dutch Shell in the middle of the seventies. A creative group of analysts worked with strategic planning and created scenario writing as a reaction against the more common quantitative methods that were used at that time. Instead of trying to perfect the methods used to forecast they accepted the uncertainty and tried to use it.

Most of the development proceeds as expected. This explains why extrapolation is useful for predicting the future. Things that grow will generally continue to grow and things that shrink will continue to shrink. But sometimes things do not happen as expected. Some things may happen as a result of random acts, but there are also some things that happen because two things develop in a way that creates logical inconsistencies. For example, exponential growth of a population will only continue to be exponential as long as there is room for an increasing population. When creating scenarios we use this kind of reasoning to reduce uncertainties. There are several uses for scenarios. Maybe the most obvious one is to find possible development paths. Another is to make people more aware of things that are happening. If one is aware of what may happen it is easier to be sensitive and spot things happening early.

Scenarios themselves are interesting as envisions of thinkable futures. By nature they are speculations although they are based on what is known today. By identifying trends and extrapolate them into the future a basis for speculation can be made. It is important to note that scenarios always come in groups. By presenting many descriptions of possible futures the risk that they are seen as *predictions* is reduced.

A.2 Making scenarios

In this section we outline the process of making a scenario. This is roughly the process followed when making scenarios, but there are variations of course.

To initiate discussions a brainstorming session is performed. During the session each participant is encouraged to think freely on the matter and write down observations, statements or questions on a note. Every string of text on these notes represents an area of thought that may be of interest. The notes are sorted, grouped and ideas deemed to be irrelevant are sorted out.

The relevant observations and ideas can be clarified by further research and they then form the basis for finding "driving forces". Driving forces are more fundamental trends that together change the society. All driving forces could have strong influence on the development. These are the core directions of development in different areas and they may be perceived only via the influence they have on more visible developments.

Similar driving forces are grouped into trends. The trends are fundamental ongoing processes with a large impact on society. When a trend has been found it is described thoroughly. The description includes a description of what is happening, the underlying reasons that the trend is happening, factors that strengthen or weaken it, changes that the trend is likely to cause and when the changes will happen and finally an estimate of the reliability of the whole trend. Creating the trends can require quite an effort.

The different trends are ranked according to importance and uncertainty. The trends that are more certain become the skeleton of all the scenarios while the ones more uncertain to us are used to create the variety of the scenarios. These "uncertain" trends then span a space of possible futures with the certain trends as a common basis.

Once the combination of trends for a scenario is determined a scenario embryo is created. This is done by creating a number of "newspaper headlines" that may come up at certain milestones or logical steps in the relevant trends. The embryo is then checked for inconsistencies and the embryos are "filled out" to a full scenario. Creating an embryo does not require a lot of effort so it is possible to create more embryos than what is finally made into full scenarios.

The scenarios are written with a number of perspectives of the envisioned future. In the referred work the scenarios include a general description of the society in the scenario, a scene from inside the telecom business and day in a normal persons life.

A.3 Scenarios used in the research process

The main focus of the three created scenarios has been to identify things that affect the direction of the development of the telecommunication. Three scenarios were, one where the development really offers no surprises and two where things happened that made the development path take another way.

Anything goes

The most striking feature of the "Anything goes" scenario is the rapid development pace. The competition is fierce. The market usually sets standards as de facto standards and in combination with a liberal regulations and competition creates rapid technological development. The cost of equipment and services is low due to global markets and competition. Most people in the industrial world can afford the communication services they want. However, it is the end customer who put various pieces of equipment together to fit his specific needs. This means that compatibility and interoperability are important properties when designing systems.

The Anything Goes scenario pictures the world where just everything goes. The main trends building up the scenario are Globalization of products, services and markets, Standardization diversification and Communicating appliances.

The development is very fast and new products and services are introduced in a very high pace. It is possible to start new networks and it is also possible for users to connect to these networks on an ad-hoc basis; access is more or less free. The requirement for access is possession of a (generic) broadband access tool and the right software, necessary to connect to the one or more of the networks.

The networks are mostly wireless LANs that belongs to companies, residences or niche operators that cover certain "Hot Spots". Outside the WLANs coverage, there are several layers of cellular and satellite systems available. As software is used to control all functions all products are easily adaptable to the type of network used, the service used and national and cultural requirements. This makes it possible for companies to sell a product worldwide, without any hardware adaptation.

Central regulation and standardization is minimal and many systems will have to coexist in the same frequency domain. As the central control has decreased, new ways of de facto standardizing is built up, combined with flexible multi-standard equipment. The major issues in standardization work are to be first out with a solution, document it well enough and make it well known in industry.

The impact on the private sphere is that the comfort offered by almost unlimited personal computing and communication is fully exploited e.g., for telecommuting from home offices and for controlling household appliances.

In this scenario each individual is responsible for buying the various components for communication. For example in order to communicate a person needs to purchase communication devices, software, connections, subscriptions and content separately. Users pay for services and content on a per use basis using electronic payment methods.

