Spectrum Sharing among Cellular Operators

From a Game Theoretical Cognitive and Cooperative Networking Perspective

Master of Science Thesis

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Wireless and Mobile Communications Group

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The undersigned hereby certify that they have read and recommend to the Faculty of Electrical Engineering, Mathematics and Computer Science for acceptance a thesis entitled:

Spectrum Sharing among Cellular Operators

From a Game Theoretical Cognitive and Cooperative Networking

By

Harun Çetin

In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Dated: February 13, 2012

Supervisors:	Dr.ir.Anthony Lo, TUDelft
	ir.Fokko Sijtsma, KPN
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Foreword

This thesis was written for the Master of Science degree in Electrical Engineering at Delft University of Technology (TUDelft). The research was executed as an internship at Royal Dutch Telecom Company (KPN). The intent of the thesis was to research on spectrum sharing between cellular operators and to provide technical solutions to enable it.

I would like to thank my supervisors Dr.ir.Anthony Lo, TUDelft, and ir. Fokko Sijtsma, KPN, as well as Dr.ir.Ertan Onur, TUDelft, and Dr.ir.Zoubir Irahhauten, KPN, for their guidance, suggestions and encouragements in writing the thesis. I also would like to thank my colleagues in KPN for their support and willingness.

Contents

Abstract

The demand for wireless services and the need for high data-rates are growing rapidly. Future generation networks are expected to provide high data-rates in the order of 1Gbps in local area and 100Mbps in wide area. It is a challenge for operators to meet this rising demand for high data-rates as the radio-spectrum is an expensive and scarce resource. In the last World Radio Communication conference (WRC'07), less than 600 MHz bandwidth has been allocated to mobile communication systems. When considering the total predicted bandwidth demand of 1200MHz - 1700MHz in 2020, it is clear that there is a spectrum scarcity for mobile communication systems. This scarcity arises due to the exclusive allocation of the spectrum among different Radio Transmission Systems (RTS). A further exclusive splitting of spectrum among different operators leads to an apparent scarcity of the resources. While doing so, it should be clear that no operator will suffice in its own to meet the rising demand for high data-rates, when the current traditional way of spectrum utilization continues.

Based on the arguments mentioned, the idea of spectrum sharing was born. When the operators share their licensed spectrum bands, they simply will reach higher bandwidths, the spectrum will always be utilized when an operator does not utilize it. Spectrum sharing among cellular operators introduces a new concept of Inter-Operator Interference (Inter-OI). Interference which is a natural result of operating in the same common spectrum band limits the capacity obtained from the spectrum. Therefore, it should be mitigated in an intelligent way. As opposed to other interference generation mechanisms known in wireless-networking, Inter-OI is a problem of two independent networks with conflicting objectives on the common resource. When this conflict is not solved, the advantages may turn into disadvantages.

To solve the Inter-OI in the uplink and downlink of the involved cellular networks, there are some considerations that one has to take into account. First of all, information exchange: How much information can we gather about the interfering signals? There are two extreme cases possible: When we do not know anything about the interfering signals, we can make a Gaussian Random Signal Approximation which is not a realistic model of Inter-OI as it can be more severe due to the overlapping-cells of two different cellular networks. When we could get the whole interfering signal structure, we could jointly construct the signal or pre-cancel it in a multi-cell processing-fashion. However, due to the limited information exchange capability of the operators, full information exchange is not desirable. Once the exchangeable amount of information is fixed, the

solution should provide enough efficiency to satisfy the operators above their non-sharing case. Furthermore, the solution should provide fairness among the operators. Of course, all should occur within an acceptable complexity.

In this thesis, to cover the considerations mentioned above, a possible solution for the uplink-problem has been proposed by the means of a receive-beamforming approach for which the basestations need the Channel State Information (CSI) of the direct channels to their intended users and crosstalk channels to their non-intended users. To capture the needed CSI in this heterogeneous environment, the mobile terminals have been given user-specific pilots which are recognized by the basestations. For this approach, registration to both operators is required in order to capture the CSI while the users get the service from their own operator. For the downlink case, a transmit-beamforming approach has been proposed. The downlink-part of the problem is different. In this case, there are two base-stations, two decision-makers with conflicting objectives. Resource sharing problems with multiple decision-makers are subjected to Game Theory of the Applied Mathematics. Game Theory provides tools to predict the results of selfish and cooperative actions in a resource sharing problem. Instead of applying their best-response strategies selfishly, this thesis has proposed to apply SLNR-based beamforming for the beamforming-dimension of the problem and to apply the power levels in a leader-follower relationship as described in the literature. The needed objective functions have been constructed for the leader operator and follower operator by the means of capacity functions and have been solved as a non-convex optimization problem. The proposed approach has been simulated in a realistic scenario with i.i.d. Rayleigh Fading. The results have been shown to be satisfactory in comparison to the non-sharing case qua efficiency and fairness.

Chapter 1

Introduction

There is a growth of the demand for wireless services and the need for high data rates: i.e. transmitting more data in less time. When considering that future wireless services are expected to provide data-rates in the order of 1Gbps in local area and 100Mbps in wide area, the challenge facing the operators is to meet the rising demand for data-rate while reducing the costs (Kumar et al., 2008).

As a short-term prediction (Norman, 2009), it is expected that total wireless network traffic generated from voice and data services will increase ten-fold by 2015 in developed regions. Traffic per cellular user per month in developed regions will rise from an average of 56MB in 2008 to 455MB in 2015, while in developing regions, a four-fold increase is predicted, as shown in figure 1.1. By 2015, 94 of traffic will be data and 74 of this will be generated indoors in developed regions. The situation is similar for developing regions. When considering those predictions, the following requirements arise for the future wireless networks: A data-oriented network architecture, an efficient network carriage per megabyte data and excellent indoor and outdoor coverage.

Traffic metric	2008 (developed)	2015 (developed)	2008 (developing)	2015 (developing)
Total traffic per month	57PB	557PB	50PB	307PB
Traffic per mobile user per month	56MB	455MB	22MB	83MB
Percentage of data in total traffic	49%	94%	7%	79%
Percentage of data traffic that is generated indoors	54%	74%	34%	62%

Figure 1.1: Forecasts for Mobile Traffic in Developed and Developing Regions (Norman, 2009)

When considering the fact that more than 70 of data-traffic will originate indoors in developed regions and more than 60 in developing regions, one possible way to ease this pressure on operators is to use femto-cells besides the traditional macro-cells. For a 3G-operator, this would mean to provide small UMTS-basestations in the consumers' homes, rather like the home Wi-Fi and the consumers can be connected to the mobile

operator's switching network through the ADSL line. By transferring some of the traffic from the macro-cell network to femto-cells, the pressure on the operators can be reduced. The wide-scale use of femto-cells is obligatory in this solution. The main difficulty of this approach is that the cellular operators will have to learn to tackle with millions of femto-cells, in comparison to tens of thousands of base stations, which was their previous experience and expertise. Furthermore, the success of the solution depends on the use of an ADSL backhaul which will experience a significant load additionally, besides the continuing technical problems of the femto-cell approach such as interference management and handover.

Other options as an alternative to the femto-cells approach to relax the pressure of indoor load include the usage of Wi-Fi combined with WiMax and ADSL. It has been shown that most of the operators in developed regions prefer to let evolve their existing GSM/UMTS network to LTE, rather than deploying a WiMax network. WiMax is majorly predicted to support UMTS in developing regions to take advantage of the opportunities where the reach of ADSL at broadband is poor. The fixed-ADSL combined with Wi-Fi still stands stronger against the approaches mentioned above due to its reliability. However, it is predicted that the long-term cost reduction per mobile user will be more downward in comparison to the fixed case, while no such cost reduction is expected in fixed (Norman, 2009).

To tackle with the combined demand of indoor and outdoor traffic, LTE proposes to increase the bandwidth (more spectrum). Figure 1.2 shows for an example mobile operator with 10 million mobile users that the growth of indoor plus outdoor traffic will exceed the HSPA capacity in 2010-2011 and HSPA-plus capacity in 2012. However, it is predicted that when combined with Wi-Fi, both HSPA and HSPA-plus will provide enough capacity in 2012 as well. LTE proposes to operate on flexible bandwidth from 1.25 MHz up to 20 MHz.In addition to this, the number of spatial streams are increased thanks to multiple antenna techniques. Next to Spatial Division Multiplexing (SDM), Multiple Input Multiple Output (MIMO) beamforming is included to improve the data-rate performance for the cell-edge users (Pollin et al., 2011).

The availability of such high spectrum requirements is actually quite questionable. Radio Spectrum is a part of electromagnetic spectrum corresponding to the radio frequencies which are the frequencies in the range of 3 kHz and 300 GHz. Different transmission systems and applications operate in different non-overlapping bands (parts) of the Radio Spectrum in order to cause no interference to each other which is called as Exclusive Allocation (EA). Interference is the presence of other radio communication links of the same frequencies in other systems. Interference limits the capacity obtained from the spectrum, and should therefore be avoided. Radio Spectrum is naturally owned by the regulatory bodies (governments). The regulatory bodies can license the bands of Radio Spectrum to the operators of private Radio Transmission Systems (RTS) (for instance, broadcast television systems, cellular mobile phone networks). The bands of allocated frequencies are often referred to by their provisioned use (for example, Cellular Spectrum or Television Spectrum).

In the last World Radio Communication conference (WRC'07), less than 600 MHz

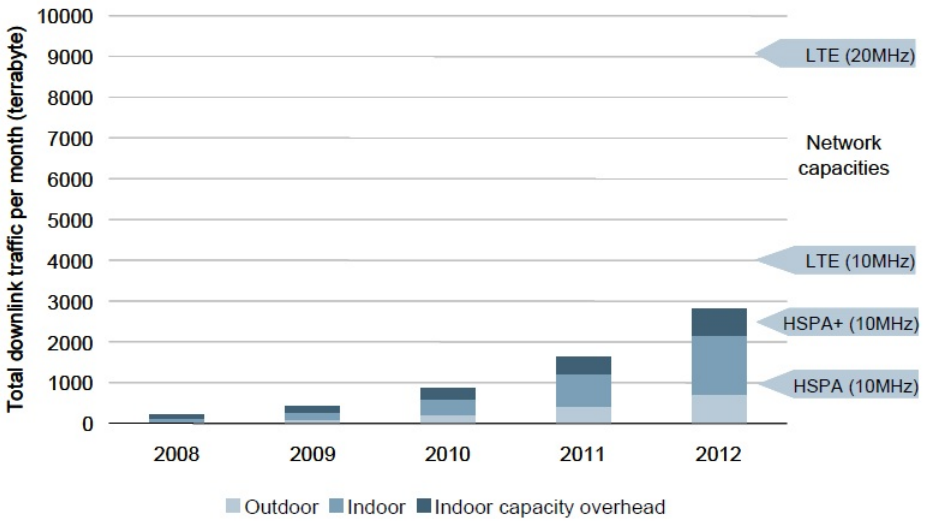

Figure 1.2: Network-traffic generated by a mobile operator for indoor and outdoor case (Norman, 2009)

of bandwidth has been allocated to mobile communication systems. A further exclusive allocation of spectrum to mobile communication systems is not likely, as the spectrum below 5GHz is already congested as shown in figure 1.3. When considering the total predicted bandwidth demand of 1200MHz - 1700MHz in 2020, it is clear that there is a spectrum scarcity for mobile communication systems. This scarcity is a natural result of non-overlapping exclusive allocation of spectrum between different communication systems (Bennis, 2009).

Based on those observations, the traditional way of spectrum utilization (i.e. EA) has become more questionable. EA leads to spectrum under-utilization when the licensed systems do not use the whole spectrum. For instance, certain parts of GSM do not show much spectral activity in certain hours; digital television spectrum shows a similar behaviour. Figure 1.3 gives the candidate bands that can be utilized by different communication systems at the same time. In this way, the idea of coexistence of different Radio Access Systems (RAS) and Radio Access Networks (RAN) (GSM, UMTS, LTE etc.) in the same spectrum band has been introduced as a result of spectrum scarcity.

This apparent scarcity is not only the result of exclusive allocation of spectrum between different RAN technologies, but also exclusive splitting of spectrum among the cellular operators causes inefficient utilization of available resources. In current cellular networks, the radio spectrum for a particular type of RAN is typically split in distinct, non-overlapping frequency-bands that are allocated to different operators as given in figure 1.4. This exclusive splitting of the bandwidth (spectrum) is inefficient because of two reasons: The spectrum is not utilized when the channels are not used by an operator while another is suffering from a scarcity of the channels. Secondly, orthogonal division of spectrum in frequency dimension does not exploit the spatial degrees of freedom, which

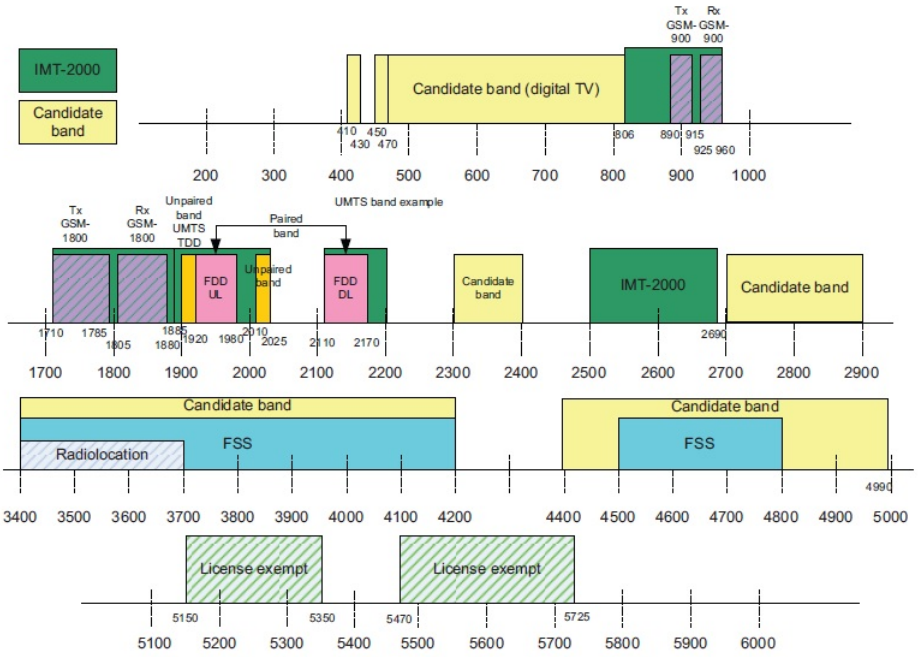

Figure 1.3: Current Spectrum Situation Ranging from 400 MHz to 5 7 GHz based on the International Telecommunication Union (Bennis, 2009)

is wasting the achievable capacity (data rate). Therefore, spectrum sharing debates will end in sharing their licensed spectrum bands in order to meet the demands.

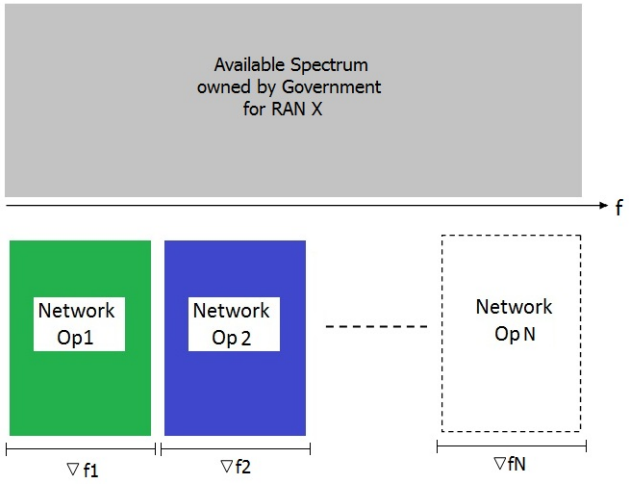

Figure 1.4: Exclusive Splitting of Spectrum between Operators

In order to achieve a better utilization of the total available spectrum, different

spectrum access methods have developed against the traditional EA of the spectrum among the operators, as shown in figure 1.5 (Bennis, 2009). Spectrum Sharing and Coexistence (SSC) among cellular operators can be considered as such a spectrum access method with its own properties. Therefore, the following spectrum access methods can be reviewed firstly to explain the scope of Spectrum Sharing.

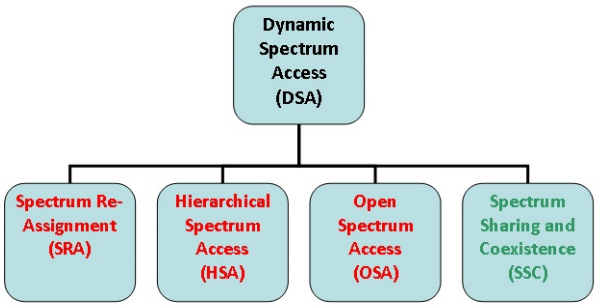

Figure 1.5: Classification of Spectrum Access Methods

To make efficient use of the available spectrum, Spectrum Re-Assignment (SRA) is a method with a centralized controller as given in figure 1.6. The network operators agreed to reassign the total available resources according to the variations of the load to the networks. A centralized controller which is called Meta-Operator or Spectrum Broker keeps records on the utilization of the spectrum by communicating with the Radio Resource Management (RRM) units of the involved operator as shown schematically in figure 1.7. It allocates the available resources as Short term or Long term according to the agreement. The centralization idea is not a practical idea yet. There is still a kind of orthogonality. The operators get only a small fraction of the total available bandwidth at a time (Salami and Tafazolli, 2009).

To make efficient use of the available spectrum, Spectrum Re-Assignment (SRA) is a method with a centralized controller as given in figure 1.6. The network operators agreed to reassign the total available resources according to the variations of the load to the networks. A centralized controller keeps records on the utilization of the spectrum. It allocates the available resources as Short term or Long term according to the agreement. The centralization idea is not a practical idea yet. There is still a kind of orthogonality. The operators get only a small fraction of the total available bandwidth (Salami and Tafazolli, 2009).

Another method for spectrum access is Hierarchical Spectrum Access (HSA). There is a hierarchy in spectrum access rights. Primary Operator owns the spectrum, and the transmitters of the secondary network try to use the same spectrum without harming the primary network performance. Cognitive radios are used in order to identify the transmission opportunities as given schemtically in figure 1.8. HSA can be performed in underlay or overlay ways. In the spectrum underlay, cognitive radios use the same channels non-orthogonally by limiting the amount of interference to the primary receivers. In the spectrum overlay, they seek the transmission opportunities (unused time

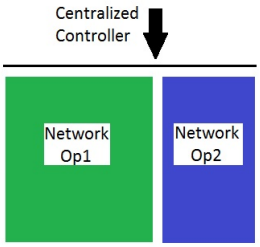

Figure 1.6: Spectrum Re-assignment

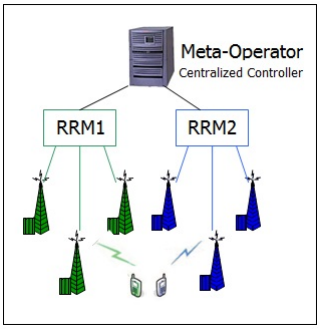

Figure 1.7: Meta Operator

or frequency slots etc.) which are called spectrum holes or white spaces and try to avoid colliding as illustrated in figure 1.9. However, in those approaches, it is not clear how the spectrum accesses will be detected by the operators as the operators should trade off between obtainable revenue and spectrum utilization (Akyildiz et al., 2006).

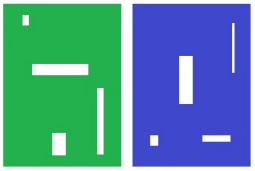

Figure 1.8: Illustration of White Spaces

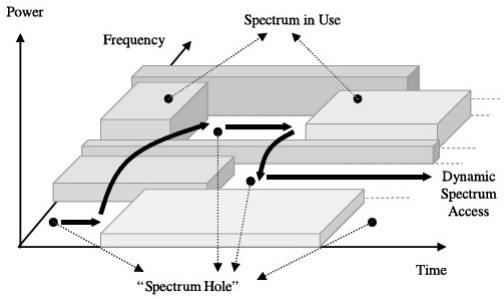

Figure 1.9: Spectrum Opportunities in HSA (Akyildiz et al., 2006)

Open Spectrum Access (OSA) is an access method where nobody owns the spectrum. The networks have the same access rights at any time. The networks may access the whole spectrum simultaneously without a common multiple access technique by implementing different coding and modulation techniques. Only limitations are put on the maximum power spectral densities. Such a spectrum access is better suited for local area networks (Wi-Fi, Zigbee, IEEE.802.15.1 etc.) with limited coverage. On the other hand, independent cellular networks have fully-overlapping cells which are aimed at full-coverage with greedy usage of power. Therefore, for cellular networks, the concept of OSA is not suited and there is the need of coordination for spectrum access (Bennis, 2009).

Spectrum Sharing and Coexistence (SSC) is a promising spectrum access method for cellular networks. SSC among the operators over a particular type of RAN can be thought as a new paradigm change aimed at replacing the current, traditional exclusive

allocation of the spectrum among the operators. A common spectrum band is formed by removing the frequency division between the individual bands. When the operators use the whole common spectrum band with equal rights, they simply can reach more bandwidth; the spectrum is always utilized when one of the operators does not use it. The limiting factor of those advantages is the so-called Inter-Operator Interference (Inter-OI) which must be managed by network-oriented as well as device-oriented methods. Exclusive allocation of the spectrum was a result of technology limitations of the past which could not manage/avoid/tolerate the so-called Inter Operator Interference. Therefore, SSC aims to solve the conflict of "Inter-Operator Interference" among the sharing operators while reaching a higher data-rate compared to the non-sharing case.

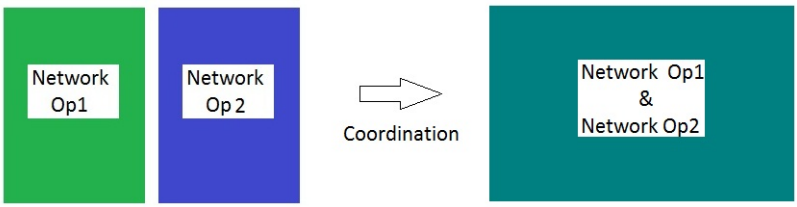

Figure 1.10: Spectrum Sharing and Coexistence

1.1 Problem Statement

In this section, the problem statement has been formed which emphasizes the scope of spectrum sharing and indicates the main difficulties and limitations against the spectrum sharing described previously.

The operators access the common spectrum with equal priority which is the sum of individual spectrum bands. The networks of the operators are independent in the sense that they obey to their own RRM-unit. The networks are of a same RAN technology reflecting the evolved networks' standards: In order to achieve data-rates comparable to their non-sharing case, both of the operators keep applying full frequency reuse in all cells. Each user gets the whole spectrum per channel-use. Due to the overlapping cells, the networks belonging to different operators cause Inter-OI. Therefore, Spectrum Sharing of the operators ends up in a conflict in physical layer, if there is no coordination. This conflict needs to be managed in such a way that the operators reach capacity(data rate) beyond their non-sharing case.
There are some important considerations related to the management of Inter-Operator Interference:

1. **Information Exchange:** In contrast to the traditional interference scenarios, Inter-OI Mitigation is a problem of two independent networks with their own infrastructures. The information exchange among two independent networks becomes a difficult issue. The ideal case of joint transmission or the cooperative interference mitigation based on multi-cell processing techniques require information

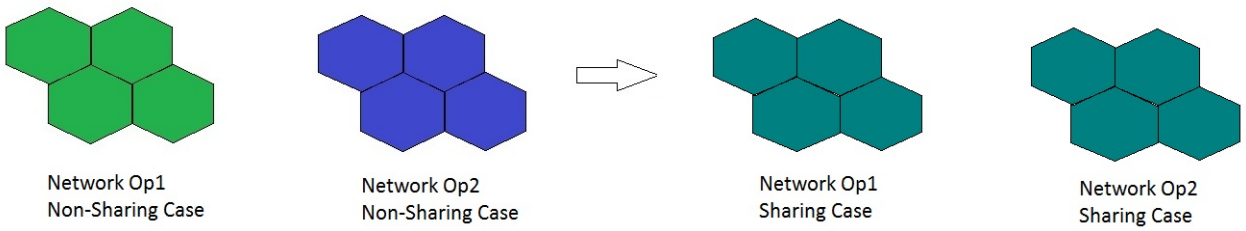

Figure 1.11: Spectrum Usage before and after Spectrum Sharing

exchange. The amount of information exchange, the way in which the information is exchanged have impact on the efficiency of Spectrum Sharing.

Defining aspects of a cellular network are base stations (or NodeB's, eNodes in 3G and beyond) that are connected to an infrastructure known as *backhaul*. The end points of the network are mobile terminals that work subject to energy constraints(battery life) as well as constraints driven by the physical size that lead to bounds on computational complexity. When it is about information exchange in such a typical cellular network, one may think of information exchange between base stations and mobile terminals and information exchange between base stations. The information exchange between the operators can occur via the core networks through the backhaul links as given in figure 1.12 and 1.13 for uplink and downlink situation respectively.

There are two extreme cases possible: The case when no information about the interfering signal available and the case when full information about the interfering signal is available (see figure 1.14).

(a) **No information about the interfering signal:** Two operators inside a common spectrum pool do not know anything about each others' interfering signals. They do not exchange information (scheduling maps, coding-decoding structures, signal power allocations, channel conditions, beam forming parameters etc.) And they are not equipped to capture those information or to mitigate or cancel the interference. In this case, the only possible way to tackle with the Inter-OI is that an operator assumes a Gaussian Random Signal Approximation about the interfering signal. This assumption is not always a correct treatment of the problem, because Inter-OI can be more severe than that of Gaussian Approximation. Therefore, this case of knowing nothing about the interfering signal is an extreme case which limits the advantages of Spectrum Sharing dramatically. So this extreme case is not an objective of Spectrum Sharing.

(b) **Full information exchange:** When two operators have full knowledge about the interfering signal structure from each other, they easily can mitigate the interference by applying interference cancellation techniques and multi-user detection algorithms. Furthermore, if all transmitters or all receivers

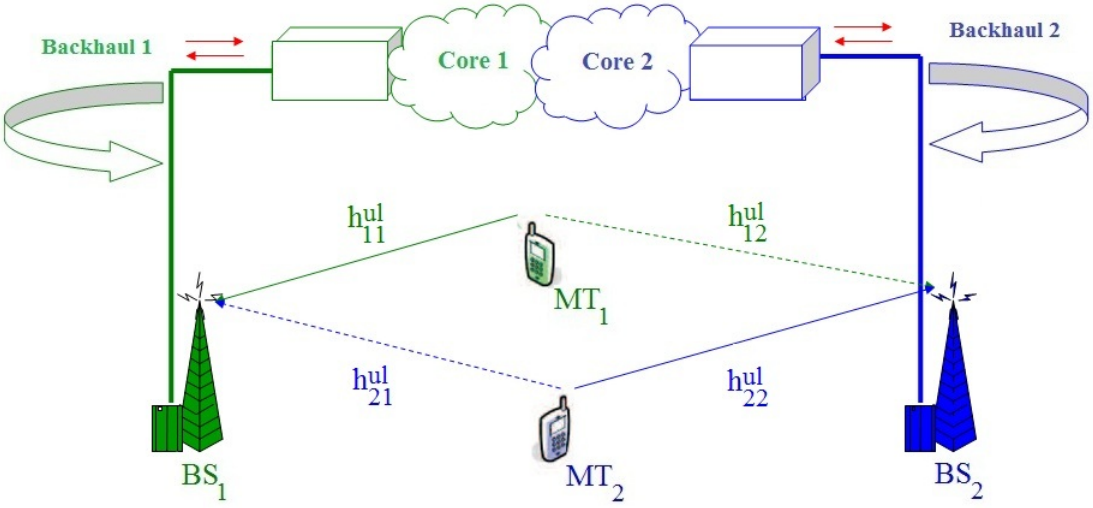

Figure 1.12: Uplink Situation for Inter-OI: Mobile terminal 1 (MT1) and Mobile terminal 2 (MT2) communicate to their intended operators' basestations (BS1) and (BS2) respectively while causing interference on the uplink to each other. h_{ij}^{ul} describes the channel conditions from mobile terminal i to basestation j in the uplink. Operators can share information through the backhaul links

of both of the operators could share the entire information, they even could perform joint transmission or joint decoding. This would make the situation conceptually equivalent to a broadcast channel and a multiple access channel (MAC). In this extreme case, the mitigation of Inter-OI is equivalent to Inter Cell Interference (ICI) mitigation of a single homogeneous infrastructure.

Depending on the amount of information that is exchangeable among the operators , the desiner should find out a way of managing the Inter-OI (by applying joint-scheduling/joint-tansmission, codebooks) or cancelling the Inter-OI (by applying precoding methods, multiple antenna techniques) or tolerating/avoiding the Inter-OI (by applying interference optimization algorithms, interference allignment techniques).

2. **Efficiency:** When the exchangeable amount of information is fixed, the designer decides on an approach mentioned above by taking the achieved efficiency into account. The efficiency is defined as the per-user achieved capacity (data-rate in bits/seconde). The selected approach is efficient with respect to the non-sharing case when the acheived data-rate outperforms that of the non-sharing case and when the operators are satisfied with it subjected to the additional complexity needed in systems.

   When there is no sharing, the per-user data-rate of i_{th} operator can be expressed as given in , assuming that there is no Intra-Operator Interference (Intra-OI) and

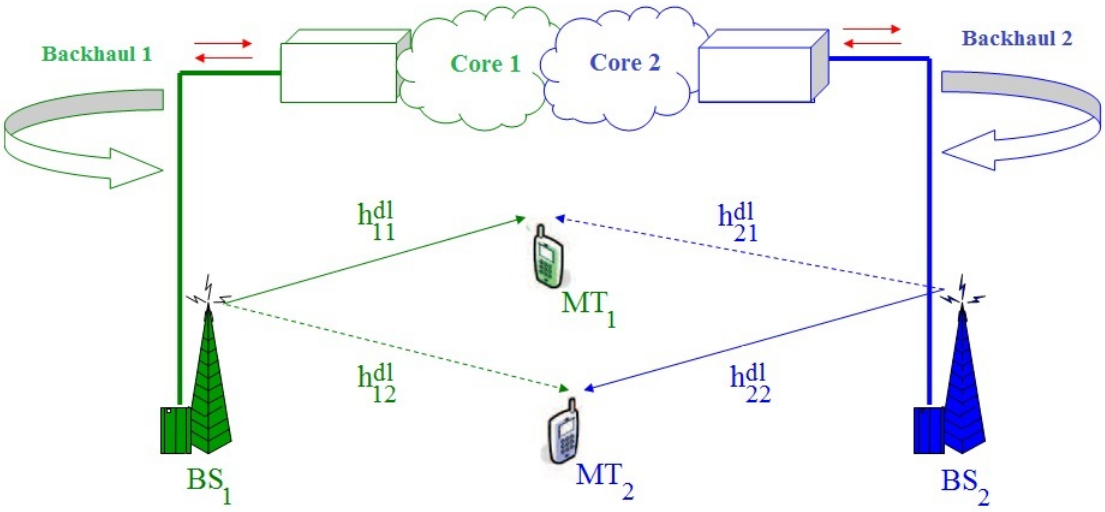

Figure 1.13: Downlink Situation for Inter-OI: Basestation 1 (BS1) and Basestation 2 (BS2) communicate to their intended mobile terminals (MT1) and (MT2) respectively while causing interference on each other's mobile terminals in the downlink.h_{ij}^{dl} describes the channel conditions from basestation i to basestation j.

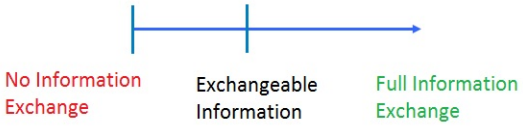

Figure 1.14: Extreme Cases and Actual Information Exchange

each user gets the whole spectrum.

$$R_i = \frac{1}{2}\log_2\left(1+\frac{P_i}{N_i}\right) = \frac{1}{2}\log(1+SNR_i) \tag{1.1}$$

where R_i is the achieved data-rate in bits/s, SNR_i is the Signal to Noise Ratio exprecienced by the user of i_{th} operator and the factor 1/2 implies that in non-sharing case each operator has only 1/2th portion of the total common spectrum band.

When the operators apply Spectrum Sharing,the per-user data-rate of i_{th} operator can be expressed as given in , if there is no attempt against Inter-Operator Interference (Inter-OI).

$$R_i = \log_2\left(1+\frac{P_i}{N_i+I_i}\right) = \log(1+SINR_i) \tag{1.2}$$

where R_i is the achieved data-rate in bits/s, $SINR_i$ is the Signal to Interference Noise Ratio including the interference power I_i exprecienced by the user of i_{th} operator and the factor $1/2$ disappears implying that each operator gets the whole common spectrum.

The achieved data-rate is a monotonic increasing function of $SINR_i$ which is a decreasing function of the interference power I_i. The objective of spectrum sharing is to mitigate this interference factor while enjoying with the total available spectrum which is normalized to 1. As mentioned, the way of mitigation is related to the degree of information exchange among the operators.

3. **Conflicting Interests:** There are two independent decision makers with conflicting interests. They have to reach a cooperative behaviour. Game Theory is an effective tool to predict the results of cooperative and non-cooperative actions in resource sharing and to find a compromise between them.

4. **Complexity:** Spectrum Sharing models and algorithms should take the complexity of the applied approaches into account.If the obtained efficiency is not in line with the required complexity, the advatages may turn into disadvantages. The base stations (or NodeB's, eNodes in 3G and beyond) that are connected to an infrastructure known as *backhaul* with a certain load capacity. The end points of the network are mobile terminals that work subject to energy constraints(battery life) as well as constraints driven by the physical size that lead to bounds on computational complexity.

   Based on these considerations, spectrum sharing of the operators should result in a satisfactory spectral efficiency which has to outperform the non-sharing case. In this thesis, the existing approaches in the literature are reviewed in terms of these design consideretions. At the end, a possible approach is proposed to enable the spectrum sharing scenario.

1.2 Contribution

To make efficient use of the total available common spectrum, the Inter-OI should be mitigated. As the operators operate through independent networks, the mitigation of Inter-OI should occur with minimal information exchange resulting in an efficient and fair sharing. For the uplink case, the thesis describes the needed techniques to enable the Interference Rejection Combining (IRC) based on receive-beamforming at the basestations. The use of user-specific pilots, the registration to both of the operators and synchronization to a common TDD-frame-time are suggested to enable the spatial cancelling of the incoming uplink interference for this heterogeneous nature of spectrum sharing.

For the downlink, the thesis proposes interference-optimization based on transmit-beamforming. The consideration here is to avoid selfishness by constructing an optimization problem by combining Signal-to-Leakage plus -Noise (SLNR)-based beamforming

vector with power allocation in a Stackelberg game (leader-follower game) framework in order to manage the Inter-OI. The utility functions of the operators have been constructed and solved with the aid of lagrangian duality theorem as a non-convex optimization problem as the major contribution to spectrum sharing discussions. The idea of relying on spatial dimensions will be become more clear in the following chapters. The proposed approach has been constructed in order to meet the considerations described above: efficiency, limited information passing capability, fairness in conflict and complexity.

1.3 Outline

The organization of the chapters can be summarized as following: In chapter 2, the design properties of cellular networks have been reviewed with the attention on interference tolerance of different multiple access schemes, multiplexing techniques, the required information exchange mechanisms for those techniques, cooperative and non-cooperative transmission strategies based on Game Theory and their complexity in terms of the heterogeneous structure of the spectrum sharing. A literature work has been provided that make use of these discussions. In chapter 3, for the uplink and downlink problems of the spectrum sharing, a solution scenario has been provided. For the uplink case, the applicability of Interference Rejection Combining (IRC) based on receive-beamforming has been discussed based on the concepts such as registration, synchronization and user-specific piloting. For the downlink case, transmit-beamforming has been proposed based on game theoretical discussions. A non-convex optimization problem has been constructed and a solution concept has been provided. In chapter 4, the proposed solution has been tested in a realistic scenario. Two operators have been represented by two transmitter/receiver pairs. Their physical layer conflicts in Rayleigh Fading conditions have been analyzed with the aid of the proposed approach. The performance of the proposed approach has been compared to three other approaches based on transmit-beamforming. In Chapter 5, conclusions have been drawn based on the results in chapter 4. Finally, some recommendation have been given as future-work in chapter 6.

