Cooperative Spatial Reuse with Transmit Beamforming

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Abstract

During the last years, the interest for WLAN which is present in homes and in many public places, is growing very fast but it still has issues. New techniques to improve WLAN have appeared such as multiple antenna techniques. In this project we want to show whether or not and how a cooperative scheme could be more efficient than the WLAN's classical TDMA-based MAC using multiple antennas. We choose to study the CSR scheme with the use of multiple antennas at the transmitter side, which allows simultaneous transmissions. Concretely, we compare the performance between the traditional MRC-TDMA transmit beamforming to the ZF-CSR transmit beamforming. We want to find out which one of these two schemes is better and when it is better with respect to the effective capacity.

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List of Abbreviations

AoA	Angle of Arrival
AoD	Angle of Departure
AP	Access Point
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CSR	Cooperative Spatial Reuse
EGC	Equal Gain Combining
FDMA	Frequency Division Multiple Access
IID	Independent Identically Distributed
ISI	Intersymbol Interference
LLC	Logical Link Control
LOS	Line Of Sight
MAC	Medium Access Control
MRC	Maximal Ratio Combining
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
OSI	Open Systems Interconnection
PDF	Probability Distribution Function

RF	Radio Frequency
SC	Selection Combining
SDMA	Space Division Multiple Access
SIMO	Simple Input Multiple Output
SISO	Simple Input Single Output
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
UE	User Equipment
WLAN	Wireless Local Area Network
ZF	Zero-Forcing

List of Symbols

B	bandwidth
C	channel capacity
d	space between each element of the antenna array
E_s	signal energy
F	array factor
G_j	gain at the j^{th} branch
h_j	channel coefficient at the j^{th} branch
$\mathbf{h}_i$	channel vector of the i^{th} MISO link
K_B	Boltzman's constant
L	losses
n_i	noise from the i^{th} number of links
n_j	noise from the j^{th} branch
N_k	number of receivers
N_R	number of receive antennas
N_T	number of transmit antennas
P	pathloss
P_{IM}	power consumption in idle mode
P_n	noise power
P_{RM}	power consumption in receiving mode
P_s	signal power
P_{TM}	power consumption in transmitting mode
P_{XM}	power consumption in transmitting or receiving mode
$r_j(t)$	received signal at the j^{th} branch
r_i	link capacity at the time slot owned by the i^{th} link in TDMA-based MAC
r_i'	link capacity at the time slot owned by the i^{th} link in CSR
r_{SN_R}	sum of N_R received signals

R_i	mean effective capacity at the time slot owned by the i^{th} link in TDMA-based MAC
R_i'	mean effective capacity at the time slot owned by the i^{th} link in CSR
SE	spectral efficiency
s_j	transmitted signal at the j^{th} branch
S_n	power spectral density of the noise after MRC
S_{CSR}	CSR capacity region
T_e	temperature
T_i	the length of the time slot of the i^{th} link
$\mathbf{w}_j$	complex weight at the j^{th} branch
γ	pathloss exponent
γ_{N_R}	SNR of the N_R received signals
λ	wavelength
μ	mean
σ_F	standard deviation
θ	Angle of Departure (AoD) or Angle of Arrival (AoA)

Preface

This report is the result of the 10^{th} semester project work carried out between 1^{st} February and 31^{st} May 2007 by the students of the Mobile Communications group 07gr1111 at the Department of Communication Technology, Aalborg University, Denmark.

Lists of figures, symbols and abbreviations are also presented at the beginning. In this report, citations are presented in the form "[reference]", where 'reference' can be seen in the bibliography.

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Acknowledgement

We would like to express our gratitude to our supervisors Frank H.P. Fitzek and Chenguang Lu for their valuable guidance throughout this project. Their inquisitiveness and motivation helped us a lot in developing this report. We would also like to thank the people who directly or indirectly helped us to accomplish this project.

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Chapter 1

Introduction

1.1 Motivation

Nowadays, Wireless Local Area Network (WLAN) is one of the most used wireless techniques worldwide relying on Radio Frequency (RF) transmissions. WLAN is popular because it is simple to deploy, it is cheap, it provides high data rates (54 Mbps), it is reliable and moreover, it can cover a reasonable area without the use of any cables. In spite of the fact that it provides mobility and a high flexibility, WLAN is subject to different issues such as multipath or interferences which implies limited connectivity and limited capacity (in crowded wireless activity areas).

On one side, multiple antennas techniques which are well known to mitigate the fading effects, can improve the capacity of WLAN thanks to several techniques:

- Diversity: obtained when the signal is transmitted (or received) under several independent paths in order to get independent signal replicas.
- Array Gain: referred as the increase of the SNR at the receiver side.
- Interference Cancelation: provides a higher spectrum efficiency by limiting co-channel interferences.

These antenna techniques are known as Multiple Input Multiple Output (MIMO), Multiple Input Single Output (MISO) and Simple Input Multiple Output (SIMO).

On the other side, the current method exploiting multiple antennas is using it solely on a single link in the TDMA method, which means that the multiple antennas' capabilities are not fully exploited.

Nevertheless, in dense networks like hotspot locations, the frequency spectrum is crowded and the co-channel interferences are high. Since the communicating nodes are close to each other, they are not allowed to operate at the same time. With interference cancelation provided by the Zero-Forcing (ZF) technique, the spatial reuse can be enabled where the transmitters in the co-channel hotspots can transmit simultaneously. Spatial reuse refers to the scheduling of multiple (mutually non-interfering) transmissions simultaneously when all the links are operating in the same channel.

Following the cooperation principle, the Cooperative Spatial Reuse (CSR) is proposed in [1] as an extension of the TDMA-based MAC enabling spatial reuse. In this project, we compare the ZF-CSR beamforming technique to the Maximal Ratio Combining (MRC)-TDMA beamforming technique. ZF-CSR gives the capability to each node to target their receiver in a coordinated way thanks to their multiple antennas and their cooperation abilities. This way, by sharing their time slots, the transmitters can transmit data simultaneously. When data are transmitted at the same time, we can expect a raise of the overall capacity compared to the MRC- TDMA scheme.

Our goal is to find out which of the two schemes presented above is better. So, we are going to study them through two points:

- Firstly, we will study how difficult it is to establish a beneficial cooperative group.
- Secondly, we will study the capacity gain of the cooperating links.

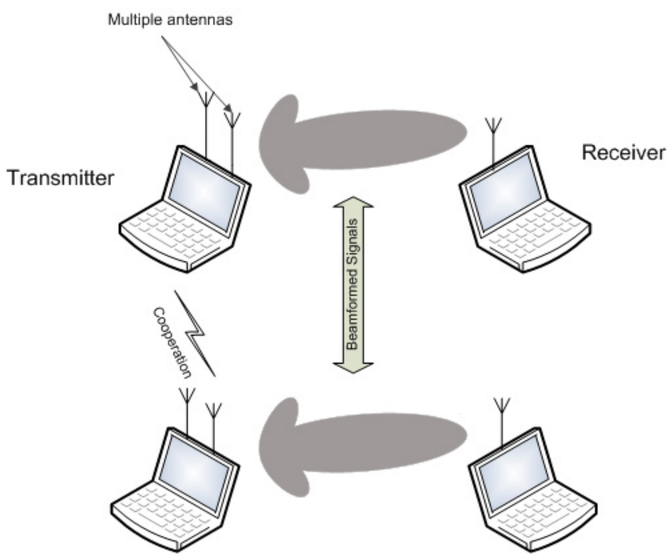

Figure 1.1: Example of CSR in a dense area network.

In Figure 1.1, there is an example of CSR's application. In the next section, the summary of what was done in the project is presented.

1.2 Project Overview

Although several studies have already been done on spatial reuse, very few of them propose a cooperative scheme to allow the use of spatial reuse in multi-rate networks. In this project, we have extended a previous work comparing ZF-CSR with transmit beamforming to classical MRC-TDMA beamforming technique. We investigate two scenarios:

- Scenario 1: 2 cooperating links.
- Scenario 2: 3 cooperating links.

In these two scenarios, the following parameters vary:

- the Rician channel model in order to see the Line Of Sight (LOS)'s effects,
- the number of antennas, and
- the SNRs among the links.

As said before, we expect ZF-CSR to be beneficial compared to the MRC-TDMA beamforming technique. We want to find out until what point it is better and what are its assets too. We do know some of its disadvantages of course. For instance, in narrow-band channels, the transmitting power in a ZF-CSR link will be lower than the one transmitted by a beamformer relying on MRC-TDMA. This is because we want to avoid as much interference as possible since the nodes are close to each other. So the capacity will be directly correlated to it. Moreover, we know that overhead due to cooperation can penalize ZF-CSR. But to what extend?

Finally, our task is to study these two different scenarios and to evaluate their performance in order to find out whether or not ZF-CSR should be used.

1.3 Outline of the Report

Chapter 2 gathers all the necessary background knowledge to understand the project. In Chapter 3, a very complete problem description is done, where the CSR scheme is detailed. The channel model, the simulation parameters, the two scenarios and the results are developed in Chapter 4. The conclusion is done in Chapter 5.

Chapter 2

Background

2.1 Basics of Wireless Networks

A wireless network is a network in which at least two terminals (laptop, mobile) are able to communicate together without using a cable as a medium. Thanks to the wireless networks two (or more) terminals can stay in touch even if they are moving. It is the notion of mobility. Nowadays, wireless networks are everywhere, they are classified as infrastructure and ad-hoc networks.

Communication always implies two parts: the transmitter and the receiver. Take for example a wireless network shown in the figure below:

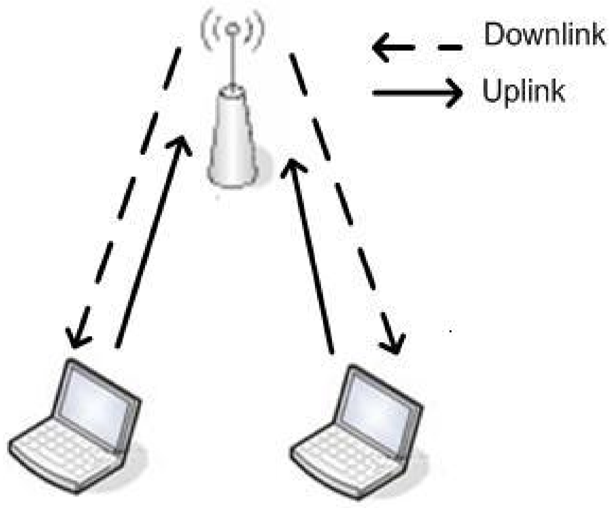

Figure 2.1: Wireless Network

The link from the Access Point (AP) to the User Equipment (UE) is called downlink (the AP sends data to the UE) and the link from the UE to the AP is called uplink (the UE sends data to the AP). So this example shows that each terminal (the AP or the UE) acts sometimes as a receiver and sometimes as a transmitter. The following section explains how the transmission is organized in the network stack.

2.2 Medium Access Control (MAC)

The MAC sublayer shares with the Logical Link Control (LLC) sublayer, the second layer of the Open Systems Interconnection (OSI) protocol stack model, so called Data Link layer. The LLC mainly deals with the frame synchronization, the flow control and the error checking. The MAC mainly deals with how to access to data and give the permission whether to transmit it or not.

OSI layers	Functions
Application layer	It is used when one computer starts communicating with another computer
Presentation layer	It is used to define the data representation and the encryption
Session layer	It is used to deal with interhost communication
Transport layer	It is used to order and to reassemble packets
Network layer	It is used for the path determination and for the the logical addressing
Data Link layer	It us used to provide one or more link between two entities (Physical addressing usingMAC and LLC)
Physical layer	It is used to deal with the physical aspects of the media being used to transmit the signal

Figure 2.2: OSI Layers [2].

In theMAC sublayer, a protocol to allow each user to communicate avoiding interference is needed. To meet this requirement, there are two main kinds of multiplexing techniques that can be classified as [3]:

- Static: For these kinds of protocols the channel's capacity is divided or shared into fixed portions. So for each user, a portion is allocated for all time. If one or many users have no data to send in their portions, then the portions go unused. Some of these fixed protocols are TDMA, FDMA, CDMA... Static protocols perform better when the traffic is predictable.

- Dynamic protocols: For these kinds of protocols, the allocation of the channel's capacity is done based on the amount of traffic generated by users. These kinds of allocations perform better when the traffic is unpredictable.

The main parameters for the MAC sublayer are [4]:

- Delay: average delay experienced by a packet during the transmission.
- Fairness: how well the MAC protocol shares the bandwidth among all users.
- Multimedia support: how well the protocol supports different types of traffic (e.g. real-time, high-priority data, etc.).
- Power consumption: how well the protocol saves power.
- Robustness: how well the protocol resists to channel fades.
- Stability: how well the protocol performs under load fluctuations.
- Throughput: average number of data that have been successfully transmitted per unit of time.

2.3 Multiple Access techniques

Multiplexing is a process in which multiple channels are combined for transmission over a single circuit or a common transmission path.

2.3.1 Time Division Multiple Access (TDMA)

This technique is one of the most commonly used in GSM systems and it is also one of the oldest multiplexing techniques [5]. In this technique, the time axis is divided into time slots of a fixed length. For each user a fixed set of time slots is allocated to transmit. By this process TDMA allows several users to share the same medium of communication using the same frequencies by dividing it into several time slots. So one after the other, each user will transmit during his allocated times slots. But if one user has nothing to send then the time slot goes unused. TDMA requires a time synchronization (extra overhead bits are needed to perform it) and requires also a guard time between time slots to separate users (to reduce cross-talk).

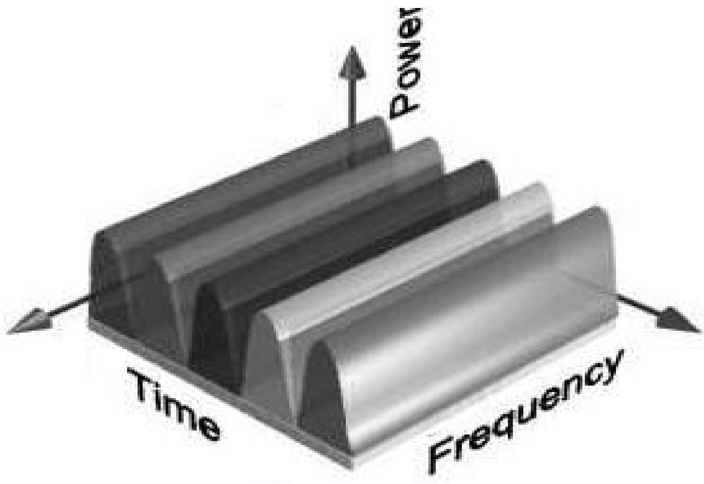

Figure 2.3: TDMA schema [6]

Some TDMA advantages are:

- This technique is cheaper because no narrowband filters are needed.
- This technique allows the save of battery power by turning off transmitter and/or receiver during slots when not transmitting or receiving data.
- This technique is bandwidth efficient, because it can allocate multiple time slots to a user to provide increased data rate.

2.3.2 Frequency Division Multiple Access (FDMA)

This technique, as TDMA, is one of the most commonly used and oldest multiplexing techniques [5]. In this technique the radio spectrum is broken into some frequency bands, which means that the available frequency bandwidth is divided into disjoint frequency bands, each one is then allocated to one user (only one user per frequency band).

So each user can transmit as long as it needs to, on its own bandwidth to transmit. Few synchronizations are needed because in FDMA the transmission is continuous (overhead are reduce compare to TDMA). However this technique requires expensive filters to reduce adjacent channel interference. This protocol requires a guard band between user frequency bands to avoid cross-talk.

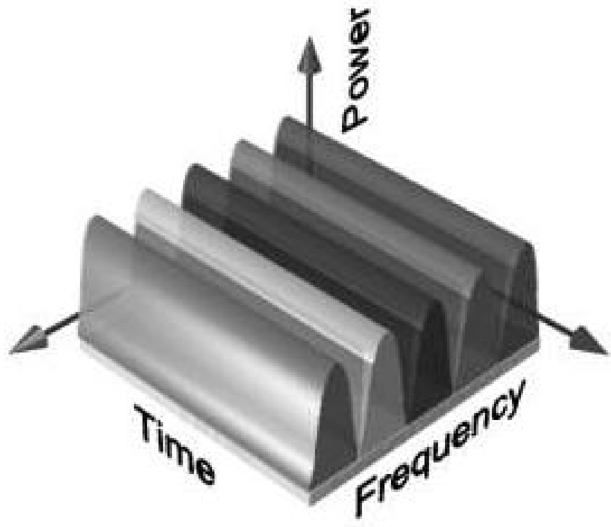

Figure 2.4: FDMA schema [6]

2.3.3 Code Division Multiple Access (CDMA)

This is a spread spectrum technique, used in many wireless networks. It allows several users to use the same time and frequency allocations in a given space or band by assigning unique codes to each communication. Indeed, in CDMA the data are encoded using a different code given to each specific channel. Some CDMA advantages are [7]:

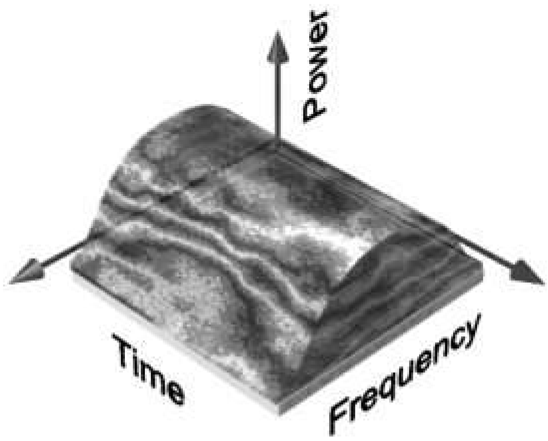

Figure 2.5: CDMA schema [6]

- Coverage: it is between 1.7 and 3 times higher than in TDMA thanks to the power control. And also the coding and interleaving allows the CDMA to cover with the same amount of available power a larger area than other systems.
- Capacity: up to 4 times higher than TDMA because the users are separated thanks

to codes and not thanks to frequencies. And also thanks to the power control (less interference leads to an augmentation of the capacity).