Big brother

In the world depicted in the "Big brother" scenario the main concern is security.

The Big brother scenario is based on the Information trading trend, where all information has a value and thus can be bought or sold. The little brothers symbolize all the people legally, or illegally, collecting information and the big brother symbolizes the government or international organization setting the rules for information handling.

The background is that the Information trading trend was dominant on the market and almost any information was available. The information available could be collected with custom methods, like company data bases, but also by combining different data bases with each other and with other information on the internet. For example email was scanned and behavior when playing the increasingly popular netgames, was mapped. As integrity and copyright was threatened, governmental organization had to intervene to protect and save the information society.

By 2010 the security and integrity are put first in every step of handling information. The governments in most developed countries cooperate to create a secure network level. This means that all citizens and companies who wants to perform computing and communication have to be certified for this, just like the systems with which it will be done.

For this, a new secure Internet level is created and the rules are enforced by a specialized Information Police Branch. Large operators that are closely controlled by the government provide communication services to individuals. Users pay for the services much in the same way as today via a monthly bill. Governments have retained and regained a lot of power. In addition to ensuring communications safety, they have a lot of influence on the standards set.

In the private sphere the change is seen since not as much information is available anymore and services adapted to a certain person are limited. Also, people are aware of the risks and they are careful in revealing personal data.

Another impact of this scenario is that the complexity of products and services increases and thus the cost. This, in turn decreases the development rate and the number of wireless systems and operators.

Pocket computing

Pocket computing pictures the world where the technological development is fast, but due to economical and educational differences, the society is divided between those who could follow the development and those who could not. Thus some parts of the population have access to a global service, and other parts are using more basic services.

Important trends are Services become independent of infrastructure, Education increasingly important, Communicating appliances and Globalization of products, services and companies. The companies providing services and content are powerful enough to set the political agenda and to set standards. Users buy services and the company providing the service ensures that required infrastructure is in place and provides the proper device. Payment is done using a normal monthly bill.

The wireless development has continued, but the system that existed at the turn of the century are still working and are inexpensive, while new systems have been introduced. The new systems offering full mobile multimedia in certain areas and high security has not penetrated the wide market and thus the pricing rates are high. This means that the range of services available on the market is very extensive and the pricing level is highly differentiated.

A consequence of the differentiated services, combined with the importance of education and knowledge is that the society has become highly differentiated. Governments have lost a lot of their power to the service providers, which has resulted in a breakdown in the welfare systems.

The differentiated society makes the lives of people quite different. People that are well off can afford to pay for high quality and secure services and their terminals are multi purpose. The poor people can only afford low quality services and have to have many low-cost terminals to use their services.

Appendix B

Dynamic Spectrum Allocation Possibilities and options

When the study of various spectrum management regimes were made[13] five interesting concepts for further research was identified. There five concepts are elaborated in this appendix. The concept number refers to the classification made in figure 2.1.

B.1 37 - Open Spectrum Access

Government spectrum agencies allocate a certain spectrum for “any-kind” of equipment meeting just a few requirements such as maximum allowed emitted power and in-band as well as out-of-band interference handling requirements (very relaxed etiquette rules). The spectrum usage is not constrained to a specific service but could be used in any fashion. Note that spectrum trading is a non issue. Since the spectrum is free to use for anyone it is unlikely that there will be any buyers[120].

The concept of unlicensed or open access operation is very close to the very successful use of license exempt spectrum. This concept is however based on an even thinner rulebook. These rules will have to be agreed upon entering the spectrum. The rules that can and should be imposed for the concept frequencies include out of band emissions, power and emission levels. Furthermore there might be a need to include other general rules such as listen before talk, automatic power level corrections, etc. in order to enable the highest possible use without risking that systems become greedy and only increase the noise floor.

This system concept relies on etiquette, but the central institutions could still imply inclusion of some rules controlled by these institutions. We will probably see interference rules, but few other rules (or etiquette) in the licenses. In order for this concept to have a significant effect, more spectrum will have to be assigned to the commons model. The spectrum assigned will have to be of the same nature as the 2.4 GHz band, i.e., without any constraints as to the service or to the technical nature of the use.

Usage of spectrum is down to milliseconds, typically a few seconds/minutes/tens of minutes, thus, the system concept is short term (ms).

End terminal access to the channel is governed by each terminal in a distributed fashion, thus, the system concept is a decentralized one.

Small, medium-sized, and large traditional telecom equipment suppliers push government bodies to initialize a portion of the spectrum to be used for “any-kind” of equipment meeting just a few power level and interference related issues on a consumer market. Regardless of from whom the telecom equipment is bought, that specific equipment can be used. No telecom operator is required to be involved in the loop of providing services. No fee for usage is necessary. Thus, this is truly a commons system concept. However, there might be a need for policing of spectrum use, and coupled with that, a fee might be appropriate to finance that policing need.