Chapter 2

Background

In this chapter, spectrum sharing of two operators is considered with the aid of the literature discussions. As mentioned in the problem statement, the most important concept in spectrum sharing is the *Inter-Operator Interference* (Inter-OI) which is a result of coexistence of operators in the common spectrum band applying full frequency reuse in all cells of both of the operators.

Due to the overlapping cells which cause signaficant interference to each other, the nature of Inter-OI resembles the *Inter-Cell Interference* (ICI) mitigation of a single network appying universial frequency reuse. The important observation is that the case of Inter-OI is a problem of two independent infrastructures while the ICI is a problem of a single infrastructure which can exchange information with its networking elements more easier to decide on a proper interference mitigation technique.

Based on the resemblance of ICI mitigation of a single cellular network inside itself, this chapter mainly aims in investigating the ICI mechnisms as well as the existing models and algorithms on spectrum sharing with the emphasis on the specific considerations about Inter-OI. Those considerations have been explained in chapter 1.1 *Problem Statement* as being: Information exchange capability, achievable efficiency, conflicting interests of multiple-decision makers (operators cooperativeness and non-cooperativeness) and the complexity introduced by spectrum sharing itself.

Clearly, depending on the exchangeable information among the operators, the approach to mitigate the interference among the operators' networks will be different. For instance, can the operators share the whole signal structures, then they can perform joint-processing and precancel the interference or can the operators exchange no information, then they can consider iterative interactions in the physical layer based on interference optimization techniques. In 2.1, the interference tolerance and complexity requirements of different access technologies have been discussed.

The information exchange between the operators is defined as message/data passing through the fixed-wired backhaul links directly connecting the two operators. The structure, the capacity and the information exchange capabilities of those links have been discussed. Different ICI-mitigation techniques require different amount and kind of information exchange. Approaches based on *Marginal Information Exchange* have

been discussed in chapter 2.2. Those approaches require only control-level information exchange leading to joint-scheduling and joint-resource allocation techniques. In chapter 2.3, techniques based on *Full Information Exchange* have been explained which are aimed at precancelling the interference by joint-encoding and joint-decoding based on multi-cell processing and multi-user detection. Chapter 2.4 is about techniques based on *Partial Information Exchange*. Those techniques require full knowledge of only Channel State Information (CSI) of the involved mobile terminal to be processed in a centralized unit/controller. Based on the CSI knowledge, different distributed multiple antenna techniques have been explained such as beamforming-based and interference alignment-based multi-cell processing. Finally, approaches based on *No Information Exchange* between the operators through the backhaul links have been discussed. Those approaches rely on interference avoidance techniques based on interference optimization in the form of physical layer interactions.

Each group of techniques have their own advantages and disadvantages related to the conflicting objectives, the obtained efficiency, the required complexity. In this chapter, conclusions are derived about those considerations in terms of spectrum sharing of two operators leading a proposed approach in chapter 3.

2.1 State-of-the-Art in Cellular Networks

A cellular network is a radio network distributed over a large geographic area divided into small structures called *cells*. Each of those cells are served by at least one fixed-located transceiver known as *cell site* or *base-station*. When joined together, these cells provide radio communication for portable transceivers which are called as *mobile terminals* as they can move from cell to cell. While travelling of the mobile terminals from cell to cell, the services are *handed off* to a new base-station. The base-stations are connected to a *core network* via fixed-wired *backhaul links*.

In cellular networks, the wireless channel which is made from radio-spectrum (bandwidth) enables the communication. The goal in the design of a cellular network is to be able to serve as many users as possible within a given bandwidth with a certain reliability. The wireless channel is an electromagnetic signal with the property that the signal power decays as a function of distance. This is the property that enables the reuse of the spectrum (reuse of the same communication channels) in different cells. The reuse of the spectrum enables the cellular network to serve more mobile terminals and hence increased network capacity compared to a network that does not reuse the spectrum. Because of the propagation properties (fading) of the electromagnetic signals, the isolation between the cells can be imperfect and hence the transmissions from different cells can interfere with each other when uncoordinated.

The interference generating mechanisms and their mitigations are different for uplink- and downlink transmissions. In uplink case, a base-station receives transmissions from the mobile terminals it is associated to (intra-cell), as well as transmissions from other cells (inter-cell) as illustrated in figure 2.1 and 2.2. Multiple mobile terminals in a cell transmit to their associated base-station with different delay offsets (the

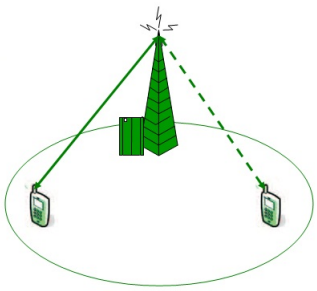

Figure 2.1: Intra-cell Interference

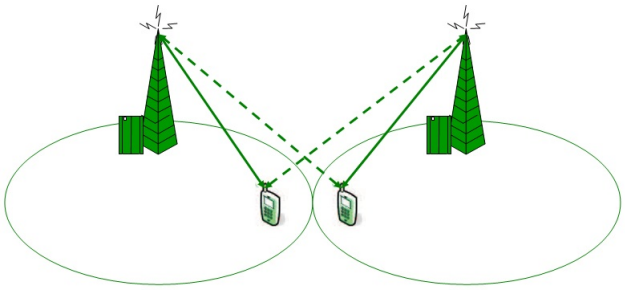

Figure 2.2: Inter-cell Interference

transmissions are asynchronious). In traditional cellular networks, the base-station regards the intra-cell uplink-transmissions as useful information-bearing signals. Intra-cell interference mitigation is aimed at preventing any interference among those useful signals while the signals received from other cells are unwanted. In downlink case, a mobile terminal receives from the base station it is registered to (intra-cell), as well as from other base-stations in different cells (inter-cell).

In order to achieve meaningful and resource efficient communication between base-station/mobile terminal pairs, the transmissions are coordinated by an *access method* to the spectrum. In traditional cellular networks, the available spectrum resource can therefore be divided into orthogonal time channels (Time Division Multiples Access, TDMA), orthogonal frequency channels (Frequency Division Multiple Access, FDMA), orthogonal hopping sequences in time-frequency grid (OFDMA), orthogonal codes (Code Division Multiple Access CDMA), spatial dimensions (Space Division Multiple Access, SDMA) or a combination of those schemes.

Multiple Access Schemes determines for the users how to share the radio-spectrum. Sharing the bandwidth efficiently among users is one of the main goals of multiple access schemes. The type of multiple access scheme affects the robustness and interference levels generated in other cells. Therefore, multiple access schemes are designed to maintain orthogonality as shown in figure 2.3 and reduce interference effects (Garg, 2007).

While all Multiple Access Schemes can provide orthogonality and reduce interference, they are not spectral-efficient equally. Spectral efficiency of a mobile communications system gives how efficiently the spectrum is used by the system. The choice of a Multiple Access Scheme has impact on the spectral efficiency of a mobile communications sytem (Garg, 2007). In FDMA, the users are separated by assigning different carrier frequencies. Frequency guard-bands provided to keep the adjacent signal spectra separated, are wasting the available bandwidth. Due to frequency division, each user gets only a small fraction of the available bandwidth. In TDMA, a similar case holds: Each user is assigned a different time-interval in which each user gets the whole channel bandwidth. Guard times are used in order to minimize interference between the channels. The capacity in a TDMA and FDMA system depends on the availability of time/frequency resources. The more the number of available resources (idle resources),

the more users can get serviced. In wideband systems, the entire system bandwidth is given to each user, and is many times larger than the bandwidth required to transmit information . Such systems are called spread spectrum (SS) systems. There are two fundamental types of spread spectrum systems: (1) direct sequence spread spectrum (DSSS) and (2) frequency hopping spread spectrum (FHSS) (Garg, 2007). In a DSSS system, the bandwidth of the baseband information carrying signals from a different user is spread by different codes. The codes have a bandwidth much larger than that of the baseband signals. The spreading codes used for different users are orthogonal or nearly orthogonal (semi-orthogonal) to each other. There may be no strict limit on the number of mobile users who can simultaneously get access. The capacity of a DSSS system depends upon the desired value of bit energy-interference ratio Eb/I0 instead of frequency-time resources as in FDMA or TDMA systems. The DSSS approach is the basis for CDMA which are called DS-CDMA together. Compared to FDMA and TDMA, DS-CDMA has the advantage that it can tolerate a fair amount of interference. As a result, the frequency band assignment and ICI is signifantly simplified with DS-CDMA. However, in FDMA and TDMA, the frequencies and time-slots must be carefully assigned so that no interference occurs. Careful filtering and guard band protection is needed. In DS-CDMA, adjacent cells share the same frequencies while it is not desirable for FDMA and TDMA networks because of interference. Therefore, in a FDMA and TDMA system, a time-consuming frequency planning is needed while it is not needed for a DS-CDMA system as the cells use the same frequencies. Furthermore, since the channel is shared among all the users, interference induced in the desired channel is reduced due to the silent interval of other interfering channels leading to even more capacity improvement. On the other hand, it is not cost-effective to exploit the voice activity in the FDMA or TDMA system because of the time delay associated with reassigning the channel resource during the speech pauses. Therefore, DS-CDMA is spectrally more efficient than FDMA and TDMA systems (Garg, 2007).

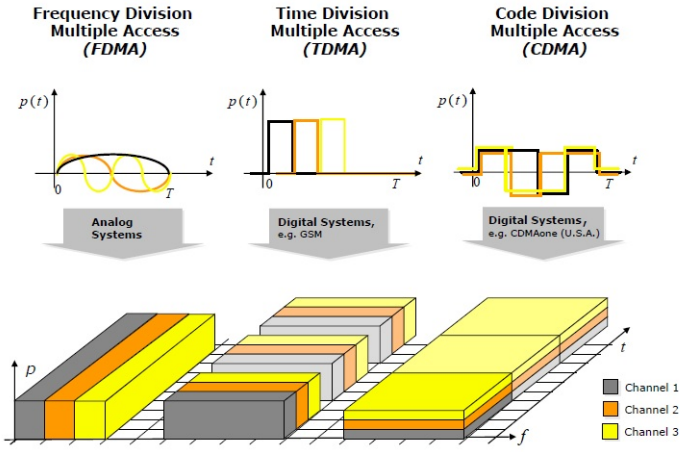

Figure 2.3: Multiple Access Schemes, FDMA, TDMA and CDMA, (Walke et al., 2003)

Another spread spectrum technique is the frequency hopping (FH). FH is the periodic changing of the frequency or the frequency set associated with the transmission. Therefore, an FH-signal can be considered as a pseudo random carrier frequencies. The set of possible frequencies is called the hopping set. FH can be implemented such that the transmitter hops out frequency channels with interference or hops out of fades. To exploit this feature, error-correcting codes and interleaving can be used. Communication based on FH does not need to be in isolation. Frequency hopping systems create interference on each other. Therefore, in frequency hopping multiple access (FHMA) networks, the transmitters coordinate their frequency transitions and their hopping sequences so that the interference is reduced compared to a non-hopping system. For lightly loaded system, FHMA can reach significant performance (Garg, 2007).

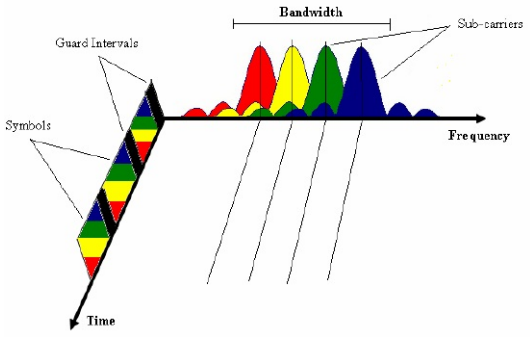

Figure 2.4: Frequency-Time Illustration of an OFDM signal, (Ricci, 2008)

Another multiplexing technique is the orthogonal frequency division multiplexing (OFDM). OFDM is a digital multi-carrier modulation scheme where the available bandwidth is divided into a large number of closely-spaced orthogonal subcarriers. The principle is that a high rate data-stream is split into a number of lower rate streams that are transmitted simultaneously over a number of subcarriers (Ricci, 2008). For instance, a data stream operates at R bps and an available bandwidth of Nf is centred at fc. When the entire bandwidth was used to transmit a data stream, the bit duration would be 1/R. By splitting the data stream into N substreams using a serial-to-parallel converter, each substream which is transmitted on a separate subcarrier with spacing of f between adjacent subcarriers has gotten a data rate of R/N. The bit duration becomes N/R. While doing so, on a multiple channel the multipath is reduced by a ratio of 1/N and thus causes less distortion in each modulated symbol. For transmissions at higher data-rates, inter-symbol interference (ISI) which is a result of smaller distance between bits or symbols is a significant problem. With OFDM, the data rate is reduced by a factor of N, which increases the symbol duration by a factor of N. Thus, if the symbol duration is Ts for the source stream, the duration of OFDM signals is NTs. This significantly reduces the effect of ISI. Moreover, OFDM is a promising solution for broadband communications, because increasing the data rate is now a matter of increasing the number of subcarriers. However, to prevent overlapping between symbols, a time

guard is needed that will reduce the achievable data rate. Furthermore, OFDM uses FH to create a spread spectrum system. Each serial/parallel converter output is multiplied with spreading code. FH has several advantages over DSSS, for example, no near-far problem, easier synchronization, less complex receivers etc (Garg, 2007).

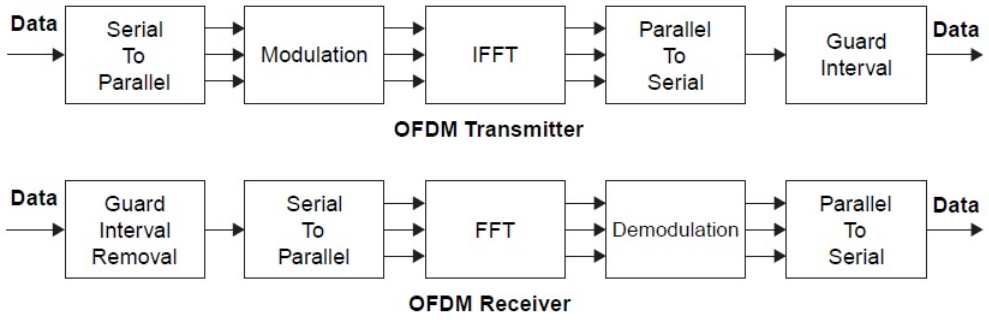

Figure 2.5: OFDM Transmitter and OFDM Receiver (Garg, 2007)

Multiple access with OFDM can be realized by using various multiple access techniques. In OFDM-TDMA, users transmit in a dedicated time-slot. OFDM-FDMA (OFDMA) is achieved by assigning subsets of subcarriers for each user so that users are separated across subcarriers. Available resources can be redistributed among the active users along the time dimension (Ricci, 2008). In OFDM-CDMA, users transmit using a set of spreading codes. There are potential benefits to combining OFDM and DS-CDMA. Frequency selective fading can be mitigated in frequency dimension by applying narrow-band OFDM subcarriers. DS-CDMA offers the advantage of orthogonality of spreading codes. In OFDM-SDMA, the transmissions are multiplexed in space-dimension to keep the transmissions separated spatially (Garg, 2007).

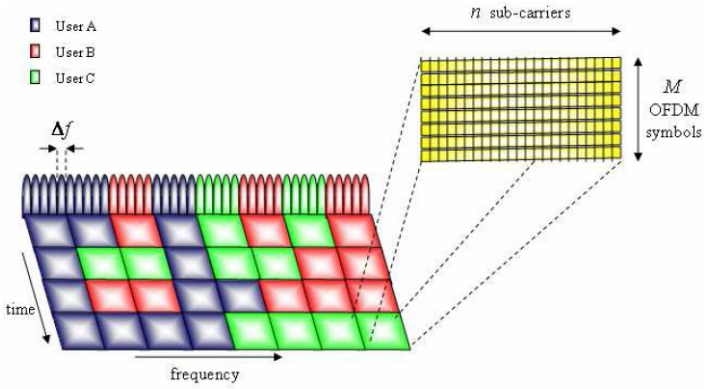

Figure 2.6: OFDM with Mutiple Access, (Ricci, 2008)

SDMA is based on multiple antenna techniques. Before we understand SDMA, some knowledge on multiple antenna sytems is useful. In a multi-antenna configuration,

there are several possibilities. The transmitter can be equipped by single antenna while the receiver has multiple antennas leading a Single Input Multiple Output (SIMO) system. The reverse situation leads to a Multiple Input Single Output (MISO) system. When both the transmitter and the receiver have multiple antennas, the system is called Multiple Input Multiple Output (MIMO) as illustrated in figure 2.7. The availability of multiple antennas at the transmitter and/or the receiver can be utilized in different ways to achieve different aims: Diversity, beamforming (space division) and spatial multiplexing (Dahlman et al., 2008).

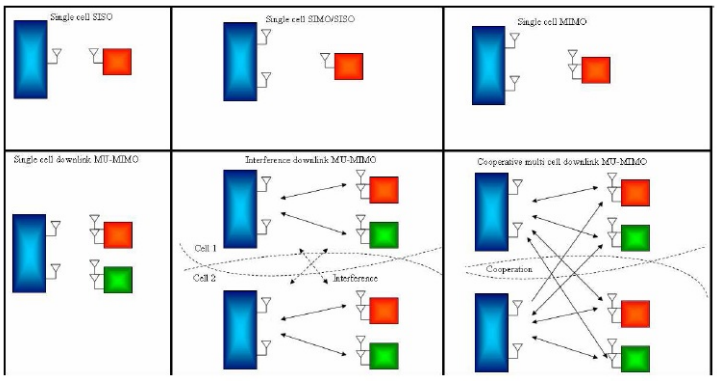

Figure 2.7: Multiple Antenna Configirations, (Ricci, 2008)

First of all, the most commonly used multi-antenna configuration is the use of multiple antennas at the receiver side. SIMO can be utilized in order to gain additional diversity against radio-channel fading. For such a purpose, the receiver can perform receive-antenna combining in a way as illustrated in figure 2.8. The received signals $\begin{bmatrix} r_1 & \dots & r_N \end{bmatrix}$ at N antennas are multiplied by complex weighting vectors $\begin{bmatrix} w_1^* & \dots & w_N^* \end{bmatrix}$ before being added together which can be expressed as:

$$\hat{s} = \begin{bmatrix} w_1^* & \dots & w_N^* \end{bmatrix} \begin{bmatrix} r_1 \\ : \\ r_N \end{bmatrix} = \mathbf{w}^H \mathbf{r} \tag{2.1}$$

Assuming that the transmitted signal is only subjected to non-frequency selective fading and white noise, based on figure 2.9, the received signal can be expressed as:

$$\mathbf{r} = \begin{bmatrix} r_1 \\ : \\ r_N \end{bmatrix} = \begin{bmatrix} h_1 \\ : \\ h_N \end{bmatrix} \mathbf{s} + \begin{bmatrix} n_1 \\ : \\ n_N \end{bmatrix} = \mathbf{hs} + \mathbf{n} \tag{2.2}$$

where $\mathbf{s}$ is the transmitted signal, $\mathbf{h}$ is a vector of N complex channel gains, $\mathbf{n}$ is a vector of noise levels at N different receive antennas.

To maximize the power-level of received signal, Maximum-Ratio Combining (MRC) technique purposes to rotate the phase of the received signals to compensate for the corresponding channel phases and to ensure that the signals are phase aligned when added

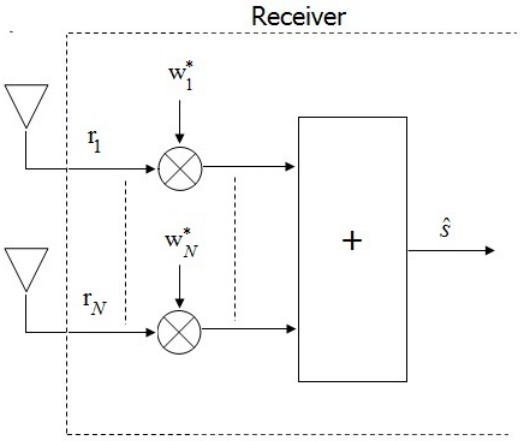

Figure 2.8: Multiple Receive-Antenna Combining

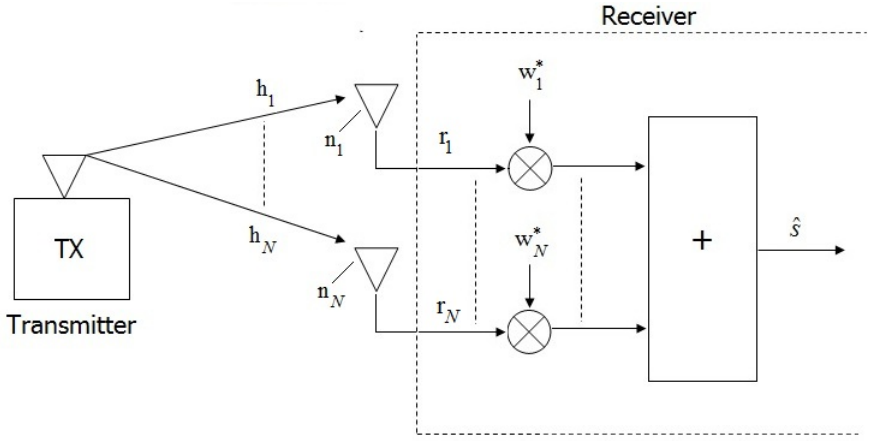

Figure 2.9: Multiple Receive-Antenna Combining with Channel Conditions

together (coherent combining). Furthermore, MRC applies higher weights for stronger received signals in proportion to their channel gains. MRC-vector that fulfils these proposes is the vector that matches the channel state and is expressed as:

$$\mathbf{w}_{MRC} = \mathbf{h} \tag{2.3}$$

MRC is an ideal combining technique when the received signal is affected by the noise only. When the received signal is impaired by multiple interfering signals or a single dominating interferer, instead of selecting MRC-vector to maximize the received signal power level, the antenna weight-vector can be selected to suppress the interference. This is achieved by forming a receive-beam to focus in the desired direction while ignoring the unwanted direction. The application of receive-antennas to suppress the unwanted interference signal is called Interference Rejection Combining (IRC). Uplink intra-cell-

interference suppression based on IRC is referred as SDMA (figure 2.10). The same technique can also be used in order to suppress inter-cell interference (figure 2.11). Both are called as receive-beamforming. Therefore, in the case of a dominating interferer, the expression in 2.2 can be extended as:

$$\mathbf{r} = \begin{bmatrix} r_1 \\ : \\ r_N \end{bmatrix} = \begin{bmatrix} h_1 \\ : \\ h_N \end{bmatrix} \mathbf{s} + \begin{bmatrix} h_{l,1} \\ : \\ h_{l,N} \end{bmatrix} \mathbf{s}_l + \begin{bmatrix} n_1 \\ : \\ n_N \end{bmatrix} = \mathbf{hs} + \mathbf{h}_l\mathbf{s}_l + \mathbf{n} \tag{2.4}$$

where $\mathbf{s}_l$ is the interfering signal, $\mathbf{h}_l$ is a vector consisting of complex channel gains of the interferer with number of elements corresponding to the number of receive antennas. IRC is achieved by selecting a complex weight-vector that fulfills the expression:

$$\mathbf{w}^H\mathbf{h} = 0 \tag{2.5}$$

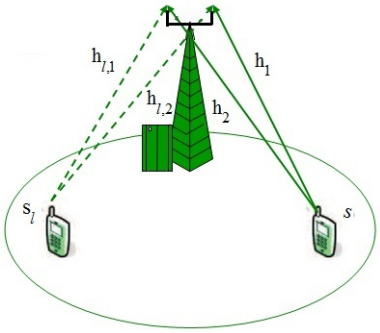

Figure 2.10: Intra-Cell IRC enabling SDMA

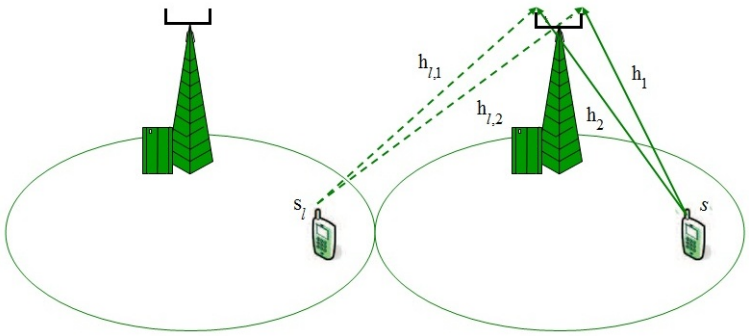

Figure 2.11: Inter-Cell IRC

As an alternative or complement to multiple receive antennas, diversity and beamforming can also be achieved by multiple transmit antennas. Multiple transmit antennas are again majorly of interest for downlink at the basestations. Diversity can be

achieved by means of cyclic-delay diversity or space-time coding. If some knowledge of the downlink channels of the different transmit antennas is available at the transmitter, transmitter can also provide beamforming as illustrated in figure 2.12

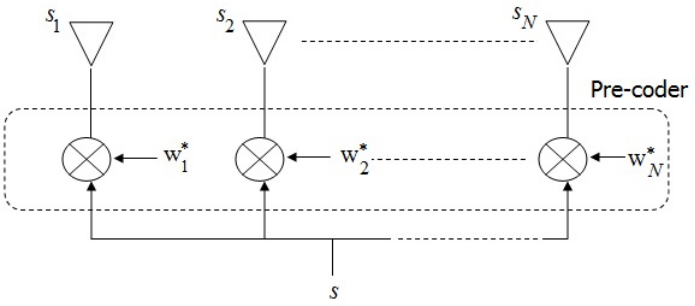

Figure 2.12: Pre-coder-based Beamforming with Multiple Transmit Antennas

The major conclusion from this chapter is that spread spectrum technologies such as DS-CDMA and FH-OFDM as well as spatial access technologies based on multiple antennas have interference tolerence which is a major advantage against to the approaches based on time/frequency schedulings. The interference tolerance is important when the information exchange is limited between the operators. At this point, we are interested in the capacity of a channel under the fading and weak and strong interference conditions.

2.1.1 Fading Channels

Fading is the deviation of signal characteristics because of the multipaths and shadowing effects. Due to the natural or man-made obstackles, the electromagnetic signal transmitted by the transmitter reach the desired receiver via different paths. These multipaths are results of reflections due to the obstackles in the surrounding environment. Therefore, the signal reaching the receiver is a sum of some original copies of the original signal. As the paths of reflected signals have different lengths, the signals arrive with different delays and gains. This changes the amplitude, phase and angle of the arriving signal. As result, the received signal shows a wide fluctuation in its power profile. As the mobile terminals move and the objects of the environment are usually non-stationary, the communication channel(the signal) and therefore its power profile is time-varying. This is called as small-scale fading.

There are types of small-scale fading. Per doppler-rate, small-scale fading can be classified into slow-fading and fast-fading. Slow-fading occurs when the symbol periode of the signal is smaller than the coherence time of the propagation channel. It means that channel variations are smaller than base-band signal variations. Fast-fading occurs when the doppler-spread is high as a result of a symbol period that is greater than the coherence time. This occurs when the channel variations are faster than the base-band signal variations.Per delay-spread, small-scale fading can be classified into flat-fading (non-frequency selective fading) and frequency selective fading. If the bandwidth of the communication channel is smaller than the coherence bandwith of the propagation

channel(environment), the signal will exprerience flat-fading. With other words, the symbol period is larger than the delay spread of the propagation channel.In flat-fading, all frequencies in a communication channel are attenuated and faded in the same way. For the frequency selective channels, the reverse coditions hold. Bandwith of the signal is greater than that of the coherence bandwidth and the symbol duration is smaller than the delay spread of the propagation channel.

Large-scale fading is due to the shadowing effects. Large-scale fading is also called as slow-fading as the mobile terminals can move for a larger distance to overcome the effects of shadowing. Large-scale fading is modelled as log-normal distribution.

In telecommunications, the designer is interested in *how much* information can be transmitted through a fading channel. In *Information Theory*, the upperbound of the rate at which *reliable* communication is possible through a channel, is given by *Shannon Capacity*. In the sense of Shannon Capacity, *reliability* is defined as the probability that the receiver will decode the transmitted message correctly. The higher the reliability, the lower the errors in decoded messages. The designer tries to achieve a preset level of reliability by applying a codebook that is suitable for the propagation channel. The input messages which jointly are encoded by using a codebook, will require a transmission rate of R_T. If the resulted transmission rate after encoding is no more than the Shannon Capacity of the channel, then the information rate (data-rate) is called as *achievable*.

Capacity of a Single-user Fading Channel:

A *single-user channel* is used between a single transmitter and a single receiver. The received signal under the influence of fading conditions and noise can be described as :

$$y[i] = h[i]x[i] + z[i] \tag{2.6}$$

where $x[i]$ is the i_{th} transmitted complex symbol, $y[i]$ is the i_{th} received complex symbol, $h[i]$ is the complex channel gain of the fading and $z[i]$ is the AWGN noise with $N_0 = \sigma^2$ the noise power. The average power constraint for the transmitter is $\mathbb{E}_i[(x[i])^2] = P$. The Shanon Capacity is then given as:

$$C_{su} = B\mathbb{E}_i \left[\log_2 \left(1 + \frac{P}{\sigma^2} |h[i]|^2 \right) \right] \tag{2.7}$$

where C_{su} is the single user capacity in $(bit/second)$,B is the bandwidth in $(Herz)$ P is the average power, $|h[i]|^2$ is the channel gain of the i_{th} transmitted complex symbol and $N_0 = \sigma^2$ is the noise power.

When K users communicate with a single receiver, the multi-user channel can be described as:

$$y[i] = \sum_{n=1}^{K} h_n[i]x_n[i] + z_n[i] \tag{2.8}$$

Capacity of Multi-user Fading Channel:

The capacity of multi-user channel can be described in term of the individual data rates. The set of individual rates form a rate vector $\mathbf{r} = [R_1, ..., R_K]$ where K is the number of the users. In the information theory literature, there are several multi-user capacity metrics:

1. **Sum-rate capacity:** This metric gives the sum of all individual rates. It is used for users with no specified constraints on the capacity sharing among the users.

$$C_{sum} = \sum_{n=1}^{K} R_n \tag{2.9}$$

2. **Maxmin capacity:** This metric maximized the minimum rates subjected to some contraints. The constraints can define the capacity allocation among the users according to an aggreed fairness.

$$C_{minmax} = minmax\mathbf{r} \tag{2.10}$$

3. **Weighted capacity:** When the objective is to allocate the capacity according a weight factor, the multi-user capacity metric can be defined as:

$$C_{sum} = \sum_{n=1}^{K} w_n R_n \tag{2.11}$$

When the fading realizations of all involved users of multi-user channel is available at the receiver, then the sum-rate of the capacities can be expressed with the following inequality assuming that each user has the same power limit $P_n = P$:

$$\sum_{n=1}^{K} R_n \leq \mathbb{E}_i \left[\log_2 \left(1 + \frac{\sum_{n=1}^{K} |h[i]|^2 P}{\sigma^2} \right) \right] \tag{2.12}$$

As a more precise quantity, the *the normalized sum-rate* gives the maximum achievable equal rate per user. The normalized sum-rate is given as:

$$R_{sum} = \frac{1}{K} \sum_{n=1}^{K} R_n = \mathbb{E}_i \left[\log_2 \left(1 + \frac{\sum_{n=1}^{K} |h[i]|^2 P}{\sigma^2} \right) \right] \tag{2.13}$$

$$R_{sum} = \frac{1}{K} \log_2 \left(1 + \frac{KP}{\sigma^2} \right) \tag{2.14}$$

The time-varing fading effects can be combated by applying diversity techniques. Diversity can be obtained by applying time, frequency and spatial techniques or a combination of them. The motivation behind the diversity is that the receiver gets multiple copies of

the transmitted signal with different characteristics (hence independent fading) in order to improve the reliablity and quality of the received signal. These multiple copies are called as diversity channels. Depending on the type of diversity, the diversity channels should be separated *sufficiently* along the diversity dimension that is employed in order to achive independent faded signals. Time diversity can be obtained in different ways: One way is that the same signal is transmitted at different time instants separated by *coherence time* of the propagation channel. Alternatively, it is exploited via interleaving, forward error-correction coding (FEC) and automatic request for repeat (ARQ) (Gibson, 2008). Frequency diversity is obtained by separating the frequency carriers with coherence bandwidth of the propagation channel. Spatial diversity can be obtained by multiple receive antennas that are separated by the *coherence distance* and by space-time coding techniques. Diversity also plays an important role against co-channel interference.

2.1.2 Co-channel Interference Management

Interference management is a central problem in wireless system design. Especially in cellular wireless networks, the system capacity is limited by the so-called co-channel inteference which arises both by intra-cell and inter-cell transmissions.

Intra-cell and inter-cell interference management problems are generally addressed separately because the two interference machanisms are very different at work (Qiu and Chawla, 1998). Intra-cell intereference is a result of simultaneous transmissions from or to mobile users in the same cell while inter-cell intereference is caused by simultanous transmissions from base stations or mobile terminals in other cells.

The management of intra-cell interference can be coordinated by one centralized base station which keep real-time information of all involved mobile terminals. In traditional cellular networks, intra-cell interference is tackled by employing multiple access schemes such as TDMA, FDMA, OFDMA, CDMA or SDMA. Those access schemes avoid interfering by allowing single transmission per channel use (Chatnizotas, 2009). This is called as *Single-cell Processing*.

As mentioned in section 2.1, TDMA and FDMA can not tolerate interference while the access schemes based on spread spectrum such as DS-CDMA and FH-OFDMA and SDMA can do that. It is worth noting the difference between the interference managements of CDMA-, SDMA and OFDM-based systems.

In DS-CDMA-based systems, mobile terminals transmit simultaneously in the same frequency band. As a result signal-to-interference ratio (S/I) of a mobile terminal at a CDMA-receiver can be less than 1 since the aggregate of the power of the signals of other users is typically larger than that of a single user. However, thanks to the orthogonal spreading-codes a mobile terminal's signal can be recovered from the sum of other user signals received. Due to the correlation filters, the intra-cell simultaneous transmissions can be isolated as long as the orthogonality among the transmissions due to the spreading-codes is guaranteed. The same holds for inter-cell transmissions: The transmissions of adjacent cells are isolated by means of scrambling codes. A basestation (NodeB) that consructs the individual signals by using user-specific spreading-codes broadcast the aggregate of the signals. The aggregate of the signals are scrambled

by the transmitter-specific/cell-specific scrambling codes before transmission. Through scambeling, the chip sequences lose their orthogonality to one another and become only quasi-orthogonal. In the uplink direction, due to asynchronous reception, the codes lose their orthogonality too. As a result, DS-CDMA has different detection techniques: Single detector detects for a particular user while ignoring the others. Joint-detection is also possible. However, this approach requires that all specific code sequences in the receiver have to be known a priori. Depending on the detection algorithm, other parameters, such as signal energy or amplitude and delay spread must also be known. Joint detection thus uses knowledge about other user signals being received at the same time in order to suppress the interference. Finally interference cancelation can be applied based on an estimated value that is produced from each user's contribution so that it can be subtracted from the received signal. Clearly, interference mitigation in a CDMA system requires good sychronization and global knowledge of user-specific information (Walke et al., 2003).

In OFDMA systems based on FH, since a user's information is spread by hopping in the time-frequency grid, the transmissions within a cell can be kept orthogonal but adjacent cells share the same bandwidth and inter-cell interference still exists. Hence, interference management is more challenging in this case (Bennis, 2009).In SDMA systems, intra-cell as well as inter-cell co-channel interference mitigation require the knowledge of user-specific Channel State Information (CSI) knowledge.

Inter-cell interference management is clearly more a distributed problem of multiple base stations which should exchange information which is called as *Multi-cell Processing* (Simeone et al., 2009). Especially for evolved networks with full frequency reuse, in order to mitigate inter-cell interference, the concept of *Cooperative Base-stations* has been introduced in the literature (Hossain et al., 2011). Cooperative Base-stations concept yields the coordination of multiple base-stations by exchanging information via the *backhaul-links* in order to perform multi-cell processing.