2.3.4 Space Division Multiple Access (SDMA)

SDMA is an interesting multiplexing technique to increase the capacity of wireless communication systems. Furthermore, it can be mixed with other multiple access techniques (TDMA, FDMA and CDMA) to increase their performance with respect to the capacity. This technique allows several users to use the same frequency band and time slot at the same time by separating them thanks to their own position. So the idea to "spatially" distinguish users, is to divide the space in several smaller regions using antenna-array processing and advanced digital signal processing techniques to reduce co-channel and/or inter-users interference. SDMA can be obtained by using beamforming weights based

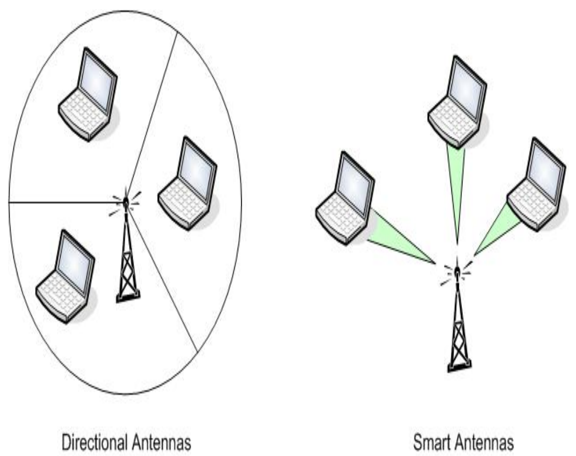

Figure 2.6: SDMA schema [5]

upon the spatial signature of each user. This technique requires efficient algorithms to deal with its computational requirements.

The next section develop the impairments related to the wireless transmission.

2.4 Channel Impairments and Characteristics

The transmission path between the transmitter and the receiver varies with respect to the environment of propagation. Indeed, in the best cases the receiver is in the LOS and in the worst cases, the transmission path is critically obstructed by natural environment's reliefs (mountains, hills, forest...) and also by buildings in cities [8].

2.4.1 Path Loss

Path loss is the attenuation that a signal (electromagnetic wave) undergoes while it has been transmitted over the wireless channel as illustrated in Figure 2.7. It's a positive quantity in dB, usually defined as the difference between the transmitted power and the received power. As mentioned by its name, the path loss is related to the path and then

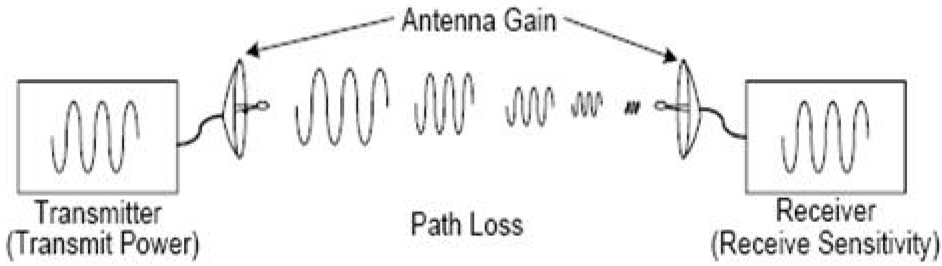

Figure 2.7: A Path Loss Representation [9]

depends on:

- Reflection: This phenomenon occurs when a wave impinges upon surfaces of obstacles which dimensions are very large compared to the wave's wavelength (building's walls/windows, ground...)
- Diffraction: This occurs when a wave impinges upon edges. It allows waves to be propagated behind obstacles.
- Scattering: This occurs when a wave impinges upon surfaces of obstacles which sizes are very small compared to the wave's wavelength (often induced when impinging a rough surface).

Refraction and absorption of the signal are some of the factors on which the path loss also depends on. Surrounding environment, terrain, and the distance between the transmitter and the receiver are also some of the important causes of path loss. More details on these topics can be found in [8]. In the simplest form the pathloss can be calculated from Equation 2.1:

$$P = 10\gamma \log d + L \tag{2.1}$$

In the equation above, P is the pathloss in dB, d is the distance between the transmitter and the receiver, γ is the pathloss exponent and L is a constant that accounts for losses occurring due to penetration through the walls of the buildings, absorption in human body etc. It also depends on antenna parameters such as antenna gain, elevation etc. [11].

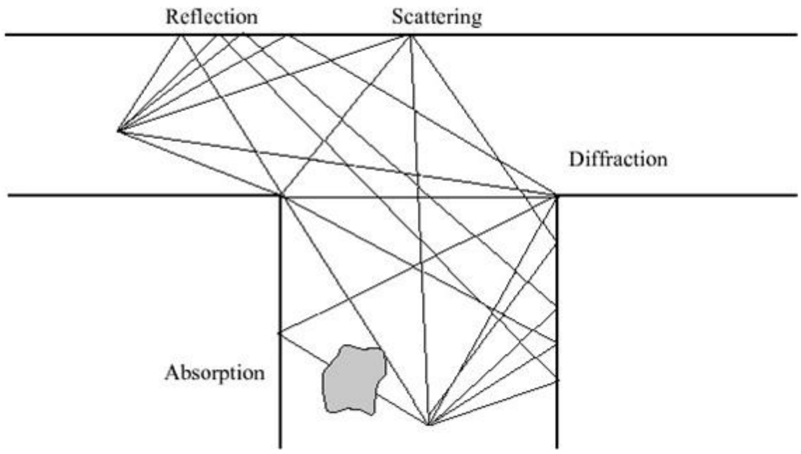

Figure 2.8: Ray mechanisms near a street corner [10]

2.4.2 Shadowing

If the received field strength due to small scale fading is averaged over a small area of the order of tens of wavelength, it is observed that this received field strength, if plotted on a logarithmic scale, follows a Gaussian distribution and has a mean μ. This distribution is called as a log-normal distribution and its PDF is:

$$pdf_F(F) = \frac{20/ln(10)}{F\sigma_F\sqrt{2\pi}} exp\left[-\frac{(20log_{10}(F) - \mu_{dB})^2}{2\sigma_F^2}\right] \tag{2.2}$$

where σ_F is the standard deviation of F, and μ_{dB} is the mean of the values of F expressed in dB (the median value of pathloss calculated in Equation 2.1) [12].

Typical values of σ_F are 4 to 10 dB. This log-normal distribution describes the shadowing effects that occurs over a large number of locations which have the same transmitter-receiver distance but different types of clutter on the propagation path.

2.4.3 Small-Scale Fading

Small-scale fading or short term fading is the description of the fast fluctuations of the amplitude of a signal averaged over small distances like in the order of a single wavelength. It is caused by two different reasons. The first reason is multipath. The idea is that there are various scatterer elements between the transmitter and the receiver, which reflect the electromagnetic signal resulting in out-of-phase components arriving at the receiver with different delays [8]. In some systems, a direct LOS path between the transmitter and the receiver may exist, but often in some urban and indoor environments, there is no LOS

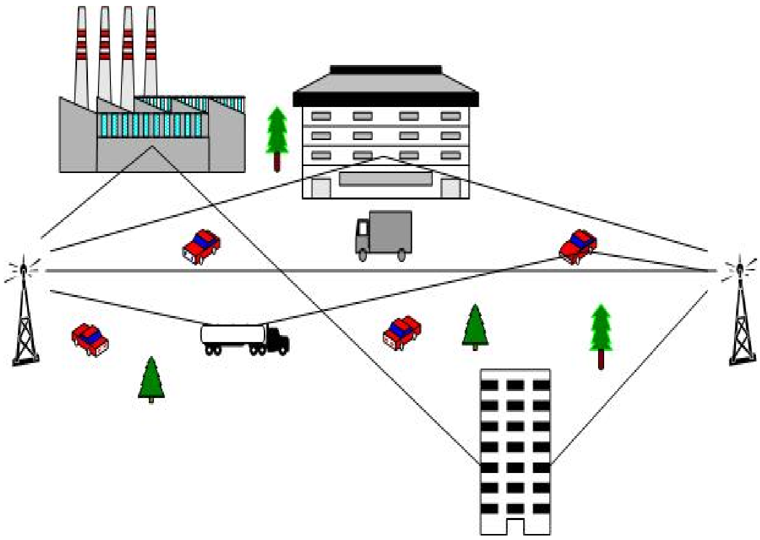

Figure 2.9: Multipath scheme

path possible. Multiple transmitted signals arrive at the receiver, some of these signals experiencing some reflections, refractions, and/or diffractions, with respect to their own transmission path. However, in many urban and indoor environments, even if there is a direct LOS path between the transmitter and the receiver, there will also be many other signals arriving at the receiver. These signals arriving at the receiver will have random amplitudes and phases. It is this phenomenon which gives rise to multipath fading, because the signals adds to each others destructively or constructively depending on the location [13].

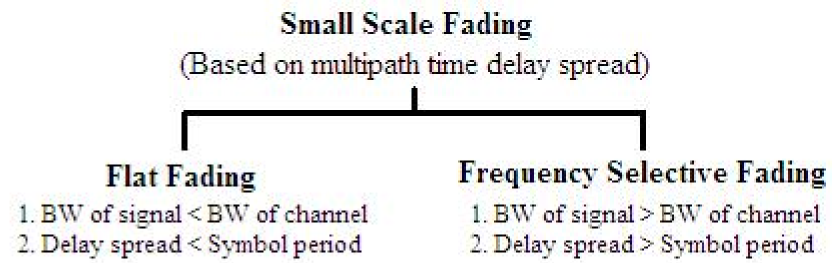

Figure 2.10: Small Scale Fading Based On Multipath Time Delay Spread [8]

The other contribution is due to the movement of the transmitter, receiver, or scattering elements in the channel itself, which is comparable to the wavelength of the operating frequency. This phenomenon is called the Doppler shift [8]. Small-scale fading refers to the dramatic changes in signal amplitude and phase that can be experienced as a result of small changes in the spatial separation between receiver and transmitter. Small-scale

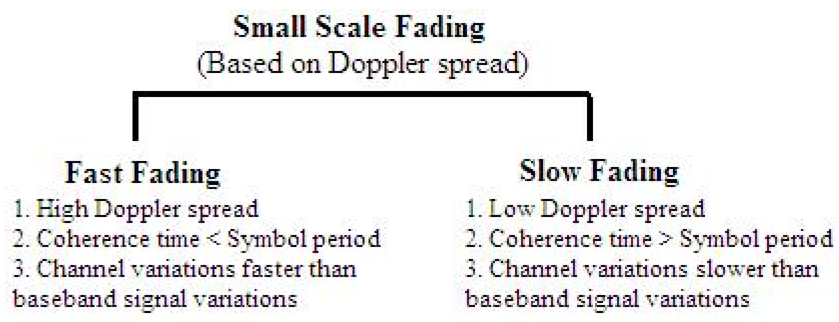

Figure 2.11: Small Scale Fading Based On Doppler Spread [8]

fading is also called Rayleigh Fading because if the multiple reflective paths are large in number and if there is no LOS signal component, the envelope of the received signal is statistically described by a Rayleigh probability density function.

2.4.4 Noise and Interference

Noise is an undesired electromagnetic energy that deteriorates the quality of the signal and it occurs in both analogical and digital systems. This is the most common problem faced by signal transmission through any channel. It is often generated at the front end of the receiver due to the thermal agitation of electronic components. It is usually called as *thermal noise*. *Thermal noise* can be calculated from the equation below as [14]:

$$P_n = K_B * Te * B \tag{2.3}$$

where P_n is the noise power in Watts, K_B is the Boltzman's constant, T_e is the temperature and B is the system bandwidth.

Furthermore, in addition to the noise, all electromagnetic waves suffer from interference from other systems and/or Intersymbol Interference (ISI) due to the multipath effects [14]. Interference is an undesired signal received along with the desired signal. There is a noticeable difference between noise and interference, indeed the noise does not suffer from fading whereas interference does [12]. Moreover, noise and interference from other users are uncorrelated from signal, whereas ISI are correlated.

2.4.5 Some Channel Characteristics

There are many ways to evaluate the quality of a wireless transmission. The most important characteristics are:

- Signal to Noise Ratio (SNR): SNR is a measurement which permits an evaluation of the signal's strength. It is defined as the ratio between the received signal power and the noise power:

$$SNR = (\frac{P_s}{P_n}) \tag{2.4}$$

  where P_s denotes the signal power and P_n denotes the noise power.

- Channel Capacity: Channel Capacity is an important issue of a wireless link. It represents the maximum data rate that can be transmitted over the channel, with arbitrarily low error probability. It is given by the Shannon's formula [14]:

$$C = Blog_2(1 + SNR) \tag{2.5}$$

  where C denotes the capacity and B denotes the bandwidth of the system.

- Spectral Efficiency: Spectral efficiency is the optimized use of bandwidth so that the achievable amount of data can be transmitted with the fewest transmission errors [14]. It is normalized with the bandwidth:

$$SE = log_2(1 + SNR) \tag{2.6}$$

2.5 Diversity and Combining Techniques

Diversity combining is a well known technique to mitigate the multipath fading. This can be applied at the base station or at the user equipment.

2.5.1 Diversity Techniques

Diversity is a communication receiver technique which provides significant link improvement. The principle is very simple: the receiver receives the signal via more than one hopefully uncorrelated (ideally independent) channel. If the signal from one channel path is under a deep fade, there is a high probability that the signals from the other channel paths are not under a deep fade. In this way, the probability that the receiver will get the signal correctly increases.

Diversity can be classified as of two types, Microdiversity and Macrodiversity. Microdiversity mainly deals with the mitigation of small scale fading while Macrodiversity helps in mitigating the effect of large scale fading. Our focus is on Microdiversity. Independent samples of the signal can be obtained in order to mitigate small-scale fading in a number of ways. Some of them are given below [12] [15]:

- Temporal diversity: In this method, independent samples are obtained by repeating the transmission after a time interval.
- Frequency diversity: In this method, independent samples are obtained by transmitting at different frequencies. This is not a viable option because of the inefficient utilization of the frequency spectrum.
- Polarization diversity: The propagation effects in wireless channels depolarize the transmitted signal. Differently polarized signals undergo independent fading. This fact is used in polarization diversity. This method is also not so attractive if sufficient depolarization is not guaranteed by the transmission path in order to achieve this diversity.
- Field diversity: The fact that the electric and magnetic components of the field at any point are uncorrelated, is used in this technique to achieve the benefit of diversity. Difficulty in designing the antennas for field diversity makes this technique difficult to implement.
- Spatial diversity: In this method, signals are obtained from two or more physically separated antennas. The antenna elements are separated so that the received signals shall be least correlated. A distinction can be done based on whether diversity is applied to the transmitter or to the receiver [16]:
  - Receive diversity: It occurs when the receiver has more than one antenna. In this case, to improve the signal quality, some combining techniques are applied. However, as they are used at the receiver side they also amplify the noise.
  - Transmit diversity: It occurs when the transmitter has more than one antenna. In this case more than one copy of the signal is sent from the transmitter, which can be then exploited at the receiver.

As MIMO systems have more than one antenna at both transmitter and receiver side, they exploit transmit diversity schemes as well as receive diversity schemes.

2.5.2 Combining Techniques

Once the appropriate versions of the signal are received, the next task is to combine these versions together to get the maximum benefit. Most of the combining techniques are linear [15] [17]. In linear combiners, different signals are weighted individually and then added together. This leads to post-detection combiners in which the addition is done af-

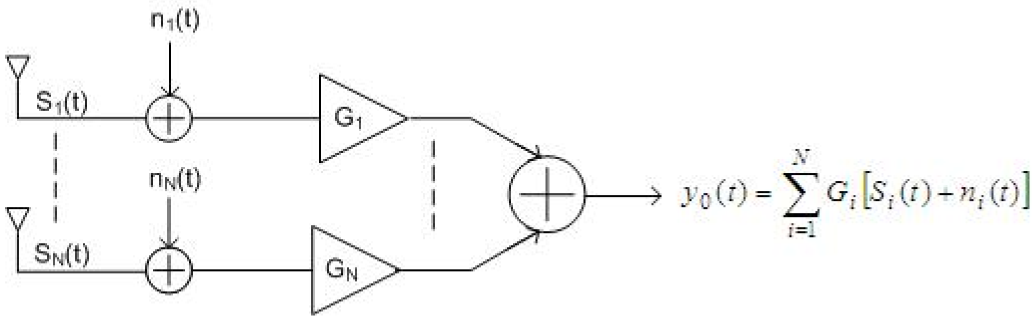

Figure 2.12: Structure of the receiving device with N antennas [18]

ter detection, and pre-detection combiners in which the addition is done before detection. Generally three types of combining techniques are used [15]:

- Selection Combining (SC): This is the simplest of all the techniques. The basic idea of SC is that the signal with the highest instantaneous SNR is selected, so the output of the combiner is equal to the best incoming signal. One advantage of SC is that it does not need any additional RF receiver chain (all receive antennas share the same).