Key regulatory aspects of the unlicensed or open access operation concept include;

- More spectrum for license exempt use
- Surveillance of power levels and usage
- Avoiding the tragedy of the commons[121][122]

There are examples of similar contemporary systems: The 2.4 GHz band for license exempt use has a very limited rulebook. This is one example of this kind of band. The band hosts a number of very successful systems such as WLAN and Bluetooth.

Role of the regulator

The regulators focus of today, aiming for eliminating interference will change to keep the interference low enough to provide the wanted system behavior.

The objective of spectrum policy would not be to minimize for example, interference, but to maximize usable capacity.

The use of methods to dynamically handle interferences opens up the need for policing of spectrum usage such that fairness is achieved. This may be implemented both by rules for the equipment to be used in the allocated spectrum and by policing from a government agency. This means that the regulatory agencies roles will change (away from command-and-control), and perhaps dramatically. The movement from long-term planning towards operational issues will commence. There is a choice of strategy to be made here: Should the regulation require certification of interference handling prior to market entry or should the policing effort notice and on occasion fine that specific device, operator, user, or equipment seller?

Possibilities and challenges

With this system concept, business opportunities for non-established, small and medium sized established businesses, as well as larger established corporations, are enhanced. The prime potential for individual businesses for this lies in a reduced time to market.

This concept will probably favor networks without the need for large investments in infrastructure due to the short term approach. A long term approach will on the other hand open up for larger infrastructure investments.

The nature of imposing a rather high level of flexibility and dynamic behavior in this system concept makes it really interesting to study. We believe that this concept has a challenging potential of a large gain in spectrum effectiveness improvement.

With a smaller regulation of what technologies to use, there is a need for more flexibility and a dynamical handling of events that occur. The main issue to take care of is interference handling, both in a sense of measuring the environment and from there, to take action when we are subject to interference and to respond to situations where we cause interference. Several sophisticated solutions may be considered; frequency hopping, adaptive antennas, software defined and agile radios and ad-hoc mesh networks. This system concept demands frequency adaptive systems (software defined radio) that can change operating frequency on a daily, hourly or even millisecond basis like. Areas of technology that are of importance are:

- Standardized Software Defined Radio (SDR) complying to, e.g., SCA (Software Communications Architecture)
- Mobile ad hoc networking, with multi-hop functionality
- Dynamic interference management
- Spectrum usage policing (government bodies)
- Spectrum usage measurements and characterization (end-terminal wise)

There might be issues regarding large, traditional style, industrial programs, where the need for risk capital is great and pay-off times are long. This track is a bigger initial step in how development is done in this business area, but leads to, potentially, many more but smaller steps in evolution and thus many more but smaller risks per investment. There might be an issue with a greater investment, end-customer wise, up-front, alongside with lesser payments while the system is in use.

One problem with a free spectrum, i.e., there is no fee for using it, is that it may be overused and that the technology may not be very spectrum efficient since spectrum is for free anyway. Due to overuse the quality of the communication would drop to really low levels. This problem is known as the "tragedy of the commons" and that problem is something that has to be dealt with.

B.2 33 - License exempt operation

The main issue with this system concept is that a few industrial actors join efforts and create a standard for a certain kind of equipment. Alongside with creating the standard, an effort is made to have government bodies controlling spectrum usage to allocate a certain part of spectrum in as many nations as possible (to create a potential market as big as possible). Dependent on what end-user value is targeted, and the estimated potential in what the end-users are willing to pay for that specific value, different degrees of complexity is designed in the system.

Large traditional telecom equipment suppliers push government bodies to initialize a portion of the spectrum to be used for "standardized" equipment on a consumer market. This makes the spectrum usage transferable or non-transferable a non-issue but still governed by strict rules and equipment use also governed by strict rules.

Little effort may go into handling in-band interference problems as transmitters/receivers conceptually might be operating not too densely.

Strict rules support that a greater effort can be made for handling in-band interference. Nevertheless the rule book may be rather thin. Strict rules also support tougher requirements on out-of-band operational aspects.

Usage of spectrum is down to milliseconds, typically a few seconds/minutes/tens of minutes, thus, the system concept is short term (ms).

End terminals access to the channel is governed by each terminal in a distributed fashion, thus, the system concept is a decentralized one.

Regardless of from whom the telecom equipment is bought that specific equipment can be used. No telecom operator is required to be involved in the loop of providing services. No fee for usage is necessary. Thus, this is truly a commons system concept.

The commercial success for systems that, to some extent like WiFi-systems, conform to this concept makes this particular concept ideal as a reference case.

Examples of similar contemporary systems

Short range devices (SRD) for instance the European DECT concept is one place holder for this concept in our work. Note that other examples, quite different from DECT, may fall within this conceptual category, Bluetooth, remote control devices (car port opener), IEEE802.11x, WiFi, WiMax...