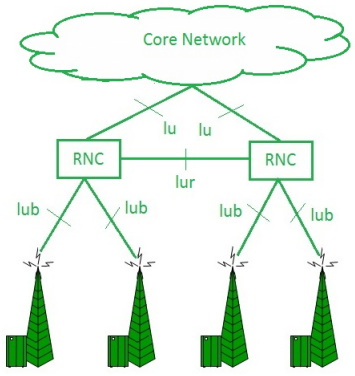

Figure 2.13: Backhaul in CDMA-networks

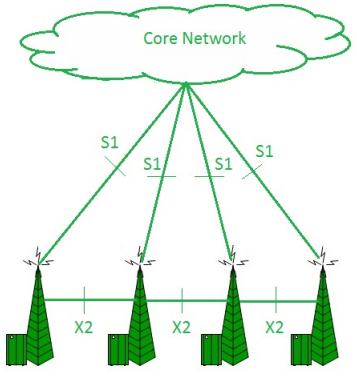

Figure 2.14: Backhaul in 3G LTE-networks

In figure 2.13 and in figure 2.14, the backhaul connections of two different evolved networks have been given. Different types of functions in a cellular system have lead to

a system architecture that is divided in to a Radio Access Network (RAN) part and a core-network part. In a CDMA based network, RAN consists of base-stations which are called NodeB's and control nodes which are called Radio Network Controller (RNC). The philosophy behind the functional split between RAN and core network in CDMA based networks, is to keep the core network unaware of radio access technology. This means that RAN must control all radio interface functionality and that cells should be hidden from the core network. As a result, the core network can be used for any radio access technology. RAN must fulfil the functions such as typical physical layer functions (coding, interleaving, modulation), typical resource control functions (Radio Resource Management (RRM), handover) and security functions (ciphering, integrity protection). When needed, cooperativeness between NodeBs in a network can be achieved through the RNCs. A nodeB connects to RNC by lub-interface and a RNC connects to another RNC by lur-interface. Core-network is responsible for charging, subcriber management, mobility management, quality of service handling, control of user data-flows and interconnection to external networks. Moreover, the functional split of RAN and core-network in a OFDM-based LTE network is similar to that of a CDMA-based network. RAN consists of eNodeBs which are interconnected by X2 interface. However the key difference is that LTE wants to be independent of the radio access technology: eNodeBs are directly connected to the core network. Most of the RAN functions for CDMA-based network remain the same. The eNodeBs take some RNC functionalities: Radio resources in cells, handover, scheduling for uplink and downlink. Core network is again responsible with interconnecting to external networks. From a cooperativeness-point of view, the eNodeBs can more easily communicate to their adjacent neighbors which is a plus in interference mitigation (Dahlman et al., 2008).

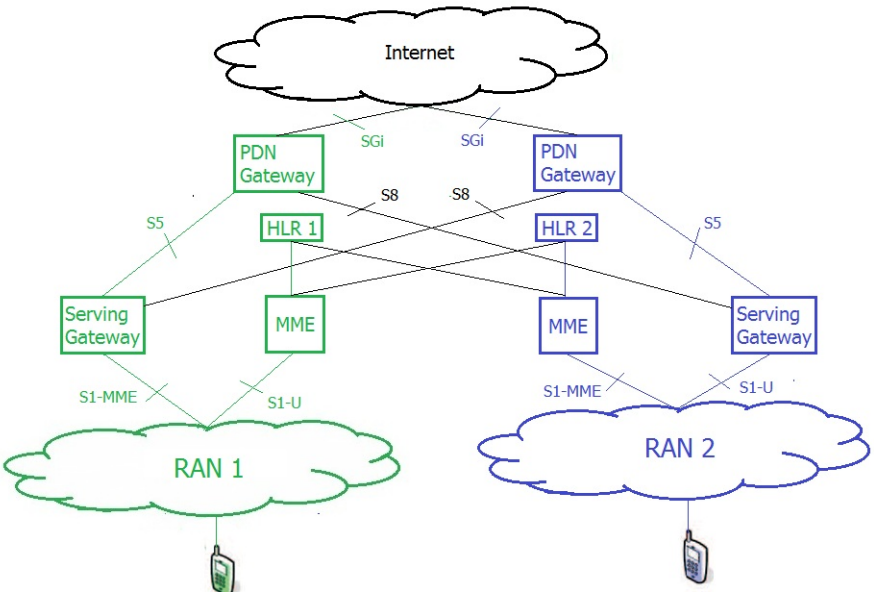

Figure 2.15: Backhaul-links Connecting two Operators

To enable the spectrum sharing between two independent networks, those networks should share information in order to manage Inter-OI. Different networks are interconnected through the core networks. Figure 2.15 shows the interconnection of the core-networks. The backhaul links connecting two operators are especially used for roaming and mobility through an interworking of Serving Gateway, PDN Gateway components of the core network by using S8 interface. Also for charging and policy control used to control the usage of packet-switched services to ensure that the user does not use more bandwidth than allowed are enabled through the core network connection. The use of core network connection in order to manage the Inter-IO is questionable. Performance of multi-cell processing depends stongly on the quality of backhaul links which generally have much higher capacity and higher reliability than the wireless links. A common assumption made in the literature is the use of ideal backhaul links with infinite capacity. However, it has been shown that sharing large amount of data between base-stations using backhaul links restricts the backhaul capabilities (Chatnizotas, 2009).

2.2 Marginal Information Exchange

There are various forms of cooperation between base-stations possible. *Joint resource allocation/joint scheduling* between adjacent cells can be regarded as the least agressive form of base station cooperation. These approaches generally possess low complexity and give small strain on backhaul links (Bhagavatula and Heath, 2011).

2.2.1 Joint Resource Allocation

Joint resource allocation rules the reuse and dynamicity of channel allocations to different cells in order to manage the interference. *Fractional frequency reuse* is just one such joint resource allocation technique between adjacent cells which has gained a lot of attention in the literature. In order to improve the performance for mobile terminals under inter-cell interference conditions, *soft frequency reuse* based on fractional frequency resue concept is applied. In a network based on soft frequency reuse, the whole cell is divided into two parts, cell-centre and cell-edge. In cell-centre, the frequency reuse factor is set as 1, while in cell-edge, it is dynamic and the frequency allocation is orthogonal with the edge of other cells, which can avoid partial inter-cell interference in cell-edge (Xu et al., 2011). Compared to the static frequency reuse, the method described above utilizes the available spectrum more efficiently. The disadvantage of this approach of spectrum utilization is that it does not take the varying user traffic into account (Bhagavatula and Heath, 2011).

2.2.2 Joint Inter-cell Scheduling

Another approach with low complexity is the *joint inter-cell scheduling* by mutiple base stations. In inter-cell scheduling, neighboring base stations cooperatively schedule their transmissions to reduce other-cell interference. The scheduling can either be dynamic (and hence require some inter-cell coordination) or pre-determined based on a universally

shared time-hopping sequence. The base stations can schedule transmission opportunictically by taking advantage of *multi-user diversity* which makes inter-cell scheduling a better alternative of static frequency reuse adopting the universal frequency reuse (Choi and Andrews, 2008).

Both methods require only control-level information causing to low load on backhaul links. inter-cell scheduling is considered as the most practical BS coordination technique since the required control message is comparable to what is required for *handoff*, which is already a feature of every cellular system (Choi and Andrews, 2008). Joint-resource allocation method to adjacent cells and joint inter-cell scheduling do not utilize all the available frequency/time resources and transmission duty-cycle, respectively and hence, do not realize the performance gains that can be potentially obtained using base station cooperation (Bhagavatula and Heath, 2011). Spectrum sharing between operators build on those mothods will also not reflect the potential gains of spectrum sharing. Therefore, the advanced forms of cooperative base stations should be considered.

2.3 Full Information Exchange

In subsection 2.1.1 various methods to avoid inter-cell interference have been mentioned based on low level cooperation between the base-stations. Even though the described approaches require only control-level information exchange among the base-stations, they do not reflect the potential of spectrum sharing because of non-utilized available frequency and/or time resources. In this section, approaches which require full cooperation between the base-stations are mentioned. Full cooperation is associated with the exchange of a greater amount of information exchange among the base-stations. The price to be paid with full cooperation is then the increased amount of load on backhaul-links. Approaches based on full cooperation describe the upper bound of the cooperative base-stations concept in cellular networks (Bhagavatula and Heath, 2011).

As described at the beginning of section 2.1, a mobile terminal communicating to its associated BS can cause unwanted interference at the base-stations in neighboring cells. This will affect the detection performance at the neighboring base-stations. However, if the base-stations cooperate, the unwanted interference signal can be treated as just a desired information-bearing signal. With other words, the cooperative base-stations can perform *joint multi-user detection* of all involved mobile terminals with the aid of a central point gathering information of all involved base-stations. This leads to the concept of *multi-cell joint decoding* in the uplink of a cellular network. The principles developed for the uplink have been extented for the downlink channel. The cooperative base-stations can precancel the interferece at the transmitters by jointly encoding the transmissions which leads to the concept of *multi-cell joint encoding* (Chatnizotas, 2009).

Dirty Paper Coding (DPC) is such a multi-cell joint encoding scheme for the downlink which is achieved by cooperative base stations that all know the interference a priori. That all base stations know the interference a priori is due to the fact that they jointly construct the transmission signals (they know the structure of encoded signals) and corresponding Channel State Information (CSI) to all involved mobile terminals.

DPC can be applied for the downlink case. For the uplink case, a similiar approach is Succesive Interference Cancellation (SIC). Upon receiving the transmissions, SIC enables the joint-decoding of the received signals where Superposition Coding (SC) is employed which implies that the received signal is a sum of multiple transmissions with no orthogonolization in time and frequency dimension. SIC starts by decoding the signal with highest certainty as illusrated in 2.17. Both DPC and SIC require full-information exchange with high level coordination of the basestations. Therefore, those scemes can be regarded as theoretic upperbounds (Chatnizotas, 2009).

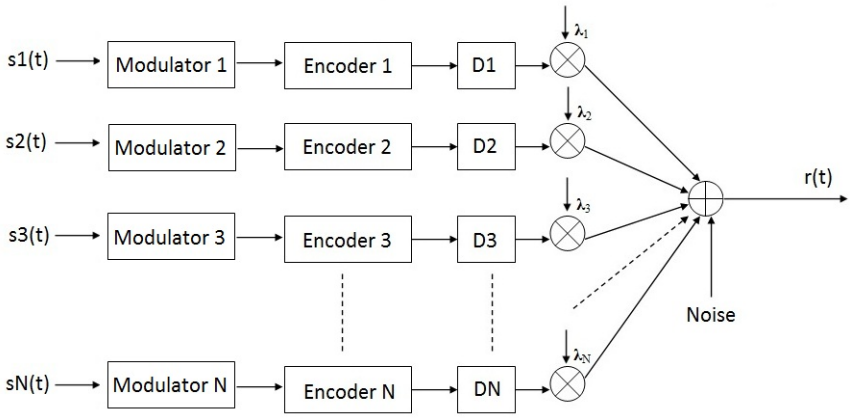

Figure 2.16: Multi-user Channel

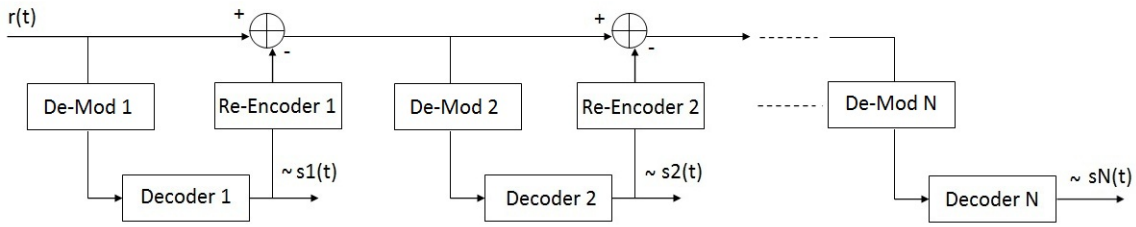

Figure 2.17: Successive Interference Cancellation (SIC)

2.4 Partial Information Exchange

This kind of approaches to enable interference mitigation requires only Channel State Information (CSI) of the involved users. The base-stations cooperate to share the CSI of the active users via the backhaul links. Although the load on the backhaul links is limited in these approaches, the base stations need to have real-time CSI exchange with high dynamicity. Based on the available CSI, the base-stations can perform some receive

and transmit techniques based on digital signal processing in order to mitigate or reduce the interference.

2.4.1 Multi-cell Beamforming

One such approach is *beamforming* based on precoding techniques. Beamforming can be achieved as transmit-beamforming as well as receive-beamforming. Transmit beamforming at the base-stations at the downlink typically is used to maximize the signal energy sent to the desired mobile terminal, while minimizing the interference sent toward interfering users. Therefore, beamforming for interference reduction is better suited to battling self-cell interference and in doing so it reduces the inter-cell interference (Andrews et al., 2007). Receive-beamforming at the base-stations at the uplink can be considered as a *spatial-filtering* as an example of linear *multiuser detection*. It is therefore a brach of *Interference Rejection Combining* (IRC) used for *Space Division Multiple Access* (SDMA) in the uplink. The mobile terminals also can perform transmit-, receive-beamforming. However, the mobile terminals are usually required to be simple (Ng et al., 2005). Therefore, the complexity is given to the base-stations which are responsible for receive-beamforming in the uplink direction as multiuser detection technique and perform transmit-beamforming as a *transmitter optimization* technique (Samardzija et al., 2007).

To obtain the necessary CSI in order to perform beamforming, there are two ways possible in the literature. The downlink channel conditions can only be captured accurately by the receiver mobile terminals. The mobile terminal can estimate the downlink channel condition with the aid of a downlink pilot/reference signal transmitted by the base-station. The downlink pilot signal has a predetermined structure with constant power. When the mobile terminal estimates the instantenous downlink channel condition, it can then be reported to the base-station as feedback. This feedback method is especially suitable for FDD systems where the downlink and uplink transmissions occur through different spectrum bands and therefore the uplink and downlink channel conditions are quite different (Dahlman et al., 2008). In (Samardzija and Mandayam, 2005), a possible CSI feedback method has been provided.

In multi-cell scenario, the base-stations, which obtain the CSI of their direct users as described above, should exchange the CSI with each other in order to reach a networking perspective to reduce the interference. In (Ng et al., 2005), a distributed downlink beamforming algorithm is proposed based on linear minimum mean square error (MMSE) estimation techniques using local message passing between base-stations, to overcome the impact of intercell interference. The transmit antenna array is formed from antennas at multiple base stations. It is assumed that there are dedicated communication links, free of interference, between neighbouring base-stations, thus enabling a cooperative sharing of information. Moreover, there is a central processing centre or controller to process information or coordinate information exchange among base-stations. The obtained information is used to design transmit symbol vectors. The convergence of these iterative approaches is actually not guaranteed (Bhagavatula and Heath, 2011). Furthermore, in (Somekh et al., 2005), a distributed beamforming scheme

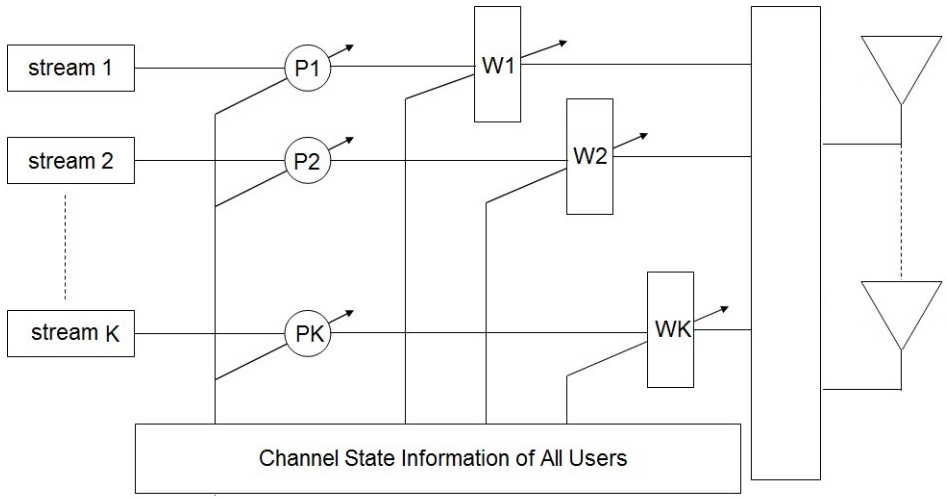

Figure 2.18: Joint Beamforming and Power Control

is proposed based on *zero-forcing* in combination with a scheduling scheme. According to this scheme, in each cell the user with the best local channel (the channel from the local cell-site) is scheduled for transmission by means of cooperative multi-cell beamforming. However, the scheme satisfies in probability only the more suitable equal per-cell power constraints asymptotically with increasing numer of mobile terminals which is not realistic for the practical case.

In (Chae et al., 2009) and (Bhagavatula and Heath, 2011), a two-cell beamforming scenario is proposed. In (Chae et al., 2009) jointly optimized transceiver algorithms called interference aware coordinated beamforming (IA-CBF) is introduced for a two-cell system where each base station is equipped with multiple transmit antennas. The algorithm aims at sum-rate maximization basen on joint optimization of minimum-mean-square error (MMSE) and zero-forcing. In (Bhagavatula and Heath, 2011), the proposed beamforming scenario is based on the *wyner model*, where neighboring base stations share only the CSI to perfrom beamforming independently towards one active user in the cell with a single co-channel interferer. In the evoluation of the algorithm, full CSI availability and high-capasity backhaul links as well as more realistic scneario of limited CSI (as the feedback links have finite bandwidth) and capasity-limited backhaul links have been considered. Limited CSI implies quantized CSI feedback instead of full CSI that will partition bits between the desired and interfering channels as a function of their relative strengths. the desired and interfering channels are quantized using random vector quantization(RVQ), i.e. the quantization vectors are independently chosen from the isotropic distribution. In the proposed model, adjacent base-stations are connected to exchange only quantized CSI of interfering channels. It is shown that the multicell beamforming approach yields sum-rates reasonably close to those obtained using multicell DPC, with

full CSI and that of feedback-bit allocation strategy is shown to be close to the full CSI case.

2.4.2 Interference Alignment

Another way to combate the interference based on CSI knowledge is *interference alignment* in signal space. Interference alignment is based on linear precoding at the transmitter and interference suppression at the receivers. Interference alignment in signal space for multi-cell scenario means that transmit and receive beamforming vectors are designed that will align and null the interference, respectively. The main difficulty is the design of transmit beamforming vectors that align all interfering signals into the same signal dimension for each involved mobile terminal.

Figure 2.19 shows transmit signal spaces for three transmitters. When the interference alignment is performed perfectly, all interfering signals will be aligned along a same signal dimensions at the mobile terminals. The mobile terminals also have multiple antennas to null the interference signals on the aligned dimension as illustrated in figure 2.20. When successifully performed, this technique results in a network capacity which is not a decreasing function of the involved users, but each user is guaranteed to obtain half the spectrum free of interference as given in (Gomadam et al., 2009):

$$C = \frac{K}{2} \log_2 (SNR) + o (\log (SNR)) \tag{2.15}$$

where C is the capacity in bits/channel-use, K is the number of the involved users, and the operator $o(.)$ is the littel Landau symbol that grows slower than $\log (SNR)$, thus can be neglected asymtotically. Clearly, this technique provides spatial degrees of freedom as the spectrum can be reused, unaffected from the increasing number of users.

In order to perform beamforming based on interference alignment, the CSI of all involved users should be available. In multi-cell scneario, the base-stations should exchange the CSI with each other which is a challenging task.

2.5 Interference Optimization and Game Theory

In the previous sections, spectrum sharing of operators have been explained with the aid of the co-channel interference mitigation models and methods. Depending on the information passing between the base-stations, various different approaches have been introduced. While methods based on marginal information exchange between the base-stations require only control-level information passing between the base-stations, those methods (joint scheduling/resource allocation) have been shown to be inefficient because of non-utilized frequency/time resources and transmission duty-cycle (see section 2.2.1). Methods that require full information exchange reach the optimal capacity (sum-rate) in downlink as well as in uplink, however those approaches require the knowledge of whole signal structure (signals jointly encoded and decoded) in order to precancel the interference or cancel the interference, respectively (see section 2.2.2). Therefore, the results are

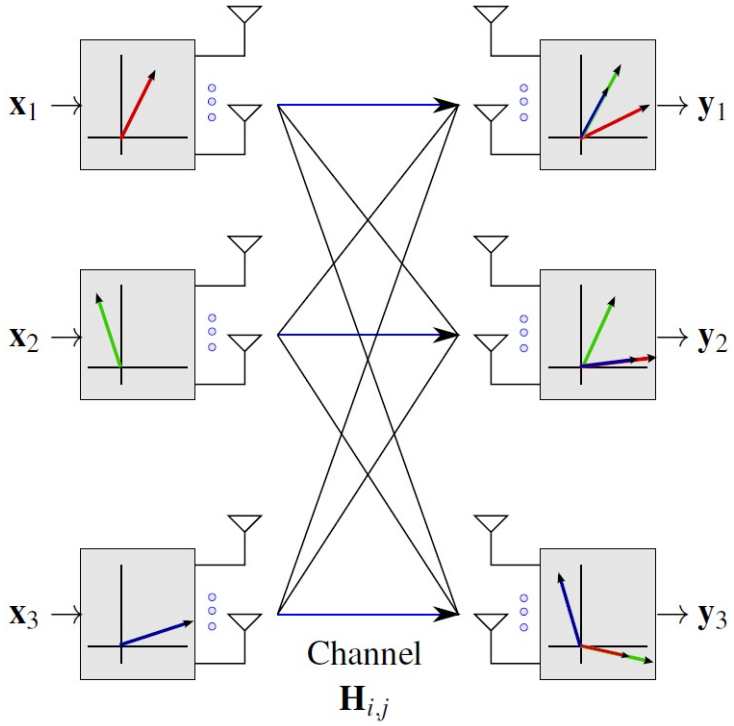

Figure 2.19: MIMO-Interference Alignment

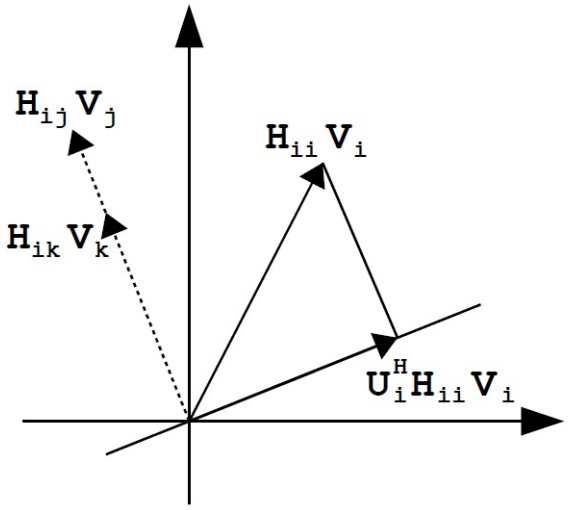

Figure 2.20: Alignment and Cancelling of Interfering Signals

only interesting as being theoretic upperbounds. Methods based on partial information exchange require only CSI passing between the base-stations (see section 2.2.3). In fact,

the methods mentioned give satisfactory results, but the assumptions on infinite capacity backhaul links or the centralized processing unit connected to base-stations has not been verified yet. Therefore, as a different approach, *interference optimization* is considered in the literature. Interference optimization is based on physical layer interactions between the basestations of different operators with no or very-limited information passing.

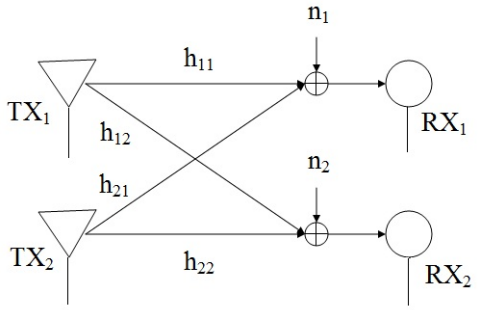

Figure 2.21: Two-User Interference Channel

In telecommunications, a communication channel can be a Multiple Acces Channel(MAC)in the uplink or Broadcast Channel(BC) in the downlink if the multi-user transmissions can be coordinated by using a common control scheme. When there is no such coordination, the transmitter/receiver pairs will generate interference on each other over the shared transmission medium (air interface). The resulting channel is called as *Interference Channel(IC)* in wireless communications. A two-user Interference Channel is characterized by four parameters: Signal-to-Noise Rations SNR_1, SNR_2 at the receivers and Interference-to-Noise Rations INR_1 and INR_2 where the transmission parameters and channel states/coefficients are included, leading to Signal-to-Interference-Noise Ratios $SINR_1$ and $SINR_2$. The achievable rates R_i are functions of obtained $SINR_i$. The received signal at the i_th receiver for flat-fading channel can be expressed as :

$$r_i = \sum_{j=1}^{K} \sqrt{p_j} h_{ji} s_j + n_j \tag{2.16}$$

where K is the number of transmitter/receiver pairs, $x_j = \sqrt{p_j} s_j$ is the transmitted signal of the j_{th} transmitter with s_j is the transmitted data with the power allocation p_j. n_j is local noise. The $SINR_i$ can then be given as:

$$SINR_i = \frac{p_i \left|h_{ii}\right|^2}{\sigma^2 + \sum_{j=1, j\neq i}^{K} p_j \left|h_{ji}\right|^2} \tag{2.17}$$

where h_{ii} is complex direct channel gain from tranmitter i to mobile terminal i and h_{ji} is crosstalk channel from transmitter j to mobile terminal i. σ^2 is the power of the white noise. The obtained capacity can then be expressed as:

$$R_i = \log_2 (1 + SINR_i) \tag{2.18}$$

The formula's above are used for flat-fading channels where the interfering signals behave noise-like. For wide-band signals divided into Orthogonal Frequency Division Multiplexing (OFDM), the subcarriers also exprience flat-fading. The received signal can be expressed as:

$$r_i^m = \sum_{j=1}^{K} \sqrt{p_j^m} h_{ji}^m s_j^m + n_j^m \tag{2.19}$$

where K is the number of transmitter/receiver pairs, $x_j^m = \sqrt{p_j^m} s_j^m$ is the transmitted signal of the j_{th} transmitter on the m_{th} carrier with s_j^m is the transmitted data with the power allocation p_j^m. n_j^m is local noise on the m_{th} carrier. $SINR_i^m$ can then be given as:

$$SINR_i^m = \frac{p_i^m \left|h_{ii}^m\right|^2}{\sigma_m^2 + \sum_{j=1, j\neq i}^{K} p_j^m \left|h_{ji}^m\right|^2} \tag{2.20}$$

where h_{ii}^m is complex direct channel gain from tranmitter i to mobile terminal i for the m_{th} carrier and h_{ji}^m is crosstalk channel from transmitter j to mobile terminal i. σ^2 is the power of the white noise. The resulting capacity on the m_{th} subcarrier.

$$R_i^m = \log_2 (1 + SINR_i^m) \tag{2.21}$$

As given in sections 2.2.2, in multi-user cooperative case, Dirty Paper Coding (DPC) in the downlink and Successive Interference Cancellation (SIC) in the uplink give the theoretical upperbounds for the interference channel. However, for those schemes, the whole signal structure should be known (full information exchange). When the whole signal structure is not known, there are different approaches possible treating the interference depending on the strength of the interference. When considering the capacity formula, the thermal noise power and interference power mathematically have the same impact. However, physically, unlike the noise, interference has a structure since it is generated. This structure can be exploited in mitigating its effect. In (Carleial, 2009), it has been shown that interference does not reduce the capacity of the two-user *Gaussian interference channel* in a very strong interference case, where each receiver can first decode the interfering signal and cancel the interference by exploiting the structure of the interfering signal completely. For two-user interference channel for interference limited regime (weak interference), the upperbound for the achievable capacities (rates) is difficult to obtain and remains an unknown problem. The best possible acievable capacity was reached by (Han and Kobayashi, 1981) 2.22: This approach splits the transmission information of both users into two parts. One of the parts is private in the sense that it can only be decoded by the desired receiver and the other part is common in the sense that it can be decoded at both of the receivers. The part that cannot be

decoded is treated as noise, while the decodable part is cancelled off. The transmit power can be split over the private and common part to optimize the achievable capacity.

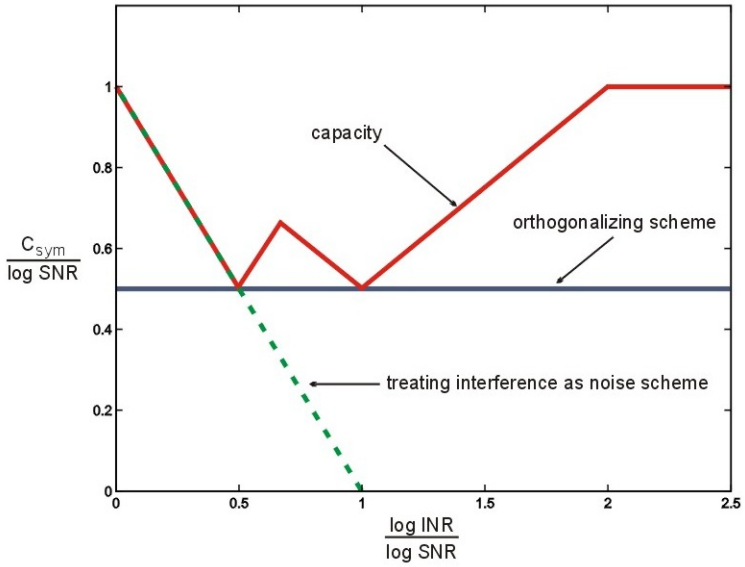

Figure 2.22: Performance of Different Approaches in treating the Interference: For weak interference, the capacity obtained from interference channel can be higher than orthogonalizing schemes,(Han and Kobayashi, 1981)

The objective of interference mitigation in the case of no or limited information exchange is therefore interference optimization based on transmission and receiver parameters (power levels, beamforming weights etc.) selected. Interference optimization is performed in order to avoid interference by treating it as noise provided that the interference is bounded (weak or comparable interference).However, in the case of spectrum sharing, there are two independent decision makers (operators) who have conflicting interests: maximizing the received power on their intended users causing significant interference on the non-intended terminals. The independent base stations have their own conflicting objectives. They can not share full information as explained in previous sections. The result is a conflict in physical layer.

Game theory is a branch of mathematics which provides rules for analyzing conflict situations where a resource is shared by two or more decision makers. In its basic definition, a game $\mathbb{G}$ can be defined with the aid three elements: There are K players who want to maximize their own utility functions U_i based on their actions, moves and strategies. The set of all strategies is called the *strategy space* S (Larsson et al., 2009).

$$\mathbb{G} = (\{1....K\}, S, \{U_1....U_K\}) \tag{2.22}$$

Depending on the move of the decision-makers, there are different types of games. When a number of players (decision-makers) have totally or partially conflicting inter-

ests in the outcome of a decision process, they are subjected to the Non-Cooperative Game Theory. For example, a number of wireless transmitters attempting to control their transmit power, given the interference generated by other transmitters. Clearly, the transmitters represent the players, the transmit-power-levels construct the strategy space within a maximal power constraint and resulting data-rates or capacities are the utility functions. In this scenario, they all want to transmit at its maximal power level in order to improve their transmissions, but the presence of interference presents a conflict, influencing the decisions. Given the possible choices of other players, a player independently prepares a strategy. It is important to note that the term *non-cooperative* does not always imply that the players do not cooperate. It implies that any cooperation that might arise must be self-enforcing with no communication or coordination of strategies. A game is called static, if the players put their strategies only once, independently of each other. Therefore, in a static game, the notion of time does not exist where no player has any knowledge of the decisions taken by the other players. In contrast, in a dynamic game, players have some information about each other's choices and can act more than once. Time plays an important role in decision-making in dynamic games (Han et al., 2012).

Once a game is expressed in its strategic (normal) form as given in 2.22, the next step is to solve the game. Solving a game implies predicting the strategies that might be adopted by each player and possible outcomes of the game. As the interference optimization of two operators in a spectrum sharing scenario results in a game with conflicting objectives, in the remainder of this section, the attention is paid to how to solve non-cooperative games.

One important solving technique is the concept of dominating strategies. The notion of dominating strategies enables to eliminate some other strategies which are likely to have no impact on the outcome of a game. A strategy $s_i \in S_i$ is said to be dominant for player i if:

$$U_i\left(s_i, \mathbf{s}_{-i}\right) \geq U_i\left(\acute{s}_i, \mathbf{s}_{-i}\right), \ \forall \acute{s}_i \in S_i \ and \ \forall \mathbf{s}_{-i} \in S_{-i} \tag{2.23}$$

where S_i and s_i are the strategy space and strategy of the i_{th} player respectively and S_{-i} and $\mathbf{s}_{-i}$ are the strategy space and strategy of the other players respectively. U_i is the utility function of the the i_{th} player. $\acute{s}_i$ is any strategy from the strategy space of the i_{th} player.

Clearly, a dominat strategy is the best response strategy that yields the highest utility for the player regardless what strategies the other players choose. When all players have such dominating strategy from their strategy space, they will not have any incentive to choose another strategy if they are rational decision-makers. This leads us for the following solution concept for non-cooperative games: A strategy profile $\mathbf{s}^* \in S$ is the dominant-strategy equilibrium if every elements of s_i^* of $\mathbf{s}^*$ is a dominant strategy for player i. The dominat-strategy equilibrium is called a natural outcome of the game assuming that the players are rational decision-makers.

While the dominant-strategy equilibrium is an intuitive solution for a given game, its existence is not guaranteed. It can happen that no player has such a dominant

strategy. For such a situation, the concept of strictly-dominated-strategy is introduced beyond the idea of dominant strategy as following:

$$U_i\left(s_i, \mathbf{s}_{-i}\right) > U_i\left(\acute{s}_i, \mathbf{s}_{-i}\right), \ \forall \mathbf{s}_{-i} \in S_{-i} \tag{2.24}$$

where S_i and s_i are the strategy space and strategy of the i_{th} player respectively and S_{-i} and $\mathbf{s}_{-i}$ are the strategy space and strategy of the other players respectively. U_i is the utility function of the the i_{th} player. $\acute{s}_i$ is any strategy from the strategy space of the i_{th} player.

The expression in 2.24 yields an important solution concept: A strategy is strictly dominated if the player possess another strategy that performs better, regardsless what strategies the other players put into the game. Therefore, a rational player can eliminate all strictly-dominated strategies before taking a decision. Eliminating the strictly-dominated strategies can be performed iteratively. The order of elimination does not affect the solution of a game.

Nevertheles, iteratively-eliminating the strictly-dominated strategies may not be sufficient to predict the outcome of a game. Alternative solution concepts have been developped. The most accepted solution concept for non-cooperative games is the Nash Equilibrium (NE). A NE is a state where no player can improve its utility by changing his strategy unilaterally, when other players maintain their strategies. The pure-strategy NE (i.e. deterministic strategies) can be expressed as:

$$U_i\left(s_i^*, \mathbf{s}_{-i}^*\right) > U_i\left(s_i, \mathbf{s}_{-i}^*\right), \ \forall \mathbf{s}_{-i} \in S_{-i} \tag{2.25}$$

where $\mathbf{s}_{-i}^*$ are the strategies of other players that are fixed.

To find the NE, one has to find the best-response functions. Then, for different combination of strategies, the possible deviations can be studied. The best-response functions can be constructed by taking the derivative of utility function U_i with respect to the strategy s_i to 0 which yields $\frac{dU_i(s_i, \mathbf{s}_{-i})}{ds_i} = 0$. For the two-players case, NE can be expressed as:

$$BR_1\left(s_2\right) = \underset{s_1}{\mathrm{a}rgmax}\ U\left(s_1, s_2\right) \tag{2.26}$$

$$s_1^{NE} = s_1^* = BR_1\left(s_2^*\right) \tag{2.27}$$

Instead of NE where all players simultaneously put their strategies into the game, non-cooperative game can also be formulated where a hierarchy exists between the actions of the players. The solution of hierarchical games is the so-called Stackelberg Equilibrium (SE) which is also called leader-follower game. In this hierarchical game, there is a leader who puts his strategy first and the follower(s) selfishly gives his best reaction. In this type of game, leader perfectly knows the set of strategies of the follower and the follower can observe the actions of the leader. Hence, the game has two levels. At the first level, the leader prepares his strategy based on the set of possible strategies of the follower and at the second level, the follower gives his best-response on the

strategies of the leader which was prepared before. Hence, the strategy of the follower becomes a function of the leader's strategy.

$$First\ Level: \quad s_1^{SE} = \underset{s_1}{argmax}\ U_1\left(s_1, s_2\left(s_1\right)\right) \tag{2.28}$$

$$Second\ Level: \quad BR_2\left(s_1\right) = \underset{s_2}{argmax}\ U_2\left(s_1, s_2\right) \tag{2.29}$$

Second level of the game takes the s_1^{SE} and produces the solution such that $s_2^{SE} = BR_2\left(s_2^{SE}\right)$. As can be seen, the strategy of the leader is a function of the follower. Therefore, Stackelberg game results in a non-convex programming problem (Bialas, 1989).

