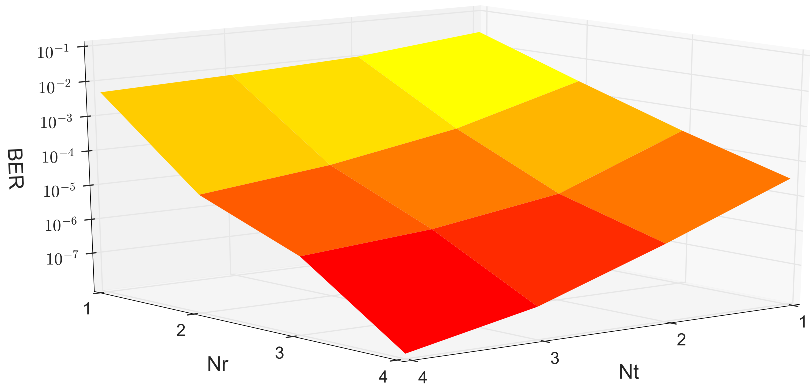

Multiple Access Strategies for Spatial Modulation

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Thesis to obtain the Master of Science Degree in

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Dedicated to my loved ones

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Abstract

The main goal of this work was to analyze the viability of Spatial Modulation as a technology to implement and support future 5G systems that are currently being developed. This was done by evaluating multiple access strategies applied with Spatial Modulation in multiple user scenarios, and finding a solution that may be viable for a real world implementation. The solution found to apply with Spatial Modulation is a Space-Time CDMA based one. The system's performance was analyzed by testing the influence of its main parameters in multiple scenarios with various detectors. Some scenarios are from 5G projects to understand its viability for 5G systems. The main influential parameters were the number of receive antennas and the number of users, the first with a gain of approximately 4 dB. The second one shows only a negligible degradation for a Maximum Likelihood decoder. For the other non-optimal detectors used, it degrades the performance due to the presence of multiple access interference. The spatial diversity associated with transmit antennas was also analyzed due to the existing trade-off between orthogonality and diversity. For the Matched filter detector, diversity does not compensate the loss of orthogonality, opposite to the other detectors, due to its vulnerability to multiple access interference. The presence of correlation between antennas also degrades performance in approximately 2 dB. For the 5G scenarios, the system shows negligible degradation for a higher number of users, demonstrating its potential to fit well in future 5G systems.

Keywords: 5G, MIMO, Spatial Modulation, ST-CDMA, BER performance, SNR gain

Resumo

O objectivo principal deste trabalho foi analisar a viabilidade da Modulação Espacial como tecnologia a implementar e suportar os futuros sistemas 5G que estão a ser actualmente desenvolvidos. Isto foi realizado avaliando estratégias de múltiplo acesso aplicadas com Modulação Espacial em cenários de múltiplos utilizadores e encontrando uma solução que possa ser viável para uma implementação no mundo real. A solução encontrada para aplicar com a Modulação Espacial é baseada num esquema de CDMA espaciotemporal. O desempenho do sistema foi analisado testando a influência dos seus parâmetros principais em múltiplos cenários com vários detectores. Alguns cenários são de projectos 5G para compreender a sua viabilidade para sistemas 5G. Os parâmetros mais influentes são o número de antenas receptoras e de utilizadores, causando o primeiro um ganho de aproximadamente 4 dB. O segundo mostra uma degradação desprezável somente no descodificador de máxima verosimilhança. Nos restantes detectores sub-óptimos usados, o desempenho do sistema é degradado devido à presença de interferência de múltiplo acesso. A diversidade espacial associada às antenas transmissoras também foi analisada devido ao compromisso existente entre ortogonalidade e diversidade. Para o filtro adaptado, a diversidade não compensa a perda de ortogonalidade, contrariamente aos outros detectores, devido à sua vulnerabilidade com interferência de múltiplo acesso. A presença de correlação entre as antenas também degrada o desempenho em aproximadamente 2 dB. Para os cenários 5G testados, o sistema mostrou degradação desprezável para números maiores de utilizadores, demonstrando o seu potencial para se enquadrar bem nos futuros sistemas 5G.

Palavras-chave: 5G, MIMO, Modulação Espacial, ST-CDMA, Desempenho de BER, ganho de SNR

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Δ	Relative Error
μ	Average value of a signal
Φ_R	Receiving Correlation Matrix
Φ_T	Transmitting Correlation Matrix
ρ	Correlation coefficient
σ	Standard Deviation
$\mathbf{c_s}$	Spatial Spreading
$\mathbf{c_t}$	Temporal Spreading
E_b	Energy per bit
$\mathbf{H}$	Channel Matrix
$k(t)$	Continuous spreading sequence
L	Size of Temporal Sequence
M	Modulation Coefficient
$\mathbf{N}$	Noise Matrix
n	Noise component
N_0	Spectral Noise Density
N_b	Number of bits
N_r	Number of Receive Antennas
N_t	Number of Transmission Antennas
N_u	Number of Users
s	Constellation symbol
$w(t)$	Output of matched filter for CDMA system

$\mathbf{X}$	Transmitting Signal Matrix
x_s	Modulated Signal
$\mathbf{x_t}$	Time spreaded Signal
$\mathbf{Y}$	Received Signal Matrix
y	Received Signal
z	Multiple Access Interference

List of Acronyms

4G fourth generation of mobile networks.

5G Fifth Generation of Mobile Networks.

AWGN Additive White Gaussian Noise.

BER Bit Error Rate.

BPSK Binary Phase Shift Keying.

BPSK Phase Shift Keying.

BS Base Station.

CDMA Code Division Multiple Access.

CSI Channel State Information.

DS-CDMA Direct Sequence CDMA.

FBMC Filter Bank Multicarrier.

FDD Frequency Division Duplex.

FDMA Frequency Division Multiple Access.

GFDM Generalized Frequency division Multiplexing.

GSM Global System for Mobile Communications.

IID Independent and Identically Distributed.

IoT Internet of Things.

KPI Key Performance Indicators.

LTE Long Term Evolution.

M2M Machine to Machine Communication.

MA Multiple Access.

MAI Multiple Access Interference.

MAP Maximum A-Posteriori.

MF Matched Filter.

MIMO Multiple-Input Multiple-Output.

ML Maximum Likelihood.

MT Mobile Terminal.

MTC Machine-Type-Communication.

MU-SM Multi-User Spatial Modulation.

NGMN Next Generation Mobile Networks.

OFDM Orthogonal Frequency-Division Multiplexing.

OFDMA Orthogonal Frequency-Division Multiple Acess.

PCSI Perfect Channel State Information.

PoC Proof-of-Concept.

QPSK Quadrature Phase Shift Keying.

RF Radio Frequency.

SIC Successive Interference Cancellation.

SM Spatial Modulation.

SMMA Spatial Modulation Multiple Access.

SNR Signal-to-Noise-Ratio.

ST-CDMA Space-Time CDMA based on Spatial Modulation.

SUSM Single User Spatial Modulation.

TDD Time Division Duplex.

TDMA Time Division Multiple Access.

UE User Equipment.

UFMC Universal Filtered Multicarrier.

WP Work Package.

1

Introduction

This chapter gives an overview of the work. First, the problems addressed in this work are presented, its motivations and its scope are clarified and the proposed solution is identified. Then the structure of this work is explained in detail.

1.1 Overview and Motivation

Nowadays, the fourth generation of mobile networks (4G) deployment with the Long Term Evolution (LTE) and LTE-Advanced technologies is well underway and with success, ”LTE has become a true global and mainstream mobile technology, and will continue to support the customer and market needs for many years to come” [1]. But wireless communications are constantly looking into new ways of improving on all possible aspects, on the existing networks and on dealing with its major issues, ”to satisfy the ever increasing demand for higher data rates and lower latencies at a lower cost” [2], creating more efficient and faster networks.