This concept does to some extent make out a subset of the Open Spectrum Access concept. The main difference is that there are more rules in this concept. Here 2.4 GHz WLAN has been taken as an example of a type of system, not an example of rulebook for the use of a specific piece of spectrum.

The commons model has very successfully been introduced already in the 2.4 GHz band for WLAN type applications, furthermore the 5GHz has been allocated at WRC03 as spectrum suitable for license exempt use. The 5 GHz band has more limitations than the 2.4 GHz band when it comes to the technical domain. For example, due to the existence of radar systems in the 5 GHz band all equipment must use DFS-technology (Dynamic Frequency Selection).

Currently three bands are available for license exempt use, namely 2.400 - 2.483 GHz, 5.150 - 5.350 GHz and 5.470 - 5.725 GHz, furthermore there are a number of frequency bands where equipment generally can be used without a licence.

Possibilities and challenges

Since this concept is well supported by larger corporations with its traditional investors behind them, this concept could perhaps be said to be well-known financially with risks and opportunities. However, also due to the traditional kind in this concept, it is associated with high investments and long term pay-off times. It may also be the case that this concept impedes non-established businesses entry into the market. Small companies are entirely dependent to production or maybe development of minor system components.

B.3 29 - Shared spectrum access

In this case a (fairly small) number of permissions to use a specific band are allocated to a number of licensees.

Allocating a limited number of licenses to a piece of spectrum may be a middle way between the dynamic behavior seen in the license exempt bands and the control of QoS that is possible in exclusive spectrum. Also knowing who the competitors are makes it easier to agree on how to cooperate.

The shared concept allows dynamic spectrum sharing, but without risking a complete breakdown, which could be the case with the commons. It is up to the licensees how to cooperate in the band. When the capacity requirements are low some simple, maybe obvious, methods for cooperation can be used.

One way is to simply split the spectrum among the licensees. This case is very similar to the traditional licensing schemes, but the licensing procedure is in some sense decentralized.

Another obvious solution is to build one network that all licensees use. This method is superior in capacity. But there are problems as well it becomes more difficult for the users of the network to differentiate service offerings. The issues here are similar to the issues for infrastructure sharing in the UMTS networks being built now.

The licensees may also choose to cooperate through a central instant spectrum manager, or access broker. The task of this may range from fairly simple frequency assignments to complicated real-time radio resource management regimes. The methods for achieving this are not completely new, but there are obviously unresolved issues.

The licensees may also choose not to cooperate and use the available technologies available for license exempt spectrum. For example, frequency hopping, dynamic channel allocation, ad-hoc networking, adaptive antennas, software defined and agile radios and mesh networks etc. may be used. In this case the issues are similar to the unlicensed spectrum.

Key regulatory aspects of the shared spectrum concept include a new definition of shared spectrum where the number users in one frequency band is established. It is also necessary to develop an interference management framework.

A less trivial case is when there are no or very few limitations to the types of technologies and services that could be used under a shared spectrum regime. In a case where for example, a radar application and a mobile system are used in the same spectrum the situation becomes more interesting. It is under a secondary trading regime relatively easy to envision a case where a license holder, such as the military could sell or lease some part of its spectrum as an “interference right” whereby the military sells or leases the right for a mobile system to cause interference to the military spectrum.

Another example of this concept is when there is an incumbent user present in the bands, and a new entrant can use part of the spectrum of that licensee. One example of this is the discussions in the US regarding the use of FWA-services (Fixed Wireless Access) in broadcasting bands (IEEE 802.22) where intelligent equipment is allowed to use broadcasting spectrum for FWA services as long as the equipment uses DFS to not cause interference to the primary user of the spectrum. This type of secondary non-exclusive use can make good use of many of the white spots in the spectrum usage maps.

This concept can be viewed as a mix of the other concepts presented here. Thus, many problems and opportunities are similar in this and the other concepts. However, some issues are unique since there are a few, not one and not many, license holders. Thus, there are not too many license holders to keep track of.

Examples of similar contemporary systems

The case of shared spectrum is not new; as a matter of fact it is a very common model for licenses, to take an example most taxi radio dispatch systems are using shared spectrum. So in a very simple case shared spectrum could be realised for a mobile data system as long as the different users are using technologies and etiquette rules that are relatively similar, as the case is for taxi radio.

Another example of current sharing of spectrum can be seen in broadcasting where the broadcasting industry is using wireless microphones in broadcasting bands. These “Services Ancillary to Broadcasting” (SAB) is a very good example of sharing based on different services, or use of “interference rights”.

Possibilities and challenges

Since only a few licenses are allocated there is an obvious risk of an oligopoly. However, there may be other means of realizing services and there may be enough players in the market to make it a functioning market.

There may be a first mover advantage. The licensee who first starts to populate the spectrum may have an upper hand when it comes to making agreements with the others.

With a shared spectrum among a moderate number of actors, co-operation and stability could be encouraged. Thus, the financial risks are limited.