2.5.1 Power Control and Game Theory

Power control is traditionally applied in cellular networks in order to minimize the near-far effects with a contraint that aims at constant uplink received power at the base-stations. While not optimal, this approach is used to provide fairness for cell-edge users in terms of aggregate throughput or spectral efficiency. Recently, power control is employed in 4G applications to componsate for a fraction of path loss as opposed to full path loss for cell-edge mobile users. In interference limited environments, it has been shown that fractional power control provides improvements in aggregate sector throughput on the order of 20 percent over traditional power control for scenarios employing inter-cell distances of 500 m to 1 km and a bandwidth of 10 MHz. On the other hand, the optimal power control scheme which is known as *waterfilling* can provide higher aggregate capacity. However, in waterfilling, every transmitter tries to maximize his own rate (capacity) by avoiding interference at his intended receiver leading to selfishness and unfair cell edge-throughput (Boudreau et al., 2009).

As an interference avoidance technique, power control treats interference as noise, hence interfence is bounded to be weak or comparable with the signal power. Therefore, it is important that the interfering signal behaves noise-like implying flat-fading conditions. For wide-band transmissions, flat-fading conditions are applicable if the spectrum is used in OFDM-fashion as discussed in the previous chapter.

As mentioned, power control aims at maximizing the $SINR$. When there are multiple decision-makers as in the case of inter-cell interference mitigation (different base-stations of a same network) or as in the case of spectrum sharing (base stations of different operators), the optimization problem of the independent decision makers turns into a *game*. The game is categorized as *a non-cooperative game* since the base-stations cannot exchange information through the backhaul links or either way (Gomadam et al., 2009).

A spectrum sharing game based on power control was expressed in (Bennis et al., 2009). The game $\mathbb{G}$ has the operators' base-stations as the *players* of the game. The utility functions that have to be maximized are expressed as in the formula 2.21 leading

to $U_i \equiv R_i$. Strategy space of i_th operator's base station consists of transmission powers $p_i^m \in S$ for the m_{th} subcarrier subjected to the maximum power constraints P_i:

$$\sum_{m=1}^{M} p_i^m \leq P_i \tag{2.30}$$

where P_i is the maximum power allowable for the i_th operator's base-station,p_i^m is the power allocation to the i_th operator's base-station on the the m_{th} subcarrier.

Subjected to the contraints in 2.30, the non-cooperative game is aimed at maximizing the utility functions by trying to find optimal set of power strategies $\{p_i^m\}$ leading to the following formulation of the game $\mathbb{G}$:

$$\mathbb{G} : \max_{p_i^m} R_i \tag{2.31}$$

where $\mathbb{G}$ indicates a game described in 2.31,p_i^m is the power allocation to the i_th operator's base-station on the the m_{th} subcarrier and R_i is the utility function to be the rate function including the transmission parameters in this case the p_i^m.

When both of the operators try to maximize their own SINR by applying their best response, they will fall into the so-called *Nash Equilibrium* (NE). Both operators will fall into the NE when they selfishly apply the SINR maximizing water-filling. In (Bennis et al., 2009), it has been shown that this point is inefficient: In the case of two transmitter/receiver pairs, water-filling power allocation for the multiple subcarriers that leads to the inefficient NE point is given as:

$$p_i^m = \left(\frac{1}{\mu_i} - \frac{\sigma_m^2 + \sum_i p_{-i}^m \left| h_{-i,i}^m \right|^2}{|h_{ii}^m|^2} \right)^+ \tag{2.32}$$

where p_i^m is the power allocation to the i_th operator's base-station on the the m_{th} subcarrier,

Since the non-cooperative NE is not efficient in spectrum sharing games, a different non-cooperative game in the game theory literature has gained alot of attention: *Stackleberg Equilibrium* (SE) which is also called as *Leader-Follower Equlibrium*. In opposed to the NE, the players do not respond to each other with their best response strategies to reach the SE. In SE, there is a hierarchy in actions. The leader player first moves to play his strategy before the follower gives his best-response. Stackelberg game has been applied for distributed relay selection and power control for multi-user case (Wang et al., 2007).In (Bennis et al., 2009), it has been applied for power allocation in spectrum sharing of two operators. It has been shown that SE-based approach can perform better than NE. The idea is that the leader firstly prepares his strategy by taking the best-response of the follower into account as given in equation 2.33.

$$p_2^m = \begin{cases} \left(P_2 + \sum_i^k \left(\sigma^2_{\pi^{-1}(i)} + p_1^{m,\pi^{-1}(i)} \left|\mathbf{h}_{12}^{m,\pi^{-1}(i)}\right|^2\right)\right) & \\ \qquad -\sigma_2^2 - p_1^m \left|\mathbf{h}_{12}^m\right|^2 & \text{for} \quad \pi(i) \leq k \\ 0 & \text{for} \quad \pi(i) > k \end{cases} \tag{2.33}$$

where π indicates a permutation function ranking all channels according to their noise plus interference and k can be found from the following condition: $\varphi_k < P_2 \leq \varphi_{k+1}$ and $\varphi_t = \sum_i^k \left(\sigma^2_{\pi^{-1}(i)} + p_1^{m,\pi^{-1}(i)} \left|\mathbf{h}_{12}^{m,\pi^{-1}(i)}\right|^2\right),\ \forall \in \{1, ..., m\}$.

2.5.2 Beamforming and Game Theory

As explained in section 2.2.3, when the CSI of all involved nodes are known, they can be used to perform distributed beamforming in a multi-cell processing fashion. As the full global knowledge of CSI through the capacity-limited backhaul links is not possible, beamforming should be done by using the local available information or by interacting through the pysical layer without exchanging information between the base-stations directly. This is called as *beamforming optimization* which is based on iterative algorithms as in the case of *power control*.

Transmit beamforming at the base-stations at the downlink typically is used to maximize the signal energy sent to the desired mobile terminal, while minimizing the interference sent toward interfering users. Therefore, beamforming for interference reduction is better suited to battling self-cell interference and in doing so it reduces the inter-cell interference (Andrews et al., 2007).

For K transmitter/receiver pairs with multiple antennas at the transmitters and single antennas at the receivers, the received signal can be expressed as:

$$\mathbf{r}_i^m = \sum_{j=1}^{K} \sqrt{p_j^m} \left(\mathbf{w}_j^m\right)^H \mathbf{h}_{ji}^m \mathbf{s}_j^m + \mathbf{n}_j^m \tag{2.34}$$

where $\mathbf{r}_i^m$ is the received signal at the i_{th} receiver on the m_{th} carrier, K gives the number of transmitter/receiver pairs, $\mathbf{p}$ is the transmit power, $\mathbf{w}$ is the applied beamforming weight-vector whose length is equal to the number of the transmit antennas when multiple antennas at the transmitter and single antenna at the receiver, $\mathbf{h}$ is the channel state vector, $\mathbf{s}$ is the transmitted data, and $\mathbf{n}$ is the local noise with noise power σ^2 The $SINR_i$ and the resulted capacities (rates) for a certain carrier can then be given as:

$$SINR_i = \frac{p_i \left|\mathbf{w}_i^H \mathbf{h}_{ii}\right|^2}{{\sigma_i}^2 + \sum_{j=1, j\neq i}^K p_j \left|\mathbf{w}_j^H \mathbf{h}_{ji}\right|^2} = \frac{p_i \mathbf{w}_i^H \mathbf{h}_{ii} \mathbf{h}_{ii}^H \mathbf{w}_i}{{\sigma_i}^2 + \sum_{j=1, j\neq i}^K p_j \mathbf{w}_j^H \mathbf{h}_{ji} \mathbf{h}_{ji}^H \mathbf{w}_j} \tag{2.35}$$

$$R_i = \log\left(1 + SINR_i\right) = \log_2\left(1 + \frac{p_i \left|\mathbf{w}_i^H \mathbf{h}_{ii}\right|^2}{\sigma_i^2 + \sum_{j=1, j\neq i}^K p_j \left|\mathbf{w}_j^H \mathbf{h}_{ji}\right|^2}\right) \tag{2.36}$$

To maximize the received power at the intended receiver, the optimal beamforming weight is the weight that matches the eigenvector of the channel state. Therefore it is also called as *Maximum Ratio Transmission* (MRT) vector which is equal to:

$$\mathbf{w}_i = \frac{\mathbf{h}_{ii}}{\|\mathbf{h}_{ii}\|} \tag{2.37}$$

where $\mathbf{w}_i$ is the applied beamforming weight-vector at the i_{th} transmitter, $\mathbf{h}_{ii}$ is the direct channel state vector to the desired receiver, $\|\mathbf{h}_{ii}\|$ is the normalization factor.The operator $\|.\|$ gives the length of a vector $\mathbf{u}$ which is equal to the square root of dot product of the vector: $\|\mathbf{u}\| = \sqrt{\mathbf{u}.\mathbf{u}}$.

The beamforming strategy based on weight-vector 2.37 is called as *eigen-beamforming*. This vector maximizes the received power at the desired user and therefore, it is the best response of a transmitter against the interference generating transmitter in a non-cooperative game. When the transmitters react on each other with the their best responses selfishly, the transmitters will fall in NE as described in the previous section. Therefore, the following equation holds:

$$\mathbf{w}_i^{MRT} = \mathbf{w}_i^{NE} = \mathbf{w}_i = \frac{\mathbf{h}_{ii}}{\|\mathbf{h}_{ii}\|} \tag{2.38}$$

Instead of selfish beamforming vector based on MRT, the transmitters can agree on *Zero-Forcing* vector (ZF) which aims at generating no interference on the non-intended mobile terminal while maximizing the received power on the intended user. In this case, only the component of the beamforming vector that is orthogonal on the interfering signal dimension is received by the intended receiver. It means that the received power is reduced in comparison to the selfish vector in 2.37. Therefore, this ZF-vector is called as *altruistic* in *game theory*. The ZF vector is given as:

$$\mathbf{w}_i^{ZF} = \frac{\prod_{\mathbf{h}_{ij}}^{\perp} \mathbf{h}_{ii}}{\left\| \prod_{\mathbf{h}_{ij}}^{\perp} \mathbf{h}_{ii} \right\|} \tag{2.39}$$

where $\prod_{\mathbf{z}} = \mathbf{z}\left(\mathbf{z}^H\mathbf{z}\right)^{-1}\mathbf{z}^H$ is the orthogonal projection onto the column space of $\mathbf{z}$ and $(.)^H$ is the hermitian transpose, while $\prod_{\mathbf{z}}^{\perp} = \mathbf{I} - \prod_{\mathbf{z}}$.

In (Larsson and Jorswieck, 2008), it has been argued that the ZF vector will perform better than the MRT vector for high SNR. For the implementation of ZF vector, the base stations have to know the direct channel $\mathbf{h}_{ii}$ and the cross-talk channel $\mathbf{h}_{ij}$ which belongs to the non-intended mobile terminal.

Due to the fact that the beamforming vectors in 2.37 and 2.39 are not optimal strategies for the Multiple Input Single Output (MISO) systems, in (Jorswieck et al., 2008), a complete characterization for the MISO Interference Channel has been given and it has been shown that the pareto-optimal beamforming weights for the MISO interference channel are linear combinations of MRT vector and ZF vector:

$$\mathbf{w}_i^{OP}(\lambda_i) = \frac{\lambda_i \mathbf{w}_i^{MRT} + (1-\lambda_i)\,\mathbf{w}_i^{ZF}}{\left\|\lambda_i \mathbf{w}_i^{MRT} + (1-\lambda_i)\,\mathbf{w}_i^{ZF}\right\|} \tag{2.40}$$

where λ_i is a scalar that defines the linear combination between the MRT and ZF vector.

Based on the conclusions in (Jorswieck et al., 2008), in (Ho and Gesbert, 2008) a distributed beamforming game-theoretic approach has been proposed for a cognitive radio scenario where the transmitters simultaneously make small increments of their beamformers that will increase the rates for all parties involved. In (Lindblom and Karipidis, 2010), a cooperative beamforming algorithm has been given for two transmitter/receiver pairs that uses the generated interference level as a bargaining value, a treat value. In this way, a linear combination of the MRT vector and ZF vector is calculated that will increase the rates for both parties which has been shown to be almost pareto-optimal. In those allgorithms, a full power contraint hase been employed with no attention on power control. The algorithms run for two transmitter antennas and on a single carrier. In (Karipidis et al., 2011), it has been shown that the nonorthogonal sharing with the aid of multiple antennas can outperform the orthogonal schemes 2.23:

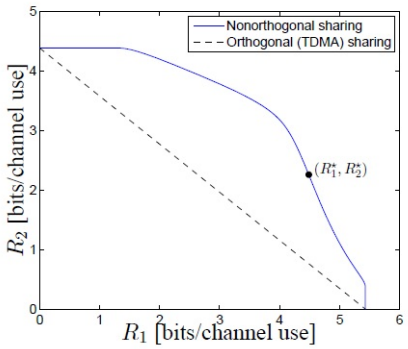

Figure 2.23: Two-user MIMO Interference Channel with a Performance better than Orthogonal Scheme (Karipidis et al., 2011)

In multi-user case, in (Ho and Gesbert, 2010) it has been emphasized that the cross-talk channels are difficult to capture as the number of the mobile terminals increase. Therefore, a bayesian game with incomplete information has been proposed where the channel state matrices of the cross-talks have been assumed to have a probability distribution as the number of the users increase. In (Zakhour et al., 2009), this case has been developed for the multi-cell case applying a distributed algorithm. In (Ho et al., 2010), this work has been extended to distributed beamforming with power control. It has been shown that this approach outperforms interference-alignment based schemes that do not use power control in the unfeasibility region on alignment.

As an inter-cell interference mitigation technique for networks with frequency reuse factor equal to 1 such as OFDMA-based networks, (Hayashi et al., 2010) proposed a transmit-beamforming technique based on iterative water-filling on Signal-to-Leakage-Plus-Noise Ratio (SLNR) instead of SINR. The SLNR for a certain carier is given as:

$$SLNR_i = \frac{p_i \left|\mathbf{w}_i \mathbf{h}_{ii}\right|^2}{{\sigma_\mathbf{i}}^2 + \sum_{j=1, j\neq i}^{K} p_i \left|\mathbf{w}_i \mathbf{h}_{ij}\right|^2} = \frac{p_i \mathbf{w}_i^H \mathbf{h}_{ii} \mathbf{h}_{ii}^H \mathbf{w}_i}{{\sigma_\mathbf{i}}^2 + \sum_{j=1, j\neq i}^{K} p_i \mathbf{w}_i^H \mathbf{h}_{ij} \mathbf{h}_{ij}^H \mathbf{w}_i} \tag{2.41}$$

The main motivation behind this approach is that the received SINR of each mobile terminal becomes a function of beamforming vectors of all involved base stations. That means too much feedback to know the applied beamforming vectors of other base-stations. To decrease the unknown parameters to only the knowledge of cross-talk channels, each beamforming vector is controlled such that the SLNR of each base-station is maximized. In (Hayashi et al., 2010) it has been shown that the SLNR-based approach can obtain comparable results according to the SINR-based approaches. The beamforming vector which maximizes 2.41 has been given as:

$$\mathbf{w}_i^m = C_i^m \left(p_i^m \mathbf{h}_{ij}^m \left(\mathbf{h}_{ij}^m\right)^H + \sigma_m^2 \mathbf{I} \right) \sqrt{p_i^m} \mathbf{h}_{ii}^m \tag{2.42}$$

When thinking in terms of spectrum sharing scenario of two operators, beamforming based on SLNR can also be beneficial. Since the base-stations cannot share much data through the bachhaul links, when the knowledge of the cross-talks are available at the base-stations, they can optimize the beamforming weights based on SLNR.

2.6 Literature Review

Spectrum Sharing among cellular operators has been considered. The emphasis has been put on the fact that spectrum sharing result in capacity gain (more data in less time) when the dedicated spectrum bands can be accessed by other operators replacing the traditional exclusive splitting of the spectrum resources (Heinonen et al., 2008). This is due to the fact that spectrum sharing enables larger bandwidths.

One of the earliest attempts in doing so is the Spectrum Re-Assignment/Re-Allocation (SRA) group of approaches. SRA is aimed at flexible spectrum access based on the variations in network load against the time. A centralized entity above the Radio Resource Management (RRM) units of the operators, which is called as Meta Operator or Spectrum Broker, answers the spectrum demands of the participating operators (Kamal et al., 2009). Such a centralized entity can re-assign/re-allocate the spectrum/channels by considering the average resource needs of each operator or directly reacting on the demands of base stations areas or simply a region (x, y) (Buddhikot et al., 2005). This group assumes that the network load variations of different operators are uncorrelated. The assumption of such a centralized entity has not been implemented yet in a realistic scenario: The use of the capacity limited backhaul links have not been verified. Furthermore, this approach is known to be an NP-hard problem. In (Subramanian et al., 2008), the existence of an near optimal solution has been demonstrated. SRA group can be further divided into Short Term and Long Term assignments depending on the time arrangement of the operators.

Other primitive approaches on spectrum sharing for cellular networks propose spectrum sharing based on Joint-Radio Resource Management (JRRM). The idea of JRRM is that the mobile terminals are always best-connected. When implemented for intra-operator case, JRRM implies that the mobile terminals can choose between the different RATs of a single operator. The inter-operator JRRM enables that a mobile terminal is served by the operator which suits better at that time and place according to its QoS requirements. Technically, this approach requires a centralized controller that needs to coordinate spectrum access demands. In (Giuppon et al., 2007), a fuzzy-logic controller is proposed where i_{th} network operator sends to the JRRM a request of admission for the potentially blocked/dropped user to another network operator, informing about the contracted QoS. However, finding a good balance between economics and RRM is challenging since pricing and resource deployment and allocation strategies determine both the user's satisfaction and operator's exploitation results.

When the idea of cognitive radio was introduced by (Mitola, 1999), spectrum sharing has gotten a new form. Cognitive radios especially became popular in hierarchical network models where a primary operator lets the cognitive radio's (secondary users) utilize his spectrum in an opportunistic way. Secondary users only can transmit by using the radio resources left unused by the primary users. The interference caused by the secondary users must be below a certain threshold. Therefore, the cognitive principle is defined as defining the transmitting parameters in order to produce no harmful results on primary users (Gomadam et al., 2009). Such a hierarchical access to the spectrum (HSA) can be achieved in two ways.: underlay and overlay approaches. With underlay, cognitive radios have to meet a certain power constraint in order to keep the interference level they generate on the primary systems always below their noise level (Bennis, 2009): hence their transmissions at a certain portion of the spectrum are regarded as noise by the primary users. Underlay spectrum sharing requires therefore sophisticated spread spectrum techniques to have a low power spectral density (Akyildiz et al., 2006). On the other hand, in overlay approach, cognitive radios access the spectrum that have not been used by the primary users, so they target the spectral white spaces in the spectrum. The overlay approach does not specify any limit on the transmit power level, as long as the spectrum sensing occurs properly: so secondary and primary users cannot transmit simultaneously through the same spectrum band The white spaces (unused, available channels) have different interpretations in different Multiple Access Schemes. The non-occupied time-slots in TDMA, frequency bands in FDMA, spatial directions in SDMA, tones/chunks in OFDMA, or spreading codes in CDMA represent the form of the white spaces (Bennis, 2009).

One application of this HSA approach is the DARPA next generation program where a cognitive radio-device (secondary user) first senses the spectrum to characterize the presence of the licensed users (primary user) and identifies the spectrum opportunities (frequency, time, space, code etc.) and transmits in a manner that avoids the interference to the primary and secondary users (Nekovee, 2006). DARPA targets military applications and is being seen unsuitable for cellular networks because of the lack of coordination of cognitive radios (Buddhikot et al., 2005). In (Wang et al., 2009),

a primary-prioritized Markov model is proposed for the interactions between the primary and secondary users considering the spectral efficiency while creating fairness in spectrum usage. In (Huang and Krishnamurthy, 2008), a zero-sum dynamic Markovian game with a delay constraint has been proposed to model the primary user activities and secondary user block fading channels as finite state markov chains. The existence and conditions for NE has been demonstrated. However, in those approaches, it is not clear how the spectrum accesses will be detected by the operators as the operators should trade off between obtainable revenue and spectrum utilization.

A new paradigm change in spectrum sharing is aimed at spectrum sharing and coexistence (SSC) in the same spectrum band with equal rights on common spectrum. The approaches based on this group propose to remove the orthogonal frequency division between the individual spectrum bands, leading Inter Operator Interference (Inter-OI). The spectrum sharing can be enabled when the capacity-limiting Inter-OI is mitigated in a way that will satisfy the operators in comparison to their non-sharing case. This group of approaches relies on technology developments on interference mitigation such as: interference alignment/cancellation techniques, multiple antenna techniques, multi-carrier systems, software defined radio and intelligent protocols etc. The generation and mitigation of Inter-OI resembles the Inter Cell Interference (ICI) of a single network, however it differs from ICI in the fact that it is a result of two independent infrastructures. The difficulty is that interference mitigation requires cooperation of interference generating parties. Therefore, the information exchange (synchronization, scheduling maps, coding structures, signal power allocations, beamforming parameters, channel-state information etc.) through the capacity-limited backhaul links of two independent networks in order to make use of multi-cell processing and cooperative base-stations concepts, is the bottleneck in treating the interference. In (Xu et al., 2011) and (Choi and Andrews, 2008), there are joint resource allocation/joint inter-cell scheduling methods are mentioned which only require control-level information passing between the backhaul links (marginal information exchange). However, those methods do not utilize all available frequency/time resources and transmission duty-cycles, respectively and therefore do not reflect the potential of spectrum sharing (see chapter 2.2). Advanced approaches such as multi-cell processing, multi-user detection or interference pre-cancelling methods such as DPC and SCI require greater amount of information exchange between the operators which is only possible in theory (full information exchange). Therefore, those approaches form the theoretical upper bounds for achievable rates (Bhagavatula and Heath, 2011) and (Chatnizotas, 2009) (see chapter 2.3). Other approaches based on partial information exchange such as multi-cell beamforming and multiple antenna interference alignment techniques require only the passing of Channel State Information (CSI) of the involved users in order to construct the transmission signals jointly. However, those approaches require centralized controllers among the home base-stations and foreign base-stations and most of them assume infinite capacity backhaul links (Bhagavatula and Heath, 2011) (see chapter 2.4).

Therefore, from a practical point of view, the problem of spectrum sharing is reduced to physical layer interactions between the operators with no centralized con-

troller and very limited information exchange. The physical-layer interactions rely on the interference optimization on the intended users and non-intended users by adjusting the transmission parameters such as: power levels which are reactive on channel conditions as well as on the interference level and beamforming weights which are flexible to increase the received power on the intended user while minimizing the interference generation on the non-intended user. Additionally, beamforming weights provide spatial degrees of freedom to reduce the overall interference in the network. During optimization of the transmit parameters, there are two independent decision-makers (individual base stations of sharing operators) which compete and cooperate with each other. Therefore, concepts such as cooperativeness and non-cooperativeness in transmission strategies are important and are subjected to game theory which is a branch of applied mathematics to predict the results of resource conflicts of multiple decision-makers. In (Bennis et al., 2009), the spectrum sharing of operators have been considered in terms of non-cooperativeness based on a game theoretical approach and it has been shown that when the operators selfishly react on each other with their best response power allocation strategies, they fall into the so-called NE point which is inefficient for both operators. Also a hierarchical Stackelberg game is formulated for the power allocation problem and it has been shown that SE point can perform better than NE. In (Jorswieck et al., 2008), the case of beamforming has been analyzed and a complete characterization of achievable capacity for two antennas has been given. It has been shown that when the transmit-beamformers react on each other with their best response vector which is the vector that matches the eigenvector of the channel state (MRT-vector), they fall into the inefficient NE (see chapter 2.5.2). The zero-forcing strategy (ZF-vector) nulls the interference generation on the non-intended user's direction while decreasing the received power on the intended user. In (Jorswieck et al., 2008), it has been shown that the optimal beamforming weight for two antenna case is a linear combination of MRT-vector and ZF-vector. In (Ho and Gesbert, 2008), a distributed game-theoretic beamforming approach has been proposed for a cognitive radio scenario. In (Lindblom and Karipidis, 2010), a cooperative beamforming algorithm has been given for two transmitter/receiver pairs that uses the generated interference level as a bargaining value, a treat value. In this way, a linear combination of the MRT vector and ZF vector is calculated that will increase the rates for both parties which has been shown to be almost pareto-optimal. In those allgorithms, a full power contraint hase been employed with no attention on power control. In multi-user case, in (Ho and Gesbert, 2010), it has been emphasized that the cross-talk channels are difficult to capture as the number of the mobile terminals increase. Therefore, a bayesian game with incomplete information has been proposed where the channel state matrices of the cross-talks have been assumed to have a probability distribution as the number of the users increase. In (Zakhour et al., 2009), this case has been developed for the multi-cell case applying a distributed algorithm. In (Ho and Gesbert, 2010), this work has been extended to distributed beamforming with power control. It has been shown that this approach outperforms interference-alignment based schemes that do not use power control in the unfeasibility region on alignment.

Clearly, the difficulty in information exchange between the operators in order

to mitigate the Inter-OI has led the scientists to use the spatial techniques as these require just the CSI of the involved users. The optimization of interference based on beamforming and power control do not avoid the interference, but they can reduce the interference by using the generated interference levels as bargining-values. Beamforming and power control provides the needed flexibility in doing so.

Chapter 3

Proposed Solution

In this chapter a possible approach has been proposed based on the conclusions from literature work given in capter 2. Going back to the problem statement, we can recall the design considerations for spectrum sharing of two cellular operators as being: Information exchange between the operators in order to manage the Inter Operator Interference (Inter-OI), the achievable efficiency, conflicting objectives of operators (rate maximization) and complexity of spectrum sharing approaches.

In chapter 2, it has been concluded that the degree of information exchange through the backhaul links (scheduling maps, coding-decoding structures, signal power allocations, beamforming parameters, channel-state information) influences how to treat and manage the Inter-OI. While the Inter-Cell Interference (ICI) mitigation approaches based on marginal information exchange can enable spectrum sharing in the form of joint-scheduling/joint-resource allocation by requiring only control-level information exchange, these approaches do not reflect the potential of spectrum sharing as explained in chapter 2.2. Approaches like joint-encoding/decoding or joint-precancelling in a multi-cell processing fashion require full information exchange through the backhaul links. However, those approaches put significant strain on capacity-limited backhaul links, even in a single network case. The backhaul interactions of two operatos have been desired to enable mobility related applications and are not designed for such purposes. While the approaches such as multi-cell beamforming with centralized controller and interference alignment based on partial information exchange can be enabled by sharing the Channel State Information (CSI) of the users, also most of those approaches assume infinite capacity bakchaul links. While those approaches can achieve considerable efficiency and fairness among the operators, due to the complexity and unfeasible assumption of perfect multi-cell processing with centralized unit, those approaches (based on full information exchange) become only a theoretical upperbounds. Therefore, from a practical point of view, the spectrum sharing among two cellular operators is reduced to physical layer interactions (power control, beamforming, modulation) with limited information exchange through the backhaul leading to interference optimization techniques. Interference optimization clearly will not achieve the efficiency of approaches based on full or partial information exchange with centralized controller, however, due to its capability of using

local available information and physical layer interactions, operators can achieve gains more satisfactory than the non-sharing case.

A cellular network is a bidirectional network with uplink (from mobile terminals to base stations) and downlink (from base stations to mobile terminals) communications. The uplinks and downlinks should carefully be planned in order to manage the harmful Inter-OI. Although the uplink and downlink problems are different problems, they influence each other. For the uplink problem of spectrum sharing, since the operators will not schedule the transmissions jointly or plan the the transmission cycles through multi-cell coordination as this approach does not reflect the potential of spectrum sharing compared the needed complexity as described in chapter 2.2, one has to rely on *spatial degrees of freedom* to manage the interference. Only for the uplink problem, if the basestation would know the direct channel states to its desired users and cross-talk channels to the undesired users, the base-stations can perform *Interference Rejection Combining* based on *Receive Beamforming*. Due to the heterogeneous status of inter-operator spectrum sharing, the difficulty for the uplink-problem is how to capture the cross-talk channel state information of the undesired interfering users. To enable this, this thesis proposes that the involved users should have to be registered to both operators' base stations. The basestations of different operators should be synchronized to a common clock. The users should have to be given *user-specific pilots/reference signals* with which different users can be recognized and the direct channels and cross-talk channels can be estimated based. It is important that the user-specific pilots can be received by both of the base-stations, hence the mobile terminals have been given single antennas. The complexity is reduced by giving the responsibility of beamforming to the base-stations (multiple antennas at the base-stations). The base-stations have also the ability to perform additional sophistificated receivers based on signal processing to improve the performance of proposed solution even more. The details of this uplink solution have been explained in chapter 3.1.

In the downlink problem of spectrum sharing, there are two decision-makers (base-stations of different operators), while in the uplink the base-station was the only decision maker. They are the base stations again which need to do something to achieve an acceptable level of received power on their intended mobile terminals, since the mobile terminals are equipped by single antennas giving the complexity to the base-stations. Therefore, the interference mitigation in the downlink is based on interference optimization of base stations. Interference optimization parameters can be the power levels and beamforming weight-vectors. Especially the beamforming weights are flexible to increase the received power on the desired user while trading off an interference level on the non-intended user. Therefore, for the downlink, a *Transmit-Beamforming* is proposed based on received power optimization on the receivers. Beamforming in broadband-telecommunications is performed in order to match the mathematical properties (phase,gain) of the propagation channel rather than geometrical direction of the users. Flat-fading conditions are needed to treat the interfering signals as noise-like. Therefore, spectrum has to be divided into narrowband OFDM subcarriers. A communication channel consists of whole spectrum (OFDM subcarriers). The optimization

problem has two dimensions: beamforming weights and power allocation per subcarrier.

When the base-stations selfishly want to maximize the received power on their desired users by applying their best-response beamforming weights(MRT-vectors) as given with the formula 2.38, they will generate maximum interference on each other and therefore, they will fall in the so-called *Nash-Equilibrium* (NE) from a game theoretical point of view, which is inefficient for both of the operators, as concluded in chapter 2.5.1. The zero-forcing vectors (ZF) are aimed at generating no interference while causing less received powers at the desired users. Approaches trying to find an optimum point between the MRT-vector and ZF-vector in a distributed way iether do not take care with the power control dimension of the problem or have complex convergence requiments as explained in chapter 2.5.2. Instead of trying to find a compomise between the selfih MRT-vector and altruistic ZF-vector, we may perform beamforming based on the criterion that the received powers on the intended users are maximized while minimizing the power to the non-intended users leading to SLNR-based beamforming vector as described as an ICI technique for a single network in chapter 2.5.2. In order to use SLNR-based beamforming vector for the ICI problem of a single network, the necessary cross-talk channels can eaisily be captured as the intended user and non-intended user are both the clients of a single operator. To be able to use the SLNR-based beamforming in spectrum sharing op two different operators, the cross-talk channels of users belonging to different operators in the downlink direction have to be available at the base-stations. As the estimated cross-talk channels for uplink can be used for downlink when the base-stations apply Time-Divison-Duplex (TDD) because of the *reciprocity principle*, the uplink channel estimations to be performed as in the described way above are very crucial. Here, it is important that the base-stations of different operators are synchronized and the user-specific pilots are known by the base-stations of different operators.

When the SLNR-based beamforming vector is ready to be used for spectrum sharing of different networks (when the cross-talks channels are obtained in the way described above), the second issue is how to utilize that SLNR-based vector. We know from chapter 2.5, when the power is allocated selfishly by applying the best-responses of operators(water-filling) against each other, this will lead to inefficient Nash Equilibrium(NE). As the Stackelberg (leader-follower) Equilibrium (SE) applied for spectrum-sharing in order to allocate the powers have been shown to be more efficient than NE , this thesis proposes to allocate the powers over the SLNR-based beamforming vector in a Stackelberg fashion. Therefore, the Stackelberg formulation described in 2.5.1 needs to be reformulated to be able to utilize the SLNR-based beamforming vector.

To sum up, two MISO-OFDM based systems are proposed where the users are assigned user-specific orthogonal pilots/reference signals to be used in channel estimations. Both operators know the mapping of the users to the orthogonal pilots. Data carrying parts of the signals are not orthogonal. Instead, the base-stations try to optimize the interference levels by applying beamforming and power-control. In order to apply SLNR-based beamforming vector for spectrum sharing of two independent operators, the cross-talk channels to non-intended users are needed. For that purpose, all users (no matter to which operator they belong) are registered to both operators which

know the mapping of all users to the pilots. The base-stations (no matter to which operator they belong) should be sychronized. As both systems apply TDD, the estimated channels for the uplink can be used for the downlink optimization. In order to prevent NE saturation, the Stackelberg game should be reformulated in order to utilize the SLNR-based beamforming vector in leader-follower relationship.

3.1 Uplink Scenario

In the proposed spectrum sharing scenario, we are aimed at finding a solution which does not require much message passing between the operators and as least as possible complexity on the mobile terminals. While doing so, the mobile terminals are equipped with single antenna. When the desired users of an operator want to communicate to the base station of its own operator in the uplink, they will generate unwanted interference on the base stations of the partner operator and vice versa. To overcome this problem, base stations are equipped with Multiple Antennas to apply Interference Rejection Combining(IRC). As explained in chapter 2.1, IRC requires Channel State Information (CSI) of the mobile terminals to suppress the interference.

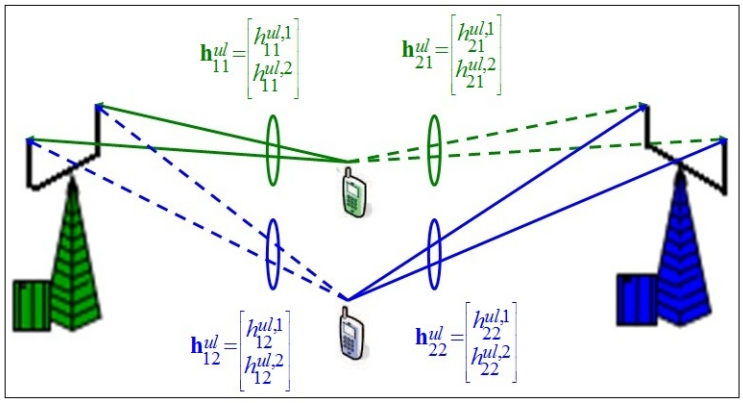

Figure 3.1: Illustration of Uplink Interference Generation: Mobile terminals possess signal antenas giving the complexity to the base-station. Base-stations need the CSI to each user in order to suppress the unwanted interference

IRC is a useful technique for receivers equipped with Multiple Receive Antennas to suppress the unwanted interfering signal. One practical problem with IRC is that the receiver (base station) needs to have Channel State Information (CSI) of the desired signal as well as the interfering signal. When applied to Spectrum Sharing case, it is even more difficult for base stations to acquire the needed CSI of the interfering mobile terminal because the mobile terminals belong to different networks. The mobile terminals belong to different networks and in order to cancel unwanted interference, the base-stations should know at least the cross-talk channels. In this section, it has been explained how to cancel the interference once the CSI of the users are available at the

basestation; in the following section, a suggestion has been provided how to capture them in this heterogenous environment.