- Maximal Ratio Combining (MRC): In this method, all the N_R received signals are weighted proportionately to their individual SNRs and then summed (Figure 2.13). The individual signals must be co-phased before combining if it takes place before

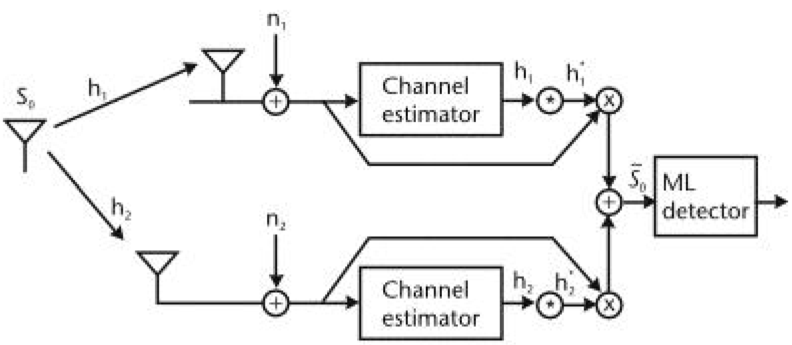

Figure 2.13: MRC with $1 \times Tx$ and $2 \times Rx$ [16]

demodulation. Contrarily to SC, MRC requires individual RF receiver tracts. Let's assume that the signals received at each branch are:

$$r_j(t) = h_j s_j(t) + n_j(t) \tag{2.7}$$

where $s_j(t)$, which is equal to $2E_s$, is the transmitted signal, $n_j(t)$ is the noise from the j^{th} branch and has a power spectral density of $2N_0$ and h_j is the channel coefficient. Let's assume that each branch has a gain G_j, we can write [16]:

$$r_{N_R} = \sum_{j=1}^{N_R} G_j r_j(t) \tag{2.8}$$

$$r_{N_R} = \sum_{j=1}^{N_R} G_j h_j s_j(t) + \sum_{j=1}^{N_R} G_j n_j(t) \tag{2.9}$$

The power spectral density of the noise after MRC is given by [16]:

$$S_n = 2N_0 \sum_{j=1}^{N_R} |G_j|^2 \tag{2.10}$$

The instantaneous signal energy is:

$$2E_s|\sum_{j=1}^{N_R} |G_j h_j|^2| \tag{2.11}$$

So we can write the SNR as:

$$\gamma_{N_R} = \frac{2E_s|\sum_{j=1}^{N_R} |G_j h_j|^2|}{2N_0 \sum_{j=1}^{N_R} |G_j|^2} \tag{2.12}$$

If we assume a perfect channel knowledge ($G_j = h_j$), the SNR per antenna becomes:

$$\gamma_{N_R} = \frac{E_s}{N_0} \sum_{j=1}^{N_R} |G_j|^2 \tag{2.13}$$

MRC is a powerful technique which shows its best result with a perfect channel knowledge.

- Equal Gain Combining (EGC): This is much similar to MRC. The only difference is that the signals are not weighted before addition.

2.6 Multi-Antennas Systems

To continue, a brief overview of the different antenna configurations possible is needed.

- Simple Input Single Output (SISO): is the simplest wireless configuration, there is one antenna at both the transmitter and the receiver side.
- Simple Input Multiple Output (SIMO): uses a single antenna transmitter and a multiple antennas receiver.
- Multiple Input Single Output (MISO): in this system there is a multiple antennas transmitter and a single antenna receiver.
- Multiple Input Multiple Output (MIMO): has multiple antennas at both the transmitter and the receiver side. All these configurations are clearly illustrated in Figure 2.14.

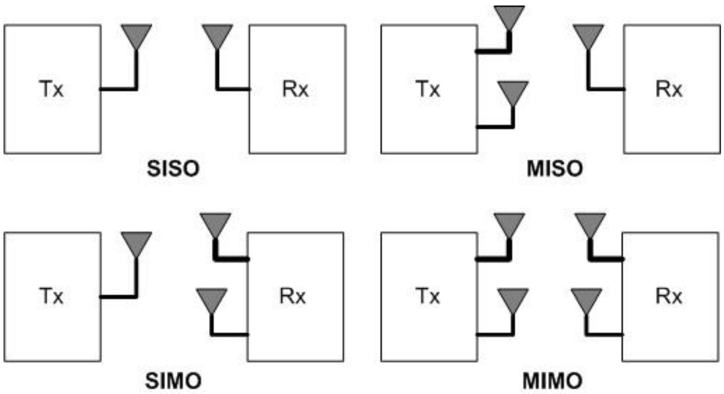

Figure 2.14: Multi-Antennas Configurations

In this project the multi-antennas configurations used is MISO.

2.7 Multiple Input Single Output (MISO)

Use of multiple antennas at the transmitter and/or receiver in wireless networks is well known to mitigate the fading effects, so it becomes a rapidly emerging technology that allows higher data rates at longer ranges without consuming extra bandwidth or transmit power. As seen above, this technology gives a wide variety of options (SIMO,MISO and MIMO). However, we have to make the distinction between two cases:

- When the transmitter does not know the channel: a pre-processing method known as space-time coding is used to achieve diversity gain, but not array gain. Space-time coding is a method used to increase the reliability of data transmission in multiple transmit antennas wireless communication systems. Its principle is to transmit several copies of signal in the hope that some of them will arrive to the receiver with a good signal strength.

- When the transmitter knows the channel, beamforming can be performed using various optimization metrics (SNR, SINR, etc.) to achieve both diversity and array gains.

In our project for example, we use a beamforming technique called transmit MRC which is a powerful antenna diversity technique that as said above, exploits both spatial diversity and array gain. In our MISO scenarios, the transmitter optimally weights the transmitted data stream across its antennas to maximize the received SNR. The use of a MISO system makes us benefit from array gain and diversity gain.

2.7.1 Array Gain

Array gain is defined as the increase of the SNR at the receiver side that appears from the coherent combining effect of multiple antennas at the receiver or at the transmitter or at both [16]. More accurately, array gain can be exploited in systems with multiple antennas at the transmitter by using beamforming. On a CDF plot, as can be seen in Figure 2.15 the array gain can be read at 50%, it used to be equal to the number of transmit antennas, here the array gain is equals to $4dB$.

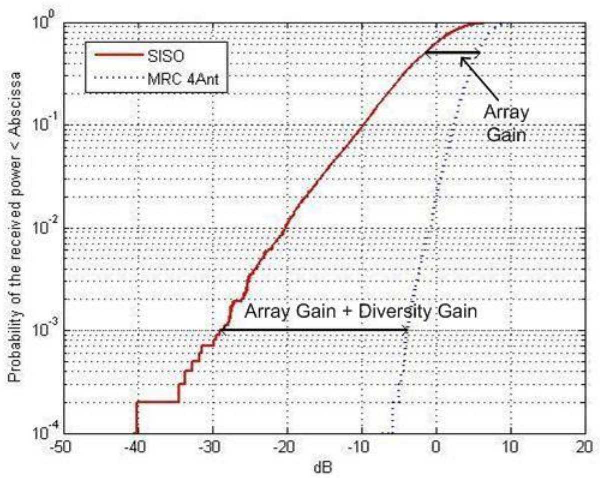

Figure 2.15: Diversity gain and array gain of MRC in a 4 transmit antennas MISO case, compared to SISO, 2 links, uncorrelated narrowband channel

2.7.2 Diversity Gain

As said before in wireless channel, the strength of a signal fluctuates with respect to the time, the frequency and the space. When the signal power drops dramatically, the channel is said to be in a fade. The diversity gain is the gain obtained from diversity, which is a well known technique to combat fading. As explained in Section 2.5.1, the diversity principle is very simple: the receiver receives the signal via more than one hopefully uncorrelated (ideally independent) channel. In this way the probability that the receiver will get the signal correctly increases.

In MISO systems, transmit diversity is applicable and does not necessarily require channel knowledge at the transmitter. However, suitable design of the transmitted signal is required to extract diversity. Space-time coding is a powerful transmit diversity technique that relies on coding across time and space to get diversity. Figure 2.16 shows a MISO system with 4 transmit antennas and 1 receive antenna.

The diversity gain can be seen on a CDF plot, as Figure 2.15. Indeed, the diversity gain can be seen by the difference of slope between the two curves and can also be read at $10^{-3}\%$ as illustrated in Figure 2.15.

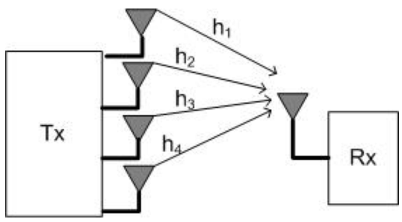

Figure 2.16: MISO Channel Configurations

2.8 Beamforming

Beamforming is the combination of radio signals from a set of small non-directional antennas to simulate a large directional antenna [19]. The simulated antenna obtained can be pointed electronically, this means that the antenna does not have to physically move. In wireless communications, the beamforming technique is commonly used to point a receiving antenna at the signal transmitter to reduce interference and then to increase communication quality.

In beamforming, both the amplitude and phase of each antenna element are controlled [19]. Indeed, by combining both amplitude and phase control side lobe levels and steer

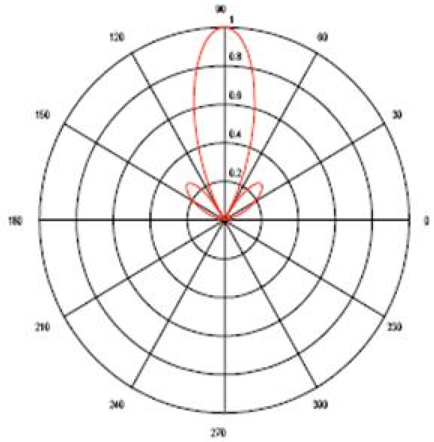

Figure 2.17: Radiation pattern of a 1.5 wavelength, 4 element array [19]

nulls can be adjusted better than if phase control is used alone. For each antenna, the combined relative amplitude and the phase shift is called complex weight $\mathbf{w}_j$ (complex constant). As can be seen on Figure 2.18, beamforming used at the transmitter side applies the complex weight to the transmitted signal. This means that for each antenna element of the array, the beamformer sets the amplitude and shifts the phase.

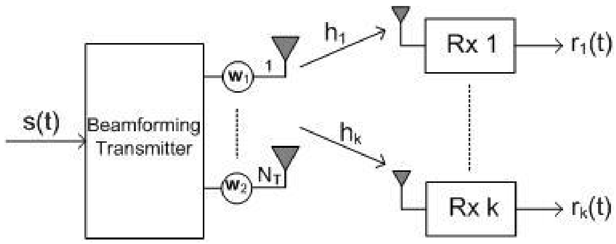

Figure 2.18: MISO configuration with transmit beamforming [1]

Beamforming used at the receiver side applies the complex weight to the received signal from each antenna element. Afterwards, the beamformer sums all of the received signals into one which has the wanted directional pattern.

2.8.1 Example of a Linear Array

As seen above, beamforming is a technique used on an array of sensors in order to adapt the radiation pattern of the antenna to control its directionality. So before starting the description of the two main beamforming techniques which are digital and adaptive beamforming, let's have a look on a linear array.

In many applications, to meet the requirements of long distance communications it is necessary to design antennas with very directive characteristics. It can be obtained by two ways: enlarging the dimensions of single elements or by forming an assembly of radiating elements referred to as an array. The total field of an array is obtained by the vector addition of the fields radiated by each elements. To achieve very directive patterns the field from the array's elements must interfere constructively in the wanted direction and destructively otherwise.

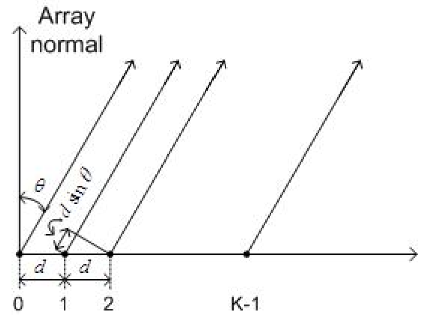

Figure 2.19: Uniformly Spaced Linear Array [20]

The figure 2.19 represents a uniformly spaced linear array with K identical isotropic elements which are weighted with V_k (complex weight) with $k = 0, 1, ..., K-1$. d represents the space between each elements and $dsin\theta$ is the differential distance along two ray paths. By arbitrarily setting the phase of the signal at the origin to zero and adding all the elements together, the array factor F is obtained [20]:

$$F(\theta) = 1V_0 + V_1 e^{jKdsin\theta} + V_2 e^{j2Kdsin\theta} + ... = \sum_{k=0}^{K-1} V_k e^{jKkdsin\theta} \tag{2.14}$$

From the Figure 2.17 can be seen the radiation pattern of 4 identical omnidirectional linear array elements where the space between each element is $\lambda/2$ and where all antennas have the same phase.

2.8.2 Digital Beamforming

At the beginning, digital beamforming was developed for applications in sonar and radar systems. The basic idea of digital beamforming is the conversion of the RF signal at each antenna elements into streams of binary baseband signals representing the amplitudes and phases of received signals at each element of the array [20]. As said before, beamforming implies weighting these signals by adjusting their phases and amplitudes in such way that when added together they form the wanted beam. In digital beamforming, all the operations of phase shifting and amplitude scaling and summation, are done digitally. The key of this technology is the accurate conversion from the analog signal to the digital one. The output at the t^{th} time, $x(t)$, is given by a linear combination of the data at the N_R sensors at time t [20]:

$$x_t(\theta) = \sum_{j=0}^{N_R-1} \mathbf{w}_j^* s_j(t) \tag{2.15}$$

where $*$ represents a complex conjugate, $\mathbf{w}_j$ is the weight applied to s_j which is the signal from the j^{th} element of the array. The main advantage to be gained from digital beamforming is added flexibility without any attendant degradation in SNR. Indeed, since beamforming instructions are driven by software routines, there is flexibility in the types of beams that can be produced such as including scanned beams, multiple beams, shaped beams and beams with steer nulls [20].

2.8.3 Adaptive Beamforming

An adaptive beamformer is able to automatically (using algorithms) optimize the array pattern by adjusting the elemental control weights until a prescribed objective function is satisfied [20]. Basically in adaptive beamforming the complex weights $\mathbf{w}_j$ for the antenna elements are meticulously chosen to achieve the wanted peaks and nulls in the radiation pattern of the array. As can be seen in Figure 2.20 in beamforming for communications, the weights are accurately chosen to obtained a radiation pattern that maximizes the quality of the received signal [19]: a peak in the pattern is pointed to the signal source and nulls are achieved in the directions of interfering sources.

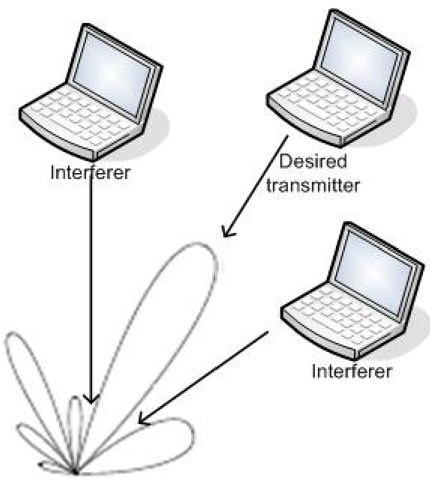

Figure 2.20: Adaptive Beamforming Scheme

2.9 Cooperation

The word cooperate comes from the Latin words *cum* which means together and *operate* which means to work. Thus, this word literally signifies working together. The cooperation can be defined as a strategy of an entities group working together in order to achieve a common or individual goal [21], the cooperating entity gains thanks to the group activity. Usually cooperation can be seen as to gain by giving, sharing or allowing something. In this project the cooperation will be seen as egoistic, indeed an entity will cooperate with another one only if it can benefit from it or at least if it loses nothing. This means that for every situation, each entity will evaluate the potential gains that it can obtain.

Chapter 3

Problem Description

3.1 Introduction

In WLAN networks, to reduce the system cost there is no centralized access control. Indeed in this case, each link takes care of its interest by competing to use the channel at a time [1]. However, wireless networks' capacity can be improved by the use of multiple antenna techniques (MIMO, MISO, SIMO). Indeed, these techniques have the capability to increase the link capacity by using spatial diversity and array gain.

As seen in Chapter 2, diversity is a proven and effective technique to combat multipath fading and it is obtained by transmitting or receiving a signal over independent fading channels. A suitable combining techniques (SC,EGC or MRC) is applied at the transmitter or at the receiver and by this way the diversity gain is obtained. In this chapter, we will first describe our CSR scheme and then we will compare it to the TDMA-based MAC using MRC transmit beamforming.

3.2 Problem Definition

In this project we extend the previous work [1] in the study of a particular cooperative scheme allowing spatial reuse (in multirate networks) which increases the network capacity, called CSR. The CSR is considered as a cooperative extension of the current TDMA-based MAC.