The risk of spectrum holding is reduced since there is a group of licensees that can use the spectrum.

B.4 4,5 - Real time spectrum exchange

The real time spectrum exchange concept is the most challenging of the concepts presented here when it comes to spectrum management and the regulatory domain. The concept represents the full realization of a market model for spectrum management. The concept as such implies that spectrum should be treated as the property of its holder, and that the license holder has a large number of degrees of freedom regarding the use of the license.

In this system concept, conventional exclusive licenses are initially sold out by the regulator (e.g., in a license auction) or given out by a beauty contest etc. The spectrum usage is not constrained to a specific service but could be used in any fashion by the spectrum usage rights holder with no, or within some very relaxed, etiquette rules. The licenses thus acquired can be resold fast by means of electronic trading mechanisms. trading can be done through the regulator, through some central “license exchange” actor or by bilateral agreements.

The degree of decentralization is naturally interesting here. Although the trading is decentralized, a central register for responsibility is probably required. But one can also play with the thought of a total deregulated trade with licenses. Information processes are becoming too complex and varied to be run in any other way as through decentralized decision processes.

Any dynamic spectrum access system may include real-time trading mechanisms enabling trade with the limited spectrum resource. This could be done either with a third party entity, i.e., broker, or directly between telecom operators with rights to use certain parts of spectrum and interested in selling and buying these rights to use them. From a technical point of view, the implementation of such mechanisms could either be of central control or with local control.

By a central control, we mean that any telecom operator engaged in such real-time trading of spectrum usage rights have one, and only one, central point where decisions are made whether or not that operator itself should keep the right to use a specific spectrum, during a specific time frame, or if they should sell its rights to an other operator. If there is a broker involved, or not, seems not to have an impact on the needed implementation for the telecom systems involved. Furthermore, traditional telecom systems such as GSM and the like, and UMTS need little change, mainly in the telecom control plane, to support secondary use trade. It is mainly a matter of keeping track of how to debit or we could say roaming in all national networks as we do while out-of-nation use.

A local control is defined by that the end user terminals themselves have authority to buy spectrum usage rights, and use them instantly, and where network access points, e.g., base stations, have authority to sell spectrum usage rights and provide service instantly. This variant does indeed require add-on functionality and puts extra attention to security aspects of system use and reliability aspects of spectrum use.

Key regulatory aspects of the real time spectrum exchange concept includes: Fully implemented secondary trading without prior consent from the regulator, liberalisation of license restrictions enabling change of use, full reconfiguration of licenses in frequency, geography and time and establishment of a trading place, centralized or decentralized.

The regulatory framework must in this concept be very light when it comes to restrictions in use. However, the restrictions that can be associated with a license under this concept can be relatively strict when it comes to boundary conditions such as maximum power and out of band emission levels.

This system concept relies on etiquette, but the central institutions could still imply inclusion of some rules controlled by these institutions. We will probably see interference rules, but few other rules in the licenses.

In regulatory terms, one of the possible solutions for implementing the concept is through the introduction of a "spectrum manager". A spectrum manager holds the license and manages the use of the spectrum. The concept of a Spectrum manager has been introduced in Australia. Such a spectrum manager could make agreements with potential users of the spectrum and lease a particular piece of the license for a period of time. The potential interference between users is a business issue between the spectrum manager and the users, restrictions and obligations can be part of the business arrangement. The Spectrum Management Authority (SMA) will only hold the spectrum manager responsible for interference outside the license. If a user is in breach of the restrictions for the license and causes harmful interference to services in other bands the spectrum manager is responsible. Whatever the operation is within the license held by the spectrum manager it is part of the business arrangement between the spectrum manager and the users. The role of a spectrum manager can easily be taken by the current license holder given that the regulatory tools to implement the concept are in place.

Examples of similar contemporary systems

Some real-time clearing of frequencies already today occurs every time we leave our home country. The typical example is roaming in GSM. Here it is not the frequency spectrum per se that is traded, but rather capacity. However, the trading mechanisms are similar.

As for monetary streams and timing of payments, even if there is an initial auction it does not necessarily have to be on the format of an upfront lump sum to be paid in advance. Another option can be that the winner of the initial auction has made the best bid on the percentage of future revenues to be paid to the coffer of the Government. A real world test of this option has been carried out in the 3G licensing process in Hong-Kong[123]. In this system concept the original license-holder could then be seen as a "reseller", perhaps charging also others on a "pay as you go" format. Extra high prices for short-term peak leases, lower prices for those willing to make a commitment for say 3 years. This principle has been used for decades in the context of reselling of capacity on satellite transponders, or IRUs (Indefeasible Rights of Use) on intercontinental cables.

Interesting examples of the introduction of tradable rights can be found in Guatemala, New Zeeland and Australia[124].