As such, the fifth generation of mobile networks, 5G, is currently being developed in order to address the demands of 2020 and beyond, to satisfy all needs and meet all requirements expected from mobile networks. 5G is an ”end-to-end ecosystem” [1] and is expected to enable a fully mobile and connected society. This is no easy task, due to the demands that the previous sentence contains. There is a tremendous growth in connectivity and density of traffic, Fig. 1.1, that 5G must be able of supporting in order to achieve its goals.

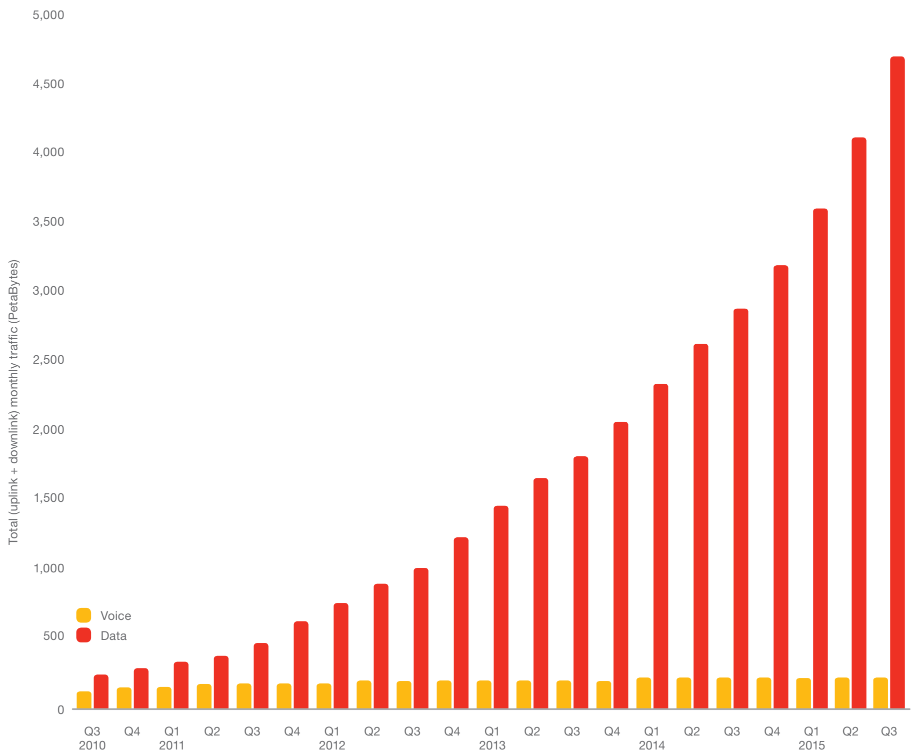

Figure 1.1: Total global monthly traffic from 2010 to 2015 (extracted from [3]).

As it can be observed, data traffic has increased from less than 500 PB in 2010 to almost 5000 PB in 2015, which means that it suffered an increase of 10 times since 2010. This shows the tremendous growth mentioned before, and it is expected that it continues growing strongly ”with a ten-fold increase forecast by the end of 2021”, [3], which means that 5G will have to support that level of traffic growth and support such a high traffic density in 2020 and beyond.

As such, in order for 5G to get to such a high level, there is the need for a big push in performance, allowing for very low latency and providing ultra-high reliability, massive machine type communications, higher throughput as well as higher connectivity density and a higher mobility range. In other words, to achieve the goals of 5G, future systems must be several levels above the currently used ones and superior in all aspects.

Although LTE can meet some of these requirements, there is a need for a new 5G radio access technology or interface to fulfill all requirements [4]. Therefore, the 5G solution that is currently being explored is one that will follow a key principle that has been followed since the development of Global System for Mobile Communications (GSM), ensuring interoperability with past generations of mobile communications [5]. This means that 5G networks will incorporate LTE to form a solution that is composed of the present technology of mobile communications and of the future one, taking advantage of both systems to create better networks in the 5G era [5].

As such, in order to create this 5G solution, it is essential to develop a new radio interface that can satisfy all requirements expected and demanded from the next generation of mobile networks. The first and main goal of this work is to investigate one specific radio interface to ascertain its potential as a new radio access technology or interface for 5G that can meet the demanded requirements. Several new radio interfaces that show potential are already being explored for this purpose too, for example Beamforming and Spatial Modulation (SM), focusing on SM. Beamforming has already been implemented with LTE and shows great promise, but this work focuses on a solution more oriented for Machine to Machine Communication (M2M), and SM shows more potential in that direction, hence it was chosen.

SM is a Multiple-Input Multiple-Output (MIMO) technique and has been rising in interest over the last years, because of its low complexity and good performances for such a low complexity system [6]. Even more recently, approximately two or three years ago, it started being applied to multiple user scenarios, because one of the major issues in wireless communications is to be able to serve simultaneously a large number of users while maintaining a good connection on all communications. Several works have been done to solve this issue, the main ones being the conventional MA strategies like Code Division Multiple Access (CDMA), Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Orthogonal Frequency-Division Multiple Acess (OFDMA).

But the search for a solution that can serve even more users and do it more efficiently never stops. As such, due to its achieved performances for single users, SM is an attractive solution to apply for multiple users. With this, the second purpose of this work is introduced, specific of SM and its applicability to multiple users. There is the need for more practical works based on SM that can cope with multiple users and the degradation they may suffer in a real world implementation. Therefore, the need for such a system that may be viable to implement in the real world and the role it can take in the 5G era are the motivation for this work.

Because of the demands of 5G, there is the need to search for a solution that can serve an even higher number of users than those conventional MA strategies, while at the same time keeping the complexity as simple as possible. This is where ”Space-Time CDMA based on Spatial Modulation”, ST-CDMA enters, the solution that is proposed and expanded in this work. Through a detailed theoretical analysis and simulation, the reasons why it is proposed here are demonstrated and the advantages compared to the other systems are exposed to understand why such solution was chosen. With it, this work shows how it can meet the requirements of complexity and number of users, but at the same time it also shows the flaws or issues it may present and how they can be dealt with. It shows the advantages of implementing SM for multiple users, but also the obstacles of such implementation and what can be done to surpass them.

It ultimately tries to explore the potential and applications of this radio interface, theoretically and practically, in order to ascertain its possible role in future 5G systems.

1.2 Structure

This work is focused on ST-CDMA, which is the solution found from an existing work to meet the demanded requirements. As such, this work expands that solution and goes further in both theoretical and practical terms, in order to comprehend its viability and applications for future mobile wireless networks such as 5G.

This work is divided into three main chapters, Chapter 2 contains all the theoretical work. It starts by giving a basis of 5G to this work, to show how it can be integrated in future 5G systems and how helpful it can be. The main requirements, such as latency and user data rates, are presented in order to comprehend what is required from a system for it to be implemented in the 5G era. Then, the main technologies being currently explored for 5G are described, introducing SM as one with significant potential and demonstrating the applications that it can have if implemented for the current and future 5G systems.

The second part of Chapter 2 focuses on SM. It starts by showing SM for one user, its model is explained and its advantages are stated. Then, it expands to SM for multiple users and reviews some existing works like Multi-User Spatial Modulation, MU-SM, and the conventional multiple access strategies like CDMA, etc.

Chapter 3 introduces the solution that is the focus of the rest of this work, ST-CDMA. This chapter is divided into a theoretical part and a more practical one. The theoretical part begins by exploring its model and how it works, the transmission, the spreading, the receiver and the detectors. Here commences the expansion of the existing work and it starts by showing the analysis of three different detectors for the ST-CDMA system. Another expansion to this work is the analysis of a non-ideal channel for the ST-CDMA system and how it will affect it. This part ends with an analysis of one of the most important issues in a multiple user scenario for the ST-CDMA system, the multiple access interference among users.