In CSR, every link that wants to do spatial reuse (allows simultaneous transmissions) will form a group in which it will contribute its time slots among the cooperating links. As said in section 2.9, the cooperation is seen as egoistic, which means that an entity will

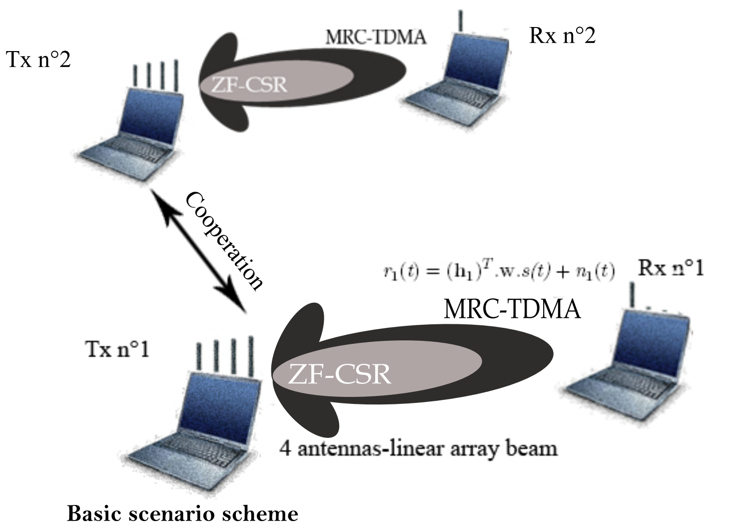

Figure 3.1: Problem Description Illustration

cooperate with another one only if it can benefit from it or at least if it loses nothing. This means that for every situation, each entity will evaluate the potential gains that it can obtain and acts as follow:

If it can benefit ⇒ the link will join the cooperative group.

Otherwise ⇒ the link stops doing CSR and goes back to the basic protocol.

In this project, we use transmit beamforming techniques on MISO links to show the improvement that can be obtained achieving CSR. Concretely, to show this improvement we compare the CSR scheme using ZF transmit beamforming to the TDMA-based MAC using MRC transmit beamforming [1], with respect to the number of cooperating links and in different configurations.

Current MAC layer protocols coordinates the link allocations as follow: when one link obtains the access, it is the only one allowed to transmit at a time, the other links in its contention region remain silent. The contention region is defined as a region specified to keep the interference level very low. Thus, links do CSR only if they gain with respect to the effective capacity. So, even if the capacity of a link is reduced during its time slots due to interferences from other links, the link can accomplish more traffic as it can use other links' time slots to transmit.

3.3 CSR Scheme Description

As seen before, TDMA-based MAC layer is designed to allow only one transmission at a time. This means that only one link is allowed to transmit during its own time slots. Whereas spatial reuse requires every links to share their time slots cooperatively among the other links. So as said before, even if each link loses capacity during its own time slots due to the mutual interference, as it uses several time slots to transmit, it gains in capacity when the sum of the capacities obtained is greater than the capacity losses. In our CSR scheme the time slots are distributed following the TDMA-based MAC, as can be seen in Figure 3.2. A link will cooperate only if it will obtain enough time slots from others to get more capacity. Also, in our scheme all the cooperating links have:

- to recognize the owner,
- to know the starting time and the duration of the next transmitting time slot and,
- to be prepared to transmit simultaneously.

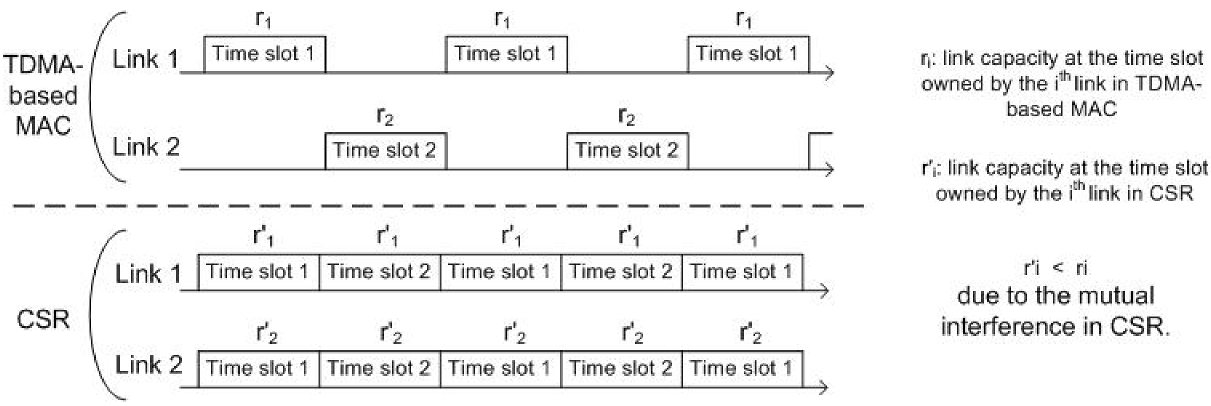

Figure 3.2: Illustration of CSR [1]

3.3.1 Assumptions and Improvement Region

For our project we made the following assumptions:

- each link has the same access probability,
- the length of each packet is assumed to be equally long,
- the power consumption parameters are assumed to be the same for each link,

- during the cooperating time slots, we calculate the mean effective capacity of each link. The mean effective capacity for the TDMA-based MAC can be written as [1]:

$$R_i = \frac{T_i}{\sum_{j=1}^{k} T_j} r_i \tag{3.1}$$

where T_i represents the length of the time slot of the i^{th} link. The mean effective capacity for the CSR can be written as [1]:

$$R'_i = r'_i \tag{3.2}$$

From these two equations, it appears clearly that if a link wants to benefit from CSR to increase its capacity it should satisfy:

$$\Rightarrow R'_i > R_i \tag{3.3}$$

$$\Leftrightarrow R'_i > r_i X_i \tag{3.4}$$

where $X_i = \frac{T_i}{\sum_{j=1}^{k} T_j}$.

- we define the CSR capacity region as the region where all cooperating links benefit from CSR:

$$S_{CSR} = \{(R'_1, R'_2, ..., R'_k) | R'_1 \in S_1, R'_2 \in S_2, ..., R'_k \in S_k\} \tag{3.5}$$

where

$$S_i = \{R'_i | R'_i > R_i\}, \text{region where the effective capacity is increased} \tag{3.6}$$

The CSR capacity region is illustrated in Figure 3.3. The line DE represents the achievable capacity with the TDMA-based MAC during the two time slots with all possible time sharing ratio (T_1/T_2 in our case), the effective capacity of the two links are reduced due to the time sharing. Points D and E depict the extreme cases when one of the two links occupies both time slots [1]:

  - When $T_1/T_2 = 0 \Rightarrow$ the link 1 achieves r_1.
  - When $T_1/T_2 = \infty \Rightarrow$ the link 2 achieves r_2.

Point C is reached in two cases:

  - When the distance between the two links is equal to infinity,
  - When the channels are well separated in a beamforming case, so the mutual interference are nulled by the optimal beams for the reception.

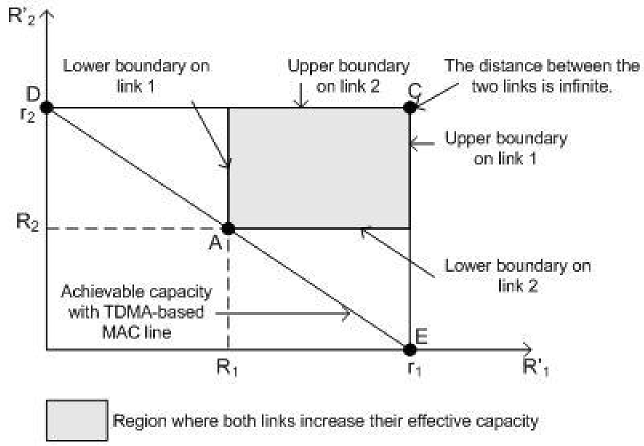

Figure 3.3: CSR capacity region of a two links scenario [1]

3.3.2 CSR with transmit beamforming

As explained above in Section 3.2, the aim of our project is to show the gain that can be obtained by using CSR. The focus is on the transmit beamforming techniques on multiple antennas systems. As illustrated in Figure 2.18, we work with a N_T antennas beamforming transmitter and k single antenna receivers so we are in a k configurations $N_T \times 1$ MISO scenarios. Only one of those receivers is the desired one. The received signal at the i^{th} receiver can be written as [1]:

$$r_i(t) = (\mathbf{h}_i)^T \mathbf{w} s(t) + n_i(t) \tag{3.7}$$

where $\mathbf{h}_i = [h_{1i} h_{2i} ... h_{N_T i}]^T$ is the channel vector of the i^{th} MISO link. As describe in Chapter 2 Section 2.8 and in Figure 3.4, $\mathbf{w} = [w_1 w_2 ... w_{N_T}]^T$ is the weight vector (the transmitter side applies the complex weight to the transmitted signal, this means that for each antenna element of the array, the beamformer sets the amplitude and shifts the phase). $s(t)$ is the transmitted information and $n_i(t)$ the noise at the i^{th} receiver [1].

By using beamforming in TDMA-based MAC, the capacity can be improved by directing the beam in the wanted receiver direction to perform array gain and diversity gain. However, transmit beamforming techniques can also cancel mutual interferences to allow CSR.

3.4 MRC versus ZF

In this section, we compare the MRC transmit beamforming to the ZF transmit beamforming with respect to the received SNR and to the achieved link capacity. Before to start the

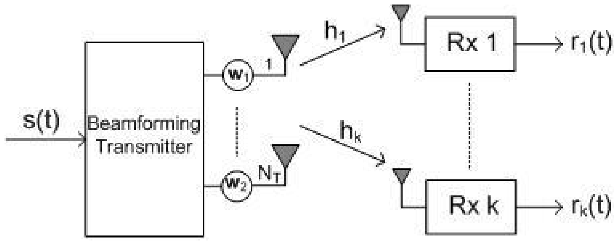

Figure 3.4: MISO configuration with transmit beamforming [1]

comparison, let's have a brief description of each schemes:

- MRC-TDMA scheme: is based on TDMA-based MAC. Each beamforming transmitter applies MRC weight vector to make the signal co-phased in order to maximize the SNR at the desired receiver and accordingly maximize the capacity of the MISO link. The weight vector for MRC-TDMAcan be written as [1]:

$$\mathbf{w}_{MRC} = \frac{(\mathbf{h}_1)^*}{\|(\mathbf{h}_1)^*\|} \tag{3.8}$$

  where $(\mathbf{h}_1)^*$ is the conjugate of the channel vector of the desired link.

- ZF-CSR scheme: is called ZF because the weight vector of each cooperating transmitter is set to cancel (forced to be zero) the received signal at the receivers of other cooperating links. So, cooperating links can transmit at the same time without being bothered by mutual interferences. The weight vector for ZF-CSR can be written as [1]:

$$\mathbf{w}_{ZF} = \frac{\mathbf{H}^{+}\mathbf{I}_{k\times 1}}{\|\mathbf{H}^{+}\mathbf{I}_{k\times 1}\|} \tag{3.9}$$

  where $\mathbf{H}^{+}$ is the pseudoinverse of the cooperating link's channel matrix ($\mathbf{H} = [\mathbf{h}_1\mathbf{h}_2...\mathbf{h}_k]^T$) and $\mathbf{I}_{k\times 1}$ represents the first column of a $k \times k$ identity.

The weight vector is normalized in order to be able to do a good comparison.

3.4.1 SNR Comparison

As explained above and as can be seen in Figure 3.5 (2 antennas, uncorrelated narrow-band channel), the MRC transmit beamforming maximizes the SNR at the desired receiver, and to cancel the interferences, the SNR of ZF transmit beamforming is lower. Here, you can see that the SNR of MRC is always higher than the SNR of ZF for a given probability. In our case for a Independent Identically Distributed (IID) complex Gaussian fading channel, the N_T-branch MRC beamforming can provide N_T-fold of diversity order, whereas for the N_T-branch ZF beamforming, canceling the interferences at N_k receivers can provide $N_T - N_k$-fold of diversity order.

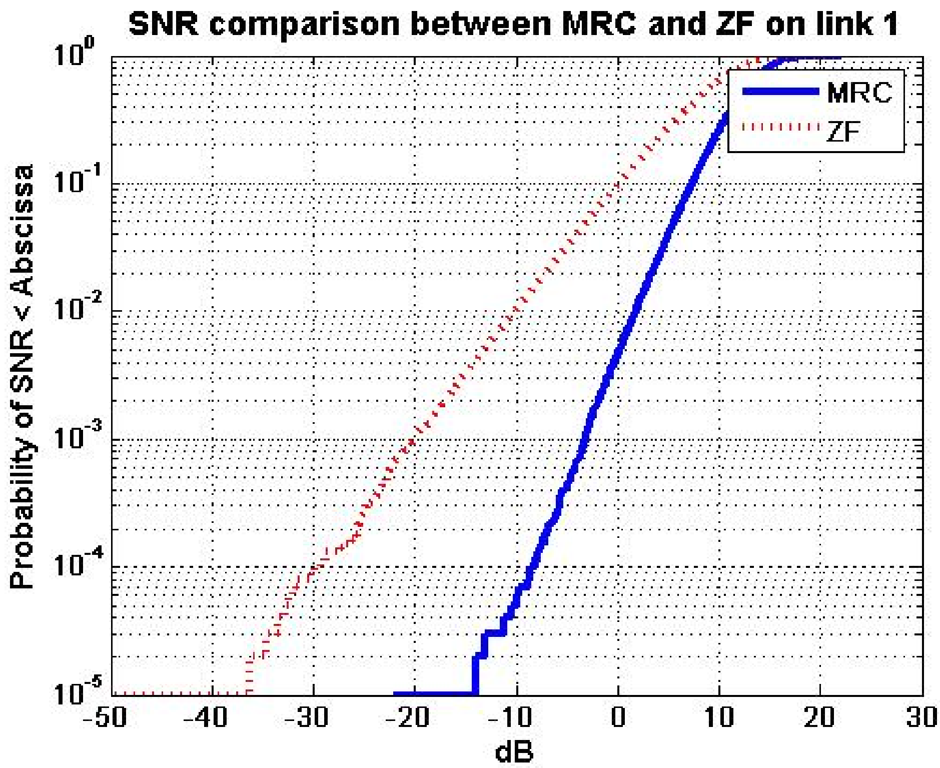

Figure 3.5: CDF of SNR of the ZF beamforming and MRC beamforming (2 links, 2 antennas, uncorrelated narrow-band channel).

3.4.2 Link Capacity Comparison

To make this comparison, we use the spectral efficiency which is the optimized use of bandwidth so that the achievable amount of data can be transmitted with the fewest transmission errors [14]. It is normalized with the bandwidth:

$$SE = log_2(1 + SNR) \tag{3.10}$$

As $SNR_{MRC} > SNR_{ZF}$, the capacity of MRC transmit beamforming is greater than the capacity of ZF transmit beamforming. However as can be seen in Figure 3.6 (2 antennas, uncorrelated narrow-band channel), for the same two links than in the subsection above, the loss in the channel capacity observed for ZF beamforming compared to MRC transmit beamforming is not critical. We observe that for a higher average SNR link, there are less losses than for a link with a lower SNR. Indeed when the SNR per branch is equal to 30 dB, in 90% cases the ZF beamforming can achieve 70% channel capacity of the MRC transmit beamforming. As in CSR a cooperating link will use several time slots to transmit, it will easily compensate this loss in capacity.

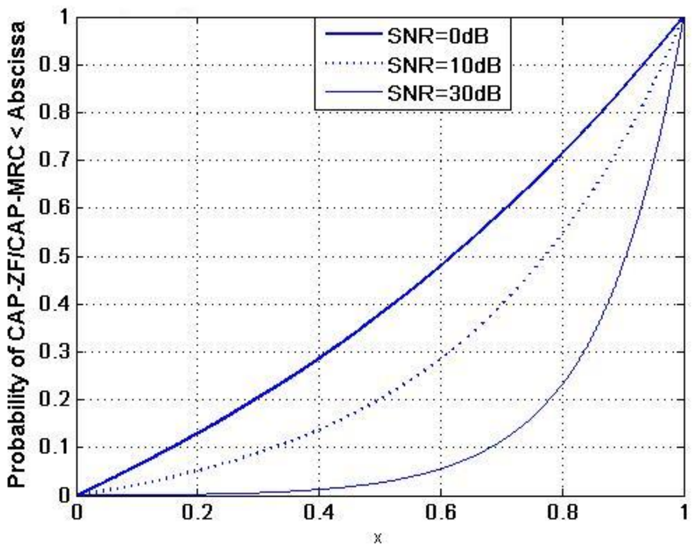

Figure 3.6: CDF of the channel capacity ratio of the ZF beamforming and MRC beamforming (2 links, 2 antennas, uncorrelated narrow-band channel).