Possibilities and challenges

This system concept implies frequency adaptive systems (e.g., software defined radio) that can change operating frequency on a daily, hourly or even millisecond basis. This can be done in a centralized or decentralized fashion. Some real-time clearing of frequencies already today occurs every time we leave our home country. Our devices, within a specific international open standard, automatically pick the strongest signal available (albeit in given frequency bands). This is a clear advantage from a user's perspective, even if it comes at "bank-robbery" rates. A possible solution could be to extend to the home captive market at more reasonable rates, even if the operators might hate the concept on both counts. Or, are there also technical constraints blocking any more large-scale surfing between any net which can offer the "lowest rate in town" at any given location and time? This should be looked into.

From an economical point of view this scenario gives a much shorter feedback-loop between success on the market and assignment of the scarce spectrum resource. Getting down to each and every base-station, and down to milli-seconds can be expected to give the most efficient use of spectrum where the least possible part of the spectrum is left idle at any point of time. This is one step towards the perfect market as described in macroeconomics.

B.5 18 - Traditional licensing

In this concept an application for a license is made to the regulator who grants exclusive use for an extended period of time. However, there are a number of conditions connected to the license. For example, a (Swedish) 3G license requires that equipment adhering to a specific standard should be used and coverage everywhere must be ensured. The license cannot be transferred to another party and if the license holder does not fulfil the requirements the license may be revoked.

Examples of similar contemporary systems

This is the traditional regime for licensing and there are many examples. GSM spectrum may be one that many know of.

Possibilities and challenges

The philosophy behind this system concept is that interference problems should be planned away. The planning process performed by the regulator when giving out licenses ensures that a license holder is not interfered with. This planning in advance makes it possible to simplify equipment since a lot of functions for mitigating interference are not needed. Also the lack of interference makes it possible to make global optimizations to maximize capacity. However, since planning must be done for the worst case most of the time a lot of capacity is sitting empty most of the time.

In this system concept the time span is quite long. Thus, planning can be done on a quite long time horizon since the rules are known beforehand. This reduces risks for actors. However, it also creates an entry barrier to new operators since there may not be licenses available. Thus, there is a risk of reduced competition and higher prices.

Since planning is a slow process the time scale that licenses are granted on is quite long to minimize the planning overhead. For example, if the planning takes half a year then the license should be granted for at least some years to avoid spending too much of the time planning. On the other hand since everybody has adapted to a slow planning process there is little incentive for the regulator to speed up the process.

Appendix C

Environments for the timeslot game evaluation

In this appendix the layout of the various systems used for numerical experiments in chapter 3 are outlined. Transmitters are denoted by a 'X' and receivers by 'o'. The line shows which transmitter is connected to which receiver. The figues show the cases with 10 users. For the 7 user environment three users are removed.

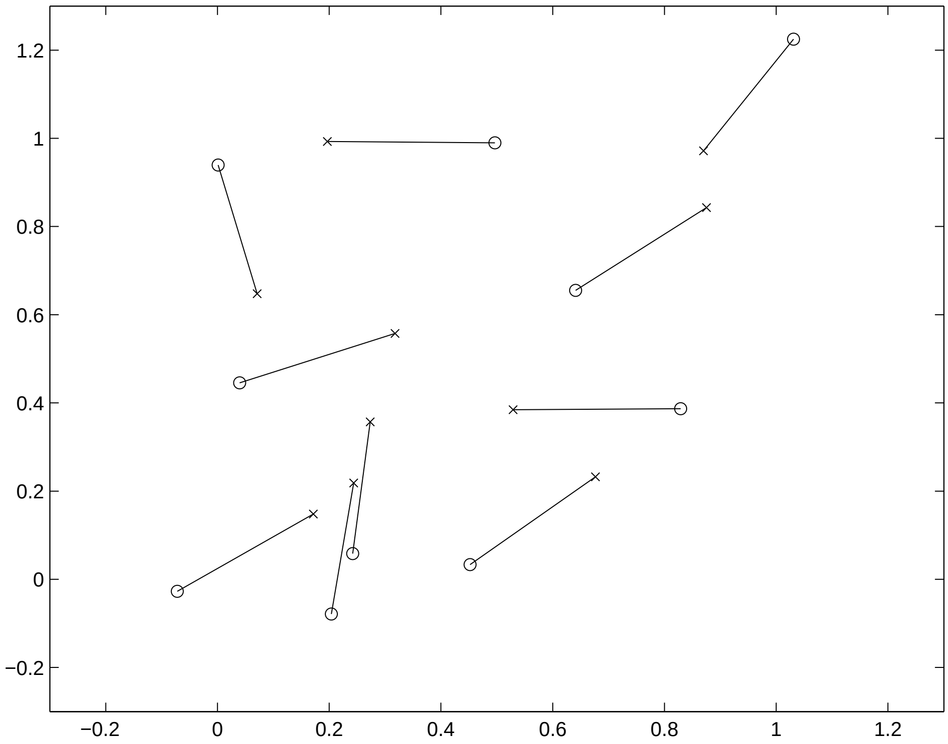

Figure C.1: The first of the scattered pairs environment. There are few Nash equilibria in this case, but the search algorithm converges most of the times.