As for the practical part of this chapter, it describes how the theoretical model of ST-CDMA was converted into an algorithm and implemented in a simulation environment. It exposes the algorithm used in this work to conduct the practical analysis of the ST-CDMA system, how it works, what decisions were made and what metrics were used, how its results were evaluated and what important assumptions were made. Ending this part of the chapter is an assessment of this algorithm that compares it with other similar works in order to confirm the validity of the results obtained here.

As for Chapter 4, this is the second part of the expansion of the existing work of ST-CDMA in practical terms. Through Python simulations the entire system is tested and its performance is analyzed. First, all scenarios tested are described and demonstrated. The performance results of these scenarios are presented and conclusions are extracted. The simulation of the system starts by varying its parameters in order to analyze its influence on the performance of the ST-CDMA system. Then certain phenomena characteristic of ST-CDMA are analyzed. The first one is the presence of diversity in the system and the second one is the existence of correlation between the channels. Lastly a 5G scenario taken from an international 5G project [7] is tested and analyzed. This way the potential of this system in the 5G era can be analyzed and its role and importance can be clarified. In chapter 5 one presents the main conclusions of this work and suggestions for future works in this subject.

1.3 Contributions

This work may have a basis on existing works but it is by expanding that basis and adding new elements and directions for further development and validation that this work contributes to the academic community. In Chapter 3, the ST-CDMA system implemented is characterized and expanded in multiple ways. First, the trade-off between transmit diversity and orthogonality is analyzed, showing how and when each of the phenomena influence the system and its degree of influence. Then, in the receiver part, two more detectors are added to the system and are fully characterized and later simulated on Chapter 4, in order to analyze the behavior of the ST-CDMA system for other detectors with different methods of detection and characteristics, as well as to compare the detectors' performance between each other, their advantages and disadvantages. In the ST-CDMA system, the channel component is also expanded, with an analysis and simulation (in Chapter 4) of a channel influenced by the presence of correlation between antennas, in order to go beyond the theoretical approach of an ideal channel and explore a scenario closer to a real world implementation, analyzing its effects on the system. Considering that Multiple Access Interference (MAI) is one of the most negatively influential phenomena in multiple user scenarios, in Chapter 3, an analysis of its presence in the ST-CDMA for all detectors is performed in order to understand its effect and how to deal with it. Finally, in Chapter 4, the parameters that positively or negatively influence the ST-CDMA system are defined and confirmed through simulations. An analysis and simulation of the effects of transmit diversity in the ST-CDMA system is given, as well as one of the presence of correlation in the channel, as previously mentioned. And lastly, the ST-CDMA system is inserted in real 5G scenarios taken from an international project, giving a demonstration of its behavior, and an analysis of its potential in future 5G systems is provided.

In sum, a more practical solution with a more extensive and broad analysis of an SM implementation for multiple users is provided and its role and viability in future 5G systems is explored.

2

Background

This chapter has two goals. The first one is to show how and where this work fits into current wireless communications, and future ones too, namely 5G. The second one is to give the reader a detailed introduction to SM and create a basis of knowledge for the rest of this work, by describing its functioning and its variations, ending with a review of the different approaches used for multiple users scenarios.

2.1 5G Development

5G is the next generation of mobile networks, following LTE, and it is still in a development stage. This work also comes as a technology that may be used in the development of 5G and as a technology that can be part of future mobile networks. Therefore, in this section the use of SM for 5G is discussed, as well as its advantages and disadvantages in order to comprehend the role of such technology in the next generation of mobile networks. Nowadays there are multiple international projects [8] working on developing 5G and achieving a solution that can meet requirements. As such, this work also gives an overview of some of these projects and shows how SM can have an important role on them and possibly improve their networks. This helps to better understand where SM stands currently on 5G networks and also more specifically on MIMO technologies.

2.1.1 5G Requirements

”The fifth generation of mobile technology 5G is positioned to address the demands and business contexts of 2020 and beyond” [1]. It is connected to concepts such as the Internet of Things (IoT) and a fully mobile and connected society, among others. This new generation of mobile networks is currently on a development stage and in search for the technologies that can help meet the requirements devised for 5G [1], established by the Next Generation Mobile Networks (NGMN) on a white paper [1] to show the main conditions and the main goals to be achieved by 5G, so that all related projects and investigation can have a guideline to follow and can advance quicker.

There are 33 requirements devised by NGMN, which can be divided into 5 main categories:

- User experience.
- System Performance.
- Device Requirements.
- Enhanced Services.
- New Business Models and Network Deployment.
- Operation and Management.

Only the first three categories are explored in this work, since they are more relevant to it, in opposition to the others.

The first one, User Experience, is important for this work, since it helps projecting what is needed in order to keep all users satisfied when they are using one or more services, hence, demanding the test of several different user scenarios for a better understanding. Of this category, there are four main requirements, starting with Consistent User Experience [1]. This requirement states that a 5G system ”should be able to deliver a consistent user experience over time for a given service everywhere the service is offered” [1]. This means that a 5G system must provide consistently a service of quality with a good performance any time and everywhere, no matter the circumstances. The second one is the User experienced Data Rate, which is the minimum required user experienced data rate to guarantee a quality service for the user when accessing a certain application. A user experienced data rate of at least 50 Mbps must be available everywhere cost-effectively and in some specific environments, like indoor offices, it must be up to 1Gbps [1]. The data rates for each use case and environment are shown on Table 2.1 in order to observe how it varies for different scenarios. The third requirement to consider about User Experience is the Latency, which is measured by two metrics related to the end user in order to define the minimum required to provide in a 5G system, which are the E2E latency metric and the User Plane Latency one [1]. As such, the 5G system must be able to provide 10 ms E2E latency in general and 1 ms E2E latency for specific use cases that require extremely low latency, Table 2.1. It also must give to the user the perception that he or she is always connected. The last requirement connected to this category is Mobility. It requires 5G systems to be able to provide a seamless service experience moving. According to [1], in order to support an increasingly large number of users/devices, 5G systems should provide mobility on demand only to the specific devices and services that need it. To understand exactly what level of Mobility is required for each use case, Table 2.1 shows the different scenarios and its respective mobility requirements.

Table 2.1: User Experience requirements for each environment (extracted from [1]).

Use case category	User Experienced Data Rate [Mbps]		E2E Latency [ms]	Mobility [km/h]
	DL	UL		
Broadband access in dense areas	300	50	10	On demand, 0-100
Indoor ultra-high broadband access	1000	500	10	Pedestrian
Broadband access in a crowd	25	50	10	Pedestrian
50+Mbps everywhere	50	25	10	0-120
Ultra-low cost broadband for low ARPU areas	10	10	50	On demand, 0-50
Mobile broadband in vehicles(cars, trains)	50	25	10	On demand, up to 500
Airplanes connectivity	15 per user	7.5 per user	10	Up to 1000
Massive low-cost/long-range/low-power MTC	Low (0.001-0.1)	Low (0.001-0.1)	Seconds to hours	On demand, 0-500
Ultra-low latency	50	25	<1	Pedestrian
Resilience and traffic surge	0.1 - 1	0.1 - 1	Regular communications: not critical	0-120
Ultra-high reliability and Ultra-low Latency	0.005 - 10	~ 0 -10	1	On demand, 0-500
Ultra-high reliability and availability	10	10	10	On demand, 0-500
Broadcast like services	Up to 200	Around 0.5	<100	On demand, 0-500

Table 2.1 shows how most of the requirements of User Experience vary according to the different scenarios and environments. As explained before, indoor spaces are required to have higher data rates (up to 1Gbps) available to users. There are some factors that influence the available data rate in certain scenarios. For example, the amount of users in a space, i.e., in a crowded one there is a lower data rate available to each user, hence, its required data rate is also smaller for spaces that are more crowded. Related to this is also the traffic, i.e., the more traffic between active users exists the less data rate will be available and required. The second factor is users' mobility, if a user is in a moving car, train or plane then the required data rate is lower due to its high mobility. As for the latency, in general it obeys to the requirements explained before and only in a few scenarios there is a lower latency requirement of the

order of 1 ms. In terms of mobility, it increases according to the size of the environment and the speed of the user. In an indoor space it can only be a pedestrian mobility but in the case of a car, a train or a plane, the mobility increases accordingly. Most of the use cases provide mobility on demand, as it is one of this requirement's purpose.