Chapter 4

Simulation results

4.1 Channel Model

In this project, we compare an uncorrelated narrow-band environment to a correlated narrow-band environment with multipath effects which means that the channel model will change. The communication will be simulated by setting up a channel matrix corresponding to the link between two entities. With the Ricean K_f-factor defined as the ratio of deterministic-to-scattered power, the channel response is given by [22]:

$$\mathbf{h} = \sqrt{\frac{K_f}{K_f + 1}} * \mathbf{h^{sp}} + \sqrt{\frac{1}{K_f + 1}} * \mathbf{h^{sc}} \tag{4.1}$$

where $\mathbf{h}$ is the MISO channel vector. The elements of the scattering component $\mathbf{h^{sc}}$ are statistically independent unit variance complex Gaussian random variables. $\mathbf{h^{sp}}$ is the channel specular component where:

$$\mathbf{h^{sp}} = \mathbf{a}(\theta_t) \tag{4.2}$$

where $\mathbf{a}(\theta_t)$ is the specular array response at the transmitter and receiver, respectively. We assume that the array response corresponding to a N_T-element linear array, is given by $[1, e^{j2\pi d \cos\theta_t}, ...e^{j2\pi d(N_T-1)\cos\theta_t}]^T$ where θ_t is the AoD, and d the antenna element spacing in wavelength. For our simulation, θ_t will be chosen randomly between $[0, 2\pi]$. When:

$$\mathbf{h} = \mathbf{h^{sc}} \tag{4.3}$$

then, $K_f = 0$. In this case, the channel vector will follow a Rayleigh distribution that simulates an uncorrelated narrow-band channel. When $K_f > 0$, the channel vector will follow a Ricean distribution.

4.2 Simulation Parameters

We will study the CSR availability and the CSR capacity gain for a 2 links MISO case in a first scenario and 3 links MISO case in a second scenario, when the following parameters vary:

- the number of transmitting antennas N_T: 2, 3 and 4,
- the Ricean factor: $K_f = 0, K_f = 10, K_f = 100$ which respectively represent three typical cases for non-LOS, strong-LOS and extremely strong-LOS, and
- the average SNR per branch: $0dB \leq SNR \leq 30dB$. These values are chosen since they are the most encountered ones in real life.

Moreover, we assume that we use an linear array antennas configuration with a spacing of $\lambda/2$ and that the number of realization of this simulation is 10000. The number of MISO links that want to cooperate is first set to 2 and later to 3.

For our project, we did a Matlab implementation. In the following sections, we present and explain the results of our 2 scenarios' simulations. For each scenario, we proceed as follows:

- we begin our analysis by a link capacity comparison,
- then we show how easy it is to form a cooperative group thanks to the CSR availability and,
- we show the obtained capacity gain.

However, in the 3 links scenario a comparison with the 2 links one is done all along the parts presented above.

4.3 2 Links Scenario

In this scenario, we have set the number of links to 2 in order to find out whether or not and how some parameters affects the CSR availability and the capacity gain. Indeed, we will study the changes on the link capacity comparison, on the CSR availability and on the capacity gain when the number of transmit antennas, the Ricean factor and average SNR per branch vary.

4.3.1 Link capacity comparison

We are going to do a link capacity comparison for a 2 links MISO case. You can see the CDF of the capacity ratio between ZF and MRC for our scenarios in Figure 4.1 and Figure 4.2. They show for 10000 realizations, the CDF of the channel capacity ratio between the ZF beamforming and the MRC beamforming. As expected, these 2 figures show the channel capacity loss by using ZF beamforming. Another important thing to notice is that the observed low channel capacity loss shows that a link needs less time slots from others to compensate it, therefore, it has more potential to benefit. Firstly, we are going to study the varying K_f's effects, secondly, the varying average SNR per branch's effects, then, thirdly and lastly, the varying number of antennas' effects.

Varying K_f effects

We are going to investigate if smaller K_f gives less capacity losses. On Figure 4.1 and Figure 4.2, when $K_f = 100$, the losses are higher than when $K_f = 10$ and when $K_f = 10$, the losses are higher than when $K_f = 0$. But, this is not true all the time. After a certain point the trend is reversed. On each curve, we can notice a cross point within the curves. It happens for the varying K_f and:

- for a same average SNR per link on Figure 4.1.
- for a same number of antennas on Figure 4.2.

We define the High Loss Region as the region where the losses are high. Indeed, in this region signals are too close to each other to make the distinction between them and a lot of energy is lost. This phenomenon is aggravated when there is a strong and an extremely strong LOS. It is possible to see this region drawn on Figure 4.1. For example, the High Loss Region with respect to an average SNR of 0 dB extends from 0 to 0.83 for $K_f = [0, 10, 100]$. It is more precisely shown on Figure 4.2. For example, on the latter figure, we assume that a group (N_T antennas, $K_f = [0, 10, 100]$) is in its High Loss Region from 0 to its cross-point:

- 0.85 for 2 antennas and different K_fs (e.g. the first group).
- 0.88 for 3 antennas and different K_fs (e.g. the second group).
- 0.9 for 4 antennas and different K_fs (e.g. the third group).

Otherwise, the group is in its Low Loss Region. The signals are spaced out enough to be distinguished which explains the trends of the curves.

Varying Average SNR per branch

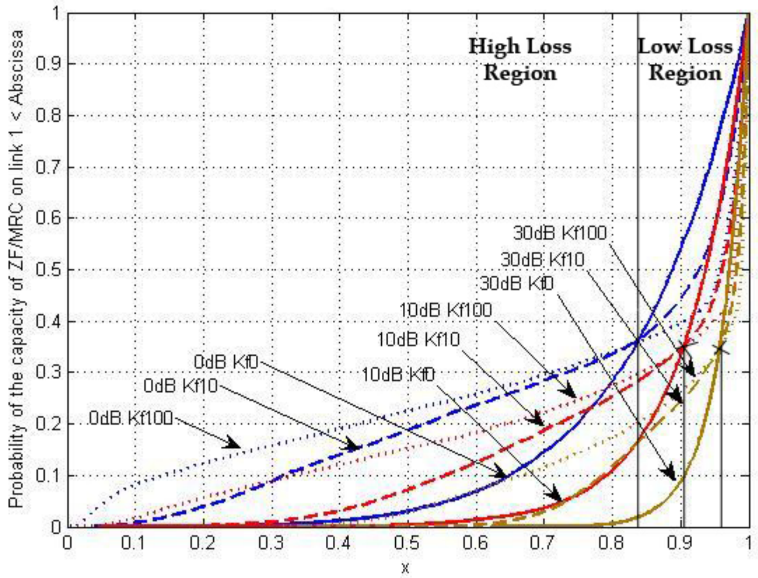

Figure 4.1: CDF of the capacity ratio of ZF and MRC for different average SNR (4 antennas, 2 links, all K_f).

In Figure 4.1, with a varying average SNR per branch, we observe that the probability that the channel capacity ratio is less than a given value decreases as the average SNR per branch increases. Moreover, changing the Ricean factor does not affect this trend. As can be seen, it is the higher average SNR that gives the less channel capacity losses. Also when the average SNR per branch is equal to 0 dB with $K_f = 0$, ZF beamforming can achieve over 80% of the MRC beamforming channel capacity in about 70% of the cases. Whereas when the average SNR per branch is equal to 30 dB with $K_f = 0$, ZF beamforming can achieve over 80% of the MRC beamforming channel capacity in about 99% of the cases.

Varying Number of antennas

From Figure 4.2, the same trend is observed: the probability that the channel capacity ratio is less than a given value decreases as the number of transmit antennas increases. Again, changing the Ricean factor does not modify this trend. It appears also that less losses are obtained when increasing the number of transmitting antennas. Indeed, it is the 4 transmit

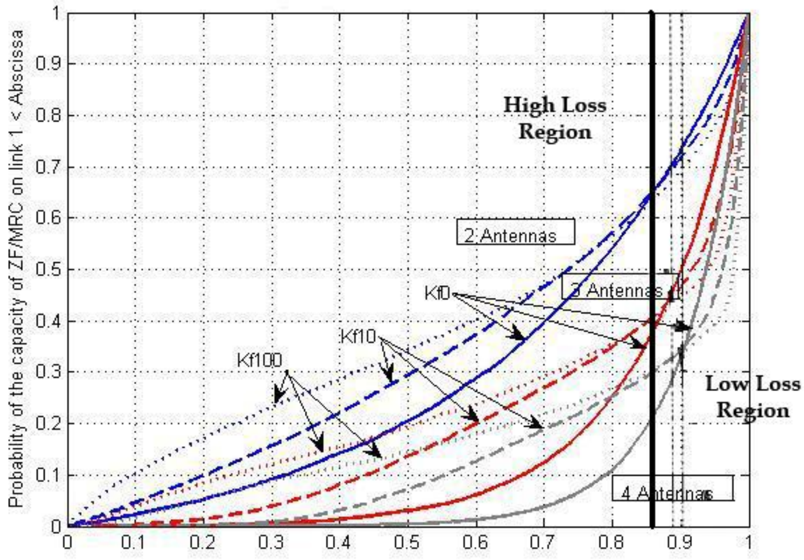

Figure 4.2: CDF of the capacity ratio of ZF and MRC for different K_f (2 to 4 antennas, 2 links, average SNR of 10dB).

antennas that gives the least channel capacity loss. However, increasing the number of transmitting antennas is less and less interesting. Indeed, for 2 transmit antennas and $K_f = 0$, ZF beamforming can achieve over 80% of the MRC beamforming channel capacity only in about 45% of the cases. Whereas when there is 4 transmit antennas and for $K_f = 0$, ZF beamforming can achieve over 80% of the MRC beamforming channel capacity in about 90% of the cases.

To conclude, we can say that the same phenomenon is observed from these 2 figures. So, we can expect that the augmentation of the average SNR per branch or the number of antennas will benefit to CSR. We will cross-check these speculations in the next section.

4.3.2 Cooperative Spatial Reuse Availability

The CSR availability is a function of all the parameters exposed in the previous section. Now, we are going to investigate the effects of the average SNR per branch on it. The availability shows how easily two links can perform a cooperative group and it is define as the probability that the cooperative links gain over the TDMA-based MAC. Meaning that the channel capacity of each links, when they perform CSR, will be higher than the channel capacity obtain with the other protocol. When this availability is low, it means that the finding process will waste more time and more power and so, lose a lot of capacity. In this case, CSR should not be used.

Our objective is to have a high availability for the high loss region as well as for the low loss region.

In the 3 different cases hereinafter, you can see the CSR availability of 2 cooperating links:

- **Case** 1: Shown in Figure 4.3 for different values of the Ricean factor K_f, 2 links cooperate, each transmitter has 2 antennas.
- **Case** 2: Shown in Figure 4.4 for different values of the Ricean factor K_f, 2 links cooperate, each transmitter has 3 antennas.
- **Case** 3: Shown in Figure 4.5 for different values of the Ricean factor K_f, 2 links cooperate, each transmitter has 4 antennas.

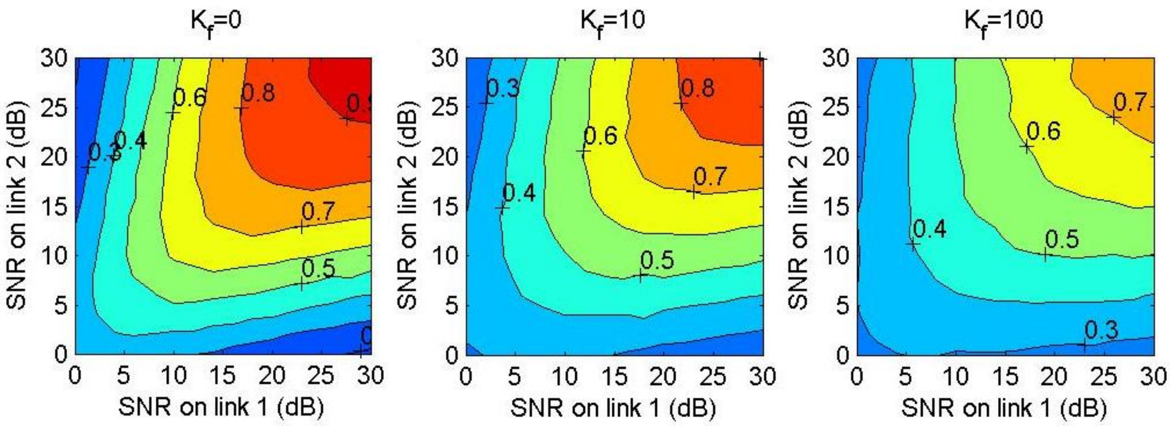

Figure 4.3: CSR Availability (2 links, 2 antennas).

Varying K_f effects

First of all, we can see that the availability varies from:

- 0.3 to 0.9 when $K_f = 0$.
- 0.3 to 0.8 when $K_f = 10$.
- 0.3 to 0.7 when $K_f = 100$.

Where the high losses region dominates, the availability decreases:

- The availability when $K_f = 0$ is higher than when $K_f = 10$.

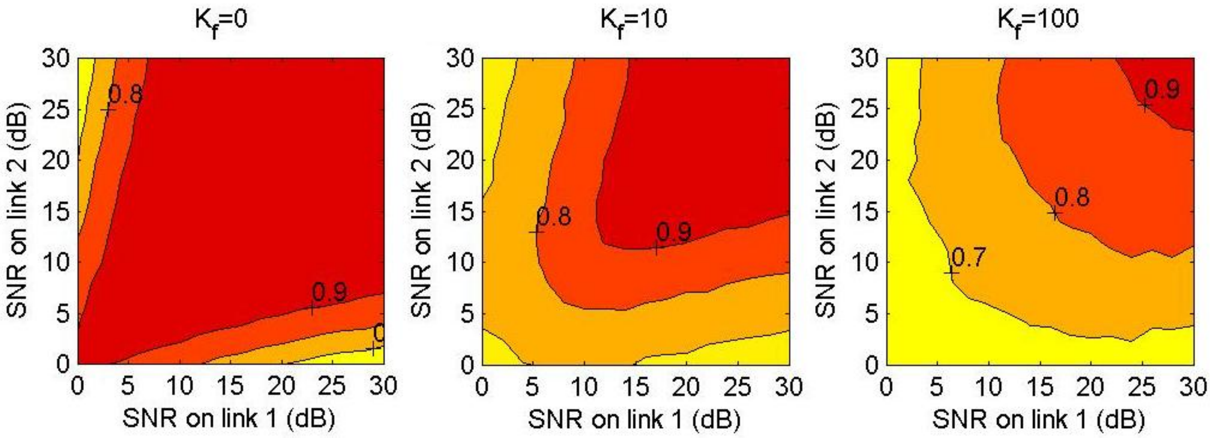

Figure 4.4: CSR Availability (2 links, 3 antennas).

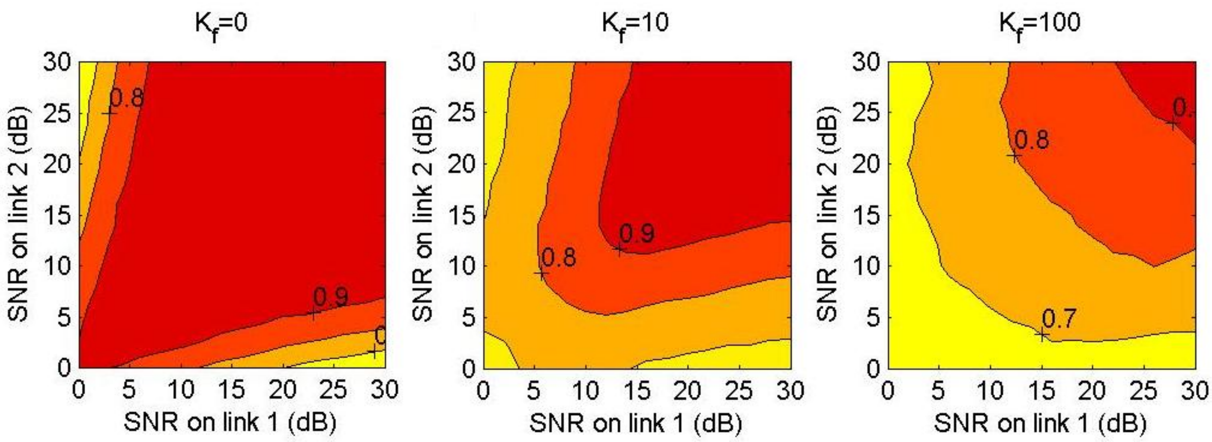

Figure 4.5: CSR Availability (2 links, 4 antennas).

- The availability when $K_f = 10$ is higher than when $K_f = 100$.

When we have 3 transmit antennas, the Figure 4.4 shows the same trend as the one shown in Figure 4.3. However, the availability is higher, it varies from 0.7 to 0.9 for all K_f.

Finally, Figure 4.5 represents the CSR availability for 4 transmit antennas and it shows very similar results than the results obtained for 3 transmit antennas.

Varying Signal to Noise Ratio

In case 1 (2 links, 2 antennas), shown in Figure 4.3, we can see that:

- As the SNR increases, the availability increases.
- When the difference between the SNR increases, the evolution of the probability is slowed down.

For example, when the SNR of link 1 and link 2 is greater than 10 dB and when $K_f = 0$, the availability is higher than 0.6 which means that cooperation is going to benefit over selfish behavior. Nevertheless, as the environment changes ($K_f = 10$ and $K_f = 100$), the previous probability has lost more than 10 points at the same coordinates (10 dB on link 1, 10 dB on link 2). As said before, this is because we are in a narrowband environment with strong and extremely strong LOS.

Varying Number of Antennas

In case 2 and 3, respectively Figure 4.4 (2 links, 3 antennas) and Figure 4.5 (2 links, 4 antennas), the availability varies from 0.7 to 0.9 for both systems. But, the results obtained when $K_f = 10$ and $K_f = 100$ are different from the ones obtained for case 1, especially in the low SNR region when there are only 2 antennas (for the same K_f). For example, we can see that when we drop the number of antennas from 4 to 2, and for a SNR of 10 dB on link 1 and on link 2, the CSR availability falls of 20 percents. Therefore, when K_f is big, it is necessary to add another antenna for the availability to be beneficial.