If the CSI of the direct channels as well as the cross-talk channels have been captured, IRC in the uplink can be explained mathematically for the two MISO transmitter/receiver pairs as following. When the power is fixed ($p = 1$), taking the figure 3.1 into account, the received signal at the base-stations can be expressed as (Dahlman et al., 2008):

$$\mathbf{r}_1^{ul} = \begin{bmatrix} h_{11}^{ul,1} \\ h_{11}^{ul,2} \\ \vdots \\ h_{11}^{ul,N_R} \end{bmatrix} \mathbf{s}_1 + \begin{bmatrix} h_{12}^{ul,1} \\ h_{12}^{ul,2} \\ \vdots \\ h_{12}^{ul,N_R} \end{bmatrix} \mathbf{s}_2 + \begin{bmatrix} n_1^1 \\ n_1^2 \\ \vdots \\ n_1^{N_R} \end{bmatrix} = \mathbf{h}_{11}^{ul}\mathbf{s}_1 + \mathbf{h}_{12}^{ul}\mathbf{s}_2 + \mathbf{n_1} \tag{3.1}$$

where $\mathbf{r}_1^{ul}$ is the received signal at the uplink at the base-station 1, the channel state vectors $\mathbf{h}_{11}^{ul}$ and $\mathbf{h}_{12}^{ul}$ consist of complex channel gains from the desired mobile terminal and the interfering mobile terminal respentively to the N_R receive antennas and $\mathbf{n}$ gives the noise to all receive antennas.

IRC is achieved by multiplying the received signal with complex weights in order to suppress the interference part of the signal. Selecting the weights can be done to zero the interfering signal:

$$\hat{\mathbf{s}}_1^{ul} = \mathbf{w}_1^H \mathbf{r}_1^{ul} \tag{3.2}$$

where $\hat{\mathbf{s}}_1^{ul}$ is the received decoded signal after zero-forcing with the receive beamforming weight $\mathbf{w}_1^H$ such that $\mathbf{w}_1^H \mathbf{h}_{12}^{ul} = 0$. When there are two receive antennas, $\mathbf{w}_1^H$ can be expressed as with the formula 2.39.

When there are more than two antennas, $\mathbf{w}_1^H \mathbf{h}_{12}^{ul} = 0$ has $N_R - 1$ non-trivial solutions, indicating flexibility in the weight-vector selection. This flexibility can be exploited to suppress additional dominating interferers (With N_R receive antennas $N_R - 1$ interferers can be suppressed. However, the noise factor is multiplied as well leading to increase in the noise level after the antenna combining. Therefore, a better approach is to select the weight-vectors to minimize the mean square vector known as *Minimum Mean Square Error Combining* (MMSE) (Dahlman et al., 2008).

Clearly, once the CSI of the desired users as well as undesired users, IRC performs a SDMA-like action similar to the uplink-intra-cell case of a single network. In this scenario, more generally, IRC can be applied once the CSIs are available at the base-stations. In the following section, a suggestion is provided how to capture the CSIs.

3.1.1 Cooperativeness in Uplink

As mentioned, for this approach, the CSI of intended and non-intended users (cross-talk channel) should be available at the intended base-station: A difficult situation as the mobile terminals belong to different networks. CSI can traditionally be obtained in two ways. When the spectrum is utilized in a Frequency Division Duplex (FDD)

fashion between the uplink and downlink transmissions, since the channel conditions are not the same in the downlink and uplink directions, the channel conditions which can be observed the best by the receivers only, the CSI is fed back to the base-station through a dedicated feedback channel. When Time Division Duplex (TDD) is applied, such feedback is not needed. In a highly dynamic and complex environment such in the spectrum sharing case, one should avoid unnecessary feedbacks. CSI in TDD system can traditionally be obtained by using pilot signals that are attached to the last part of the uplink frame. One such frame configuration is specified in 3GPP-specifications as shown in figure 3.2. Figure 3.3 gives more details on the pilot signals. Pilots can be sent by mobile terminals priodically and the base-stations receiving them can estimate the channel conditions since the pilots have a predetermined structure with constant power as described in chapter 2. In (Samardzija et al., 2007), a single-cell scenario has been given where the mobile terminals are assigned orthogonal pilots. This case can be extended to the two-cell case of spectrum sharing of different base-stations.

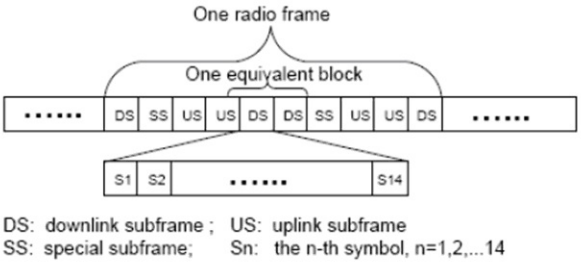

Figure 3.2: One of the seven frame-configurations in 3GPP standard allowing user-specific pilots on the uplink-subframe (Samardzija et al., 2007)

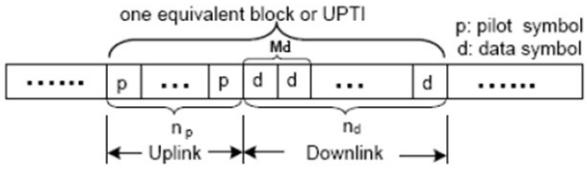

Figure 3.3: Detailed view of the last part of Uplink-subframe with User-specific Pilots

The proposed solution for that problem is a multi-user TDD system that uses user-specific pilot signals where the base stations of the operators must be synchronized to a common TDD frame-time. The mobile terminals (of both of the operators) must be registered to both of the base stations. Each mobile terminal remains acquiring service from his own operator. The registration is only needed to keep record of the CSI of the interferer. During the uplink-subframe of every TDD frame or periodically from time to time, a mobile terminal transmits his uplink symbols to his intended receiver

base station as usual in evolved 3GPP systems. In spectrum sharig case, it will also be received by the non-intended base station because the users have only a single antenna. Since the users apply user-specific pilots, the base-stations can recognize the intended and non-intended users. Figure 3.4 shows that the base-stations can estimate the channel from the transmission received in the uplink because the pilot-signals have a pre-determined structure. For this approach, the synchronization of the operators as well as the recognizing the intended and non-intended users are crucial. These issues require control-level message passing between the operators.

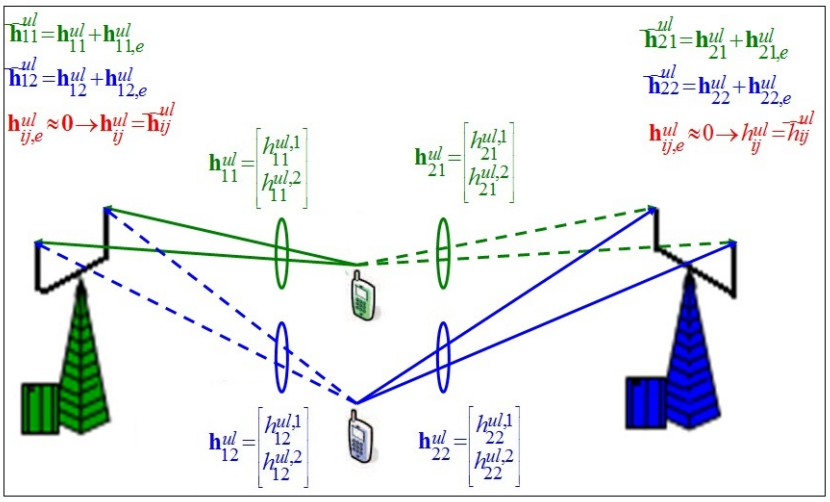

Figure 3.4: CSI capturing based on user-specific pilots on the TDD-frame for the heterogenous-case

3.2 Downlink Scenario

In the uplink scenario, a base station equipped with multiple antennas can apply interference suppression in an ideal way when it has the direct and cross CSI, as explained. In uplink, the base station is the only decision maker. Since the mobile terminals do not have multiple antennas (giving the complexity to the base stations), the mobile terminals cannot do the same as the base stations which ideally can suppress the interference based on the CSI.

In the downlink scenario, they are the base stations again which need to do something to achieve an acceptable level of received power on their intended mobile terminals as illustrated in figure 3.5. In this case, there are two independent decision makers who have conflicting interests: maximizing the received power on their intended users by causing significant interference on the non-intended terminals. Therefore, the interference mitigation is based on interference optimization. To make use of spatial degrees of freedom together with power allocation, transmit-beamforming based transmitter opti-

mization is needed in the downlink

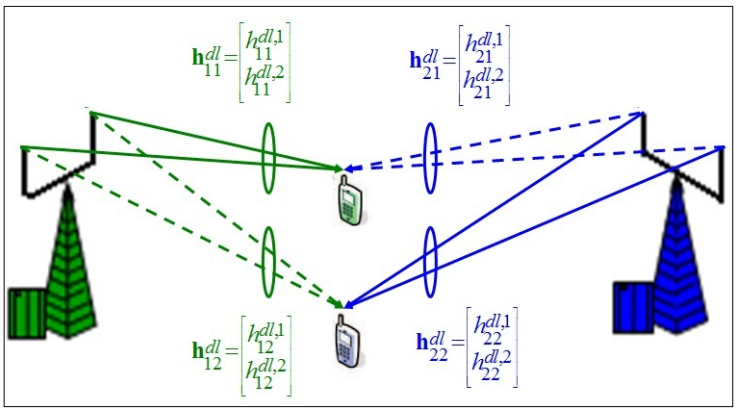

Figure 3.5: Illustration of Downlink Interference Generation: Base-stations equipped with two antennas try to optimize the interference on the mobile terminals with single antennas

Also in this case, to be able to optimize the beam-forming vectors, the CSI is needed in downlink direction. In a FDD system, the uplink CSI is generally not equal to downlink-CSI. Therefore, additional feedback is needed. In a TDD-system, this feedback is avoided since the uplink-CSI is then a good approximation for the downlink-CSI.

As mentioned before, we have two TDD-sytems. The figure 3.6 shows that the CSI obtained in the uplink can approximately be used in the downlink thanks to reciprocity principle. The mobile terminals transmit their user-specific pilots via their single antennas. Hence the interference between the pilot signals is avoided thanks to the orthogonal pilots. As explained, to acquire the CSI of the cross-link, the interfering mobile terminal is also registered by the foreign operator. The base stations listen to the orthogonal pilots and estimate the downlink CSI based on the uplink CSI(see section 3.1).

When the base stations estimate the CSI of the mobile terminals as explained above, they can start with Transmit beam-forming based on transmitter optimization. The independent base stations have their own conflicting objectives. They can not share full information as explained in previous sections. The result is a conflict in physical layer. Game Theoretical tools are needed to tackle with the conflict as explained in the previous section.

3.2.1 Game Theory in Downlink

As explained in chapter 2.5, when the operators react on each other with their best responses, the obtained result is the so-called Nash Equilibrium (NE). A NE is a strategy profile where no player can improve his utility by changing strategy unilaterally. If both of the players are satisfied with their utilities (data rates), they can continue with NE. Otherwise, they have to change their strategy profile to achieve higher utilities. With

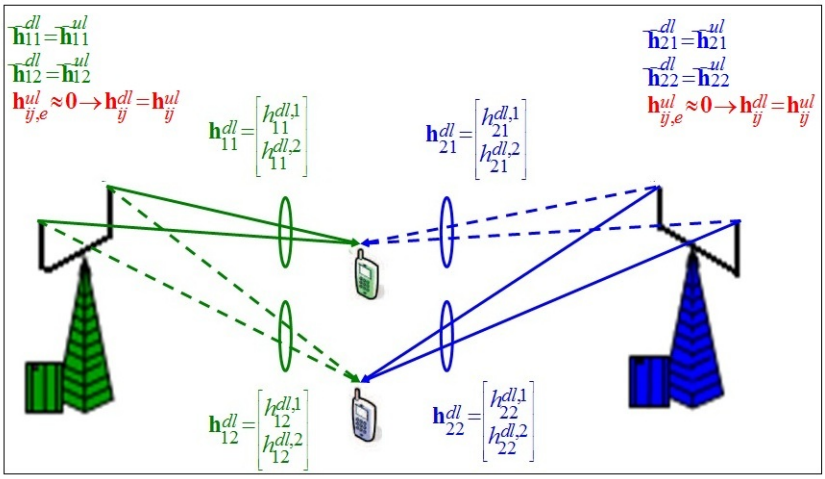

Figure 3.6: CSIs needed for the downlink case are estimated values of uplink CSIs thanks to the reciprocity principle for TDD-systems.

other words, they have to cooperate. And cooperation requires information exchange or interaction in some way. The advantage of NE is that it does not require any cooperation between the players once the channels states haven been given.

As mentioned in section 2.5.2, such a cooperation between the operators can be achieved by trying to find a balance between the selfish MRT-vector and altruistic ZF-vector by iteratively interacting on the air-interface. However, those approaches do ignore the power-allocation-dimension of the problem and the real-time iteration on the air interface is time-comsuming. The proposed cooperation is to form the beamforming weights in such a way that only the carriers which have a larger direct channel response than cross-channel response will get more power. As mentioned, this strategy corresponds to SLNR maximizing beamforming which has been applied in (Hayashi et al., 2010) for ICI mitigation of a single network as explained in chapter 2.5.2. To utilize the SLNR-based beamforming vector for the spectrum sharing of two distinct networks, the cross-talk channels needed are obtained in the way described above. When we express the received signals in the downlink as:

$$\mathbf{r}_i^m = \sqrt{p_i^m}\left(\mathbf{w}_i^m\right)^H \mathbf{h}_{ii}^m \mathbf{s}_i^m + \sqrt{p_j^m}\left(\mathbf{w}_j^m\right)^H \mathbf{h}_{ij}^m \mathbf{s}_2^m + \mathbf{n_i} \tag{3.3}$$

where $\mathbf{r}_i^m$ is the received signal at the mobile terminal belonging to the i_{th} operator for the m_{th} carrier, p_i^m is transmit power of i_{th} operator for the m_{th} carrier , $\mathbf{w}_i^m$ is the applied beamforming vector, $\mathbf{h}_{ii}$ is the direct channel and $\mathbf{h}_{ij}$ is the cross-channel, $\mathbf{s}_i^m$ is the transmitted signal and $(.)^H \equiv (.^*)^T$ is the hermitian transpose. The noise vector $\mathbf{n_i}$ has the power of σ_i^2. With this, the SLNR at the i_{th} operator's mobile terminal for two transmitter/receiver pairs can be expressed as:

$$SLNR_i^m = \frac{p_i^m \left|(\mathbf{w}_i^m)^H \mathbf{h}_{ii}^m\right|^2}{p_i^m \left|(\mathbf{w}_i^m)^H \mathbf{h}_{ij}\right|^2 + {\sigma_\mathbf{i}}^2} = \frac{p_i^m (\mathbf{w}_i^m)^H \mathbf{h}_{ii}^m (\mathbf{h}_{ii}^m)^H \mathbf{w}_i^m}{p_i (\mathbf{w}_i^m)^H \mathbf{h}_{ij} \left(\mathbf{h}_{ij}^m\right)^H \mathbf{w}_i^m + {\sigma_\mathbf{i}}^2} \tag{3.4}$$

Taking the first derivative of this ratio in 3.4 with respect to the weight-vector $\mathbf{w}_i^m$, the formulation of the SLNR-based vector is obtained as the eigenvector corresponding to the maximum eigenvalue of $\left[p_i^m \mathbf{h}_{ij}^m \left(\mathbf{h}_{ij}^m\right)^H + \sigma_i^2 \mathbf{I}\right]^{-1} \left[p_{ii}^m \mathbf{h}_{ii}^m (\mathbf{h}_{ii}^m)^H\right]$ leading to the SLNR-based beamforming vector (Hayashi et al., 2010):

$$\mathbf{w}_i^m = C_i^m \left(p_i^m \mathbf{h}_{ij}^m \left(\mathbf{h}_{ij}^m\right)^H + \sigma_m^2 \mathbf{I}\right)^{-1} \sqrt{p_i^m} \mathbf{h}_{ii}^m \tag{3.5}$$

where $\mathbf{w}_i^m$ is the SLNR-maximizing beamforming vector (beamforming vector that allocates more power to the larger direct channel/cross channel pair), p_i^m is transmit power of i_{th} operator for the m_{th} carrier $\mathbf{h}_{ii}$ is the direct channel and $\mathbf{h}_{ij}$ is the cross-channel, $(.)^H \equiv (.^*)^T$ is the hermitian transpose. C_i^m is a normalization factor. The noise vector $\mathbf{n_i}$ has the power of σ_i^2.

In (Hayashi et al., 2010), this vector is utilized for Inter-Cell Interference (ICI) mitigation for a single homogeneous network by applying iterative waterfilling algorithm. However, we have seen in chapter 2.5 that when reacting with best-response transmit strategies (waterfilling the power levels), the game results in a NE which is inefficient for both of the operators. Therefore, this thesis proposes to apply Stackelberg Equilibrium game (SE, leader-follower game) which may be more efficient than NE. In order to utilize the SLNR-based beamforming vector in a Stackelberg fashion (one operator will be the leader and the other one follower, instead of reacting with best-response transmit strategies), the Stackelberg game formulated in (Bennis et al., 2009) for only power-allocation without beamforming, will be reformulated for power-allocation on SLNR-based beamforming-vector.

While doing so, we firstly need to express the objective functions in terms of SLNR-based beamforming-vector. Therefore, we need to modify the rate-functions. As discussed in chapter 2, the rate functions of the operators for two operators case can be given as:

$$R_1 = \sum_{m=1}^{M} \log_2 \left(1 + \frac{p_1^m \left|(\mathbf{w}_1^m)^H \mathbf{h}_{11}^m\right|^2}{p_2^m \left|(\mathbf{w}_2^m)^H \mathbf{h}_{21}^m\right|^2 + \sigma_1^2}\right) \tag{3.6}$$

$$R_2 = \sum_{m=1}^{M} \log_2 \left(1 + \frac{p_2^m \left|(\mathbf{w}_2^m)^H \mathbf{h}_{22}^m\right|^2}{p_1^m \left|(\mathbf{w}_1^m)^H \mathbf{h}_{12}^m\right|^2 + \sigma_2^2}\right) \tag{3.7}$$

where R_1 and R_1 are the rates expressed in bits per channel-use. Note that a communication channel is made from whole spectrum consisting of M OFDM subcarriers. p_1^m

and p_2^m are the transmit powers of operator 1 and 2 respectively for the m_{th} carrier, $\mathbf{w}_1^m$ and $\mathbf{w}_2^m$ are the applied beamforming vectors, $\mathbf{h}_{11}^m$ and $\mathbf{h}_{22}^m$ are the complex direct-channel gains for operator 1 and 2 respectively for the m_{th} carrier and $(.)^H \equiv (.^*)^T$ is the hermitian transpose. The noise vector $\mathbf{n_i}$ has the power of σ_i^2.

When inserting the SLNR-based beamforming vector of 3.5 in the rate-fucntions, the objective functions 3.6 and 3.7 are obtained as following:

$$R_1 = \sum_{m=1}^{M} \log_2 \left(1 + \frac{\dfrac{p_1^m \left| \left(\left(p_1^m \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_1^m} \mathbf{h}_{11}^m \right)^H \mathbf{h}_{11}^m \right|^2}{\left\| \left(p_1^m \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_1^m} \mathbf{h}_{11}^m \right\|^2}}{\dfrac{p_2^m \left| \left(\left(p_2^m \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m} \mathbf{h}_{22}^m \right)^H \mathbf{h}_{21}^m \right|^2}{\left\| \left(p_2^m \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m} \mathbf{h}_{22}^m \right\|^2} + \sigma_m^2} \right) \tag{3.8}$$

$$R_2 = \sum_{m=1}^{M} \log_2 \left(1 + \frac{\dfrac{p_2^m \left| \left(\left(p_2^m \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m} \mathbf{h}_{22}^m \right)^H \mathbf{h}_{22}^m \right|^2}{\left\| \left(p_2^m \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m} \mathbf{h}_{22}^m \right\|^2}}{\dfrac{p_1^m \left| \left(\left(p_1^m \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_1^m} \mathbf{h}_{11}^m \right)^H \mathbf{h}_{12}^m \right|^2}{\left\| \left(p_1^m \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_1^m} \mathbf{h}_{11}^m \right\|^2} + \sigma_m^2} \right) \tag{3.9}$$

The obtained objective functions are interesting, because compared to the pure rate functions 3.8 and 3.9, the obtained obtained functions are functions of all complex channel gains of interference channel. Furthermore, SLNR-based beamforming vector will allocate the subcarriers with larger direct-channel-response than crosstalk-channel-response more power.

After treating the selfishness in beamforming-dimension of the problem by taking the SLNR-based beamforming-vector into the objective functions, this thesis further proposes to include in the advantage of Stackelberg-power-allocation for the power-allocation-dimension of the problem instead of selfishly allocation the powers. Therefore, the main contribution of this thesis is to construct the objective functions by combining both the SLNR-based bemaforming vector and Stackelberg game and solving it to find the sets of powers that utilize the objective function the best.

In the Stackelberg game, the game is played in two levels hierarchically as described in section 2.5 instead of simultaneously giving the best responses. There is a leader-operator which moves first in power allocation on the common spectrum and when the leader is determined with his strategy (power allocation per subcarrier), he will enforce his strategy to the follower. Then the follower will react with his best best-response (power allocation set that maximizes his objective function, in this case the rate function) as explained in chapter 2.5.2.

Based on this, the game can be constructed such that: $\mathbb{G} = (\{1....K\}, S_k, \{U_1....U_K\})$, where the number of players K corresponds to 2, the strategy space of the operator 1 is S_1 that consists of sets of power allocations to the subcarriers such that $\sum_{m=1}^{M} p_1^m \leq P_1$ and $p_1^m \geq 0$ and that of operator 2 consists of sets of power allocations such that $\sum_{m=1}^{M} p_2^m \leq P_2$ and $p_2^m \geq 0$. The utility functions become $U_1 \equiv R_1$ as expressed in 3.8 and $U_2 \equiv R_2$ as expressed in 3.9. Here, the maximal allowable transmit power levels P_1 and P_2 are both normalized to 1. The fist level of the game can be expressed as following:

First Level :

$$\begin{aligned}
&\underset{p_1^m}{\text{maximize}} \quad \sum_{m=1}^{M} \log\left(1 + \frac{\dfrac{p_1^m \left| \left(\left(p_1^m \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I}\right)^{-1} \sqrt{p_1^m}\mathbf{h}_{11}^m \right)^H \mathbf{h}_{11}^m \right|^2}{\left\| \left(p_1^m \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I}\right)^{-1} \sqrt{p_1^m}\mathbf{h}_{11}^m \right\|^2}}{\dfrac{p_2^m\left(p_1^m\right) \left| \left(\left(p_2^m\left(p_1^m\right) \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I}\right)^{-1} \sqrt{p_2^m}\left(p_1^m\right)\mathbf{h}_{22}^m \right)^H \mathbf{h}_{21}^m \right|^2}{\left\| \left(p_2^m\left(p_1^m\right) \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I}\right)^{-1} \sqrt{p_2^m}\left(p_1^m\right)\mathbf{h}_{22}^m \right\|^2} + \sigma_m^2}\right) \\
&\text{s.t.d to} \quad \sum_{m=1}^{M} p_1^m \leq P_1 \quad \text{and} \quad p_1^m \geq 0
\end{aligned} \tag{3.10}$$

The second level of the game can be expressed as following:

Second Level:

$$\begin{aligned}
&\underset{p_2^m}{\text{maximize}} \quad \sum_{m=1}^{M} \log\left(1 + \frac{\dfrac{p_2^m \left| \left(\left(p_2^m \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I}\right)^{-1} \sqrt{p_2^m}\mathbf{h}_{22}^m \right)^H \mathbf{h}_{22}^m \right|^2}{\left\| \left(p_2^m \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I}\right)^{-1} \sqrt{p_2^m}\mathbf{h}_{22}^m \right\|^2}}{\dfrac{\left(p_1^m\right)^{SE} \left| \left(\left(\left(p_1^m\right)^{SE} \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I}\right)^{-1} \sqrt{\left(p_1^m\right)^{SE}}\mathbf{h}_{11}^m \right)^H \mathbf{h}_{12}^m \right|^2}{\left\| \left(\left(p_1^m\right)^{SE} \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I}\right)^{-1} \sqrt{\left(p_1^m\right)^{SE}}\mathbf{h}_{11}^m \right\|^2} + \sigma_m^2}\right) \\
&\text{s.t.d to} \quad \sum_{m=1}^{M} p_2^m \leq P_2 \quad \text{and} \quad p_2^m \geq 0
\end{aligned} \tag{3.11}$$

As described in section 2.5, in the optimization problem of the leader (first level game), the strategy of the follower is a function of the strategy of the leader. The idea in the first level game is that the leader prepares his strategy based on the strategy space of the follower. The leader does not know which strategies the follower will take, but he possess the the strategy space of the follower to construct his strategy (the set

of power allocations to the subcarriers). The strategy space of the follower consists of possible sets of power-allocations that satisfy the constraints given in equation 3.11. Based on the strategy space of the follower, the leader predicts the best-responses of the follower to the interference levels that he creates on the follower system. In (Bennis et al., 2009), the best-responses of the follower have been implemented by the closed-form expression of the water-filling algorithm. Equation 2.33 describes this behavior by taking the power-levels only. In this thesis, we re-express that equation to take the beamforming-vector into account as well. Including the beamforming-vector (as this contributes to the interference generated on the follower), the closed-form expression of the water-filling algorithm becomes:

$$p_2^m = \begin{cases} \left(P_2 + \sum_i^k \left(\sigma^2_{\pi^{-1}(i)} + p_1^{m,\pi^{-1}(i)} \left|(\mathbf{w}_1^m)^H \mathbf{h}_{12}^{m,\pi^{-1}(i)}\right|^2\right)\right) \\ \qquad -\sigma_2^2 - p_1^m \left|(\mathbf{w}_1^m)^H \mathbf{h}_{12}^m\right|^2 \quad \text{for} \quad \pi(i) \leq k \\ 0 \quad \text{for} \quad \pi(i) > k \end{cases} \tag{3.12}$$

where the term $\left|(\mathbf{w}_1^m)^H \mathbf{h}_{12}^{m,\pi^{-1}(i)}\right|^2$ takes the effect (generated interference) of beamforming-vector into account, π indicates a permutation function ranking all channels according to their noise plus interference and k can be found from the following condition: $\varphi_k < P_2 \leq \varphi_{k+1}$ and $\varphi_t = \sum_i^k \left(\sigma^2_{\pi^{-1}(i)} + p_1^{m,\pi^{-1}(i)} \left|(\mathbf{w}_1^m)^H \mathbf{h}_{12}^{m,\pi^{-1}(i)}\right|^2\right)$, $\forall \in \{1, ..., m\}$.

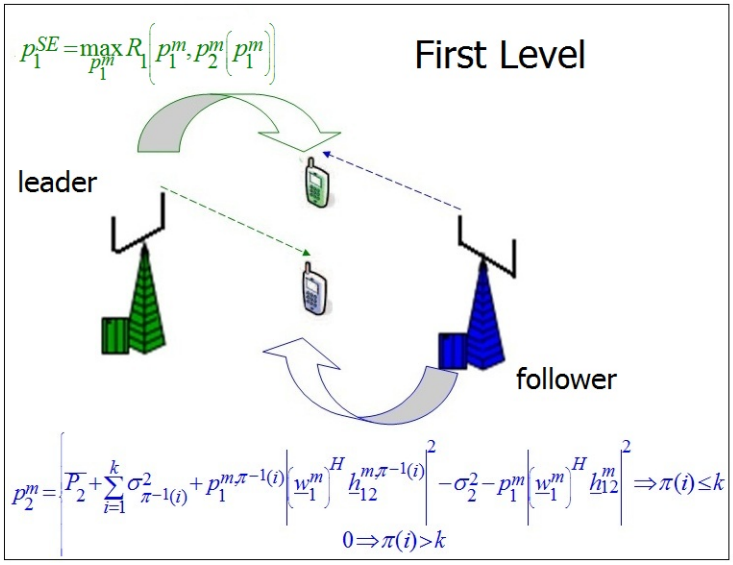

Figure 3.7: Illustration of the First Level: Leader prepares his best response to the possible best response of the follower untill convergence to the set of p_1^{SE}

First level of the game takes the function $p_2(p_1)$ as expressed in equation 3.12 and produces a set of power allocations that converges to p_1^{SE}. The second level of the problem takes the converged set p_1^{SE} in and gives the best response of the follower implying $BR_2\left(p_1^{SE}\right) = p_2^{SE}$. The key problem is how to get the best-response functions BR_1 and BR_2 based on the utility functions expressed in 3.10 and 3.11 (see section 2.5). This first level and second level of the game have been illustrated in figure 3.7 and 3.8:

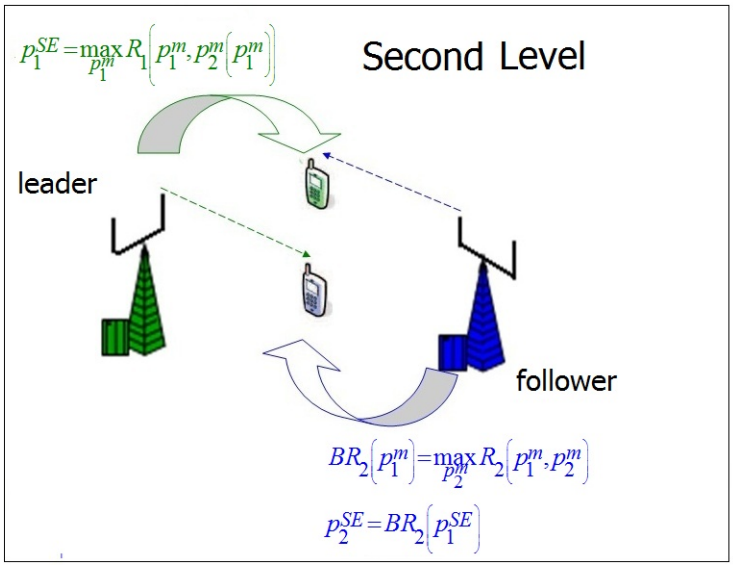

Figure 3.8: Illustration of the Second Level: Follower gives his best-reaction to the strategy of the leader untill convergence to p_2^{SE}

3.2.2 Cognition in Downlink

As described, the game starts with the first move of the leader operator. The leader operator prepares his strategy based on the known strategy space of the follower. The preparation of the leader results in a converged set of power allocations. This action of the leader takes place offline (the follower is not involved yet, he has not replied yet). After that, the leader constructs his signal and transmits. The transmission of the leader based on the converged set of transmission parameters causes a certain amount of interference on each subcarrier. This interference generation is real-time and the follower experiences it as an unwanted signal. To be able to perform his strategy, the follower needs the knowledge of interference level on each subcarrier. This is only possible if the mobile terminal of the follower party has the capability to sense the environment and report it to the follower-basestation as illustrated in figure 3.9.

The cognitive capability refers to the ability of the radiotechnology to capture or sense the information from its environment as defined in (Akyildiz et al., 2006). In our

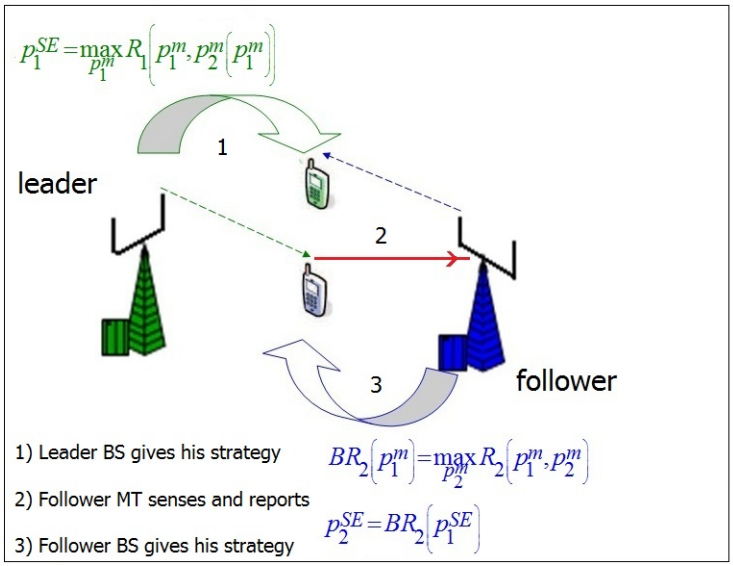

Figure 3.9: Cognition in Downlink: Follower mobile terminal has to sense and report the experienced power-level to the follower basestation so that the downlink transmission strategy can be prepared based on the second level game

scenario, this capability can be seen as only monitoring the power level in the frequency-band that is commonly shared by the operators. Therefore, the reconfiguration capability of the general Cognitive Radios (CR) is not needed when the mobile terminals get the whole common-spectrum per channel-use leading to a less complex terminal-device compared to a general CR.

Once the power-levels are captured in the received signal, the second step is to report to the follower basestation. This capability is similar to the Channel-Status Reporting (CSR) in evolved networks such as LTE. In general, CSR is used by the basestation to select the downlink transmission configuration and related parameters depending on the instantaneous downlink channel conditions. Especially for the spatial-multiplexing transmission modes in LTE, CRS are defined to report information about Channel Rank Indication (CRI), Precoder Matrix Indication (PMI) and Channel Quality Indication (CQI). Such a channel-status reporting can be periodic or a-periodic (trigger-based reporting) (Dahlman et al., 2008). For our case of power-level reporting, a periodic CSR can be employed synchronized to the uplink-subframe.

3.2.3 Cooperativeness in Downlink

In the previous section, the utility functions have been constructed. Each utility function is a function of power allocations of both of the operators and the complex channel gains. Each operator has gotten his direct-channel ($\mathbf{h}_{ii}$) to his intended mobile terminal and his crosstalk channel ($\mathbf{h}_{ij}$) to the non-intended user as described in the uplink-scenario. To be able to perform the optimization, each operator must have the knowledge

of experienced interference on his desired mobile terminal. In the previous section, the way how to inform the follower basestation about the experienced interference has been described. Once the leader has prepared his strategy, he adjusts his transmission parameters accordingly and transmits to his desired mobile terminal causing unwanted interference to the follower mobile terminal. The follower mobile terminal can observe the real-time interference and report to the follower basestation. However, to be able to perform the optimization, the leader operator must know all of the four channel conditions as he has to prepare his strategy offline without interacting with the follower. This implies that the leader operator must have the direct- as well as crosstalk channel of the follower as well. Such a cooperative behaviour requires message passing between the operators through the backhaul links as illustrated in figure 3.10.

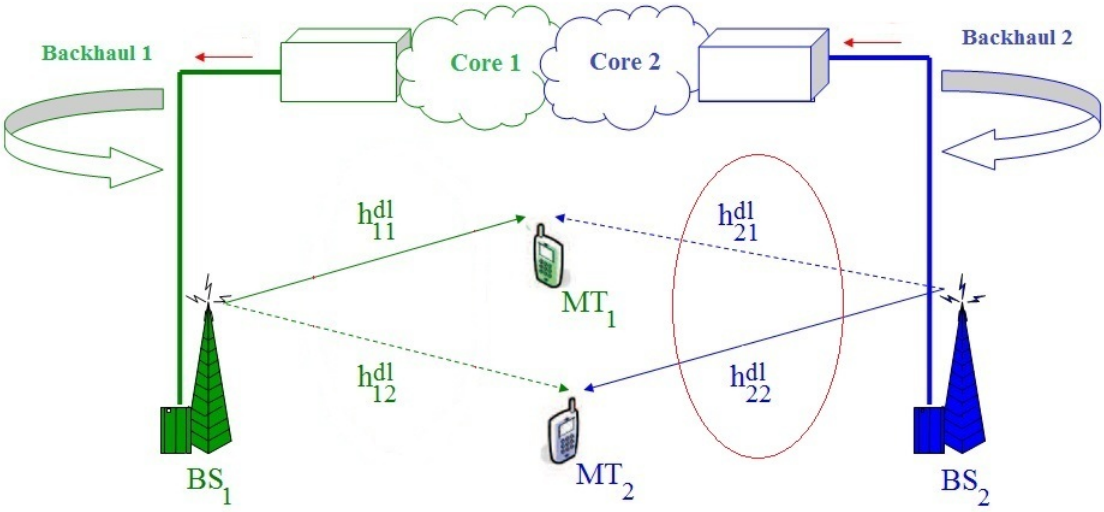

Figure 3.10: Cooperativeness in Downlink: The follower shares his direct- and crosstalk channels with the leader through the backhaul links

By recalling the uplink scenario where the channels were estimated first, we can summarize the role of the channel conditions as following: Thanks to the orthogonal user-specific pilots attached in the uplink-subframe of the TDD frame, each operator has the opportunity to capture the uplink channel-states of his direct-channel and the cross-talk channel (this action requires that the operators should be sychronized and that the mobile terminals are registered to both of the operators while being served by only their own operator). With the aid of the captured channel states, the base-stations can perform IRC to cancel the interference in the uplink case as explained in section 3.1. Each operator can reuse the estimated direct- and crosstalk channel states for the downlink case in order to use SLNR-based beamforming-vector. However, to optimize the utility functions described in the previous section, the leader operator also needs the direct- ans crosstalk channels of the follower. With the proposed approach, it is enough when the follower shares two of the four channel conditions of the interference

channel problem, as the other two (own direct- and crosstalk channels) already have been captured in the uplink-part of the solution of the leader.