As for the second category of requirements, System Performance, they define the system capabilities that are required to satisfy all kinds of users and use cases [1]. They are divided into five requirements in order to best define systems' performance. The first one is the connection density, which defines the amount of simultaneous active connections per square kilometer that can be supported by the system. In this case, an active connection symbolizes when the devices are exchanging information with the network [1]. This requirement is of special importance, since it helps defining the amount of users that can be simultaneously active in the network for a certain area. In Table 2.2 the connection density that is required for each environment and scenario is defined, considering that a single operator is assumed in the considered area.

Next is the traffic density requirement, which is measured in bps/m^2 and defined as the total amount of traffic exchanged by all devices over a certain area. According to [1], in extreme cases, the 5G system must be able to provide data rates of at least several tens of Mbps to support tens of thousands of users in crowded areas (less favorable scenario). In the opposite scenario, it must be able to provide simultaneously 1 Gbps to tens of workers in the same office floor (a more favorable scenario).

To better comprehend exactly how much data rate must be provided for a certain area in each environment, in Table 2.2 all traffic densities required are defined.

Table 2.2: System Performance requirements for each environment (extracted from [1]).

Use case category	Connection Density [/km^2]	Traffic Density [Gbps/km^2]	
		DL	UL
Broadband access in dense areas	200-2500	750	125
Indoor ultra-high broadband access	75,000	15000	2000
Broadband access in a crowd	150,000	3750	7500
50+Mbps in suburban	400	20	10
50+Mbps in rural	100	5	2.5
Ultra-low cost broadband for low ARPU areas	16	0.016	0.016
Mobile broadband in cars	2000 (1 active user/car x2000 cars)	100 (0.05/car)	50 (0.025/car)
Mobile broadband in trains	2000 (500 active users/train x4 trains)	100 (25/train)	50 (12.5/train)
Airplanes connectivity	80/plane	1.2/plane	600/plane
Massive low-cost/long-range/low-power MTC	Up to 200,000	Non critical	Non critical
Ultra-low latency	Not critical	Potentially high	Potentially high
Resilience and traffic surge	10,000	Potentially high	Potentially high
Ultra-high reliability and Ultra-low Latency	Not critical	Potentially high	Potentially high
Ultra-high reliability and availability	Not critical	Potentially high	Potentially high
Broadcast like services	Not Relevant	Not Relevant	Not Relevant

In Table 2.2, the same scenarios from Table 2.1 are considered, for a better and clearer understanding of these scenarios. Regarding the Connection Density, it is influenced mainly by the concentration of active users in a certain area. This means that a scenario where there are more active users will have a higher connection density. For example, in the scenario of access in a crowd, there are more users present in the same area than in the indoor scenario. Therefore, the 5G system must support a higher number of simultaneous active connections in order to support a higher number of active users in that crowded scenario. The same goes for example for a rural area, where the amount of active users is much lower than in an indoor scenario or even lower compared to the crowded area scenario. As such, the amount of active users supported there is adequate to the scenario but much lower compared to the other scenarios since it is a rural scenario with a low number of active users. As for vehicles, such as cars, trains and planes, the amount of active users allowed is directly connected to the size of each one. As for the traffic density, what affects it the most is the amount of simultaneously active users in a certain area. For example, in a rural scenario the data rates that are required to be provided are much lower than the scenario of a crowd or the indoor one. This happens again due to the low amount of active users in this scenario, which means that there is less traffic of information in a rural environment, justifying the lower data rate that is provided and that is still adequate to satisfy all users in this scenario.

As for the third requirement, Spectrum Efficiency, it is not as defined as the previous ones, yet, but in [1] it is compared with the spectrum efficiency that 4G systems are able to achieve. Compared to the 4G level, spectrum efficiency must be significantly enhanced ”in order for the operators to sustain such huge traffic demands under spectrum constraints, while keeping the number of sites reasonable” [1]. In general, the spectrum efficiency that is required is much higher than the level of efficiency used in 4G systems and it is required for all kinds of scenarios and environments.

The fourth requirement for system performance is Coverage. According to [1] it is not completely defined yet, needing further study for a number of environments and scenarios. But for rural areas, the 5G system must be able to provide the data rates required with only the current grid of macro-cells.

The last requirement for system performance is resource and signaling efficiencies. This requirement is important because the higher this efficiency is, the less resources are needed in order to obtain the same results. As such, signaling efficiency must be enhanced in order to minimize the related radio resources and energy consumption, so that their consumption is justified only by the needs of applications.

The last important category of requirements for this work is Device Requirements. Since the network is required to improve, so are the devices that connect to it. In order to be able of supporting all communications performed in 5G networks, smart devices must grow in capabilities and complexity, in both hardware and software [1].

There are four requirements to define what is needed from a device from the 5G era, starting with the operator control capabilities of devices. This requirement states the necessary capabilities operators must have to assure a high level of quality for a 5G system.

With this first requirement it is important to present a specific notion, the User Equipment (UE), which represents any device used directly by an end-user to communicate[1]. For this requirement to be accomplished, the 5G system must assure flexible and dynamic UE capability handling.

As such, 5G devices must provide to operators the capabilities of checking, updating, diagnosing malfunctions and even fix problems on smart devices over the air, which means that they must have a high degree of programming and configuration capabilities over the hardware and software of the devices, as well as collecting data from them and optimizing them with the help of those data [1].

Next is the Multi-Band-Multi-Mode Support in Devices, which is essential for enabling global roaming [1]. For this to happen, smart devices must be able of supporting multiple bands as well as multiple nodes, like Time Division Duplex (TDD), Frequency Division Duplex (FDD) or even mixed, except for the case of Machine-Type-Communication (MTC) devices and IoT devices since they may be stationary. This requirement also influences data rates, because to have higher data rates, devices must be able of using multiple bands simultaneously, without having a single impact on network performance.

The last two requirements relate to two kinds of device efficiency. The first is the device power efficiency. This requirement states that the battery life of all devices must be significantly increased, at least 3 days for a smartphone and up to 15 years for a low-cost MTC device. The second one is the device's resource and signaling efficiency. According to [1], this requirement is even more crucial on the device's side than on the system's one, because of the significant impact that signaling has on the battery's life. The same definitions of the requirement previously described on the category of System Performance apply here on the device's side.

2.1.2 Perspectives for Radio Interfaces

To meet the requirements described in the previous section, such as, ultra low latency, ultra-reliable communication and massive M2M, several technologies have been explored for 5G, for example Beamforming, new waveforms for 5G, and MIMO technologies, namely Spatial Modulation in this case. This also introduces the concept of Massive MIMO, to accomplish massive M2M communication and as one of the main hypothesis for the development of 5G [9].

Beamforming, or more specifically adaptive beamforming, consists of flexibly directing a focused beam towards a desired user instead of broadcasting and scattering it in all directions, taking advantage of the antenna array gain and increasing signal quality and network coverage, as well as reducing inter-cell interference [10]. It is normally used in scenarios with closely-spaced antenna arrays and it can transmit multiple beams to multiple desired users, depending on the number of transmit antennas, Fig. 2.1. By identifying the signal direction of arrival of a Mobile Terminal (MT), the Base Station (BS) can direct the radio beam towards the MT, creating transmitted signals that add up constructively on the MT's location and add up destructively ”almost everywhere else” [9], thus forming the directed and focused radio beam that is transmitted to the MT instead of broadcasting the signal in all directions, Fig. 2.1.