Worst case results in high SNR region

The high SNR regions are the regions of interest of dense networks and they represents the points where the average SNR of each link is greater than 10 dB. We assume that the worst cases are when the lowest beneficial availabilities (greater than 0.5) are achieved. We seek them by changing the SNR of one link (link 1) while the other one is set on a low value (link 2). It was defined by taking case 1 (Figure 4.3) for $K_f = 0$ as a reference.

Figure 4.6 represents the worst case when one link sets its average SNR at 10 dB and when the other link goes through all the SNR from 10 dB to 30 dB. At the same time, we make the number of antennas in the array increase from 2 to 4 with the K_f factor: 0, 10 and 100. From this figure, we notice that:

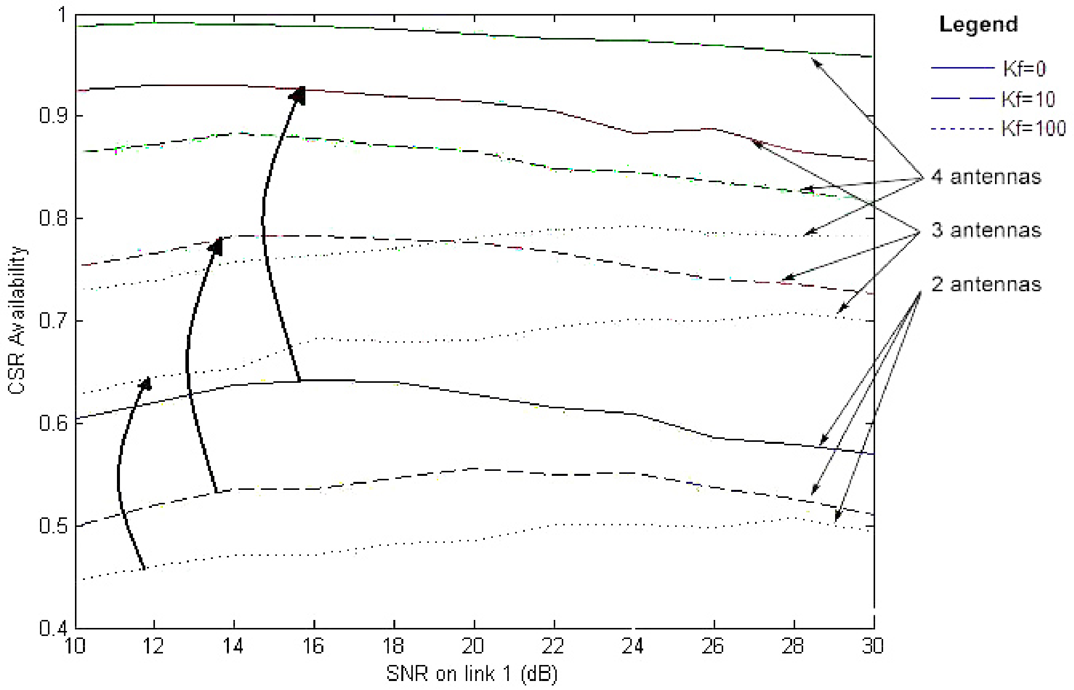

Figure 4.6: CSR Availability (2 to 4 antennas, SNR=10dB on link 1, varying SNR on link 2, all K_f).

- The availability of each case vary within 0.1 which means that high SNR should continue cooperating with low SNR.
- The number of antennas influences the availability.

As seen before, when the SNR increases, the time slot to compensate the loss is shorten, so the 10 dB link's gain decreases but the other link may get more gain. Moreover, there is a gain when we switch from 2 to 3 antennas of 0.6 to 0.9 when $K_f = 0$, of 0.5 to 0.75 when $K_f = 10$ and of 0.45 to 0.65 when $K_f = 100$. These gains are for 10 dB on link 1 and link 2, but even when the SNR of link 1 increases, the gap stays the same. Finally, in the low availability region, one more antenna can improve significantly the results. This is because of array gain and the diversity gain.

4.3.3 CSR Capacity Gain

In this part, a study of the capacity gain that can be obtained when a cooperative group is formed, is done. The main goal of this study is to show how the number of transmit antennas, the Ricean factor and the average SNR per branch affects the capacity gain.

To begin let's have a look on capacity gain of link 1 and link 2, shown in Figure 4.7. The following observation can be done: the link which has the higher average SNR per branch always obtains more gain. The reason of this phenomenon is that the packet length is fixed for each time slot. The link with the higher SNR has a shorter time slot than the one owned by the lower SNR link, as it has the higher data rate. This leads to the higher SNR link benefit from the lower SNR link's longer time slot to compensate the capacity losses during its own time slot.

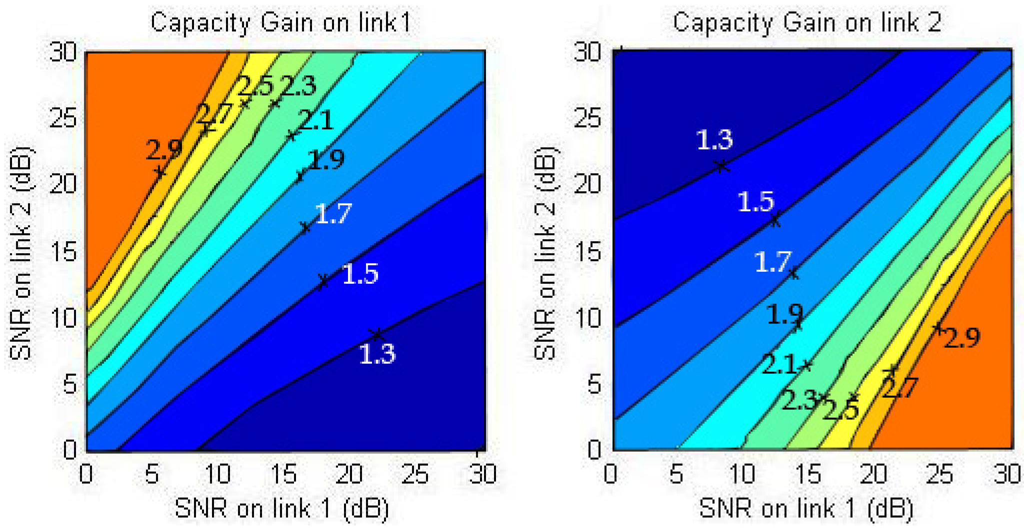

Figure 4.7: CSR Capacity gain of link 2 on link 1 and CSR Capacity gain of link 1 on link 2 (2 antennas, $K_f = 0$).

Now, let's have a look on the total average capacity gain of both links in the following 3 different cases. An important thing to know is that all links have the same number of transmit antennas.

- **Case** 1: Shown in Figure 4.8 for different values of the Ricean factor K_f, 2 links cooperate, each transmitter has 2 antennas.
- **Case** 2: Shown in Figure 4.9 for different values of the Ricean factor K_f, 2 links cooperate, each transmitter has 3 antennas.
- **Case** 3: Shown in Figure 4.10 for different values of the Ricean factor K_f, 2 links cooperate, each transmitter has 4 antennas.

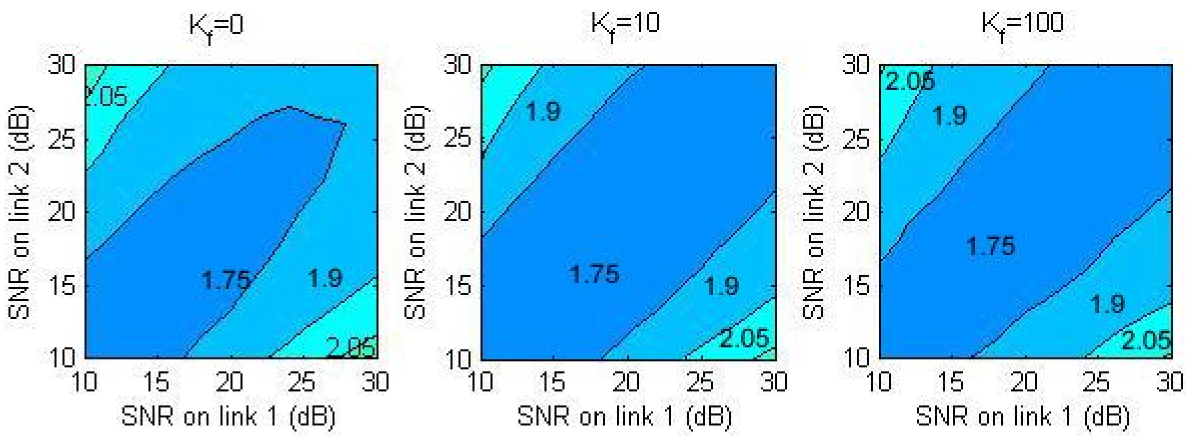

Figure 4.8: Total CSR Capacity gain (2 links, 2 antennas, all K_f).

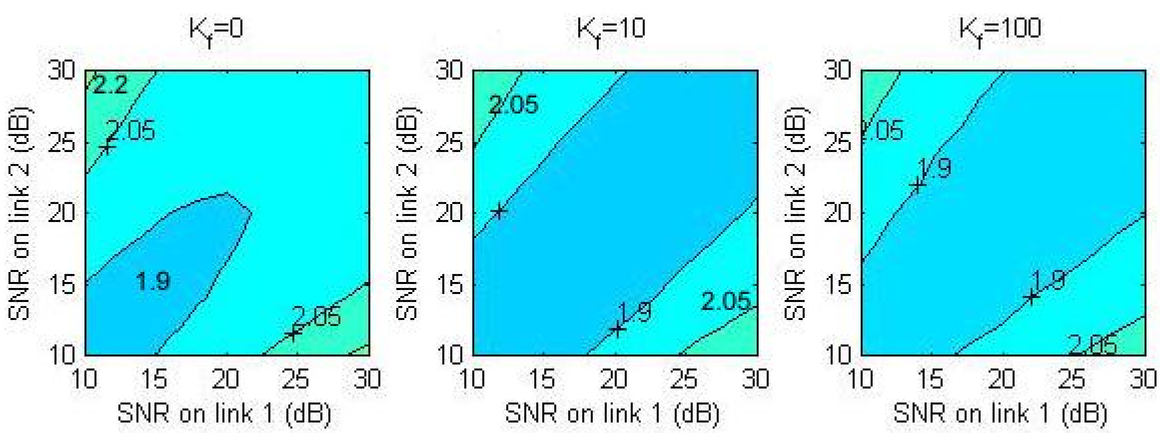

Figure 4.9: CSR Capacity gain (2 links, 3 antennas, all K_f).

The most important variation shown in these 3 figures, is the one obtained by changing the number of transmit antennas. Indeed, the capacity gain is improved when the number

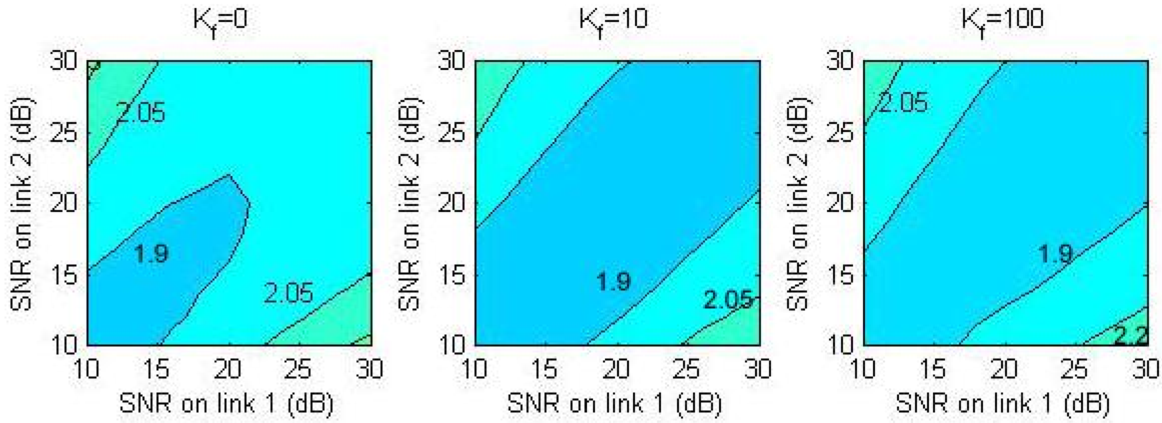

Figure 4.10: CSR Capacity gain (2 links, 4 antennas, all K_f).

of transmit antennas varies from 2 to 3. For both links at 10 dB, the capacity gain reaches 1.75 with 2 transmit antennas and 1.9 with 3 transmit antennas. This shows that for case 1 (2 links, 2 antennas), one more antenna is only needed in the low SNRs region. It is relevant to notice that the capacity gain improvement between 3 and 4 transmit antennas can barely be seen comparing Figure 4.9 to Figure 4.10. This shows that the capacity gain does not really benefit from another degree of freedom by adding a 4^{th} antenna. Therefore, for 2 cooperating links this clearly shows that it is useless and uninteresting to use 4 transmit antennas. Another thing to observe is that the variation of the Ricean factor has not an important impact on the capacity gain. So, the Ricean factor has to be carefully studied in the protocol design, since it has a significant impact on the CSR availability.

To conclude the capacity gain varies with respect to the number of transmit antennas, the average SNR per branch and the Ricean factor K_f. Indeed, increasing the number of transmit antennas improves the capacity gain. However, to have more than one degree of freedom does not give a significant improvement. It also appeares that the higher the average SNR per branch is, the higher the capacity gain is. Another important phenomenon is observed: when the two links have unequal average SNR per branch, the one with the higher SNR has also a higher capacity gain. The last important thing to notice is that the Ricean factor does not have an important impact on the capacity gain, but on the availability. As a conclusion for this scenario, it is clear that many parameters can improve the signal (average SNR per branch, number of antennas,...). Anyway, there is still a limit to it: the biggest gains are from two to three antennas for instance and not for three to four. But this is for a two links scenario, and not mostly a so usual one. In the next scenario, the 3 links case is covered.

4.4 3 Links Scenario

In this scenario, we have a network point of view. We have set the number of links to 3 in order to find out whether or not it is better to cooperate over 3 links when we have the opportunity to do so. We will study the CSR availability and the CSR capacity gain when the following parameters vary: number of transmit antennas, Ricean factor and average SNR per branch.

4.4.1 Link capacity comparison

The Figure 4.11 shows the capacity ratio between ZF and MRC, when 3 links cooperate, each transmitter has 3 then 4 transmit antennas. By comparing Figure 4.11 to Figure 4.2 which shows the effects of the variation of the number of transmit antennas on 2 cooperating links, we notice that similar results are shown:

- less losses are obtained when increasing the number of transmitting antennas and,
- there is a high and a low loss region.

However, we observed that the curves obtained for 2 cooperating links are deeper than for 3 cooperating links. This means that there are some more capacity losses when 3 links cooperate. Therefore, we can expected that the CSR availability obtained for 3 cooperating links will be lower than the one obtained for 2 cooperating links.

4.4.2 CSR Availability

The availability is found and studied the same way as in the first scenario. Although, we have set the SNR of one of the links in order to do the contour plots. We are going to have a look at the CSR availability in 2 different cases:

- **Case 1**: Shown in Figure 4.12 and in Figure 4.13 for different values of K_f, 3 links cooperate, each transmitter has 3 antennas. The average SNR of the 3^{rd} link is respectively to figures, set to 10 dB and then to 20 dB.
- **Case 2**: Shown in Figure 4.14 and in Figure 4.15 for different values of K_f, 3 links cooperate, each transmitter has 4 antennas. The average SNR of the 3^{rd} link is respectively to figures, set to 10 dB and then to 20 dB.

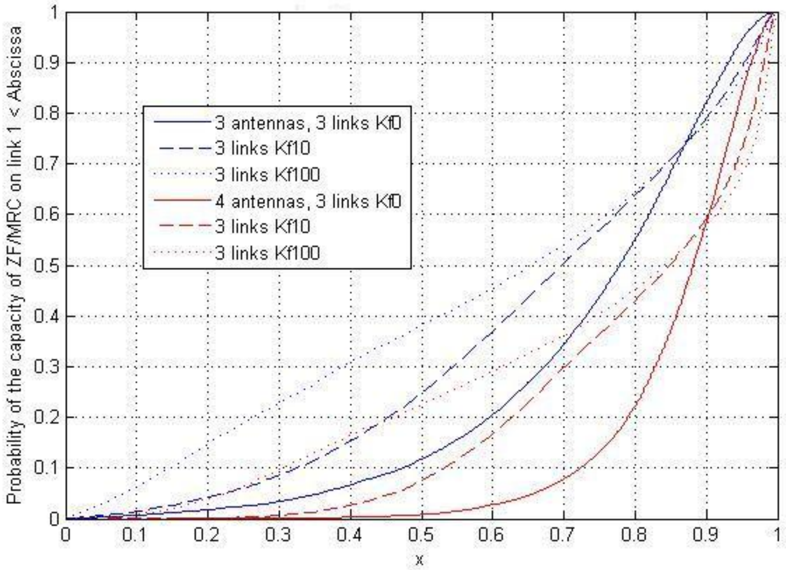

Figure 4.11: CDF of the capacity ratio of ZF and MRC (3 to 4 antennas, 3 links, average SNR of 10dB, all K_f).