3.2.4 Optimization in Downlink

After the game theoretical relationship between the involved parties has been established, the resulting mathematical expressions are generally subjected to the optimization field of applied mathematics. The utility functions expressed in equations 3.10 and 3.11 are monotonic increasing functions of the applied transmit-powers (more power, more capacity) when the set of power allocations of one of the parties is fixed. Therefore, every increase in power allocations will result in a better utility. The utility functions try to find the optimal set of power allocations that will maximize the equations subjected to the provided constraints in section 3.2.1.

In optimization problems, one is interested in whether the problem is convex or non-convex. Depending on this condition, there are different approaches possible to solve the problem. A convex optimization problem consists of minimizing convex functions over convex sets or maximizing concave functions again over convex sets. A function is called convex if the graph of the function lies below the line segment connecting any two points of the graph. A set S is called convex if for all pints x and y in S and for all t in interval t$\in$ $[0, 1]$, the point $(1 - t)\, x + ty$ is in S. A concave function is the negative of a convex function. The logarithmic capacity function (rate-function) is a concave function and the power constraints provided in section 3.2.1 are lineair and all linear constaints satisfy the above condition of being a convex set. Therefore, multicarrier power allocation problem of a single-user channel is known as a convex optimization problem. The well-known waterfilling algorithm provides the optimal solution for this problem (Yu and Cioffi, 2006). When the follower operator takes the converged set of power allocations, the resulting interference levels can be regarded as fixed noise levels leading to a convex problem. However, in the optimization problem of the leader, the optimization variable is a function of the optimization variable of the follower. Therefore, the maximization of the leader does not only depend on its convex constraint set but also choices of the follower. As a result, the optimization problem of the leader in Stackelberg games of this type is non-convex(Bialas, 1989).

Convex optimization problems with lineair constraints can easily be solved with the aid of lagrangian duality theorem. The lagrangian dual problem uses non-negative multipliers to add the constraints to the optimization functions. The solution of the optimization problem is obtained as a function on the lagrangian multiplier. The original optimization is called the primal problem. The dual problem gives a lower bound to the solution of the primal problem. The difference between the primal problem and its dual problem is called the duality gap. For convex problems, the duality gap is equal to zero. When the problem is non-convex, the duality gap is non-zero and the solution to the dual problem remains to be a lower bound except for certain objective function with the so-called time-sharing property. The capacity function with contant channel gains and noise level has this property and therefore dual problem will give the optimal solutions even if the objective function is non-convex (Yu and Cioffi, 2006). The lagrangian dual

functions of the leader and follower in our case can be expressed as following:

Lagrangian dual of the leader :

$$\mathcal{L}_1 = \sum_{m=1}^{M} \log_2 \left(1 + \frac{\dfrac{p_1^m \left| \left(\left(p_1^m \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m \right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_1^m} \mathbf{h}_{11}^m \right)^H \mathbf{h}_{11}^m \right|^2}{\left\| \left(p_1^m \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m \right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_1^m} \mathbf{h}_{11}^m \right\|^2}}{\dfrac{p_2^m \left(p_1^m \right) \left| \left(\left(p_2^m \left(p_1^m \right) \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m \right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m} \left(p_1^m \right) \mathbf{h}_{22}^m \right)^H \mathbf{h}_{21}^m \right|^2}{\left\| \left(p_2^m \left(p_1^m \right) \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m \right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m} \left(p_1^m \right) \mathbf{h}_{22}^m \right\|^2} + \sigma_m^2} \right) + \mu_1 \left(P_1 - \sum_{m=1}^{M} p_1^m \right) \tag{3.13}$$

Lagrangian dual of the follower :

$$\mathcal{L}_2 = \sum_{m=1}^{M} \log_2 \left(1 + \frac{\dfrac{p_2^m \left| \left(\left(p_2^m \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m \right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m} \mathbf{h}_{22}^m \right)^H \mathbf{h}_{22}^m \right|^2}{\left\| \left(p_2^m \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m \right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m} \mathbf{h}_{22}^m \right\|^2}}{\dfrac{\left(p_1^m \right)^{SE} \left| \left(\left(\left(p_1^m \right)^{SE} \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m \right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{\left(p_1^m \right)^{SE}} \mathbf{h}_{11}^m \right)^H \mathbf{h}_{12}^m \right|^2}{\left\| \left(\left(p_1^m \right)^{SE} \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m \right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{\left(p_1^m \right)^{SE}} \mathbf{h}_{11}^m \right\|^2} + \sigma_m^2} \right) + \mu_2 \left(P_2 - \sum_{m=1}^{M} p_2^m \right) \tag{3.14}$$

With the functions given above, the dual optimization problems can be expressed as:

$$g_1 \left(\mu_1 \right) = \max_{p_1^m} \mathcal{L}_1 \left(p_1^m \right) \tag{3.15}$$

$$g_2 \left(\mu_2 \right) = \max_{p_2^m} \mathcal{L}_2 \left(p_2^m \right) \tag{3.16}$$

The obtained dual problems are now convex. The idea is to maximize $g\left(\mu\right)$ directly by updating all components of μ (as there are multiple variables; each subcarrier has a component of μ) at the same time along some search direction. Because $g\left(\mu\right)$ is convex, a gradient-type of search is quaranteed to converge to a global optimum. One such method is the subgradient method. The idea of subgradient method is to design a step-size s to update μ in the subgradient direction. The update can be performed by (Yu and Cioffi, 2006):

$$\mu^{l+1} = \left[\mu^l - s^l \left(C - \sum_n h_n \left(x_n \right) \right) \right]^+ \tag{3.17}$$

where $[.]^+$ is defined as $[.]^+ = max(., 0)$, C is the bound of the contraint and the expression $\left(C - \sum_n h_n \left(x_n \right)\right)$ corresponds to a subgradient of the function $g\left(\mu\right)$ with the

constraint $\sum_n h_n(x_n) \leq C$. The stepsize s^l should be square summable leading to example stepsize such as $s^l = \beta/l$, $s^l = \beta$ or $s^l = \beta/\sqrt{l}$ where β is some constant and l is the iteration number. In our case, this corresponds for $(P_1 - \sum_m p_1^m)$ and $(P_2 - \sum_m p_2^m)$ for the leader's problem and follower's problem respectively. By doing so, the optimization of the leader and follower can be described like in (Bennis et al., 2009):

First Level :

initialize μ_1, P_1, P_2

repeat
  for m = 1,.....,M

$$\textbf{set } p_1^m = \underset{p_1^m}{\operatorname{argmax}} \sum_{m=1}^{M} \log_2 \left(1 + \frac{\frac{p_1^m \left| \left(\left(p_1^m \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_1^m} \mathbf{h}_{11}^m \right)^H \mathbf{h}_{11}^m \right|^2}{\left\| \left(p_1^m \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_1^m} \mathbf{h}_{11}^m \right\|^2}}{\frac{p_2^m\left(p_1^m\right) \left| \left(\left(p_2^m\left(p_1^m\right) \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m}\left(p_1^m\right) \mathbf{h}_{22}^m \right)^H \mathbf{h}_{21}^m \right|^2}{\left\| \left(p_2^m\left(p_1^m\right) \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m}\left(p_1^m\right) \mathbf{h}_{22}^m \right\|^2} + \sigma_m^2} \right) + \mu_1 \left(P_1 - \sum_{m=1}^{M} p_1^m \right)$$

  by keeping p_1^1, p_1^2, ..., p_1^M fixed
  end
until $\left(p_1^1, ..., p_1^M\right)$ converges
update $\mu_1 = max\left(0, \left[\mu_1^l - s^l \left(P_1 - \sum_{m=1}^{M} p_1^m\right)\right]\right)$ until it converges

$$\text{where } p_2^m\left(p_i^m\right) = \begin{cases} \left(P_2 + \sum_i^k \left(\sigma^2_{\pi^{-1}(i)} + p_1^{m,\pi^{-1}(i)} \left| \left(\mathbf{w}_1^m\right)^H \mathbf{h}_{12}^{m,\pi^{-1}(i)} \right|^2 \right) \right) & \\ \qquad - \sigma_2^2 - p_1^m \left| \left(\mathbf{w}_1^m\right)^H \mathbf{h}_{12}^m \right|^2 & \text{for} \quad \pi(i) \leq k \\ 0 & \text{for} \quad \pi(i) > k \end{cases}$$

Second Level :

initialize μ_2, P_1, P_2

repeat
  for m = 1,.....,M

$$\textbf{set } p_2^m = \underset{p_2^m}{\operatorname{argmax}} \sum_{m=1}^{M} \log_2 \left(1 + \frac{\frac{p_2^m \left| \left(\left(p_2^m \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m} \mathbf{h}_{22}^m \right)^H \mathbf{h}_{22}^m \right|^2}{\left\| \left(p_2^m \mathbf{h}_{21}^m \left(\mathbf{h}_{21}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{p_2^m} \mathbf{h}_{22}^m \right\|^2}}{\frac{\left(p_1^m\right)^{SE} \left| \left(\left(\left(p_1^m\right)^{SE} \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{\left(p_1^m\right)^{SE}} \mathbf{h}_{11}^m \right)^H \mathbf{h}_{12}^m \right|^2}{\left\| \left(\left(p_1^m\right)^{SE} \mathbf{h}_{12}^m \left(\mathbf{h}_{12}^m\right)^H + \sigma_m^2 \mathbf{I} \right)^{-1} \sqrt{\left(p_1^m\right)^{SE}} \mathbf{h}_{11}^m \right\|^2} + \sigma_m^2} \right) + \mu_2 \left(P_2 - \sum_{m=1}^{M} p_2^m \right)$$

  by keeping p_1^1, p_1^2, ..., p_1^M fixed
  end
until $\left(p_2^1, ..., p_2^M\right)$ converges
update $\mu_2 = max\left(0, \left[\mu_2^l - s^l \left(P_2 - \sum_{m=1}^{M} p_2^m\right)\right]\right)$ until it converges

In the optimization problems described above, when the power set is fixed, the functions become only a function of one element of the power set. When doing so, the *argmax* operator working on one element of the power set corresponds to the first order derivative of the objective functions. The optimization variable p_i^m appears in the objective functions as a scalar outside the absolute-operator as well as a parameter

inside a matrix. Therefore, to take the first derivative in each inner-iteration with respect to the optimization variable, a useful method is to use the matlab-command: *fminbnd* which finds the minimum of a function of one variable within a fixed interval. As we are interested in maximization as it is the case, fminbnd should be applied on the negative of the operant (the function in use). Therefore, the following expressions are equivalent: $p_i^m = \underset{p_i^m}{\operatorname{argmax}} (\mathcal{L}_i) \equiv p_i^m = BR_i \left(p_i^m, p_j^m\right) \equiv p_i^m = -fminbnd\,(\mathcal{L}_i, 0, P_i)$ when keeping $\left[p_i^1, ..., p_i^M\right]$ fixed, where M is the total number of subcarriers and $i \in \{1, 2\}$ indicating the operators.

In this section, we described the optimization problems and constructed the solution algorithms. In the following chapter, the performances of these solutions have been tested with a realistic simulation scenario for a configuration of two MISO-OFDM systems for a two-cell-case.

Chapter 4

Simulations

Downlinks of two MISO-OFDM systems are considered. Each system is represented with one base station and one mobile terminal. As mentioned, two systems share the same spectrum. The common spectrum consists of OFDM sub-carriers. Both systems use the whole spectrum to transmit to their desired mobile terminals. The systems cause interference to each other. In order to manage the interference, the systems have agreed to apply transmit-beamforming based on the optimization problems described in section 3.2.4. In the following sections, the signal model to be used as well as the simulation scenario have been described. Based on the simulation scenario, the proposed approach has been compared to other different approaches. The results have been discussed, followed by conclusions.

4.1 Signal Model

The frequency domain transmitted signal as ith base station to its desired mobile terminal is given as:

The frequency domain transmitted signal as ith base station to its desired mobile terminal is given as:

$$\mathbf{s}_i = \left[s_i^0, ..., s_i^{M-1}\right]^T \tag{4.1}$$

where $\mathbf{s}_i$ is the signal sequence transmitted by the i_{th} operator's base-station and M is the number of subcarriers.

p_i^m is the applied transmit power from the i_{th} base-station to the i_{th} mobile terminal. The set of power allocations of a base-station is given by:

$$\mathbf{p}_i = \left[p_i^1, ..., p_i^M\right] \tag{4.2}$$

When there are K antennas, the transmit beam-forming weight vector on the m_{th} sub-carrier of the transmitted signal can be defined as:

$$\mathbf{w}_i^m = \left[w_i^{m,1}, ..., w_i^{m,1}\right] \tag{4.3}$$

The channel impulse response between the k_{th} antenna element of the i_{th} base station and j_{th} mobile terminal can be given as:

$$\mathbf{h}_{ij}^{k} = \left[h_{ij}^{k}, ..., h_{ij}^{k}\left(L-1\right)\right] \tag{4.4}$$

The frequency response between the k_{th} antenna element of the i_{th} base station and the j-th mobile terminal can be calculated as following:

$$\begin{bmatrix} \hat{h}_{ij}^{0,k} \\ \vdots \\ \hat{h}_{ij}^{M-1,k} \end{bmatrix} = \mathbf{D} \begin{bmatrix} \mathbf{h}_{ij}^{k} \\ \mathbf{0}_{(M-L)\times 1} \end{bmatrix} \tag{4.5}$$

where $\mathbf{D}$ is $M \times M$ Discrete Fourier Transform (DFT) matrix. The $\{m, n\}$ element of $\mathbf{D}$ is given as (Hayashi et al., 2010):

$$\{\mathbf{D}\} = \frac{1}{\sqrt{M}} e^{(-j\frac{2}{M})} \tag{4.6}$$

The frequency response vector on the m_{th} subcarrier through K antennas can be expressed as:

$$\hat{\mathbf{h}}_{ij}^{m} = \left[\hat{h}_{ij}^{m,1}, ..., \hat{h}_{ij}^{m,K}\right] \tag{4.7}$$

In our case of two transmitter/receiver pairs, each pair beloning to one of the operators, the received signals on the m_{th} subcarrier at the indented users can be expressed as (Hayashi et al., 2010):

$$\mathbf{r}_{i}^{m} = \sqrt{p_{i}^{m}}\left(\mathbf{w}_{i}^{H}\hat{\mathbf{h}}_{ii}^{m}s_{i}^{m}\right) + \sqrt{p_{j}^{m}}\left(\mathbf{w}_{j}^{H}\hat{\mathbf{h}}_{ji}^{m}s_{j}^{m}\right) + \mathbf{n}_{i}^{m} \tag{4.8}$$

4.2 Simulation Parameters

The parameters of the interference channel are the direct channels $\mathbf{h}_{ii}$, $\mathbf{h}_{jj}$, the cross-talk channels $\mathbf{h}_{ij}$, $\mathbf{h}_{ji}$, the noise factors with powers σ_i^2 and σ_j^2 the applied transmit powers and the beamforming vectors $\mathbf{w}_i$ and $\mathbf{w}_j$ which are again functions of the desired direct channel and cross-talk channel and local noise at the non-intended user. The channels $\mathbf{h}_{ii}$, $\mathbf{h}_{jj}$, $\mathbf{h}_{ij}$, $\mathbf{h}_{ji}$ as well as the beamforming vectors $\mathbf{w}_i$, $\mathbf{w}_j$ have elements as many as the number of antennas at the base-station ($K = 2$) as the mobile terminals have single antennas.

The channels are generated from the Rayleigh Fading distribution. The local noise at the mobile terminals are assumed to equal to each other and assummed to be common knowledge at both of the operators leading to the expression: $\sigma_i^2 = \sigma_j^2$. The power allocation set on the subcarriers are subjected to the constraints $\sum_{m=1}^{M} p_i^m \leq P_i = 1$ and the bemaforming vectors apply full power with $\|\mathbf{w}_i^m\| = 1$.

4.3 Generating the Channels

For the simulations, the direct channels $\{\mathbf{h}_{ii}\}$ and crosstalk channels $\{\mathbf{h}_{ij}\}$ are generated for two different cases. In the first case, $\{h_{ii}\}$ and $\{h_{ij}\}$ have independent zero-mean Gaussian elements with unit-variance (i.i.d. Rayleigh). The channels are generated with the matlab command:

```
x = randn(K,L);
y = randn(K,L);
h = (1/sqrt(2))*(x+jy)
```

where K is the number of antennas and L is the number of channel instances.

This corresponds to weak spatial correlation and weak interference. In the case of strong interference, the channel vectors are correlated with certain correlation factor μ_i according to the formula (Lindblom and Karipidis, 2010):

$$\mathbf{h}_{ij} = \mu_i \mathbf{h}_{ii} + \sqrt{1-\mu_i^2}\tilde{\mathbf{h}}_{ij} \tag{4.9}$$

where $\{\mathbf{h}_{ii}\}$ and $\{\tilde{\mathbf{h}}_{ij}\}$ are drawn independently.

4.4 Simulation Scenario

In this section, the simulation scenario is described to show the efficiency of the proposed approach. The efficiency is defined as the achievable data-rate. For different conditions, the proposed beamforming optimization is compared to different beamforming strategies:

4.4.1 Different Conditions

Interference Power Level: One of the important performance metrics affecting the achievable data rate is the amount of interference generated on the mobile terminals. Clearly, the interference generated on the non-desired mobile terminal will increase as the direct channel and crosstalk channel states $\{\mathbf{h}_{ii}\}$ and $\{\mathbf{h}_{ij}\}$ become more correlated. There is a weak interference when the vectors $\{\mathbf{h}_{ii}\}$ and $\{\mathbf{h}_{ij}\}$ are independently drawn (no correlation) and stronger interference if they become correlated. By increasing the correlation factor, the efficiency will be tested for different amount of interference. To make the channel correlated the formula in 4.9 is used.

Noise Power Level: Another important metric is the noise power that is present locally. To test the robustness of the proposed approach and other beam-forming strategies, they are tested with different amount of noise power. Noise power σ_i^2 affects the achievable SNR level which defined as $1/\sigma_i^2$ when the transmitter applies full power. By increasing the SNR (decreasing noise power σ_i^2) the achievable utilization of different approaches will be demonstrated. The noise levels will be varied from 2dB up to 30dB.

Note that that the noise levels at both of the mobile teminals have been assummed to be equal for simplicity.

4.4.2 Lower-bound vs Upper-bound

In order to judge the performance of the proposed approach, we need a lower-bound and upper-bound performacens. The lower-bound in this thesis is defined as the non-sharing case as described in chapter 1. When the operators do not share the spectrum, they only can possess the half of the total common spectrum. In this case, there is no interference generation because the individual spectrum bands are split exclusively. Therefore, the achievable capacity per operator is now with respect to the fading channel conditions without interference term. In order to make comparisons only with respect to the amount of spectrum, we assume that the operator apply beamforming in their non-sharing case by excluding the antenna gain. In this case, the operators can perform MRT-vector $\mathbf{w}_i^m = \mathbf{h}_{ii}^m / \|\mathbf{h}_{ii}^m\|$ to match to the channel conditions in order to achieve maximum received power selfishly as this behaviour will not harm anybody. The general rate-functions expressed in formula 3.6 are reduced to the following:

$$R_i = \frac{1}{2}\sum_{m=1}^{M} \log_2\left(1 + \frac{p_i^m \left|(\mathbf{w}_i^m)^H \mathbf{h}_{ii}^m\right|^2}{\sigma_i^2}\right) = \frac{1}{2}\sum_{m=1}^{M} \log_2\left(1 + \frac{p_i^m \|\mathbf{h}_{ii}^m\|^2}{\sigma_i^2}\right) \tag{4.10}$$

where $i \in \{1, 2\}$ indicating the operators. Other parameters have already been described in formula 3.6. The optimal power allocation problem with respect to channel conditions can be expressed as following:

$$\begin{aligned} \underset{p_i^m}{\text{maximize}} \quad & \frac{1}{2}\sum_{m=1}^{M} \log_2\left(1 + \frac{p_i^m \|\mathbf{h}_{ii}^m\|^2}{\sigma_i^2}\right) \\ \text{s.t.d to} \quad & \sum_{m=1}^{M} p_i^m \leq P_i \;\text{ and }\; p_i^m \geq 0 \end{aligned} \tag{4.11}$$

where the optimal solution corresponds to the first-order derivative at each iteration in a waterfilling fashion leading to :

$$p_i^m = \left(\frac{1}{\mu_i} - \frac{\sigma_i^2}{\|\mathbf{h}_{ii}^m\|^2}\right)^+ \tag{4.12}$$

where $(.)^+ = max(., 0)$ and μ_i is the lagrangian multiplier as described in section 3.2.4 and $i \in \{1, 2\}$ indicating the operators. This solution has been implemented as an iterative algorithm in Matlab File.

As explained in section 2.5, an upper-bound for the general interference channel is not known yet. In this thesis, we consider the case where each operator would cancel the whole interference while using the whole common spectrum as the upper-bound.

This corresponds to the interference pre-cancelling as described in section 2.3 when the operators would construct the transmissions jointly. Of course, the achievable capacity is an extreme-theoretic upper-bound as joint-processing is not desirable for the operators. When cancelling the interferece generated, the resulting capacities for the operators can be expressed as:

$$R_i = \sum_{m=1}^{M} \log_2 \left(1 + \frac{p_i^m \left| (\mathbf{w}_i^m)^H \mathbf{h}_{ii}^m \right|^2}{\sigma_i^2} \right) = \sum_{m=1}^{M} \log_2 \left(1 + \frac{p_i^m \left\| \mathbf{h}_{ii}^m \right\|^2}{\sigma_i^2} \right) \tag{4.13}$$

The power allocations in this can be expressed as in the non-sharing case. However, calculating the obtained utilities is performed with full spectrum usage: Factor 1 instead of 1/2. This calculations have been implemented in Matlab File.

4.4.3 Different Beamforming Approaches

Another important metric to test the efficiency of the proposed algorithm is to compare it with different beamforming strategies. As described, the transmit beamforming based interference optimization can be characterized as an interaction of base stations based on their decisions on transmit beamforming weights and applied transmit powers. Depending on their selfishness and cooperativeness on selecting the weights and power level per sub-carrier, different beamforming strategies can be considered and compared to the proposed approach. The compassion between the different approaches should be done for different conditions described above. As a performance metric, the sum-rate of the operators per subcarrier is used as described in section 2.1.1 which can be expressed for two operators case as:

$$\frac{1}{M} \sum_{i=1}^{2} \sum_{m=1}^{M} \log_2 \left(1 + SINR_i \right) \tag{4.14}$$

Approach 1: Selfish in beamforming weights and Selfish in power allocation. In this approach, the operators react to each other with their best responses when selecting the beamforming weights as well as allocating power to sub-carriers. As described in section 2.5, the operators will operate with their NE-strategies. It is known that the operators will behave selfishly if they appply MRT-vector $\mathbf{w}_i^m = \mathbf{h}_{ii}^m / \|\mathbf{h}_{ii}^m\|$. The general rate-function given in the formule 3.6 can be expressed as:

$$R_i = \sum_{m=1}^{M} \log_2 \left(1 + \frac{p_i^m \left| (\mathbf{w}_i^m)^H \mathbf{h}_{ii}^m \right|^2}{p_j^m \left| \left(\mathbf{w}_j^m \right)^H \mathbf{h}_{ji}^m \right|^2 + \sigma_i^2} \right) = \sum_{m=1}^{M} \log_2 \left(1 + \frac{p_i^m \left(\mathbf{w}_i^m \right)^H \mathbf{h}_{ii}^m \left(\mathbf{h}_{ii}^m \right)^H \mathbf{w}_i^m}{p_j^m \left(\mathbf{w}_j^m \right)^H \mathbf{h}_{ji}^m \left(\mathbf{h}_{ji}^m \right)^H \mathbf{w}_j^m + \sigma_j^2} \right) \tag{4.15}$$

When inserting the MRT-vector in the formula above, it becomes:

$$R_i = \sum_{m=1}^{M} \log_2 \left(1 + \frac{p_i^m \left(\frac{\mathbf{h}_{ii}^m}{\|\mathbf{h}_{ii}^m\|} \right)^H \mathbf{h}_{ii}^m \left(\mathbf{h}_{ii}^m\right)^H \frac{\mathbf{h}_{ii}^m}{\|\mathbf{h}_{ii}^m\|}}{p_j^m \left(\frac{\mathbf{h}_{jj}^m}{\|\mathbf{h}_{jj}^m\|} \right)^H \mathbf{h}_{ji}^m \left(\mathbf{h}_{ji}^m\right)^H \frac{\mathbf{h}_{jj}^m}{\|\mathbf{h}_{jj}^m\|} + \sigma_j^2} \right) = \sum_{m=1}^{M} \log_2 \left(1 + \frac{p_i^m \|\mathbf{h}_{ii}^m\|^2}{p_j^m \left(\frac{\left|\mathbf{h}_{jj}^H \mathbf{h}_{ji}^m\right|^2}{\|\mathbf{h}_{jj}^m\|^2} \right) + \sigma_i^2} \right) \tag{4.16}$$

The optimal power allocation problem for the operators in this approach can be implemented as:

$$\begin{aligned} \underset{p_i^m}{\text{maximize}} \quad & \sum_{m=1}^{M} \log_2 \left(1 + \frac{p_i^m \|\mathbf{h}_{ii}^m\|^2}{p_j^m \left(\frac{\left|\mathbf{h}_{jj}^H \mathbf{h}_{ji}^m\right|^2}{\|\mathbf{h}_{jj}^m\|^2} \right) + \sigma_i^2} \right) \\ \text{s.t.d to} \quad & \sum_{m=1}^{M} p_i^m \leq P_i \ \text{ and } \ p_i^m \geq 0 \end{aligned} \tag{4.17}$$

where the optimal solution corresponds to the first-order derivative at each iteration in a waterfilling fashion leading to :

$$p_i^m = \left(\frac{1}{\mu_i} - \frac{p_j^m \left(\frac{\left|\mathbf{h}_{jj}^H \mathbf{h}_{ji}^m\right|^2}{\|\mathbf{h}_{jj}^m\|^2} \right) + \sigma_i^2}{\|\mathbf{h}_{ii}^m\|^2} \right)^+ \tag{4.18}$$

where $(.)^+ = max(., 0)$ and μ_i is the lagrangian multiplier as described in section 3.2.4 and $i \in \{1, 2\}$ indicating the operators. This solution has been implemented as an iterative algorithm in Matlab File.

Approach 2: In this approach, we let the operators apply MRT-vector which is the selfish bemaforming strategy. Power allocations will be in a leader-follower relationship as described in section 3.2.4. The optimization functions can be expressed as:

$$\mathcal{L}_1 = \sum_{m=1}^{M} \log_2 \left(1 + \frac{p_1^m \|\mathbf{h}_{11}^m\|^2}{p_2^m \left(p_1^m\right) \left(\frac{\left|\mathbf{h}_{22}^H \mathbf{h}_{21}^m\right|^2}{\|\mathbf{h}_{22}^m\|^2} \right) + \sigma_1^2} \right) + \mu_1 \left(P_1 - \sum_{m=1}^{M} p_1^m \right) \tag{4.19}$$

$$\mathcal{L}_2 = \sum_{m=1}^{M} \log_2 \left(1 + \frac{p_2^m \|\mathbf{h}_{22}^m\|^2}{\left(p_1^m\right)^{SE} \left(\frac{\left|\mathbf{h}_{11}^H \mathbf{h}_{12}^m\right|^2}{\|\mathbf{h}_{11}^m\|^2} \right) + \sigma_2^2} \right) + \mu_2 \left(P_2 - \sum_{m=1}^{M} p_2^m \right) \tag{4.20}$$

where the function p_2^m (p_1^m) has been described as in equation 3.12. The general solution-procedure of this kind of problem has been provided in section 3.2.4 and implemented in Matlab File.

Approach 3: This approach corresponds to an existing approach in the literature . This approach is aimed at optimizing the SLNR-vector with the aid of the iterative waterfilling algorithm. The basestations do not apply selfish beamforming, but power-levels have been alocated selfishly. For this large algorithm, we refer the reader to the reference (Hayashi et al., 2010). We implemented this algorithm in a Matlab File.

4.5 Results

In this section, the results of the spectrum sharing approaches described in the previous section have been discussed. The proposed approach has been compared to the other approaches in terms of its efficiency in correlated and uncorrelated direct- and crosstalk channel conditions as well as in low and high SNR regime. Also the fairness obtained from the proposed approach has been discussed. The complexity needed per approach has been discussed for further comparison.

4.5.1 Uncorrelated Case

In this section, the obtained results are given when the direct- and crosstalk channels of each operator are uncorrelated based on the formula 4.9. This implies that $\mu_i = 0$. As mentioned in 4.4.1, this corresponds to weak interference generation. Figure 4.1 shows the obtained sum-rate capacity per subcarrier per approach. It can be observed that the proposed approach outperforms the other approaches implying that when the direct- and crosstalk channel of the operators are uncorrelated, the selfishness in beamforming dimension as well as in power allocation dimension does not work. This is because the operators may gain the advantage of a bad crosstalk channel. When an operator has a direct channel with good properties (implying that the uncorrelated crosstalk channel may have bad properties), this operator may take the advantage of increasing power level while causing poor interference instead of selfishly increasing the power level only based on the direct channel conditions.

From figure 4.1, it can further be observed that there is almost no difference between the proposed approach and approach 3. Clearly, the SLNR-based vector which is also used in this approach prevents the selfishness in beamforming dimension. Figure 4.2 and figure 4.3 show the resulting power allocation strategies of the proposed approach and approach 3 respectively. We observe that these two different approaches converge to different sets of power allocations while resulting in comparable capacities. This means that in uncorrelated case, the beamforming dimension plays a more major role than the power allocation. Figure 4.4 shows the power allocation strategy of approach 1 which is selfish in power allocation dimension as well as in beamforming dimension. We can observe that the power allocation strategy of this approach is more aggressive yielding

in poor performance. Figure 4.5 shows the power allocations of approach 2. Clearly, when the beamforming strategies are selected selfishly and when there is a hierarchy in action in power allocation, this results in poorest gain. Because, the operator which is higher in the hierarchy maximizes his received power by causing maximal possible interference. Therefore, the most important conclusion is that for Stackelberg game, the leader operator should give the follower operator the opportunity to follow him by not closing the bargaining at the very first stage. We further can observe from figure 4.1, that all of the approaches keep their behaviour the same for the low and high SNR regimes. This is due to the fact that when the direct and crosstalk channels are uncorrelated, the interference ratio is more likely to become larger than the signal-to-noise ratio.

Furthermore, in figure 4.5, the obtained capacities of the two operators in the proposed approach have been shown in order to get insight in the fairness of the proposed approach. The figure shows that there is almost no difference in obtained results for the leader and follower operators.

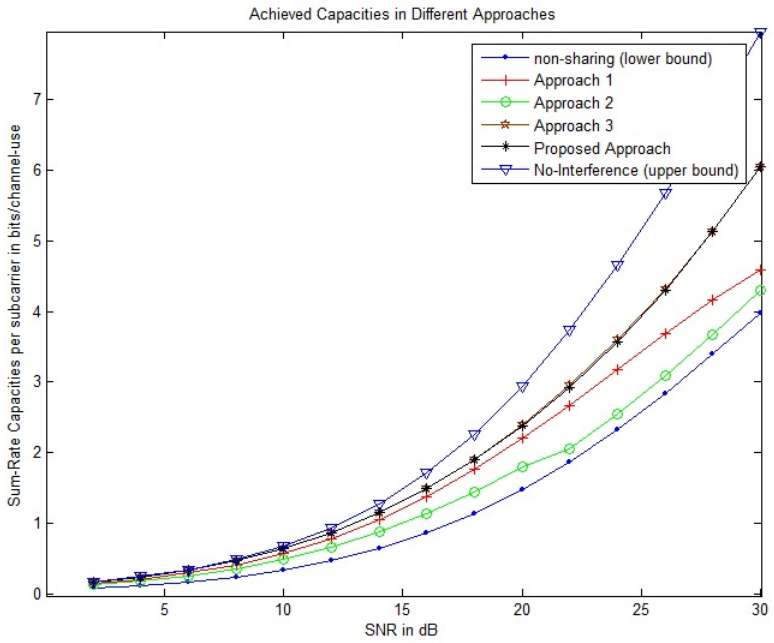

Figure 4.1: Performances of Different Approaches for Uncorrelated Direct- and Crosstalk Channels, $\mu_i = 0$

4.5.2 Correlated Case

In this section, the case of strong correlated direct- and crosstalk channels has been discussed. We apply a correlation factor of $\mu_i = 0.8$. This results in a stronger interference on the foreign mobile terminal. Figure 4.7 shows that the proposed solution outperforms the other approaches in the low SNR-regime (up to 15dB), while the approach 1 outper-

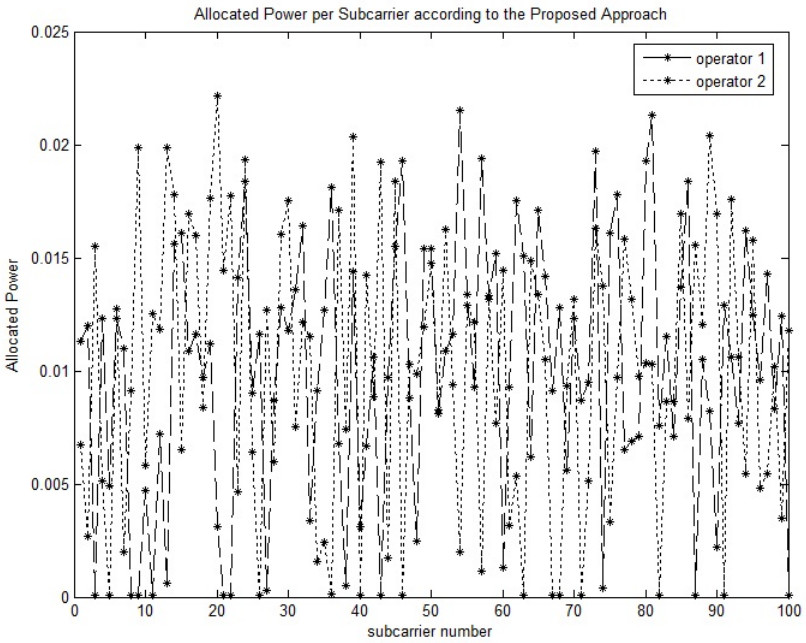

Figure 4.2: Power Allocation Strategies of the Proposed Approach for Uncorrelated Direct- and Crosstalk Channels $\mu_i = 0$

forms all other approaches for the higher SNR-regime. In this case of strong correlation, we observe a more clear difference between the proposed approach and approach 3. For very large SNR (higher than 20 dB), approach 3 wins again from the proposed approach. For SNR-levels higher than 25 dB, we observe that all approaches except the approach 1 converge to the same sum-rate capacity. Figure 4.8, 4.9 and **??** show aggressive power allocation strategies (up to 0.025). Clearly, when the interference generation becomes aggressive (due the correlated channels),the operators will win more if they act selfishly for high SNR regime (so when the interference term is larger than the noise term). However, for the worst case of low SNR level and moderate level up to 15 dB, the proposed approach perform better than all other approaches.