This technology can be applied to MIMO, and in order to be applied to 5G and meet the 5G requirements explored before, a more recent concept is being explored, Massive Beamforming, which exploits Massive MIMO in order to get to more users and take better advantage of the number of antennas to meet the requirements that 5G brings.

Another subject that is currently being explored for 5G are new waveforms. According to [11], Or-

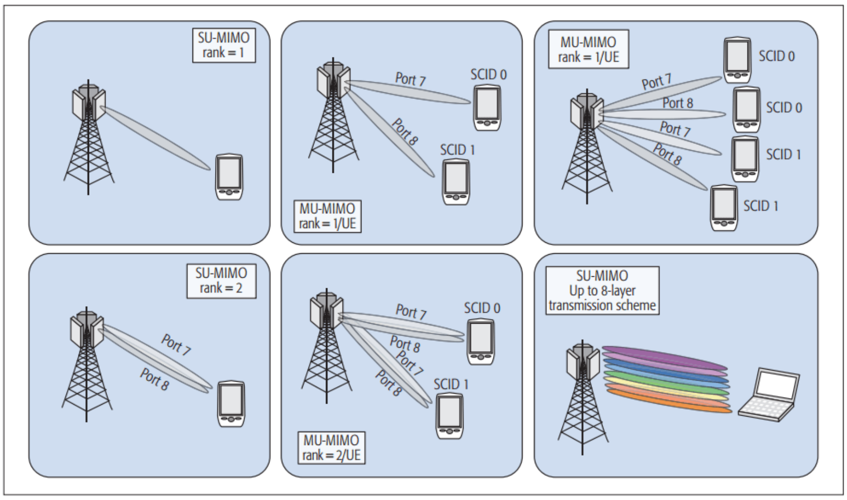

Figure 2.1: Beamforming schemes in LTE/LTE-Advanced (extracted from [10]).

thogonal Frequency-Division Multiplexing (OFDM) has been the dominant waveform in LTE. OFDM ”is known to be a perfect choice for point-to-point and downlink communications” [11] and achieves a good bandwidth efficiency, while keeping a low complexity. But OFDM also faces some challenges that are hard to solve. As such, for the 5G era, new waveforms that can surpass OFDM and its current challenges are being explored. Currently the main waveforms that are being investigated are [4]:

- FBMC, Filter Bank Multicarrier.
- UFMC, Universal Filtered Multicarrier.
- GFDM, Generalized Frequency division Multiplexing.
- Improved versions of OFDM such as filtered OFDM for example, f-OFDM.

Another technology currently being explored is SM, and it has been gaining more interest over the last years [12], since it is a MIMO technology it has gained interest for 5G due to its advantages. Since it is known for achieving good performances with a low computational and implementation complexity, it is an attractive technology that can help M2M. Furthermore, it can capitalize on the antennas’ position as well as on having multiple antennas, increasing its use and interest for mobile networks, since it can help coping with a higher number of users in the network.

As such, this work comes as a contribution to understanding the advantages and disadvantages SM can bring to a mobile network with multiple users and how it can fit in 5G networks. This is just an introduction to SM and in the next chapters it will be explored with more detail in order to see exactly how it behaves and what it can bring to the future generations of mobile communications, namely 5G.

2.1.3 Current Aplications for Spatial Modulation

In order to better understand where and how SM can be applied in a 5G system, some of the international projects from [8] are explored here, due to the use that SM can have in these projects.

First is the METIS-I project [13], whose main objective is to lay the foundations for future 5G systems, to show the directions that 5G can take and the various steps to take in order to develop the 5G systems. As such, the METIS-I project took a technical approach shown in [13], which includes Multi-node/Multi-antenna Transmissions and states that it ”will design Multi-node/Multi-antenna technologies to achieve the performance and capability targets for future wireless systems”.SM is included in here, because it provides a multi-antenna technology that may meet the targets of performance and capability that a 5G system requires from it.

Another project is TROPIC [14], which focuses on exploring the concept of small cells clouding and its feasibility as a 5G technology. Small cells clouding is the result of combining the small cells network infrastructure with cloud computing, optimizing energy, computation and communication resources. For this project, the contributions that SM can give are located in the Physical Layer. One of the objectives of TROPIC is to enhance spectral efficiency in dense small cells scenarios. And one of the ways to do it is by a network-MIMO interference management that is incorporated into distributed network coordination mechanisms that were developed in TROPIC [14].SM as a MIMO technology helps with the interference management in these mechanisms and enhance the spectral efficiency of the scenarios considered.

Another project of interest is the FANTASTIC 5G, whose objective is to develop ”a new multi-service Air Interface (AI) for below 6 GHz through a modular design” for 5G [15]. By analyzing the main requirements for future 5G systems, it sets a vision for the new 5G air interface below 6 GHz and what its main characteristics must be. In order to make that vision into a reality, it defines the goals to achieve by FANTASTIC 5G and other related 5G projects, the core services that will serve as a baseline for a 5G system. One of the key characteristics for this project is scalability to support a high number of devices and one of the core services mentioned is massive machine communications, which are both subjects directly connected to the purposes of 5G MIMO technologies and more importantly of SM. In fact, according to [15], one of its goals is to specify scalable MIMO and cooperation modes for new waveforms in 5G. As such, Spatial Modulation can have an important role in FANTASTIC 5G, helping to achieve its scalability goals due to its advantages as a multi-antenna system, and also helping with the new 5G waveforms that are being explored.

Lastly there is the project Flex5Gware. Its objective is, according to [7], to deliver highly reconfigurable hardware platforms together with hardware agnostic software platforms targeting both network elements and devices. The project includes work on use cases and scenarios for 5G systems. Some of these use cases and scenarios have already been described before in Section 2.1.1. Besides this, [7] also defines the project’s main Key Performance Indicators (KPI), and uses the already defined Proof-of-Concept (PoC) originated from other 5G projects such as METIS-I that was explored previously.

A PoC is a HW or SW platform used to show certain technologies or services and in this project there is one specific PoC that is important and related to this work, PoC11. Massive MIMO and its advantages are well regarded in this project, in increasing the spectral efficiency and lower the bandwidth requirement for certain scenarios by means of MIMO operations. This requires the existence of multiple antennas at both the base station and the terminals, which can be considered as HW enhancements for the system. As such, support for Massive MIMO implementations is defended and encouraged.

Thus PoC11 is a Multi-chain massive MIMO transmitter and comes as a support for implementing MIMO solutions in Flex5Gware. According to [7], this transmitter must be able of generating multiple Radio Frequency (RF) signals in one digital device, which is equivalent to the principle of using SM for multiple users, but that is explained in further chapters of this work. Furthermore, this multi-chain MIMO transmitter also serves to increase energy efficiency in order to support massive MIMO, to support a higher number of users, while keeping a high cost and energy efficiency.

As a MIMO technology, SM fits well with this project's needs, it can transmit multiple RF signals with its multiple antennas setup and can take advantage of their multiplicity by capitalizing on each antenna's position. Given its low complexity, it can provide a higher energy efficiency for high numbers of users. As such, Spatial Modulation has the potential to help this project meet its goals and implement Massive MIMO in it.

In Chapter 4 a practical analysis is shown to demonstrate how a SM implementation for multiple users would perform for this project and its conditions.

2.2 Multiple Access Strategies for Spatial Modulation

The theoretical background that supports this thesis is shown in what follows. From basic notions and simple schematics to thorough analysis of certain events and complete system models, all of these are explained and fundamented. It starts with the simplest case of SM, for one user, and through the reading of this work the complexity of SM increases more and more with the addition of more influential variables in its system. This way showing the evolution from this simple case of SM to the more complex cases with multiple users and multiple access strategies to cope with them, whose analysis is the key part in this theoretical analysis.

2.2.1 Single User Spatial Modulation

As explained before, the first thing to do is to analyze SM for just one user. As such, the system model chosen for this analysis is the model represented in [6]. SM by itself is a MIMO transmission technique. Nowadays, it is an important technique because of its efficient performance while maintaining low computational and implementation complexities.