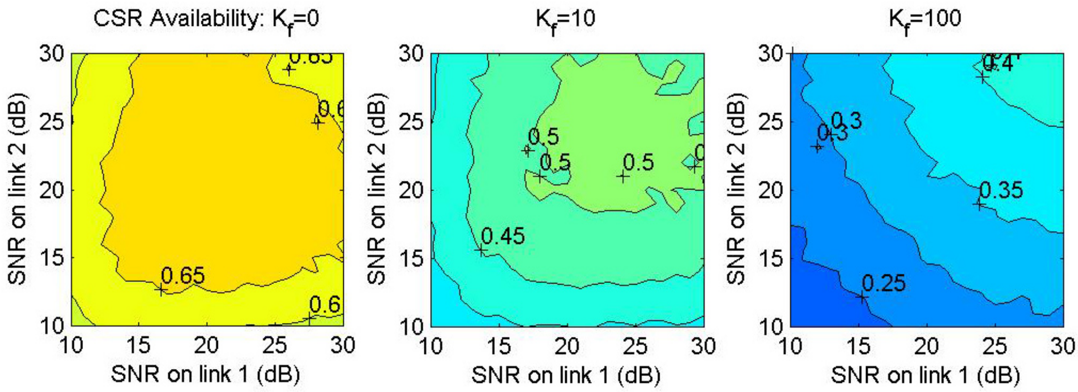

Figure 4.12: CSR Availability (3 links, 3 antennas, average SNR of 10dB on link 3).

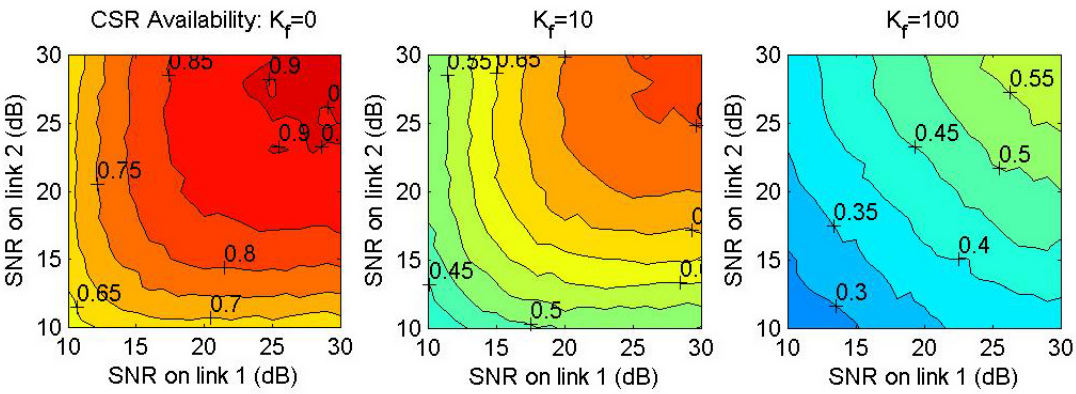

Figure 4.13: CSR Availability (3 links, 3 antennas, average SNR of 20dB on link 3).

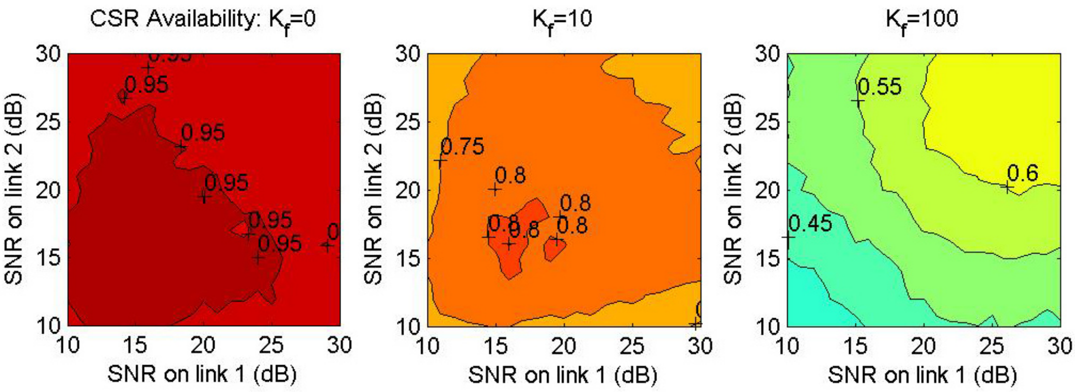

Figure 4.14: CSR Availability (3 links, 4 antennas, average SNR of 10dB on link 3).

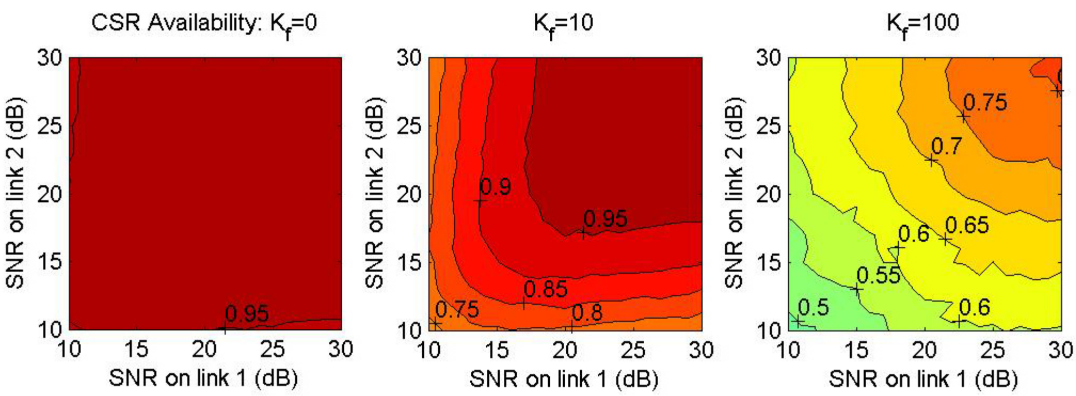

Figure 4.15: CSR Availability (3 links, 4 antennas, average SNR of 20dB on link 3).

In the following sections, we are going to compare the cases above with the 2 links scenario. Let us notice that these figures are not so smooth due to the low resolution of the simulations. However, when we focus on the trends, the results are acceptable.

Varying K_f effects

When we look at the K_f effects in both cases, we notice that the highest CSR availability is achieved when $K_f = 0$ for any number of antennas. On the contrary, the worst CSR availability is obtained when the Ricean factor $K_f = 100$. Moreover, we can see two general trends.

- There are circular curves when $K_f = 0$ and $K_f = 10$ in Figure 4.12 and Figure 4.14.
- The impact of the Ricean factor is more important when 3 links cooperates.

Firstly, we can see that the circular curves cannot be improved anymore. The center area represents the highest availability that can be achieved although the SNR combinations are different. Indeed, it means that the CSR availability is limited by the 3^d link's SNR.

Secondly, in the 2 links scenario, the K_f had a little impact on the availability (0.2 difference maximum for any SNR combination on link 1 and on link 2). Now, there is at least 0.35 and it reaches 0.5 as can be seen for example in Figure 4.14. There are more losses for the 3 links case and therefore, we notice that the K_f affects the availability much more than in the 2 links case.

Varying SNR

In each different case, the SNR is primarily set to 10 dB, which corresponds to the worst case in relation with the high SNR region defined in the 2 links scenario, then to 20 dB. By increasing this SNR, we see that the availability limitation expressed previously is avoided (Figure 4.12 compared to Figure 4.13 in case 1 or Figure 4.14 compared to Figure 4.15 in case 2). Thus, the SNR of the 3^d links produces a hard limitation of the availability when it is low(≈ 10 dB). Anyway, a raise of SNR induces a raise of the CSR availability. So, we can extract important points out of these 4 figures:

- For such environments, it is not good to try a low SNR link as a partner.
- Including a low SNR link reduces a lot the availability.
- Including a high SNR link, for low Kf, does not reduces the availability very much.

Varying Number of Antennas

From a general point of view, the 4 antennas configuration gives a higher availability than the 3 antennas one. For the worst case (on link set at 10 dB), the availability is higher when 2 links cooperate than for 3 cooperating links: the availability is improved from 0.7 to 0.9 when we focus on the high loss region for the worst case with 2 links and 3 to 4 antennas, against from 0.25 to 0.6 minimum for the the same region but with 3 links and 3 antennas. But when we set the number of antennas to 4 in the 3 links case, this gap closes in: 0.45 to 0.6 in the worst case. Finally, we see that one more antenna (4 antennas) can improve a lot the availability and this fourth antenna is even needed in the low availability region.

However, it appears that in some cases, the cooperation is not a good choice even if one more antenna is added (Figure 4.12 and Figure 4.14 with $K_f = 100$). Because adding an antenna cannot make the availability reach a reasonable high level. Maybe a fifth antennas should be included here.

To conclude, we can say that including one more link reduces the availability. In the following curve, Figure 4.16, the SNR is changed according to the boundary region of scenario 1. Meaning that the 3 links are going to take respectively [10;10;10] [10;10;20] [10;10;30] [10;20;20] [10;20;30] and [10;30;30]dB. It represents a detailed case of the CSR availability.

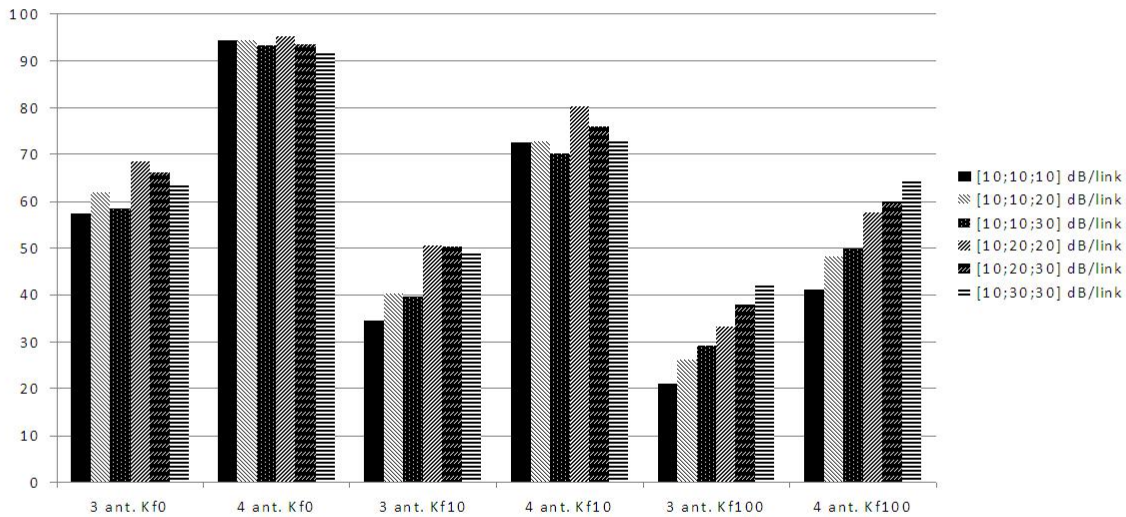

Figure 4.16: CSR Availability (3 links, 3 to 4 antennas, and different couples of SNR).

We can see that the 4 array system always obtains a higher availability than the 3 array one. For example, when $K_f = 10$, there is a 40 percent gap between 3 and 4 antennas.

Then, depending on the K_f factor, the highest CSR availability is not achieved by the same SNR couple.

4.4.3 CSR Capacity Gain

In this section, first we will describe and analyze the results obtained for 3 links. Afterwards, a comparison will be done between the capacity gain obtained with 2 and 3 links.

CSR Capacity Gain - 3 links

From the results shown above, it appears that for 3 links it is not as easy to form a cooperative group where all links will get more capacity as it is for 2 links.

To begin, let's have a look on the total average capacity gain in these 2 different cases:

- **Case 1**: Shown in Figure 4.17 and in Figure 4.18 for different values of K_f, 3 links cooperate, each transmitter has 3 antennas. The average SNR of the 3^{rd} link is respectively to figures, set to 10 dB and then to 20 dB.
- **Case 2**: Shown in Figure 4.19 and in Figure 4.20 for different values of K_f, 3 links cooperate, each transmitter has 4 antennas. The average SNR of the 3^{rd} link is respectively to figures, set to 10 dB and then to 20 dB.

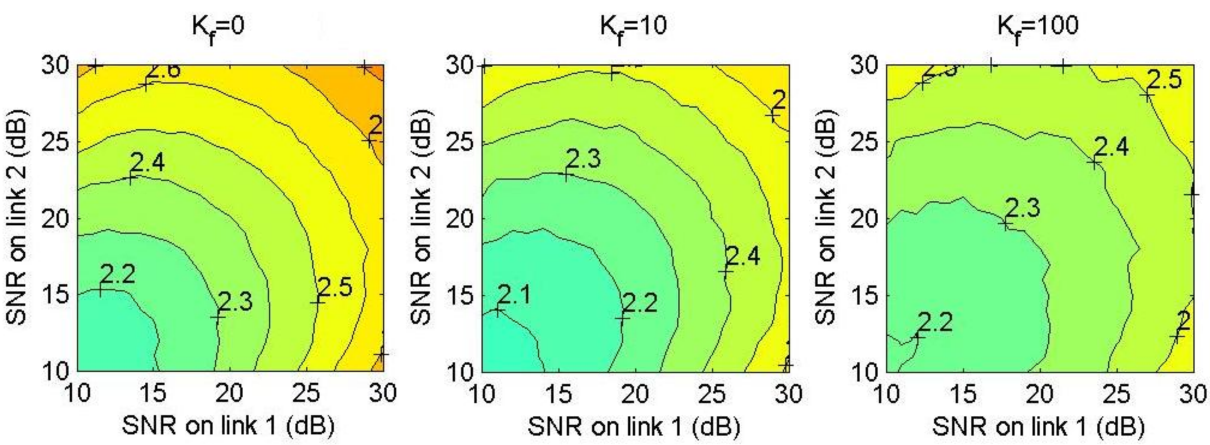

Figure 4.17: Total CSR Capacity gain (3 links, 3 antennas, average SNR of 10dB on link 3).

These 4 figures show that capacity gain does not fluctuate so much. Indeed, the most important variation shown in these 4 Figures, is the one obtained when we change the number of transmit antennas. The capacity gain is slightly improved when the number of transmit antennas varies from 3 to 4. For instance, if the links' average SNR are set to

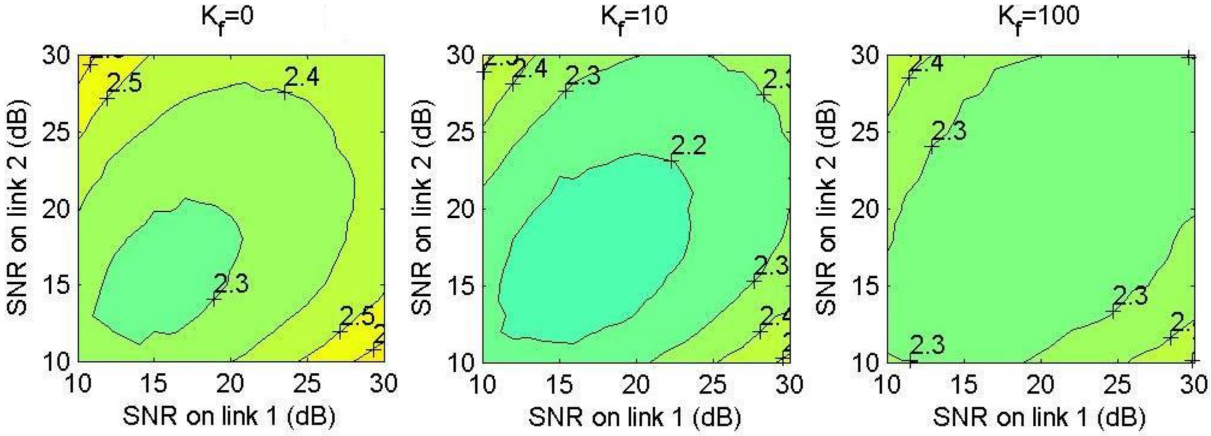

Figure 4.18: Total CSR Capacity gain (3 links, 3 antennas, average SNR of 20dB on link 3).

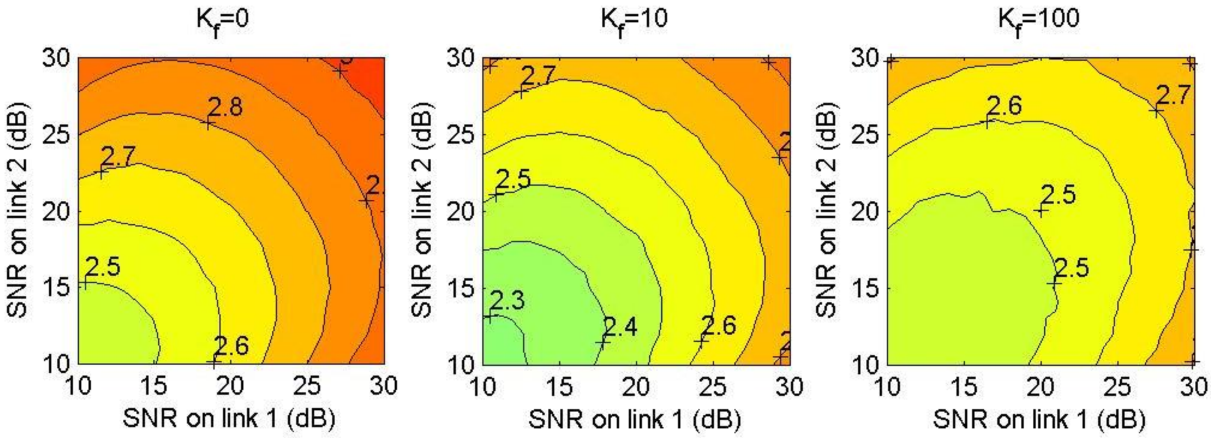

Figure 4.19: Total CSR Capacity gain (3 links, 4 antennas, average SNR of 10dB on link 3).