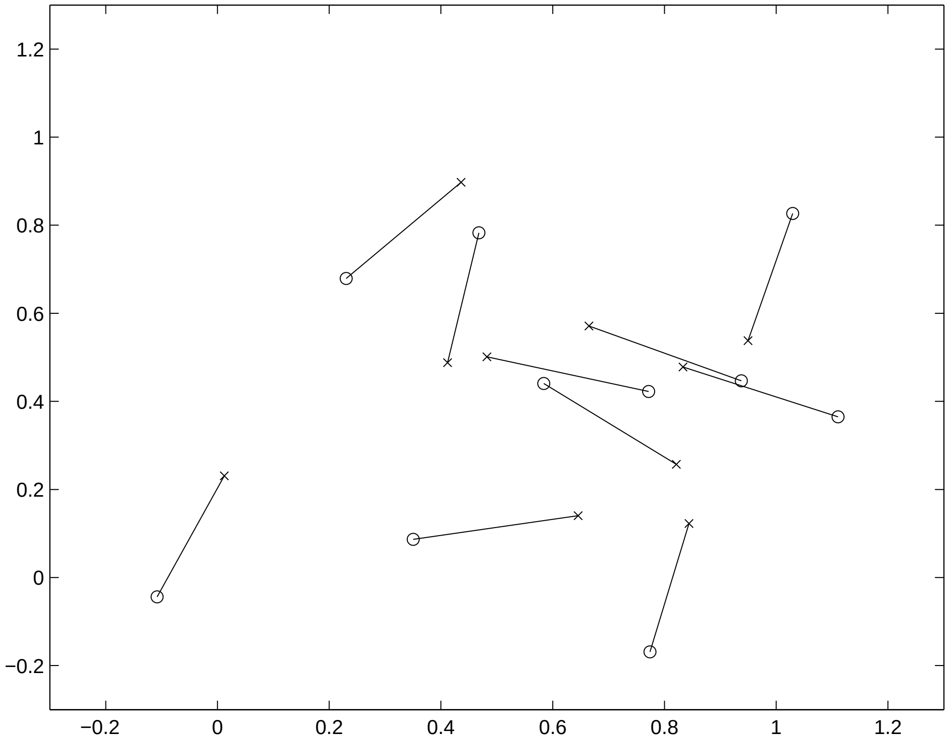

Figure C.2: The second scattered pairs environment. The search algorithm has difficulties in finding Nash equilibria in this environment.

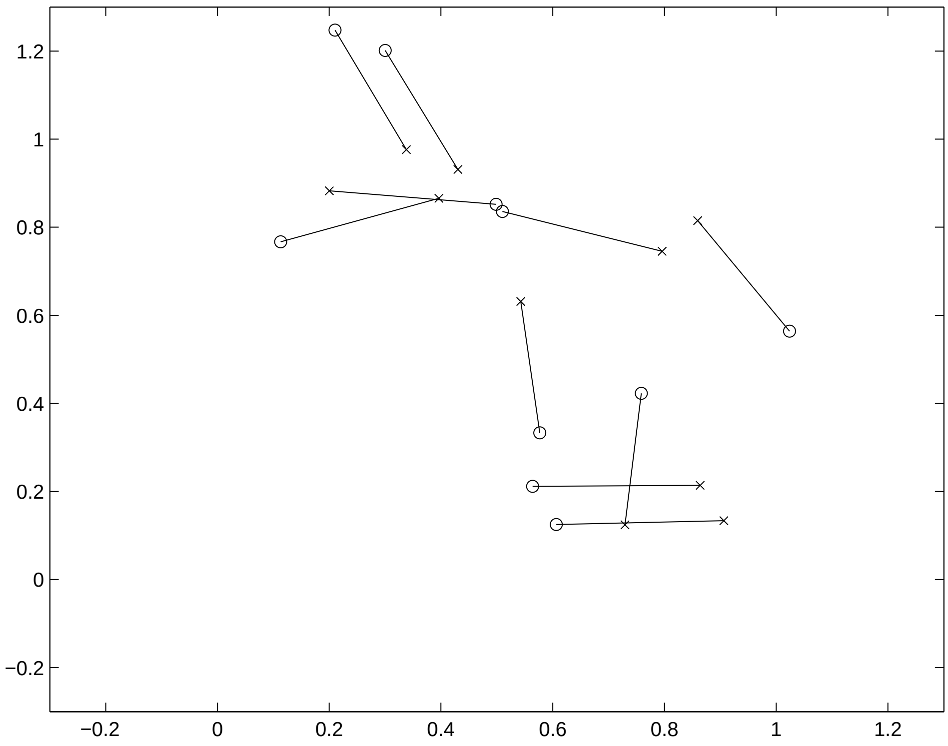

Figure C.3: The third scattered pairs environment. In this environment there are many Nash equilibria found.