This technique explores the advantages of switching between transmit antennas to carry the information more efficiently. Its second major advantage is also important and restricted to single user scenarios, as shown in Fig. 2.2, which is the fact that inter-channel interference is minimized. SM activates one single transmit antenna per time instant, therefore, there is only one channel being used and no possibility of existing any kind of inter-channel interference [6].

So, first of all, the scenarios considered for single-user are downlink and single-cell, which means that the communication flows from the BS to the user [6]. Therefore, the BS takes care of the transmission of the information and the user receives and decodes that information.

Following the notation from [6], the Base Station's transmission antennas are represented by N_t and the user's receiving antennas are represented by N_r. These are two of the most important variables on SM and its effects are studied throughout this work. Another important variable is the Modulation coefficient, M, which is important for the modulation of the transmission signal and is calculated through

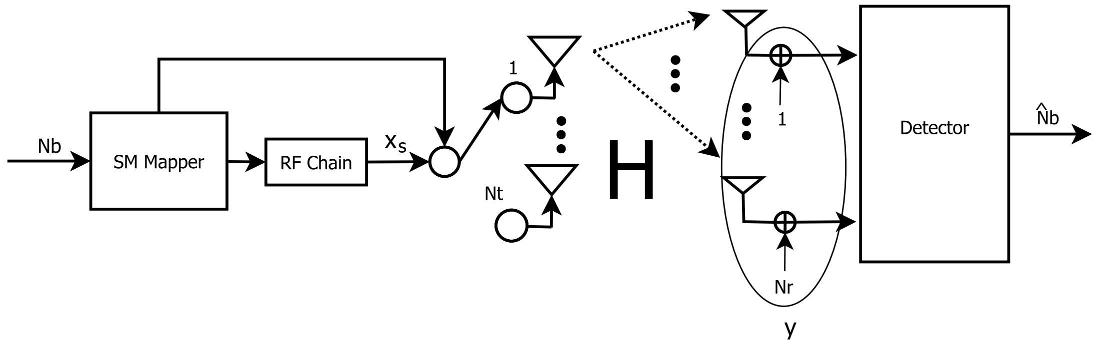

Figure 2.2: System Model of Single User Spatial Modulation (SUSM).

the number of bits,

$$M = 2^{N_b} \ , \tag{2.1}$$

with:

- N_b : number of bits.

But the most important variable is the number of users, N_{u}. In the case of a single user it is not used, but for the multi-user analysis it has great significance and influence.

From the model shown in Fig. 2.2, the signal is firstly mapped and transmitted, Fig. 2.3, then it passes through a channel **H** and lastly the signal is received and detected. So the model can be separated into three parts, i.e., transmission, channel and receiver.

In order to transmit the signal, there are some important steps and concepts to consider. To better understand them and how transmission works, the model is shown in Fig. 2.3.

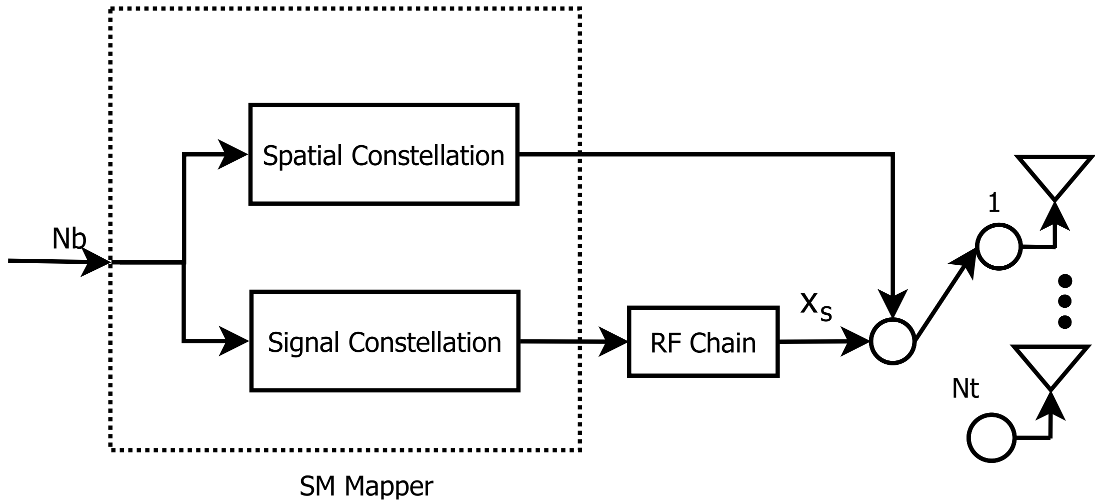

Figure 2.3: System Model of transmission in SUSM.

There are two parts to this transmitter, the SM Mapper, and the RF chain plus the antennas that transmit the signal, x_s.

Starting with the SM Mapper, it receives a certain number of information bits, N_b, that the base station wants to transmit, being the basis of the signal that is created. And after receiving it, the signal is mapped through two differently purposed constellations that are going to carry these information bits.

These information bits are separated into two parts. There is one part that is the data used for the signal constellation, which is responsible for creating and modulating a signal with that data [6]. To modulate it, the modulation coefficient M is used, because it defines the used modulation for the signal and its size, for example M-PSK, M-QAM, etc, i.e., it defines the signal constellation from where a symbol of that constellation, s, is chosen to be transmitted by one of the antennas. The other part is the transmit antennas' index, used for the spatial constellation, through which an antenna is chosen from the N_t antennas and activated to transmit the symbol previously mentioned, s. But, between the symbol and the chosen antenna there is still one other block, the radio-frequency RF chain.

In single user SM, as seen in Fig. 2.3, there is only one single radio-frequency RF chain, which shows the third of the most important advantages in using single user SM. By always using the same RF chain, it saves significant power at the power amplifier stage [6], and it uses permanently only one RF chain because only one antenna is activated per time instant.

So, after defining the symbol to transmit, s, and choosing the antenna to activate, the transmission occurs, through the channel to the receiver, as seen in Fig. 2.3. So the next step is to analyze the received signal and its receiver. The receiver gets a signal that is not exactly the same that was transmitted. Instead, it comes in the form of

$$y_r = h_{r,m} x_s + n_r \ , \tag{2.2}$$

where:

- y_r : received signal in the r^{th} receive antenna.
- $h_{r,m}$: channel coefficient for the r^{th} receive antenna and m^{th} transmit one.
- x_s : transmitted signal for the symbol s.
- n_r : noise component in the received signal.

As observed in (2.2), the received signal y_r comprises more than just the transmitted signal, x_s, i.e., the channel coefficients $h_{m,r}$ due to the transmitted signal passing through the channel and the existence of noise in the connection, n_r.

The channel is described through a matrix **H** of channel coefficients with **H**$\epsilon\ \mathbb{C}^{N_r \times N_t}$, depending on the number of transmitting and receiving antennas, because it represents the relation between the two groups of antennas.

For simulation purposes, throughout this work the channel coefficients follow complex Gaussian distributions, except for one specific case that is introduced later on. This means that each coefficient is "a zero-mean, mutually uncorrelated, and circularly symmetric complex Gaussian random variable with unit variance" [6], $h_{r,m} \sim \mathcal{CN}(0, 1)$.

It is important to note that Perfect Channel State Information (PCSI) is assumed in order to have an ideal channel scenario [6]. As for noise, in order to better evaluate single user spatial modulation, the existence of noise is accounted for. As such, there is an added component in the received signal as mentioned before, n_r, which is described by a sample of complex Additive White Gaussian Noise (AWGN), $n_r \sim \mathcal{CN}(0, \sigma_N^2)$. Another important detail is that noise components are statistically independent in between the receive antennas.