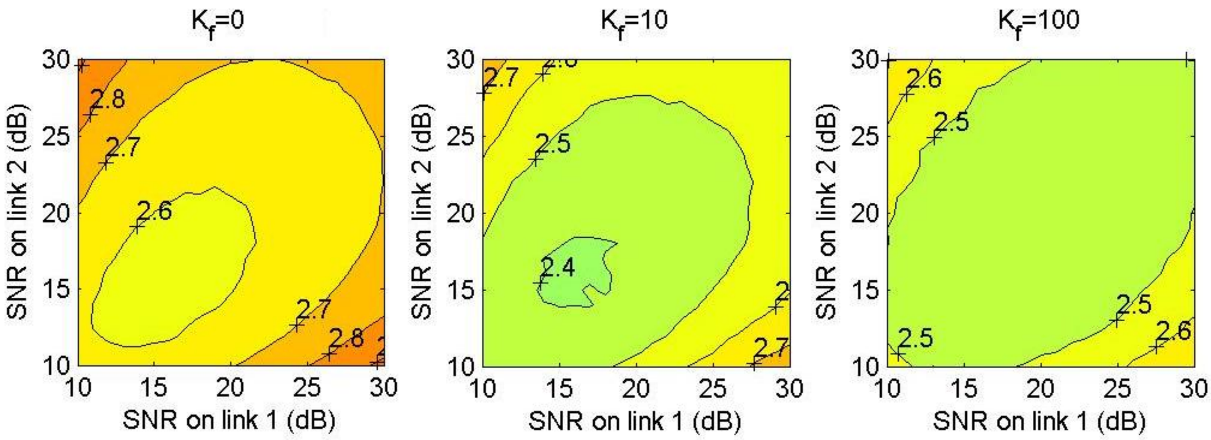

Figure 4.20: Total CSR Capacity gain (3 links, 4 antennas, average SNR of 20dB on link 3).

(10dB,10dB,15dB), the capacity gain is about 0.3 between 3 and 4 transmit antennas.

Another thing to notice is that, once again, the variation of the Ricean factor has not an important impact on the capacity gain.

To conclude the capacity gain varies with respect to the number of transmit antennas, the average SNR per branch and the Ricean factor K_f. Indeed, increasing the number of transmit antennas improves the capacity gain. The average SNR per branch comparison is very difficult to achieve as we show the total CSR capacity gain. Another important phenomenon is observed: when the 3 links have unequal average SNR per branch, the 2 links with the higher SNR have also a higher capacity gain. The last important thing to notice is that the Ricean factor does not have an important impact on the capacity gain.

2 links Versus 3 links

In this part, we compare the total CSR capacity gain obtained for 2 and 3 links with respect to the TDMA-based MAC for $K_f = 0$, with 3 transmit antennas shown in Figure 4.21 and with 4 transmit antennas shown in Figure 4.22.

The Figure 4.21 shows that for 3 transmit antennas, 3 links always get more capacity gain than 2 links. Indeed, for 3 links the smallest capacity gain achieved is about 2.2, which is the highest capacity gain obtained for 2 links. However, we have to notice that the capacity gain is more important for high SNRs (for 10 dB on link 3).

The Figure 4.22 shows that for 4 transmit antennas, 3 links always get more capacity gain than 2 links again. Indeed, for 3 links the smallest capacity gain achieved is about 2.5, whereas the highest capacity gain obtained for 2 links is about 2.2. However as for 3 transmit antennas, we have to notice that the capacity gain is more important for high SNRs (for 10 dB on link 3).

Therefore, it clearly appears that for a 3 transmit antennas array, 3 links achieve higher capacity gain than 2 links. This improvement is even better with 4 transmit antennas. Indeed, the whole cooperative group (3 links) can obtain an increased capacity:

- from 2.2 to 2.8 times the capacity of the MRC-TDMA scheme, for 3 transmit antennas.
- from 2.5 to 3 times the capacity of the MRC-TDMA scheme, for 4 transmit antennas.

Whereas, 2 cooperating links can obtain an increased capacity from 1.9 to 2.2 for both 3 or 4 transmit antennas.

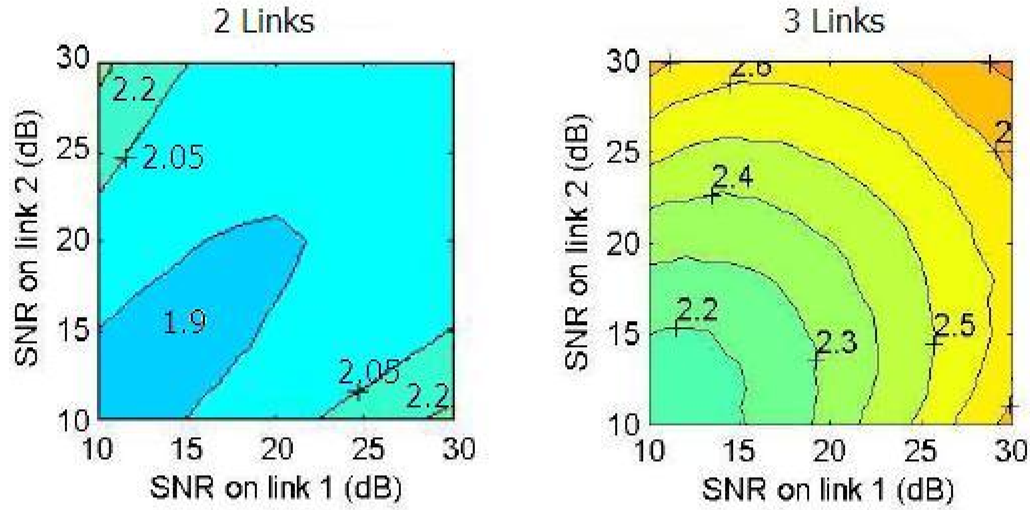

Figure 4.21: Total CSR Capacity gain (2 and 3 links, 3 antennas, $K_f = 0$, average SNR of 10dB on one link).

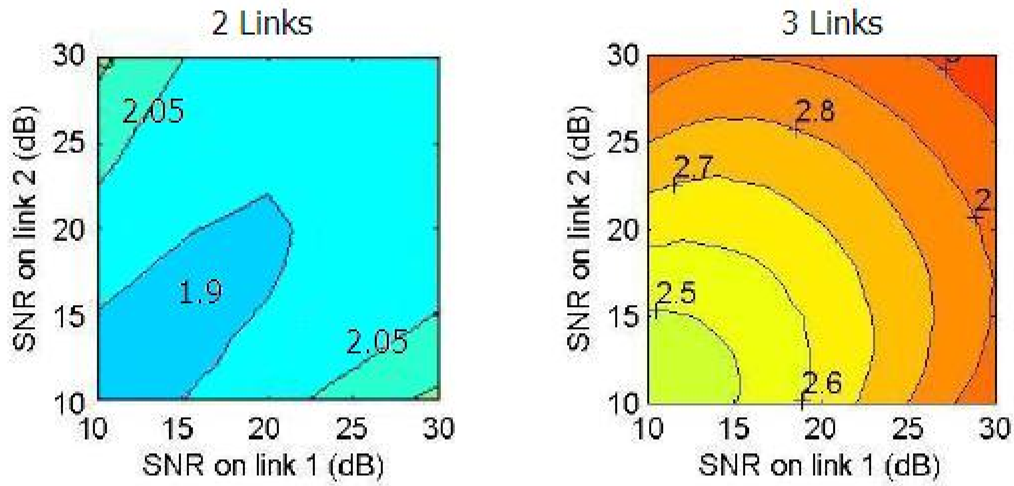

Figure 4.22: Total CSR Capacity gain (2 and 3 links, 4 antennas, $K_f = 0$, average SNR of 10dB on one link).

After extracting all of these informations from the different parameters in use, we are going to quote them in the conclusion part.

Chapter 5

Conclusion

We have investigated the performance of Cooperative Spatial Reuse under several scenarios in varying number of links, SNR, K_f and antennas. We have calculated the availability as well as the capacity gain. In this chapter, conclusions and further works are presented.

5.1 Conclusion

Several points can be extracted from our results and analysis:

- The more the Ricean factor is ($K_f = 10$ or $K_f = 100$), the less the availability is.
- When the number of links is larger than two, the impact of the Ricean is higher on the availability. It could be a important hint for protocol design.
- Nevertheless, the capacity throughput is not much affected by the K_f-factor.
- For high SNR, the availability is increased and the capacity too.
- Adding antennas to the array in order to have a better beamformer always increases the CSR availability and the capacity.
- When the degree of freedom of the antenna/link exceeds one, the improvements are not significant for both availability and capacity. It is not an asset anymore to add antennas because the gain is low.
- When the number of links increases, the availability decreases.
- On the contrary, the capacity gain of CSR increases with the number of links.

- The most capacity gain improvements are found when the number of links is more than two.
- However, when the number of links runs over 3, we can speculate and say that if the number of links is too high, the losses due to overhead are going to make CSR worst than classical WLAN TDMA.

We have shown that a higher capacity throughput is achieved for 2 and 3 cooperating links. Regarding this capacity gain, it is worth trying to cooperate since the availability is mostly acceptable (higher than 0.6). To conclude, we can say that CSR is better than the classic TDMA-based MAC with multiple antennas beamforming when a cooperative group is easily formed (when the CSR availability is larger than 0,5).

5.2 Further work

In order to fulfill this study, it would be interesting to extend the environment to cover more realistic everyday cases. Then, the following issues could be included:

- Change parameters in our simulation like the AoD and add a time or space variation (movement).
- Consider a wideband environment in addition to a narrowband one.
- Study multipath fading and intersymbol interference. Or add fading effects and pathloss as well as scattering in the channel matrix.
- Consider protocol characteristics like different packet size for every link, packet loss (CSMA/CA) or overhead.
- Consider the type of cooperation communication protocol (Bluetooth, Wifi,...).
- Introduce individual throughput to study fairness in the transmissions.
- Study the power consumption of both types of communication (CSR vs TDMA).

As a result, we could investigate the impact of cooperation among the type of environment and protocol in order to extract important information such as QoS, reliability and efficiency. This could give us a clue of the development and the utilization costs.

Appendix A

Appendix: Statistical Parameters

In order to describe the channel behavior we need to introduce some knowledge about a random variable, stochastic process and probability distributions.

A random variable X is a function:

$$X : \mathbf{Q} \longrightarrow R \tag{A.1}$$

Where **Q** the space of outcome of a random experiment, called the sample space [23]. A random experiment is an experiment whose outcome is not known and a collection of its possible outcome is an event *E*. A possible outcome ω of the random experiment is an element of the event *E* and the event *E* is a subset of the sample space **Q**, thus **Q** represents the certain event.

Let's define Σ as a σ-algebra of subsets of **Q**.
Thus:

$$\varnothing \in \Sigma \; where \; \varnothing \; is \; the \; null \; event \tag{A.2}$$

$$if \; E \in \Sigma \; then \; also \; its \; complement \; \mathbf{Q} - E \in \Sigma \tag{A.3}$$

$$if \; E_n \in \Sigma \; where \; (n = 1, 2, \dots) \; then \; also \; \bigcup_{n=1}^{\infty} E_n \in \Sigma \tag{A.4}$$

The probability is a measure on Σ, it means that it is a function defined on Σ:

$$P : \Sigma \longrightarrow R \tag{A.5}$$

It has the properties of being a real number between 0 and 1, of giving 1 if valuated in all the sample space **Q** and the probability of n independent events is the sum of the probabilities of each single event [24]. In formulas:

$$if\ E \in \mathbf{Q}\ then\ 0 \leq P(E) \leq 1 \tag{A.6}$$

$$P(\mathbf{Q}) = 1 \tag{A.7}$$

$$if\ E_n \in \Sigma\ where\ (n = 1, 2, \dots)\ with\ \bigcup_{n=1}^{\infty} E_n \in \Sigma\ and\ E_i \bigcap E_j = 0\ for\ every\ i \neq j \tag{A.8}$$

$$then\ P(\bigcup_{n=1}^{\infty} E_n)\ = \sum_{n=1}^{\infty} P(E_n) \tag{A.9}$$

As said before, random variable $X \in \mathbf{Q}$ is a function of the sample space **Q** that assigns to every outcome ω of a random experiment the number $X(\omega)$, i.e.

$$X : \omega \in \mathbf{Q} \longrightarrow X(\omega) \in R \tag{A.10}$$

In general a stochastic process $X(t)$ is a family of sample functions of time; this function, for example, can represent the thermal noise voltage inside a resistor. A stochastic process depends on two variables t and x , so the correct form is $X(t, x)$. We can consider the stochastic process in any set of instant time $t_1 > t_2 > \dots > t_n$ and when $t = t_0$ the stochastic process depends only on the assumed value x, so, for fixed time, the stochastic process is a random variable.
Now we define some functions used to describe a radio channel.

A.1 Cumulative Distribution Function (CDF)

If X is a random variable in **R**, the cumulative distribution function of X represents the probability that the variable is less or equal to a value x, where x can take all the values from $-\infty$ to $+\infty$.

The CDF of the variable X is called $F_X(x)$ and has these properties:

$$F(-\infty) = 0;$$

$$F(+\infty) = 1$$

it's a non decreasing function of x, i.e.

$$F(x_1) \leqslant F(x_2)\ if\ x_1 \leqslant x_2$$

[24].

A.2 Probability Distribution Function (PDF)

This function can be obtained by differentiating the CDF with respect to x, on assuming that X is differentiable with respect to x; the PDF of the random variable X is denoted by $p(x)$ and satisfies some properties [24]:

$$p(x) \geq 0 \; \forall x \tag{A.11}$$

$$\int_{-\infty}^{\infty} p(x) dx = 1. \tag{A.12}$$

A.3 Statistical Model for Fading Channel

To describe the small scale fading there are several probability distributions that can be considered, in particular the *Rayleigh* and the *Ricean* distributions. When there is a scenario with LOS propagation path, the channel gain follows a *Ricean* distribution, otherwise if there is no LOS the channel gain follows a *Rayleigh* distribution, for example in an urban zone with a lot of buildings and other objects between the transmitter and the receiver. If we consider a channel with a lot of scatterers, the received signal is a complex Gaussian process model with a standard deviation that depends on the frequency of the signal transmitted and on the scenario; if it is a zero-mean Gaussian process, than the envelope is *Rayleigh* distributed and the phase is uniform in [0,2π] [23].

A *Ricean* distribution is given from the pdf of the envelope component given below

$$p_\gamma(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2 + r_s^2}{2\sigma^2}\right) I_0\left(\frac{r\, r_s}{\sigma^2}\right) \tag{A.13}$$

where r_s is the dominant component and I_0 is the modified Bessel function of the first kind and zero order.

In the Figure A.1 we can observe that the PDF of the envelope follows a *Rayleigh* distribution for $K \longrightarrow 0$ and a Gaussian distribution with mean value r_s for$K \gg 1$.

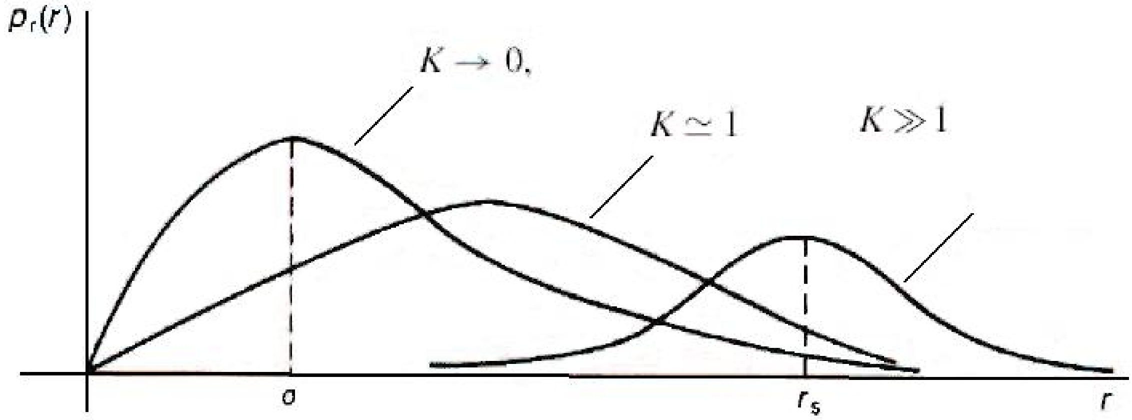

Figure A.1: Ricean Distribution for Different Values of K-factor

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