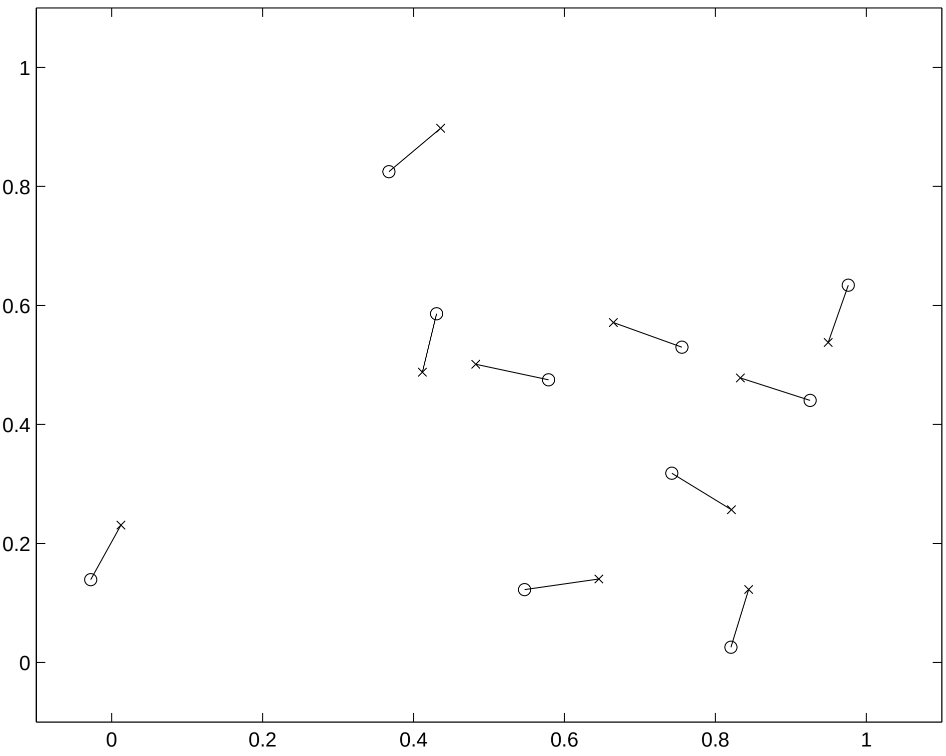

Figure C.4: This scattered pairs environment the interference is less pronounced since the distance between transmitter is shorter than in the other environments. Here the algorithm finds one Nash equilibrium.

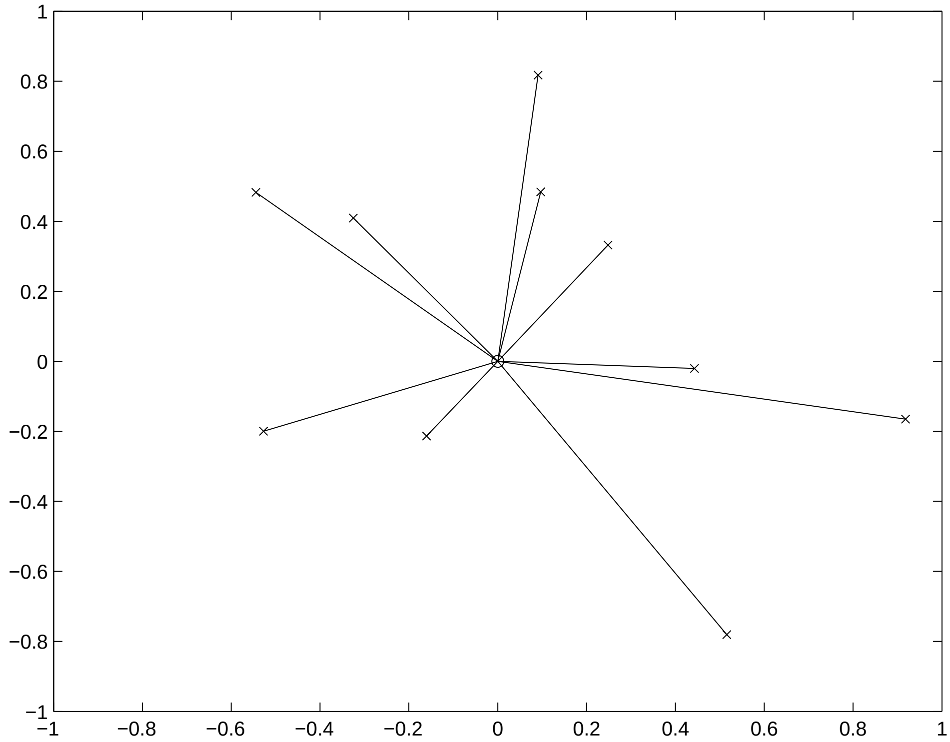

Figure C.5: Layout of the uplink environment. The downlink environment is identical with the only difference in the direction of the links.

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