To retrieve the transmitted signal x_s, a detector is used so that it retrieves the information from the received signal as effectively as possible. In this case, because of the low complexity of single user SM, the chosen detector is the joint ML decoder, which is optimal [6]. This decoder's computational complexity increases with the modulation coefficient M and the number of transmit antennas, being described by

$$(\hat{m}, \hat{s}) = arg_{m,s}min \sum_{r=1}^{Nr} ||y_r - h_{r,m}x_s||^2 \ , \tag{2.3}$$

where:

- $\hat{m}$: estimated index of activated antenna.
- $\hat{s}$: estimated symbol transmitted.
- y_r : received signal in the r^{th} receive antenna.
- $h_{r,m}$: channel coefficient for the r^{th} receive antenna and m^{th} transmit one.
- x_s : transmitted signal for the symbol s.

This estimation results from searching through all the possible combinations of active antenna and symbol, m and s, for the transmitted signal which is closest to the received signal, for all receiving antennas.

2.2.2 Multiple Access Schemes based on Spatial Modulation

Some of the existing MA schemes based on SM are analyzed to understand them and their viability, theoretically and practically.

In a more realistic situation there is not just one user trying to connect to the BS, but rather several of them, and all must have a good connection to the BS. For that to happen, a model of SM for multiple users is needed in order to successfully implement SM in the real world.

When comparing multiple user SM to single user SM, it is still based on the same system with a transmitter to send the information that passes through the channel and is then received and decoded by a user. But now, each of these parts becomes more complex and there is not just one user, there are several. Each of these users has a receiver with N_r antennas that decodes the information specific to that user.

In transmission there is a similar structure to the transmitter in Fig. 2.3, but this time for multiple users, having only one RF chain per user that carries the information to the transmit antennas and the transmit antennas that are chosen accordingly and activated to transmit the information to the correspondent users. Note that each user can be assigned several transmit antennas to transmit information, activating only one antenna per instance of time for each user.

Each user has N_r receive antennas ready to receive information from the BS and it must efficiently transmit the information to all users, hence, a multiple access scheme is needed for the transmission.

The purpose is to transmit the information to all users in the most efficient way possible. It manages all the transmission antennas in a way that enables the use of them all as efficiently as possible to transmit the information to all users.

For example, if one antenna is already transmitting to a user, instead of waiting for it to be available it must transmit the information through another available antenna to the other users or the same user too, this way adaptively allocating the antennas to users.

The multiple access scheme enables to do this and takes full advantage of the diversity in between transmit antennas by using spreading sequences or codes that choose the transmit antennas to be activated for each user in the most efficient way.

But there is an important issue to be dealt with, the number of users itself. The existence of multiple users causes degradation in the performance of SM with the increase of the number of users, hence, different systems were created to better cope with this degradation, like SMMA. The advantage of SMMA is that it reduces significantly the degradation that is caused due to effects such as MAI, [6].

Nowadays, this is still a recent and modern technology, as such there is still some research to be made into the matter and a need for more practical multiple access schemes for SM that may later be considered for a real world implementation. This work contributes to this matter and analyzes a solution that may have that potential.

The solution is derived from the CDMA approach to SM, being called Space-Time CDMA based on Spatial Modulation, ST-CDMA, where two different spreadings are used for the multiple access scheme, a temporal one and, most importantly, a spatial one [16]. The focus of this model is more on the spreadings and how the system behaves with them as on the other parameters that characterize it.

In this chapter, some of the approaches that were already explored are introduced in order to understand where this technology stands right now and its difficulties, as well as to compare with the ST-CDMA solution. This solution is introduced later on and explained with detail, from the transmission to the receiver, with the use of three different detectors in order to better comprehend the more adequate detectors and its limitations.

There is a specific environment that is also analyzed, because it represents a more realistic situation. That is when the channel is not ideal and it has correlation in its coefficients. As stated before, the MAI is an important issue in multiple users scenarios, as such it is also analyzed in detail to understand it better, and also to understand in more detail how the two existent spreadings combine with each other and the consequent trade-offs from those combinations.

Before focusing more on spatial modulation, a vision on the conventional MA strategies is shown. Some of those are for example, FDMA, TDMA, CDMA and OFDMA [17]. In Table 2.3, it is possible to see how each of them performs the allocation of users [17].

Table 2.3: Comparison between MA strategies of the method of allocation of users [17].

Strategies	Allocation of users
TDMA	Time-slots
FDMA	Frequency carriers
CDMA	Codes
OFDMA	Set of subcarriers

These are the main conventional MA strategies. Each of them has a different user allocation method, whether it is TDMA that allocates time-slots to users or FDMA with frequencies for each user, as well as

OFDMA with a set of subcarriers for each user and CDMA with a certain amount of spreading codes to serve a certain amount of users.

By considering these strategies, the idea is to find a solution with SM that may have a better performance than these approaches, or even use one of the approaches to help with that demand.

According to [6], there are two main ways of implementing SM for multiple users, the first one is called Multi-User Spatial Modulation MU-SM and the second one is SMMA. To better compare them, Table 2.4 shows their main differences.

Table 2.4: Main differences between MU-SM and SMMA.

Implementation	Antennas Arrangement	Complexity	Receive Antennas	Degradation with increase of users
MU-SM	Fixed	Lower	1/user	Low
SMMA	Adaptive	Higher	≥1/user	Low

Both systems are for multiple users scenarios and use precoding techniques to perform more efficiently and coordinate multi-user interference [6]. In the case of MU-SM, the transmitter has groups of transmit antennas defined and designated to each user, which means that each group of transmit antennas is fixed on transmitting to a specific user and always to that one. As such, to take the most out of the capacity in MU-SM there has to be a very efficient and crucial management and selection of the transmit antennas, which can be very hard and it only gets worse with the increase of the number of users, because there are more users to satisfy with the same number of transmit antennas that are being managed [6].

Even if the number of transmit antennas would be increased, it would not solve permanently that issue. This represents an important limitation that SMMA does not have.

In order not to lose focus on the purposes of this work, this is not explained in more detail but in [18] there is a very detailed research of MU-SM and in [6] there is a thorough analysis and comparison of both that shows why SMMA is considered better.

The main idea in [6] is that SMMA can take full advantage of the benefits of SM while MU-SM cannot.The main reasons for this are the fact that MU-SM works with a fixed arrangement of transmit antennas for each user and it only allows to have one receive antenna per user. These are two limitations that SMMA does not have, and therefore can reach the full potential of SM for multiple users, because it is able to adaptively allocate the transmit antennas to multiple users instead of fixing groups of them always to the same user. This gives a bigger flexibility and adaptability to the system as it is possible to observe in Fig. 2.4.

As for the receive antennas, as it can be seen in [6], the performance of SMMA increases greatly with its increase, although each user can still only use one of its receive antennas due to the precoding techniques. But by having more receive antennas, it can outperform MU-SM up to 6 dB, since the last one is confined to just one antenna per user.

In conclusion, SMMA may be considered as an upgrade of MU-SM, since it also uses precoding techniques but does not suffer the same limitations that MU-SM does.