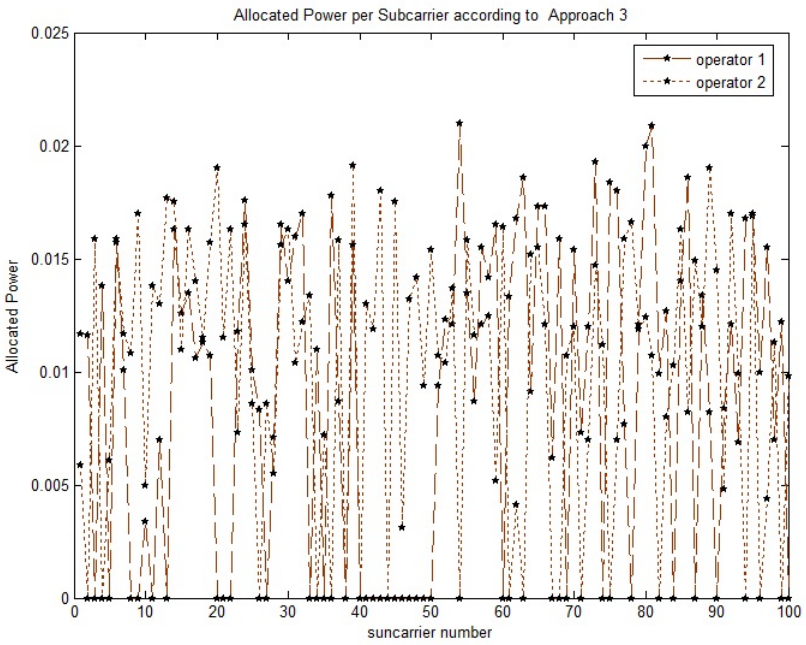

Figure 4.3: Power Allocation Strategies ofApproach 3 for Uncorrelated Direct- and Crosstalk Channels $\mu_i = 0$

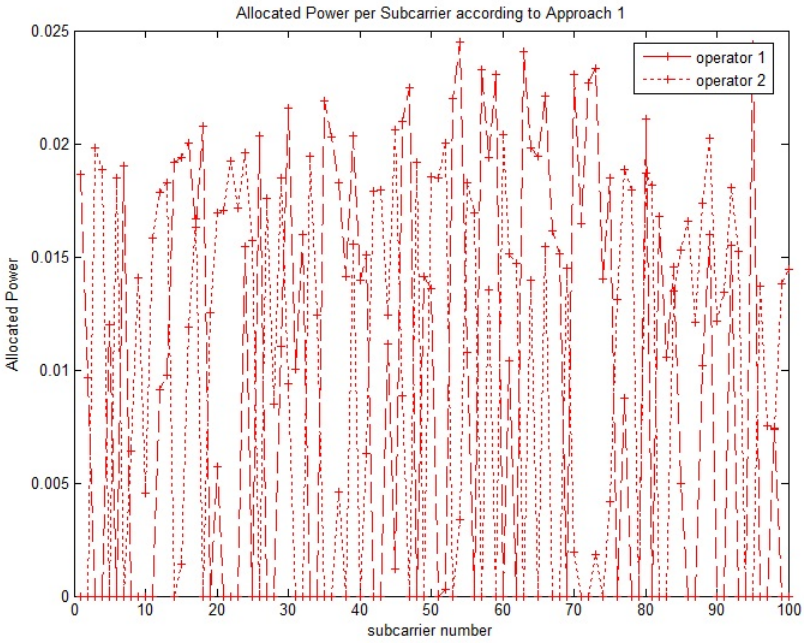

Figure 4.4: Power Allocation Strategies of Approach 1 for Uncorrelated Direct- and Crosstalk Channels $\mu_i = 0$

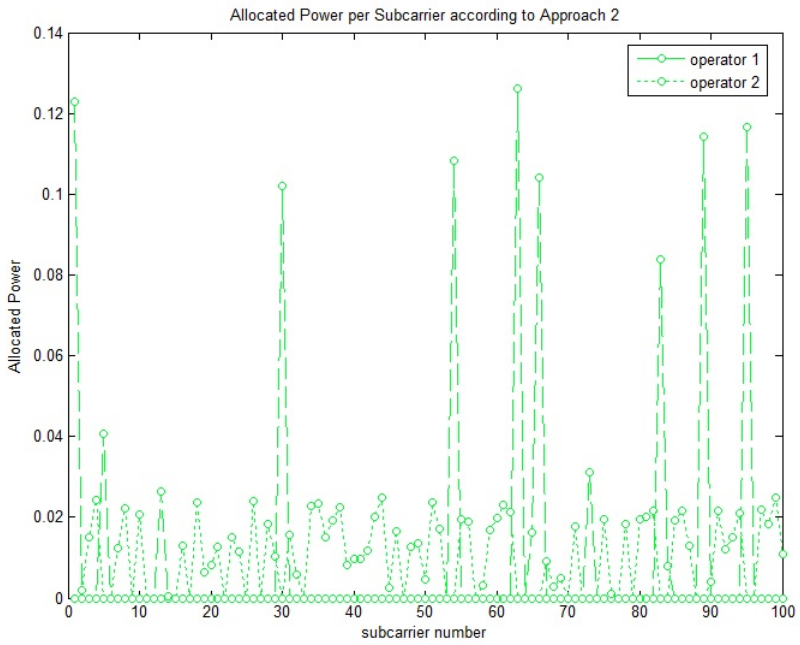

Figure 4.5: Power Allocation Strategies of Approach 2 for Uncorrelated Direct- and Crosstalk Channels $\mu_i = 0$

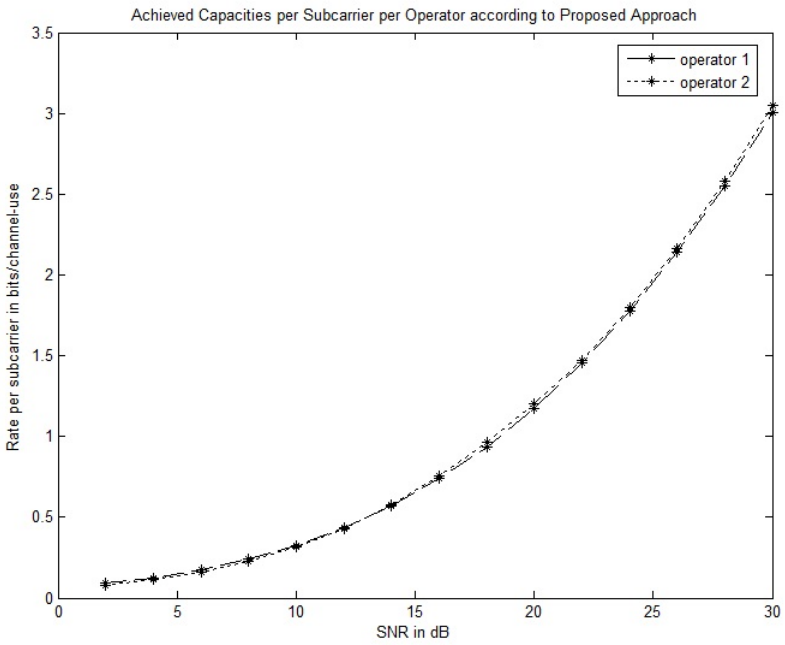

Figure 4.6: Comparison of the Obtained Capacities per Operator in the Proposed Approach for Uncorrelated Direct- and Crosstalk Channels $\mu_i = 0$

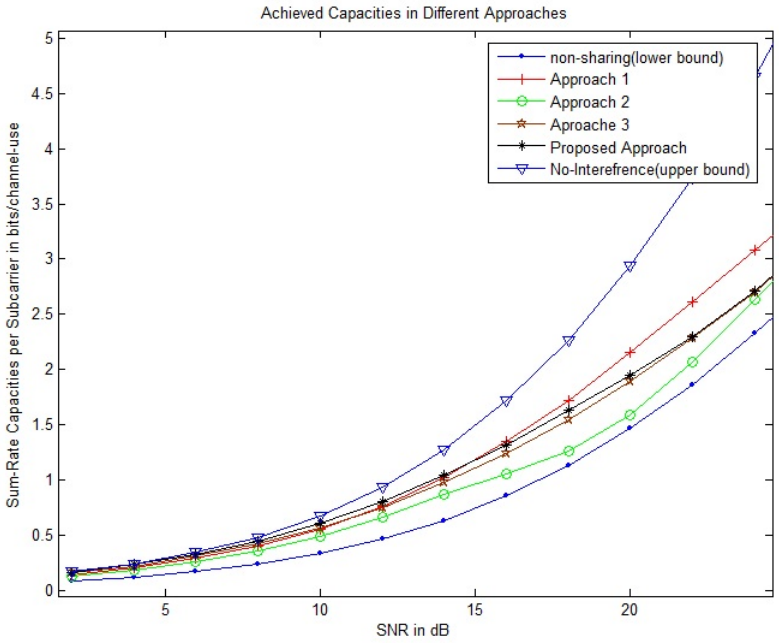

Figure 4.7: Performances of Different Approaches for Correlated Direct- and Crosstalk Channels, $\mu_i = 0.8$

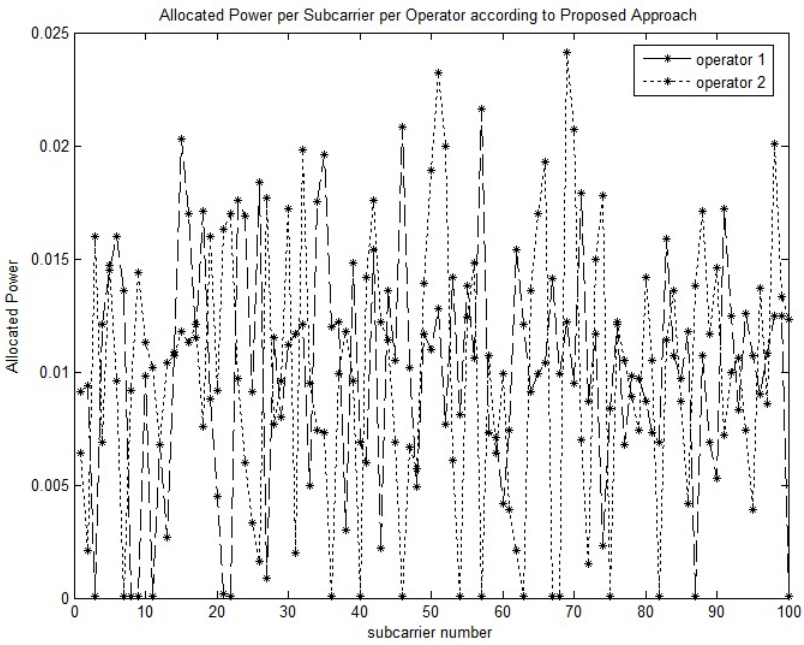

Figure 4.8: Power Allocation Strategies of the Proposed Approach for Correlated Direct- and Crosstalk Channels, $\mu_i = 0.8$

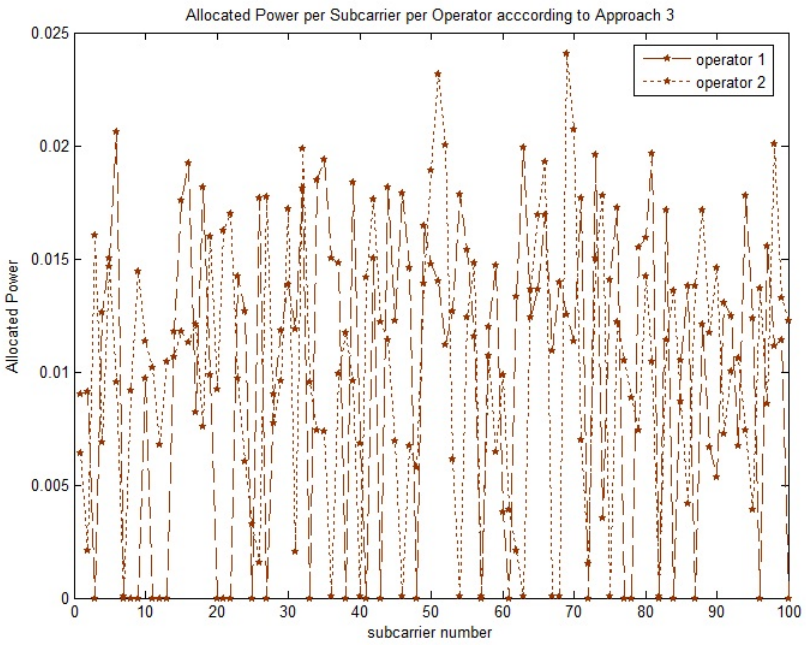

Figure 4.9: Power Allocation Strategies ofApproach 3 for Correlated Direct- and Crosstalk Channels $\mu_i = 0.8$

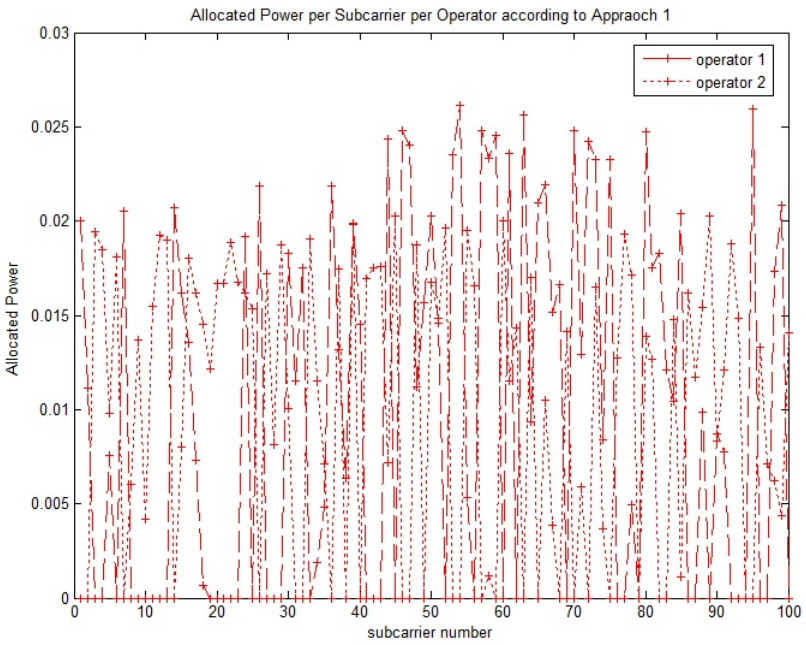

Figure 4.10: Power Allocation Strategies of Approach 1 for Correlated Direct- and Crosstalk Channels $\mu_i = 0.8$

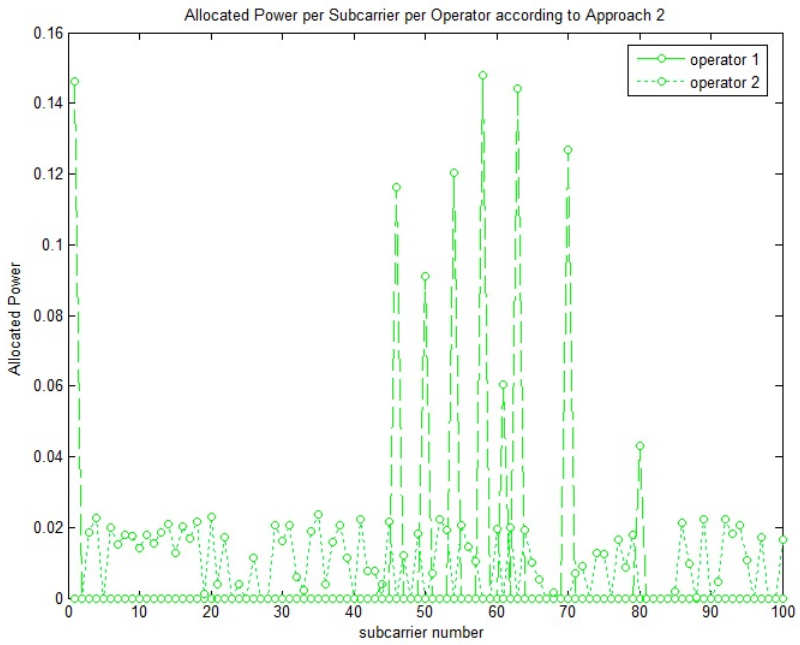

Figure 4.11: Power Allocation Strategies of Approach 2 for Correlated Direct- and Crosstalk Channels $\mu_i = 0.8$

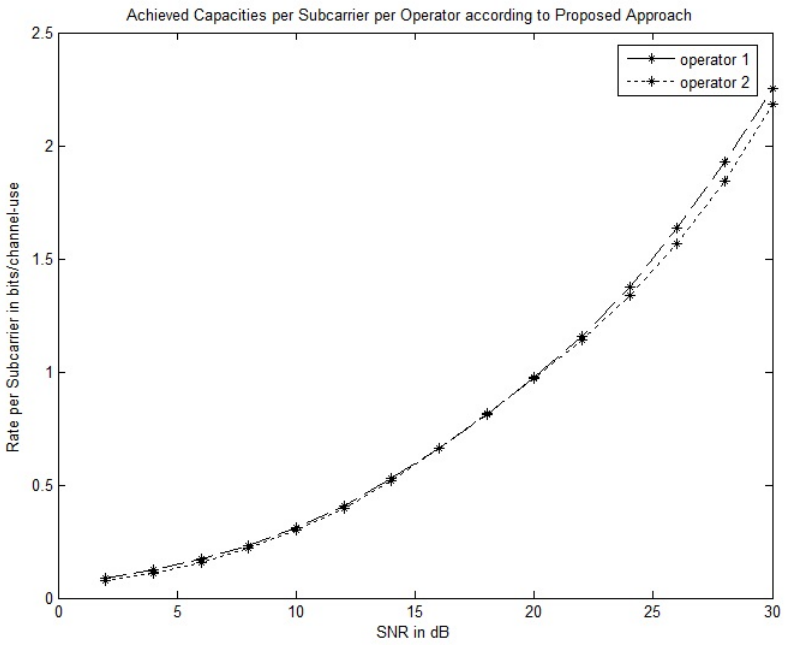

Figure 4.12: Comparison of the Obtained Capacities per Operator in the Proposed Approach for Correlated Direct- and Crosstalk Channels $\mu_i = 0.8$

Chapter 5

Conclusions

In this thesis, the spectrum sharing of two cellular operators has been considered in terms of obtained capacities. Firstly, the spectrum scarcity for mobile telecommunication systems has been emphasized as a natural result of the exclusive splitting of the available spectrum between different Radio Access Systems (RAS) and further exclusive splitting between the operators. Instead of this exclusive sharing of the available resources, we discussed the case of Spectrum and Sharing Coexistence (SSC) on the same spectrum band to achieve more bandwidth to meet the future capacity-demands for high data-rate communications.

The Inter-OI is the limiting factor against the advantages of SSC. In order to mitigate the Inter-OI, a lot of different approaches have been discussed based on their efficiency, complexity and applicability and provided fairness. This thesis proposed to use Interference Rejection Combining (IRC) based on receive-beamforming in the uplink where the users of different operators are registered to both of the operators and are assigned user-specific pilots. This was needed, because, among the other approaches based on the utilization of time and frequency resource, the approaches based on spatial dimensions require very low-level information exchange among the operators with separated infrastructures: just the Channel State Information (CSI) of the involved users. Furthermore, when operating in the common spectrum band, the scheduling with respect to time/frequency dimension is a complicated task while the approaches based on spatial parameters can solve the problem locally. Moreover, when we abstract the whole network of operator 1 and operator 2 as two gigantic cells, the frequency/time divisions do not exploit the spatial degrees of freedom which simplifies the achievability of number of interference-free paths which means more users with more bandwidth. In addition to this, we have seen that the evolved networks such as LTE-Advanced already has features to support such spatial solutions. For the downlink case of the problem, the advantage of the beamforming technique is also clear. In the downlink , there are two decision makers with conflicting objectives. In order to treat interference level as a bargaining value, we need some flexibility to adjust the interference level. The needed flexibility is obtained by optimizing the interference in beamforming dimension and power allocation dimension. Because the information exchange capability of the operators is limited, the

beamforming optimization in the downlink which just requires the CSI exchange is again an advantage.

In order to avoid the selfishness in downlink which result in NE, we proposed an SLNR-based beamforming which takes care on the undesired mobile terminal in combination with Stackelberg game which allocates the powers in a leader-follower relationship. The results have shown that the proposed approach performs better than the selfish approaches in the uncorrelated channels-case for low and high SNR regimes, while in the correlated case, the proposed approach outperforms other approaches for the low and moderate SNR-level (up to 15dB). We also have seen that the fairness in resource allocation is provided successfully.

However, the proposed approach requires more complexity in comparison to other approaches. We assumed that the leader operator perfectly get the direct- and crosstalk channels of the follower and that the follower perfectly can sense the interference of the leader and perfectly can report it to the follower basestation. Those assumptions can make the approach 3 a better possibility for the uncorrelated case and approach 1 for the correlated case as these approaches do not require these complexities.One thing is clear: If the operators want to share the spectrum, the information exchange in order to manage the Inter-OI should be enabled with no significant strain on the backhaul links. This is an obligatory work for the operators who would like to share the spectrum through independent networks.

Chapter 6

Future Work

In this thesis, we considered the case of spectrum sharing among cellular operators in a two-cell scenario. In the uplink, it has been proposed to assign user-specific pilots to the users of the different operators synchronized to a common TDD-frame-time so that the operators can capture the CSI of different users to enable the receive beamforming. In the downlink, we assumed a perfect sensing by the follower operator and perfect CSI exchange between the operators. In the literature, while exchanging CSI, most of the works assume infinite capacity backhaul links, or just assuming that the CSI is exchangable through the bakchaul links. However, some numerical analysis could provide insights about the impact of delayed CSI on Quality of Service (QoS) or information on how much we can rely on those links when CSI bacomes the goal of message passing? Multiple-cell and multiple-user cases of the problem can be understood even further. Secondly,the literature gives some insights on infrastructure sharing together with spectrum sharing. Infrastructure sharing based on relay node sharing combined with spectrum sharing becomes a hot-topic as in this case there is a single decision-maker which can utilize the inputs such as operator's objectives (more satisfied users more revenue), users' objectives (more data-rate) and actual channel conditions of the involved users (multi-user diversity) in a more efficient way without significant information exchange.

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Matlab Files

```
%%Approach 1%%%
%Approach 1 makes the optimization for the game where operators
%are selfish in beamforming dimension as well as in power allocations

clear all
close all
clc

%noise levels
sigma2v = [(1/10^0.2) (1/10^0.4) (1/10^0.6) (1/10^0.8) (1/10^1.0) (1/10^1.2) (1/10^1.4)
(1/10^1.6) (1/10^1.8) (1/10^2.0) (1/10^2.2) (1/10^2.4) (1/10^2.6) (1/10^2.8) (1/10^3.0)];

%initializations
dih = 1;
M = 100;
P = 1;
p1isg=zeros(15,M);
L = 90;

%Generating the channels
x11 = randn(2,L);
y11 = randn(2, L);
h11 = (1/sqrt(2))*(x11 + j*y11);

x12 = randn(2,L);
y12 = randn(2,L);
h12 = (1/sqrt(2))*(x12 + j*y12);

x22 = randn(2,L);
y22 = randn(2,L);
h22 = (1/sqrt(2))*(x22 + j*y22);

x21 = randn(2,L);
y21 = randn(2,L);
h21 = (1/sqrt(2))*(x21 + j*y21);

h11a =h11(1:1,1:L);
h11b =h11(2:2,1:L);

h12a =h12(1:1,1:L);
h12b =h12(2:2,1:L);

h21a =h21(1:1,1:L);
h21b =h21(2:2,1:L);

h22a =h22(1:1,1:L);
h22b =h22(2:2,1:L);

D = zeros(M,M);
```

```
for m=1:1:10
   for n = 1:1:10
      D(m,n)=(1/sqrt(M))*exp(-(0+(2*pi*m*n/M)*i));
   end
end

%Vectors with length 10
V11a = zeros(1,M);
V11b = zeros(1,M);

V12a = zeros(1,M);
V12b = zeros(1,M);

V21a = zeros(1,M);
V21b = zeros(1,M);

V22a = zeros(1,M);
V22b = zeros(1,M);

%Put channel states hij with last elements zeros
V11a(1:1, 1:L)= h11a;
V11a = transpose(V11a);
V11b(1:1, 1:L)= h11b;
V11b = transpose(V11b);

V12a(1:1, 1:L)= h12a;
V12a = transpose(V12a);
V12b(1:1, 1:L)= h12b;
V12b = transpose(V12b);

V21a(1:1, 1:L)= h21a;
V21a = transpose(V21a);
V21b(1:1, 1:L)= h21b;
V21b = transpose(V21b);

V22a(1:1, 1:L)= h22a;
V22a = transpose(V22a);
V22b(1:1, 1:L)= h22b;
V22b = transpose(V22b);

%Fourier Transform

k11a = D*V11a;
k11b = D*V11b;

k12a = D*V12a;
k12b = D*V12b;

k21a = D*V21a;
k21b = D*V21b;
```

```
k22a = D*V22a;
k22b = D*V22b;

%correlations
mich = 1;
mu = 0.8;

k12a = mu.*k11a + sqrt(1-mu^2).*k12a;

k12b = mu.*k11b + sqrt(1-mu^2).*k12b;

k21a = mu.*k22a + sqrt(1-mu^2).*k21a;

k21b= mu.*k22b + sqrt(1-mu^2).*k21b;

   p1 = zeros(1,100);
   for him = 1:length(p1)
      p1(him)=0.01;

         p2 = zeros(1,100);
   for him = 1:length(p2)
      p2(him)=0.01;
   end
      u = zeros(1,100);
   for him = 1:length(u)
      u(him)=0.01;
   end

   p1isg=zeros(15,M);

 for isg = 1:1:length(sigma2v)
   noise = sigma2v(isg);
   for buiten = 1:1:200
      for iter = 1:1:20
         for m = 1:1:100
            k22x = [k22a(m);k22a(m)];
            k21x = [k21a(m);k21b(m)];
            k22 = k22x/sqrt((dot(k22x,k22x)));
            k11x = [k11a(m);k11a(m)];
            k12x = [k12a(m);k12b(m)];
            k11 = k11x/sqrt((dot(k11x,k11x)));
            p1rm =(1./(u(m)))-
((noise+p2(m).*abs(k22'*k21x*k21x'*k22))./abs(k11'*k11x*k11x'*k11));
            p1(m) = max(p1rm,0);
         end

         for m = 1:1:M
            k22x = [k22a(m);k22a(m)];
            k21x = [k21a(m);k21b(m)];
```

```
            k22 = k22x/sqrt((dot(k22x,k22x)));
            k11x = [k11a(m);k11a(m)];
            k12x = [k12a(m);k12b(m)];
            k11 = k11x/sqrt((dot(k11x,k11x)));
            p2rm =(1./(u(m)))-
((noise+p1(m).*abs(k11'*k12x*k12x'*k11)./abs(k22'*k22x*k22x'*k22));
            p2(m) = max(p2rm,0);
         end
      end

      summ1 = 0;
      for m = 1:1:M
         summ1 = summ1 + p1(m);
      end

      i = 1;
      for yy=1:1:M
         u(yy) = max(0,(u(yy) - (1/i)*(1-summ1)));
      end
   end
   p1isg(isg:isg, 1:M) = p1;
end


    p1 = zeros(1,100);
   for him = 1:length(p1)
      p1(him)=0.01;
   end

      p2 = zeros(1,100);
   for him = 1:length(p2)
      p2(him)=0.01;
   end

      u = zeros(1,100);
   for him = 1:length(p1)
      u(him)=0.01;
   end

   p2isg=zeros(15,M);

for isg = 1:1:length(sigma2v)
   noise = sigma2v(isg);
   for buiten = 1:1:200
      for iter = 1:1:20
         for m = 1:1:100
            k22x = [k22a(m);k22a(m)];
            k21x = [k21a(m);k21b(m)];
            k22 = k22x/sqrt((dot(k22x,k22x)));
            k11x = [k11a(m);k11a(m)];
```

```
            k12x = [k12a(m);k12b(m)];
            k11 = k11x/sqrt((dot(k11x,k11x)));
            p1rm =(1./(u(m)))-
((noise+p2(m).*abs(k22'*k21x*k21x'*k22))./abs(k11'*k11x*k11x'*k11));
            p1(m) = max(p1rm,0);
         end

         for m = 1:1:M
            k22x = [k22a(m);k22a(m)];
            k21x = [k21a(m);k21b(m)];
            k22 = k22x/sqrt((dot(k22x,k22x)));
            k11x = [k11a(m);k11a(m)];
            k12x = [k12a(m);k12b(m)];
            k11 = k11x/sqrt((dot(k11x,k11x)));
            p2rm =(1./(u(m)))-
((noise+p1(m).*abs(k11'*k12x*k12x'*k11))./abs(k22'*k22x*k22x'*k22));
            p2(m) = max(p2rm,0);
         end
      end

      summ2 = 0;
      for m = 1:1:M
         summ2 = summ2 + p2(m);
      end

      i = 1;
      for xx=1:1:M
         u(xx) = max(0,(u(xx) - (1/i)*(1-summ2)));
      end
   end
   p2isg(isg:isg, 1:M) = p2;
end

p1dir =p1isg;
p2dur = p2isg;

for isg = 1:1:length(sigma2v)
   noise(isg) = sigma2v(isg);

   srate1 = 0;
   srate2 = 0;

   for m = 1:1:M
      k11x = [k11a(m);k11b(m)];
      k12x = [k12a(m);k12b(m)];
      k22x = [k22a(m);k22b(m)];
      k21x = [k21a(m);k21b(m)];

      wm1 = k11x;
      wm1 = wm1/(sqrt(dot(wm1,wm1)));
```

```
        tf1 = isnan(wm1);

        if(tf1(1)==1)
           wm1(1)=0;
           wm1(2)=0;
        end
        rp11(m)= p1dir(isg,m)*(wm1'*k11x*k11x'*wm1);
        rp12(m)= p1dir(isg,m)*(wm1'*k12x*k12x'*wm1);


        wm2 = k22x;
        wm2 = wm2/(sqrt(dot(wm2,wm2)));
        tf2 = isnan(wm2);

        if(tf2(1)==1)
           wm2(1)=0;
           wm2(2)=0;
        end
        rp22(m)= p2dur(isg,m)*(wm2'*k22x*k22x'*wm2);
        rp21(m)= p2dur(isg,m)*(wm2'*k21x*k21x'*wm2);

        srate1= srate1 + (log2(1+(abs(rp11(m))/(noise(isg)+abs(rp21(m))))));
        srate2= srate2 + (log2(1+(abs(rp22(m))/(noise(isg)+abs(rp12(m))))));
    end

    rate1(dih,isg) = srate1;
    rate2(dih,isg) = srate2;
end

tp2 = zeros(1,15);

for ik = 1:1:15
for m = 1:1:M
    tp2(1,ik) = tp2(1,ik) + p2isg(ik, m);
end
end

tp = zeros(1,15);
for ik = 1:1:15
    for m = 1:1:M
        tp(1,ik) = tp(1,ik) + p1isg(ik, m);
    end
end
```

```
%%Approach 2%%
%Approach 2 calculates with selfish MRT-vector and Stackelberg Game

clear all
close all
clc

sigma2v = [(1/10^0.2) (1/10^0.4) (1/10^0.6) (1/10^0.8) (1/10^1.0) (1/10^1.2) (1/10^1.4)
(1/10^1.6) (1/10^1.8) (1/10^2.0) (1/10^2.2) (1/10^2.4) (1/10^2.6) (1/10^2.8) (1/10^3.0)];

dih = 1;
M = 100;
P = 1;
p1isg=zeros(15,M);

load k11a;
load k11b;
load k12a;
load k12b;
load k21a;
load k21b;
load k22a;
load k22b;

mich = 1;
mu = 0;
k12a = mu.*k11a + sqrt(1-mu^2).*k12a;

% k12b= k12bdir(mich:mich,1:10);
k12b = mu.*k11b + sqrt(1-mu^2).*k12b;
k21a = mu.*k22a + sqrt(1-mu^2).*k21a;

% k21b= k21bdir(mich:mich,1:10);
k21b= mu.*k22b + sqrt(1-mu^2).*k21b;

for isg = 1:1:length(sigma2v)

noise = sigma2v(isg);

sum = 0;
p1 = zeros(1,100);
   for him = 1:length(p1)
      p1(him)=0.01;
   end
p2 = zeros(1,M);
X1 = zeros(2,M);
for m = 1:1:M
      k11x = [k11a(m);k11a(m)];
      k12x = [k12a(m);k12b(m)];
      k11 = k11x/sqrt((dot(k11x,k11x)));
```

```
   X1(1,m) = (noise + abs(p1(m)*k11'*k12x*k12x'*k11));
   X1(2,m) = m;
end

%p2;
hh = zeros(2,M);
ku = X1(1:2,1:1);
for f = 1:1:M
   for g = 1:1:M
      if(X1(1,g)<=ku(1,1))
         ku(1:2,1:1) = X1(1:2,g:g);
         index = g;
      end
   end
   hh(1:2,f:f)=ku;
   X1(1,index) = 5000;
   ku = X1(1:2,1:1);
end
X1= hh;
Qt = zeros(1,M);
teller = 0;
for k = 1:1:M
   for i = 1:1:k
      teller = teller + X1(1,i);
   end
   Qt(k)=teller;
   teller = 0;
end

teken = M;
for k = 1:1:(M-1)
   if((Qt(k)<(P))&&((P)<=Qt(k+1)))
      teken = k;
   end
end

som = Qt(teken);

for s= 1:1:M
   if(teken==M)
      p2(s)=((P)+ Qt(M))-X1(1,s);
   end
end

if (teken<M)
   for i = 1:1:teken
      nn(i) = X1(2:2,i:i);
      ni = nn(i);
      p2(ni)= ((P)+ som)-X1(1,i);
   end
```

```
    end

    s = [1:1:M];

    if(teken<M)
        for uu= 1:1:M
            for yy =1:1:length(nn)
                if(s(uu)==nn(yy))
                    s(uu)=0;
                end
            end
        end
    end

    if(teken<M)
        for rr = 1:1:M
            if(s(rr)~=0)
                p2(rr)=0;
            end
        end
    end


if(isg<=5)
    sinir = 100;
end

if((6<=isg)&&(isg<=10))
    sinir = 200;
end

if(10<isg)
    sinir = 250;
end

for buiten = 1:1:sinir
    for iter = 1:1:50
        for m = 1:1:M
            k22x = [k22a(m);k22a(m)];
            k21x = [k21a(m);k21b(m)];
            k22 = k22x/sqrt((dot(k22x,k22x)));
            k11x = [k11a(m);k11a(m)];
            k12x = [k12a(m);k12b(m)];
            k11 = k11x/sqrt((dot(k11x,k11x)));

            p1rm =(1/u(m))-
((noise+p2(m)*abs(k22'*k21x*k21x'*k22))./abs(k11'*k11x*k11x'*k11));
            p1(m) = max(p1rm,0);
        end
```

```
    for m = 1:1:M
        k22x = [k22a(m);k22a(m)];
        k21x = [k21a(m);k21b(m)];
        k22 = k22x/sqrt((dot(k22x,k22x)));
        k11x = [k11a(m);k11a(m)];
        k12x = [k12a(m);k12b(m)];
        k11 = k11x/sqrt((dot(k11x,k11x)));

        X1(1,m)=(noise+ p1(m)*abs(k11'*k12x*k12x'*k11));
        X1(2,m) = m;
    end
    %Now, p2 will react on those p1's in a stackelberg fashion

    hh = zeros(2,M);
    ku = X1(1:2,1:1);
    som = 0;


for f = 1:1:M
    for g = 1:1:M
        if(X1(1,g)<=ku(1,1))
            ku(1:2,1:1) = X1(1:2,g:g);
            index = g;
        end
    end
    hh(1:2,f:f)=ku;
    X1(1,index) = 5000;
    ku = X1(1:2,1:1);
end
X1= hh;
Qt = zeros(1,M);
teller = 0;
for k = 1:1:M
    for i = 1:1:k
        teller = teller + X1(1,i);
    end
    Qt(k)=teller;
    teller = 0;
end

teken = M;
for k = 1:1:(M-1)
    if((Qt(k)<(P))&&((P)<=Qt(k+1)))
        teken = k;
    end
end

som = Qt(teken);

for s= 1:1:M
```

```
        if(teken==M)
            p2(s)=((P)+ Qt(M))-X1(1,s);
        end
    end

    if (teken<M)
        for i = 1:1:teken
            nn(i) = X1(2:2,i:i);
            ni = nn(i);
            p2(ni)= ((P)+ som)-X1(1,i);
        end
    end

    s = [1:1:M];

    if(teken<M)
        for uu= 1:1:M
            for yy =1:1:length(nn)
                if(s(uu)==nn(yy))
                    s(uu)=0;
                end
            end
        end
    end

    if(teken<M)
        for rr = 1:1:M
            if(s(rr)~=0)
                p2(rr)=0;
            end
        end
    end
        p1;

    end

    summ = 0;
    for m = 1:1:M
        summ = summ + p1(m);
    end
    i =1;
    for xx=1:1:M
        %old(xx) = u(xx);
        u(xx) = max(0,(u(xx) - (1/i)*(1-summ)));
        %new(xx) = u(xx);
        %verschil = old(xx)-new(xx);
    end
end

p1isg(isg:isg,1:M)=p1;
```

```
end

p2 = zeros(1,100);
for him = 1:length(p2)
   p2(him)=0.01;
end

u = zeros(1,100);
for him = 1:length(u)
   u(him)=3;
end

 p2isg=zeros(15,M);

 for isg = 1:1:length(sigma2v)
   noise = sigma2v(isg);
 for buiten = 1:1:200
       for m = 1:1:M
          k22x = [k22a(m);k22a(m)];
           k21x = [k21a(m);k21b(m)];
           k22 = k22x/sqrt((dot(k22x,k22x)));
           k11x = [k11a(m);k11a(m)];
           k12x = [k12a(m);k12b(m)];
           k11 = k11x/sqrt((dot(k11x,k11x)));

           p2rm =(1/u(m))-
((noise+p1isg(isg,m)*abs(k11'*k12x*k12x'*k11))./abs(k22'*k21x*k21x'*k22));
           p2(m) = max(p2rm,0);
       end


       summ2 = 0;
       for m = 1:1:M
          summ2 = summ2 + p2(m);
       end
       i = 1;
       for yy=1:1:M
          u(yy) = max(0,(u(yy) - (1/i)*(1-summ2)));
       end
 end
 p2isg(isg:isg, 1:M) = p2;
end
 %rates

 for isg = 1:1:length(sigma2v)
   noise = sigma2v(isg);
  srate1 = 0;
  srate2 = 0;

    for m = 1:1:M
```

```
        k22x = [k22a(m);k22a(m)];
        k21x = [k21a(m);k21b(m)];
        k22 = k22x/sqrt((dot(k22x,k22x)));
        k11x = [k11a(m);k11a(m)];
        k12x = [k12a(m);k12b(m)];
        k11 = k11x/sqrt((dot(k11x,k11x)));

        rp11(m)= p1isg(isg,m)*abs(k11'*k11x*k11x'*k11);
        rp22(m)= p2isg(isg,m)*abs(k22'*k22x*k22x'*k22);

        rp12(m)= p1isg(isg,m)*abs(k11'*k12x*k12x'*k11);
        rp21(m)= p2isg(isg,m)*abs(k22'*k21x*k21x'*k22);

        srate1= srate1 + (log2(1+(abs(rp11(m))/(noise+abs(rp21(m))))));
        srate2= srate2 + (log2(1+(abs(rp22(m))/(noise+abs(rp12(m))))));
    end

    rate1(dih,isg) = srate1;
    rate2(dih,isg) = srate2;
end


tp2 = zeros(1,15);

for ik = 1:1:15
for m = 1:1:M
    tp2(1,ik) = tp2(1,ik) + p2isg(ik, m);
end
end

tp2


tp = zeros(1,15);
for ik = 1:1:15
    for m = 1:1:M
        tp(1,ik) = tp(1,ik) + p1isg(ik, m);
    end
end

tp
```

```
%%Approach 3%%
%%Approach 3 utilizes the SLNR-based vector in an iterative waterfilling
%fashion

clear all
close all
clc


%noise levels
for dih = 1:1:1
sigma2v = [(1/10^0.2) (1/10^0.4) (1/10^0.6) (1/10^0.8) (1/10^1.0) (1/10^1.2) (1/10^1.4)
(1/10^1.6) (1/10^1.8) (1/10^2.0) (1/10^2.2) (1/10^2.4) (1/10^2.6) (1/10^2.8) (1/10^3.0)];

%Initialization
p1slisg = zeros(15,100);
Q = 2;
M = 100;
L = 90;

   load k11a;
   load k11b;
   load k12a;
   load k12b;
   load k21a;
   load k21b;
   load k22a;
   load k22b;

 mu = 0.8;
 k12a = mu.*k11a + sqrt(1-mu^2).*k12a;
 k12b = mu.*k11b + sqrt(1-mu^2).*k12b;
 k21a = mu.*k22a + sqrt(1-mu^2).*k21a;
 k21b= mu.*k22b + sqrt(1-mu^2).*k21b;
 for isg = 1:1:length(sigma2v)
   noise(isg) = sigma2v(isg);
   P = 1;
   p1 = zeros(1,100);
   for him = 1:length(p1)
      p1(him)=0.01;
   end

   sum = 0;
   X1 = zeros(2,M);

  %operator 1
   for ki = 1:1:60
      for m = 1:1:M
         k11x = [k11a(m);k11b(m)];
         k12x = [k12a(m);k12b(m)];
```

```
    k22x = [k22a(m);k22b(m)];
    k21x = [k21a(m);k21b(m)];

    wm1 = (inv(p1(m)*k12x*(k12x)'+noise(isg)*eye(2))*sqrt(p1(m))*k11x);
    wm1 = wm1/(sqrt(dot(wm1,wm1)));
    tf1 = isnan(wm1);

    if(tf1(1)==1)
       wm1(1)=0;
       wm1(2)=0;
    end

    rp11= (wm1'*k11x*k11x'*wm1);
    rp12= p1(m)*(wm1'*k12x*k12x'*wm1);

    X1(1,m) = (rp12 + noise(isg))/(rp11);
    X1(2,m) = m;

    sum = sum + X1(1,m);
end
X1;
maksi = abs(max(X1(1:1,1:M)));
Rn = abs((P+sum)/M);
if(Rn>maksi)
    for pim = 1:1:M
       carrierm=X1(2,pim);
       p1(carrierm) = Rn-X1(1,carrierm);
    end
end
p1;
mX1 = X1
mm=M;

while(Rn<=maksi)
    mm = length(X1);
    mX1 = X1;
    mnX = X1;
    naX1 = X1;
    teller =0;

    for f = 1:1:mm
       for g = 1:1:mm
          if(Rn<=mX1(1,g))
             teller=teller+1;
             index = g;
             mX1(1,index)=-5000;
          end
       end
    end
    A = zeros(1, teller);
```

```
teller = 0;
mnX
for f = 1:1:mm
   for g = 1:1:mm
      if(Rn<=mnX(1,g))
         teller = teller+1;
         index = g;
         A(teller)=mnX(2:2,index:index);
         mnX(1,index)=-5000;
      end
   end
end
A;
K=length(A);
nleng = mm-K;
mxX1 = zeros(2,nleng);
for uu=1:1:K
   for op = 1:1:length(X1)
      fg = A(uu);
      if(naX1(2,op)==fg)
         naX1(1,op)=NaN;
      end
   end
end
ind = 1;
for op = 1:1:length(naX1)
   if(~isnan(naX1(1,op)))
      kin = op;
      mxX1(1:2,ind:ind)=naX1(1:2,kin:kin);
      ind = ind+1;
   end
end
mxX1;
newsum = 0;
hj= size(mxX1);
if(hj(2)==1)
   newsum=mxX1(1,1);
else
   for pp = 1:1:length(mxX1)
      newsum = newsum+abs(mxX1(1,pp));
   end
end
newsum
Rn = abs((P+newsum)/(M-K));

if(hj(2)==1)
   maksi = abs(mxX1(1,1));
else
   maksi = max(mxX1(1:1,1:length(mxX1)));
end
```

```
        %     X1 = zeros(2,length(mxX1));
        %     X1=mxX1
      end


      lemX =length(X1);
      X1;
      if(hj(2)==1)
        car= X1(2);
        p1(car)=Rn-X1(1);
      else
        for q = 1:1:lemX
          carrierm(q)=X1(2,q);
          carrierm(q);
          p1(carrierm(q)) = Rn-X1(1,q);
        end
      end
      leA = length(A);
      A
      if(leA>0)
        for w = 1:1:leA
          cm(w) = A(w);
          p1(cm(w)) = 0;
        end
      end
      p1 = abs(p1);
      sum = 0;
    end
    p1;
    p1slisg(isg:isg, 1:M)= p1;
  end

  %operator 2
p2dir = zeros(15,M);

for isg = 1:1:length(sigma2v)
    noise(isg) = sigma2v(isg);

    P = 1;
    % sigma2 = 0.1;

    p2 = zeros(1,100);
    for him = 1:length(p2)
      p2(him)=0.01;
    end
    sum = 0;
    X1 = zeros(2,M);
    %
    for ki = 1:1:60
      for m = 1:1:M
```

```
    k11x = [k11a(m);k11b(m)];
    k12x = [k12a(m);k12b(m)];
    k22x = [k22a(m);k22b(m)];
    k21x = [k21a(m);k21b(m)];

    wm1 = (inv(p2(m)*k21x*(k21x)'+noise(isg)*eye(2))*sqrt(p2(m))*k22x);
    wm1 = wm1/(sqrt(dot(wm1,wm1)));
    tf1 = isnan(wm1);

    if(tf1(1)==1)
       wm1(1)=0;
       wm1(2)=0;
    end

    rp22= (wm1'*k22x*k22x'*wm1);
    rp21= p2(m)*(wm1'*k21x*k21x'*wm1);

    X1(1,m) = (rp21 + noise(isg))/(rp22);
    X1(2,m) = m;

    sum = sum + X1(1,m);
end
X1;
maksi = abs(max(X1(1:1,1:M)));
Rn = abs((P+sum)/M);

if(Rn>maksi)
    for pim2 = 1:1:M
       carrierm2=X1(2,pim2);
       p1(carrierm2) = Rn-X1(1,carrierm2);
    end
end
p2;

mX1 = X1
mm=M;

while(Rn<=maksi)
    mm = length(X1);
    mX1 = X1;
    mnX = X1;
    naX1 = X1;
    teller =0;

    for f = 1:1:mm
       for g = 1:1:mm
          if(Rn<=mX1(1,g))
             teller=teller+1;
             index = g;
             mX1(1,index)=-5000;
```

```
        end
    end
end
A = zeros(1, teller);
teller = 0;
mnX
for f = 1:1:mm
    for g = 1:1:mm
        if(Rn<=mnX(1,g))
            teller = teller+1;
            index = g;
            A(teller)=mnX(2:2,index:index);
            mnX(1,index)=-5000;
        end
    end
end
A;
K=length(A);
nleng = mm-K;
mxX1 = zeros(2,nleng);
for uu=1:1:K
    for op = 1:1:length(X1)
        fg = A(uu);
        if(naX1(2,op)==fg)
            naX1(1,op)=NaN;
        end
    end
end
ind = 1;
for op = 1:1:length(naX1)
    if(~isnan(naX1(1,op)))
        kin = op;
        mxX1(1:2,ind:ind)=naX1(1:2,kin:kin);
        ind = ind+1;
    end
end
mxX1;
newsum = 0;
hj= size(mxX1);
if(hj(2)==1)
    newsum=mxX1(1,1);
else
    for pp = 1:1:length(mxX1)
        newsum = newsum+abs(mxX1(1,pp));
    end
end
newsum
Rn = abs((P+newsum)/(M-K));

if(hj(2)==1)
```

```
            maksi = abs(mxX1(1,1));
        else
            maksi = max(mxX1(1:1,1:length(mxX1)));
        end
        %     X1 = zeros(2,length(mxX1));
        %     X1=mxX1
    end


    lemX =length(X1);
    X1;
    if(hj(2)==1)
        car= X1(2);
        p2(car)=Rn-X1(1);
    else
        for q = 1:1:lemX
            carrierm(q)=X1(2,q);
            carrierm(q);
            p2(carrierm(q)) = Rn-X1(1,q);
        end
    end
    leA = length(A);
    A
    if(leA>0)
        for w = 1:1:leA
            cm(w) = A(w);
            p2(cm(w)) = 0;
        end
    end
    p2 = abs(p2);
    sum = 0;
  end
  p2;
  p2dir(isg:isg, 1:M)= p2;
end

%%Rates
sigma2v = [(1/10^0.2) (1/10^0.4) (1/10^0.6) (1/10^0.8) (1/10^1.0) (1/10^1.2) (1/10^1.4)
(1/10^1.6) (1/10^1.8) (1/10^2.0) (1/10^2.2) (1/10^2.4) (1/10^2.6) (1/10^2.8) (1/10^3.0)];
p2slisg = zeros(15,M);
Q = 2;
L = 7;

for isg = 1:1:length(sigma2v)
  noise(isg) = sigma2v(isg);
  toplam1 = 0;
  toplam2 = 0;
  for m = 1:1:M
    k11x = [k11a(m);k11b(m)];
    k12x = [k12a(m);k12b(m)];
```

```
        k22x = [k22a(m);k22b(m)];
        k21x = [k21a(m);k21b(m)];

        wm1 =
(inv(p1slisg(isg,m)*k12x*(k12x)'+noise(isg)*eye(2))*sqrt(p1slisg(isg,m))*k11x);
        wm1 = wm1/(sqrt(dot(wm1,wm1)));
        tf1 = isnan(wm1);

        if(tf1(1)==1)
           wm1(1)=0;
           wm1(2)=0;
        end
        rp11(m)= p1slisg(isg,m)*(wm1'*k11x*k11x'*wm1);
        rp12(m)= p1slisg(isg,m)*(wm1'*k12x*k12x'*wm1);


        wm2 = (inv(p2dir(isg,m)*k21x*(k21x)'+noise(isg)*eye(2))*sqrt(p2dir(isg,m))*k22x);
        wm2 = wm2/(sqrt(dot(wm2,wm2)));
        tf2 = isnan(wm2);

        if(tf2(1)==1)
           wm2(1)=0;
           wm2(2)=0;
        end
        rp22(m)= p2dir(isg,m)*(wm2'*k22x*k22x'*wm2);
        rp21(m)= p2dir(isg,m)*(wm2'*k21x*k21x'*wm2);

        toplam1 = toplam1+ (log2(1+(abs(rp11(m))/(noise(isg)+abs(rp21(m))))));
        toplam2 = toplam2+ (log2(1+(abs(rp22(m))/(noise(isg)+abs(rp12(m))))));
    end

    rate1sl(dih,isg) = toplam1;
    rate2sl(dih,isg) = toplam2;
end
end

tp2 = zeros(1,15);

for ik = 1:1:15
for m = 1:1:100
    tp2(1,ik) = tp2(1,ik) + p2dir(ik, m);
end
end

tp = zeros(1,15);
for ik = 1:1:15
    for m = 1:1:100
        tp(1,ik) = tp(1,ik) + p1slisg(ik, m);
    end
end
```

```
%%%%Proposed Approach%%%%
%This m-file enables the SLNR-based Stackelberg Game for channel realizations
%with L instances, and for a set of SNR (2-30dB) and different correlations


clear all
close all
clc

%noise levels
sigma2v = [(1/10^0.2) (1/10^0.4) (1/10^0.6) (1/10^0.8) (1/10^1.0) (1/10^1.2) (1/10^1.4)
(1/10^1.6) (1/10^1.8) (1/10^2.0) (1/10^2.2) (1/10^2.4) (1/10^2.6) (1/10^2.8) (1/10^3.0)];

%initializations
dih = 1;
M = 100;
P = 1;
p1isg=zeros(15,M);
L = 90;

%Generating the channels
load k11a;
load k11b;
load k12a;
load k12b;
load k21a;
load k21b;
load k22a;
load k22b;

mich = 1;
mu = 0;

k12a = mu.*k11a + sqrt(1-mu^2).*k12a;
k12b = mu.*k11b + sqrt(1-mu^2).*k12b;

k21a = mu.*k22a + sqrt(1-mu^2).*k21a;
k21b= mu.*k22b + sqrt(1-mu^2).*k21b;

for isg = 1:1:length(sigma2v)
   noise = sigma2v(isg);
   sum = 0;

   p1 = zeros(1,100);
   for him = 1:length(p1)
      p1(him)=0.01;
   end

   p2 = zeros(1,M);
   X1 = zeros(2,M);
```

```
for m = 1:1:M
   k11x = [k11a(m);k11b(m)];
   k12x = [k12a(m);k12b(m)];
   wm1 = (inv(p1(m)*k12x*(k12x)'+noise*eye(2))*sqrt(p1(m))*k11x);
   wm1 = wm1/(sqrt(dot(wm1,wm1)));

   tf1 = isnan(wm1);
   if(tf1(1)==1)
      wm1(1)=0;
      wm1(2)=0;
   end
   X1(1,m)=(noise + p1(m)*abs(wm1'*k12x*k12x'*wm1));
   X1(2,m) = m;
end

%p2;
hh = zeros(2,M);
ku = X1(1:2,1:1);
for f = 1:1:M
   for g = 1:1:M
      if(X1(1,g)<=ku(1,1))
         ku(1:2,1:1) = X1(1:2,g:g);
         index = g;
      end
   end
   hh(1:2,f:f)=ku;
   X1(1,index) = 5000;
   ku = X1(1:2,1:1);
end
X1= hh;
Qt = zeros(1,M);
teller = 0;
for k = 1:1:M
   for i = 1:1:k
      teller = teller + X1(1,i);
   end
   Qt(k)=teller;
   teller = 0;
end

teken = M;
for k = 1:1:(M-1)
   if((Qt(k)<(P))&&((P)<=Qt(k+1)))
      teken = k;
   end
end

som = Qt(teken);
```

```
for s= 1:1:M
   if(teken==M)
      p2(s)=((P)+ Qt(M))-X1(1,s);
   end
end

if (teken<M)
   for i = 1:1:teken
      nn(i) = X1(2:2,i:i);
      ni = nn(i);
      p2(ni)= ((P)+ som)-X1(1,i);
   end
end

s = [1:1:M];

if(teken<M)
   for uu= 1:1:M
      for yy =1:1:length(nn)
         if(s(uu)==nn(yy))
            s(uu)=0;
         end
      end
   end
end

if(teken<M)
   for rr = 1:1:M
      if(s(rr)~=0)
         p2(rr)=0;
      end
   end
end

if(isg<=5)
sinir = 100;
end
if((6<=isg)&&(isg<=10))
sinir = 200;
end

if(10<isg)
   sinir = 250;
end

u = zeros(1,100);
for yk = 1:1:100
   u(yk) = 90;
end
```

```
sinir = 10;

%Leader's Preparation

for buiten = 1:1:sinir
   for iter = 1:1:10
      for m = 1:1:M
         k11x = [k11a(m);k11b(m)];
         k12x = [k12a(m);k12b(m)];
         k22x = [k22a(m);k22b(m)];
         k21x = [k21a(m);k21b(m)];

         wm2 = (inv(p2(m)*k21x*(k21x)'+noise*eye(2))*sqrt(p2(m))*k22x);
         wm2 = wm2/(sqrt(dot(wm2,wm2)));
         tf2 = isnan(wm2);

         if(tf2(1)==1)
            wm2(1)=0;
            wm2(2)=0;
         end
         rp2(m) = wm2'*k21x*k21x'*wm2;

         yi = @(p1) -
1.*(log2(1+abs(p1.*(((inv(p1.*(k12x*k12x')+noise*eye(2)).*sqrt(p1)*k11x)'*k11x*k11x'*(in
v(p1.*(k12x*k12x')+noise*eye(2)).*sqrt(p1)*k11x))./(dot((inv(p1.*(k12x*k12x')+noise*eye(
2)).*sqrt(p1)*k11x),(inv(p1.*(k12x*k12x')+noise*eye(2)).*sqrt(p1)*k11x))))))./(noise+p2(m)
*abs(rp2(m))))+u(m).*(-1.*p1));

         optimump = fminbnd(yi,0,1);

         p1(m) = max(0,optimump);
      end

      for m = 1:1:M
         k11x = [k11a(m);k11b(m)];
         k12x = [k12a(m);k12b(m)];
         wm1 = (inv(p1(m)*k12x*(k12x)'+noise*eye(2))*sqrt(p1(m))*k11x);
         wm1 = wm1/(sqrt(dot(wm1,wm1)));
         tf1 = isnan(wm1);

         if(tf1(1)==1)
            wm1(1)=0;
            wm1(2)=0;
         end

         X1(1,m)=(noise+ p1(m)*abs(wm1'*k12x*k12x'*wm1));
         X1(2,m) = m;
      end

      %Now, p2 will react on those p1's in a stackelberg fashion
```

```
hh = zeros(2,M);
ku = X1(1:2,1:1);
som = 0;

for f = 1:1:M
   for g = 1:1:M
      if(X1(1,g)<=ku(1,1))
         ku(1:2,1:1) = X1(1:2,g:g);
         index = g;
      end
   end
   hh(1:2,f:f)=ku;
   X1(1,index) = 5000;
   ku = X1(1:2,1:1);
end

X1= hh;
Qt = zeros(1,M);
teller = 0;

for k = 1:1:M
   for i = 1:1:k
      teller = teller + X1(1,i);
   end

   Qt(k)=teller;
   teller = 0;
end

teken = M;
for k = 1:1:(M-1)
   if((Qt(k)<(P))&&((P)<=Qt(k+1)))
      teken = k;
   end
end

som = Qt(teken);

for s= 1:1:M
   if(teken==M)
      p2(s)=((P)+ Qt(M))-X1(1,s);
   end
end

if (teken<M)
   for i = 1:1:teken
      nn(i) = X1(2:2,i:i);
      ni = nn(i);
      p2(ni)= ((P)+ som)-X1(1,i);
```

```
            end
        end

        s = [1:1:M];
        if(teken<M)
            for uu= 1:1:M
                for yy =1:1:length(nn)
                    if(s(uu)==nn(yy))
                        s(uu)=0;
                    end
                end
            end
        end

        if(teken<M)
            for rr = 1:1:M
                if(s(rr)~=0)
                    p2(rr)=0;
                end
            end
        end

        p1;
    end

    summ = 0;
    for m = 1:1:M
        summ = summ + p1(m);
    end
    i =1;
    for xx=1:1:M
        u(xx) = max(0,(u(xx) - (i)*(1-summ)));
    end
  end
  p1isg(isg:isg,1:M)=p1;
end

%Follower's Preparation

p2 = zeros(1,100);
for him = 1:length(p2)
  p2(him)=0.01;
end

u = zeros(1,100);
for him = 1:length(u)
  u(him)=3;
end

p2isg=zeros(15,M);
```

```
for isg = 1:1:length(sigma2v)
   noise = sigma2v(isg);
   for buiten = 1:1:10
      for m = 1:1:M
         k11x = [k11a(m);k11b(m)];
         k12x = [k12a(m);k12b(m)];
         k22x = [k22a(m);k22b(m)];
         k21x = [k21a(m);k21b(m)];

         wm1 = (inv(p1isg(isg,m)*k12x*(k12x)'+noise*eye(2))*sqrt(p1isg(isg,m))*k11x);
         wm1 = wm1/(sqrt(dot(wm1,wm1)));
         tf1 = isnan(wm1);
         if(tf1(1)==1)
            wm1(1)=0;
            wm1(2)=0;
         end
         rp1(m) = wm1'*k12x*k12x'*wm1;

         yj = @(p2) -
1.*(log2(1+abs(p2.*(((inv(p2.*(k21x*k21x')+noise*eye(2)).*sqrt(p2)*k22x)'*k22x*k22x'*(in
v(p2.*(k21x*k21x')+noise*eye(2)).*sqrt(p2)*k22x))./(dot((inv(p2.*(k21x*k21x')+noise*eye(
2)).*sqrt(p2)*k22x),(inv(p2.*(k21x*k21x')+noise*eye(2)).*sqrt(p2)*k22x))))))./(noise+p1isg(i
sg,m)*abs(rp1(m))))+u(m).*(-1.*p2));
         optimump = fminbnd(yj,0,1);

         p2(m) = max(0,optimump);
      end

      summ2 = 0;
      for m = 1:1:M
         summ2 = summ2 + p2(m);
      end
      i = 1;

      for yy=1:1:M
         u(yy) = max(0,(u(yy) - (i)*(1-summ2)));
      end
   end
   p2isg(isg:isg, 1:M) = p2;
end

 %rates

 for isg = 1:1:length(sigma2v)
    noise = sigma2v(isg);
    srate1 = 0;
    srate2 = 0;

    for m = 1:1:M
```

```
        k11x = [k11a(m);k11b(m)];
        k12x = [k12a(m);k12b(m)];
        k22x = [k22a(m);k22b(m)];
        k21x = [k21a(m);k21b(m)];

        wm1 = (inv(p1isg(isg,m)*k12x*(k12x)'+noise*eye(2))*sqrt(p1isg(isg,m))*k11x);
        wm1 = wm1/(sqrt(dot(wm1,wm1)));
        tf1 = isnan(wm1);

        if(tf1(1)==1)
           wm1(1)=0;
           wm1(2)=0;
        end

        rp11(m)= p1isg(isg,m)*(wm1'*k11x*k11x'*wm1);
        rp12(m)= p1isg(isg,m)*(wm1'*k12x*k12x'*wm1);

        wm2 = (inv(p2isg(isg,m)*k21x*(k21x)'+noise*eye(2))*sqrt(p2isg(isg,m))*k22x);
        wm2 = wm2/(sqrt(dot(wm2,wm2)));
        tf2 = isnan(wm2);

        if(tf2(1)==1)
           wm2(1)=0;
           wm2(2)=0;
        end

        rp22(m)= p2isg(isg,m)*(wm2'*k22x*k22x'*wm2);
        rp21(m)= p2isg(isg,m)*(wm2'*k21x*k21x'*wm2);

        srate1= srate1 + (log2(1+(abs(rp11(m))/(noise+abs(rp21(m))))));
        srate2= srate2 + (log2(1+(abs(rp22(m))/(noise+abs(rp12(m))))));
    end

    rate1(dih,isg) = srate1;
    rate2(dih,isg) = srate2;
end

tp2 = zeros(1,15);
for ik = 1:1:15
    for m = 1:1:M
        tp2(1,ik) = tp2(1,ik) + p2isg(ik, m);
    end
end

tp = zeros(1,15);
for ik = 1:1:15
    for m = 1:1:M
        tp(1,ik) = tp(1,ik) + p1isg(ik, m);
    end
end
```

```
%%Non-Sharing Case%%
%This m-file implements the case where the operators do not share

clear all
close all
clc

M = 100;

%noise levels
for dih = 1:1:1
sigma2v = [(1/10^0.2) (1/10^0.4) (1/10^0.6) (1/10^0.8) (1/10^1.0) (1/10^1.2) (1/10^1.4)
(1/10^1.6) (1/10^1.8) (1/10^2.0) (1/10^2.2) (1/10^2.4) (1/10^2.6) (1/10^2.8) (1/10^3.0)];

%initials
p1slisg = zeros(15,100);
Q = 2;
L = 100;

%Generating the channels
   mich = dih;
   load k11a;
   load k11b;
   load k12a;
   load k12b;
   load k21a;
   load k21b;
   load k22a;
   load k22b;

 mu = 0.8;
 k12a = mu.*k11a + sqrt(1-mu^2).*k12a;
 k12b = mu.*k11b + sqrt(1-mu^2).*k12b;


 k21a = mu.*k22a + sqrt(1-mu^2).*k21a;
 k21b= mu.*k22b + sqrt(1-mu^2).*k21b;

 %operator 1
for isg = 1:1:length(sigma2v)
   noise(isg) = sigma2v(isg);P = 1;
   p1 = zeros(1,100);
   for him = 1:length(p1)
      p1(him)=0.01;
   end
   sum = 0;
   X1 = zeros(2,M);
   %
   for ki = 1:1:80
      for m = 1:1:M
```

```
    k11x = [k11a(m);k11b(m)];
    h11a = k11x/sqrt(dot(k11x,k11x));
    rp11 = abs(h11a'*k11x*k11x'*h11a);
    X1(1,m) = (noise(isg))/(rp11);
    X1(2,m) = m;

    sum = sum + X1(1,m);
 end
 X1;
 maksi = abs(max(X1(1:1,1:M)));
 Rn = abs((P+sum)/M);

if(Rn>maksi)
    for pim = 1:1:M
       carrierm=X1(2,pim);
       p1(carrierm) = Rn-X1(1,carrierm);
    end
 end
 p1;

 mX1 = X1
 mm=M;

 while(Rn<=maksi)
    mm = length(X1);
    mX1 = X1;
    mnX = X1;
    naX1 = X1;
    teller =0;

    for f = 1:1:mm
       for g = 1:1:mm
          if(Rn<=mX1(1,g))
             teller=teller+1;
             index = g;
             mX1(1,index)=-5000;
          end
       end
    end
    A = zeros(1, teller);
    teller = 0;
    mnX
    for f = 1:1:mm
       for g = 1:1:mm
          if(Rn<=mnX(1,g))
             teller = teller+1;
             index = g;
             A(teller)=mnX(2:2,index:index);
             mnX(1,index)=-5000;
          end
```

```
        end
    end
    A;
    K=length(A);
    nleng = mm-K;
    mxX1 = zeros(2,nleng);
    for uu=1:1:K
        for op = 1:1:length(X1)
            fg = A(uu);
            if(naX1(2,op)==fg)
                naX1(1,op)=NaN;
            end
        end
    end
    ind = 1;
    for op = 1:1:length(naX1)
        if(~isnan(naX1(1,op)))
            kin = op;
            mxX1(1:2,ind:ind)=naX1(1:2,kin:kin);
            ind = ind+1;
        end
    end
    mxX1;
    newsum = 0;
    hj= size(mxX1);
    if(hj(2)==1)
        newsum=mxX1(1,1);
    else
        for pp = 1:1:length(mxX1)
            newsum = newsum+abs(mxX1(1,pp));
        end
    end
    newsum
    Rn = abs((P+newsum)/(M-K));

    if(hj(2)==1)
        maksi = abs(mxX1(1,1));
    else
        maksi = max(mxX1(1:1,1:length(mxX1)));
    end
    %     X1 = zeros(2,length(mxX1));
    %     X1=mxX1
end


lemX =length(X1);
X1;
if(hj(2)==1)
    car= X1(2);
    p1(car)=Rn-X1(1);
```

```
        else
            for q = 1:1:lemX
                carrierm(q)=X1(2,q);
                carrierm(q);
                p1(carrierm(q)) = Rn-X1(1,q);
            end
        end
        leA = length(A);
        A
        if(leA>0)
            for w = 1:1:leA
                cm(w) = A(w);
                p1(cm(w)) = 0;
            end
        end
        p1 = abs(p1);
        sum = 0;
    end
    p1;
    p1slisg(isg:isg, 1:M)= p1;
end

%operator 2
p2dir = zeros(15,M);
for isg = 1:1:length(sigma2v)
    noise(isg) = sigma2v(isg);
    P = 1;
    p2 = zeros(1,100);
    for him = 1:length(p2)
        p2(him)=0.01;
    end

    sum = 0;
    X1 = zeros(2,M);
    %
    for ki = 1:1:80
        for m = 1:1:M
%
            k22x = [k22a(m);k22b(m)];
            h22a = k22x/sqrt(dot(k22x,k22x));
%
            rp22 = abs(h22a'*k22x*k22x'*h22a);
            X1(1,m) = (noise(isg))/(rp22);
            X1(2,m) = m;

            sum = sum + X1(1,m);
        end
        X1;
        maksi = abs(max(X1(1:1,1:M)));
        Rn = abs((P+sum)/M);
```

```
if(Rn>maksi)
   for pim2 = 1:1:M
      carrierm2=X1(2,pim2);
      p1(carrierm2) = Rn-X1(1,carrierm2);
   end
end
p2;

mX1 = X1
mm=M;

while(Rn<=maksi)
   mm = length(X1);
   mX1 = X1;
   mnX = X1;
   naX1 = X1;
   teller =0;

   for f = 1:1:mm
      for g = 1:1:mm
         if(Rn<=mX1(1,g))
            teller=teller+1;
            index = g;
            mX1(1,index)=-5000;
         end
      end
   end
   A = zeros(1, teller);
   teller = 0;
   mnX
   for f = 1:1:mm
      for g = 1:1:mm
         if(Rn<=mnX(1,g))
            teller = teller+1;
            index = g;
            A(teller)=mnX(2:2,index:index);
            mnX(1,index)=-5000;
         end
      end
   end
   A;
   K=length(A);
   nleng = mm-K;
   mxX1 = zeros(2,nleng);
   for uu=1:1:K
      for op = 1:1:length(X1)
         fg = A(uu);
         if(naX1(2,op)==fg)
            naX1(1,op)=NaN;
```

```
        end
      end
   end
   ind = 1;
   for op = 1:1:length(naX1)
      if(~isnan(naX1(1,op)))
         kin = op;
         mxX1(1:2,ind:ind)=naX1(1:2,kin:kin);
         ind = ind+1;
      end
   end
   mxX1;
   newsum = 0;
   hj= size(mxX1);
   if(hj(2)==1)
      newsum=mxX1(1,1);
   else
      for pp = 1:1:length(mxX1)
         newsum = newsum+abs(mxX1(1,pp));
      end
   end
   newsum
   Rn = abs((P+newsum)/(M-K));

   if(hj(2)==1)
      maksi = abs(mxX1(1,1));
   else
      maksi = max(mxX1(1:1,1:length(mxX1)));
   end
   %     X1 = zeros(2,length(mxX1));
   %     X1=mxX1
end


lemX =length(X1);
X1;
if(hj(2)==1)
   car= X1(2);
   p2(car)=Rn-X1(1);
else
   for q = 1:1:lemX
      carrierm(q)=X1(2,q);
      carrierm(q);
      p2(carrierm(q)) = Rn-X1(1,q);
   end
end
leA = length(A);
A
if(leA>0)
   for w = 1:1:leA
```

```
            cm(w) = A(w);
            p2(cm(w)) = 0;
          end
        end
        p2 = abs(p2);
        sum = 0;
    end
    p2;
    p2dir(isg:isg, 1:M)= p2;
end


%%Rates
sigma2v = [(1/10^0.2) (1/10^0.4) (1/10^0.6) (1/10^0.8) (1/10^1.0) (1/10^1.2) (1/10^1.4)
(1/10^1.6) (1/10^1.8) (1/10^2.0) (1/10^2.2) (1/10^2.4) (1/10^2.6) (1/10^2.8) (1/10^3.0)];
p2slisg = zeros(15,100);
Q = 2;
L = 7;
for isg = 1:1:length(sigma2v)
    noise(isg) = sigma2v(isg);

    toplam1 = 0;%herbir noise icin ayri bir toplam var
    toplam2 = 0;
    for m = 1:1:M
        k11x = [k11a(m);k11b(m)];
        k12x = [k12a(m);k12b(m)];
        k22x = [k22a(m);k22b(m)];
        k21x = [k21a(m);k21b(m)];

        h11a = k11x/sqrt(dot(k11x,k11x));
        h22a = k22x/sqrt(dot(k22x,k22x));
        rp11(m)= p1slisg(isg,m)*abs(h11a'*k11x*k11x'*h11a);
        rp22(m)= p2dir(isg,m)*abs(h22a'*k22x*k22x'*h22a);

        toplam1 = toplam1+ (log2(1+(abs(rp11(m))/(noise(isg)))));
        toplam2 = toplam2+ (log2(1+(abs(rp22(m))/(noise(isg)))));
    end

    rate1sl(dih,isg) = toplam1;
    rate2sl(dih,isg) = toplam2;
end
end


tp2 = zeros(1,15);

for ik = 1:1:15
for m = 1:1:100
    tp2(1,ik) = tp2(1,ik) + p2dir(ik, m);
end
```

```
end

tp2

tp = zeros(1,15);
for ik = 1:1:15
    for m = 1:1:100
        tp(1,ik) = tp(1,ik) + p1slisg(ik, m);
    end
end

tp
```