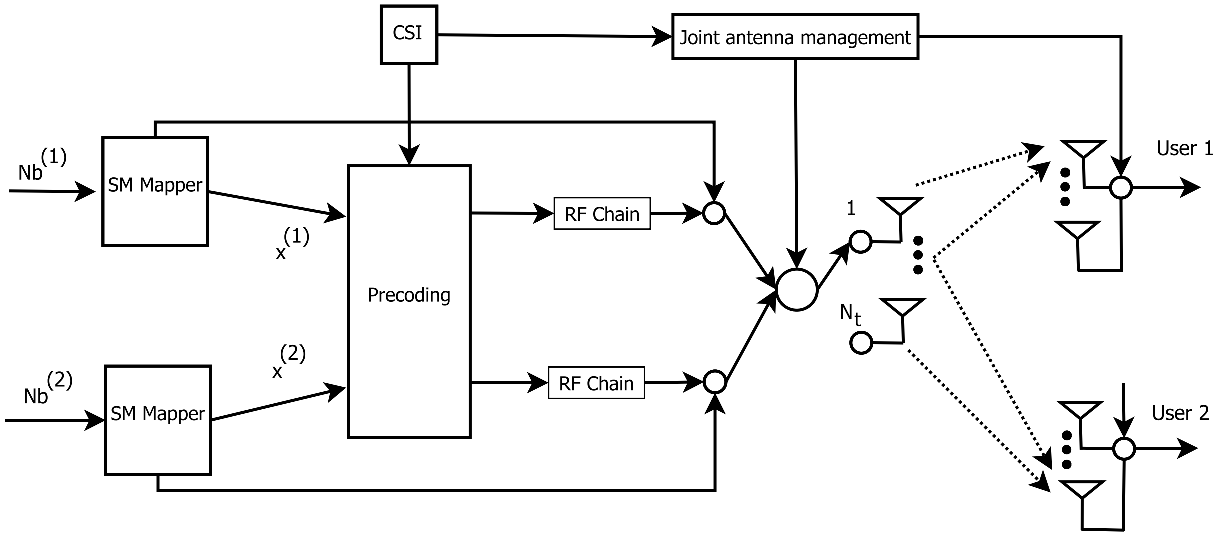

Figure 2.4: SMMA system model (extracted from [6]).

Despite that, SMMA also has one important disadvantage, because it uses precoding techniques to deal with MAI, which require Channel State Information (CSI) [6]. This requirement can be hard to fulfill, as such, there is the need to find a more practical scheme without such requirements and in general, with less requirements.

The solution for these problems is Space-Time CDMA based on Spatial Modulation, ST-CDMA.

3

Model Development

This chapter focuses on describing every aspect of the model that is implemented in this work, theoretically and practically. It describes the theoretical model, its architecture and its main effects. Then it describes the practical part, the simulator. The algorithm that simulates the system's behavior is explained, as well as its evaluation metrics. Finally, an assessment was made, to show the validity of the practical work performed.

3.1 Theoretical Model

As mentioned before, this is a solution created with the help of CDMA and SM to achieve transmit diversity. Its name is Space-Time CDMA based on Spatial Modulation, proposed in [16], being expanded here in a more deep and practical point of view.

3.1.1 ST-CDMA System Architecture

The intention is to create a system that can efficiently generate a larger number of spreading codes than the numbers generated by the conventional systems previously mentioned, while maintaining the complexity of the system low [16]. This way, it can serve a larger number of users.

The conventional CDMA approach is categorized as temporal CDMA for better understanding of the system [16]. This gives to the multiple access system what will be called from now on, a *temporal spreading code*. But there is another different spreading in this system, one based on SM.

In this system, SM is used specifically for the realization of the multiple access, to be able of generating the demanded high number of spreading codes. According to [16], there are some works that use SM for the increase of transmission rate, but by using SM instead for the multiple access part, it generates a *spatial spreading code* that takes advantage of the different antenna switching patterns characteristic of SM and the diversity obtained from it.

As such, when combining the *temporal spreading codes* from CDMA and the *spatial spreading code* from SM, the number of spreading codes increases largely, especially considering all the possible combinations between the two spreading codes and not just both separately. This creates an MA scheme, based on the spreading codes strategy from CDMA, that is able to meet requirements. Due to this combination between temporal and spatial spreadings, an important trade-off exists between them, one between the orthogonality of the temporal spreading and the transmit diversity of the spatial one.

The scenario considered here is a multiple-access uplink scenario with N_{u} users that want to simultaneously transmit their own information to a common receiver with N_r receive antennas, Fig. 3.1. Each of the users has respectively N_t transmit antennas to transmit their information through a single RF chain, since only one of the transmit antennas per user is activated at a certain instance of time, which depends on the multiple access system and its spreading codes.

After receiving the signal, the receiver decodes the information transmitted by each user with the help of a detector. But there are different detectors and each with its limitations and advantages so this thesis explores specifically three detectors, two being of lower complexity and not optimal, and one of higher complexity and optimal. Those are the MF, the SIC and the optimal one, the Maximum Likelihood decoder ML, which was already explored for the single user scenario and now is explored for the multiple user scenario.

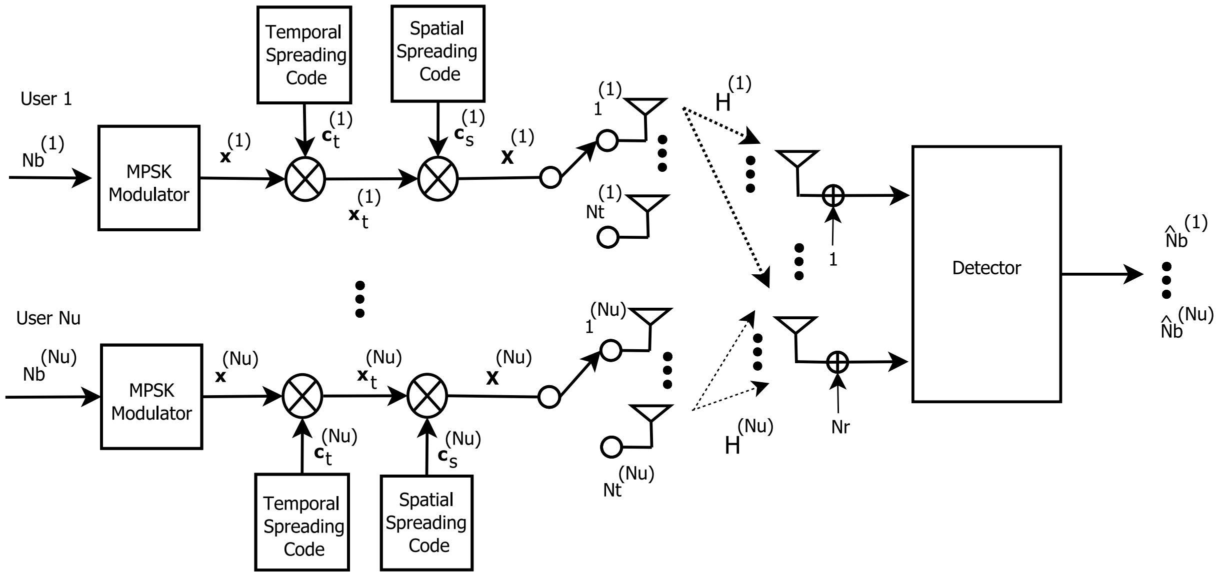

Figure 3.1: System Model of ST-CDMA (extracted from [16]).

3.1.2 Transmitter

The first step is to analyze the signals that will be transmitted by users. Like in SUSM, everything starts with the information bits that each user wants to transmit, $N_b^{(\mathrm{u})}$. There are two phases in order to get to the final transmitting signal and they can be see in Fig. 3.1. First is the modulation of the information bits and then is the encoding by the MA strategy with the use of the temporal and spatial spreading code, getting the final transmitting signal matrix, $\mathbf{X}^{(\mathrm{u})}$ [16].

The first phase is to modulate the information bits with a M-PSK modulator, creating a constellation χ of size M, and then choose a signal from that constellation to represent the modulated signal, $x^{(\mathrm{u})}\epsilon\mathcal{X}$.

Then the modulated signal, $x^{(\mathrm{u})}$, is encoded by the temporal and spatial spreadings. First is the temporal spreading, for which there is an important variable to consider, L, which is the length of a temporal spreading code. This variable is also very important for simulation purposes, knowing that, the signal $x^{(\mathrm{u})}$ is encoded by the temporal spreading code through the following expression

$$\boldsymbol{x}_t^{(\mathrm{u})} = x^{(\mathrm{u})} \cdot \boldsymbol{c}_t^{(\mathrm{u})} \quad , \ \boldsymbol{c}_t^{(\mathrm{u})}\epsilon\{-1,+1\}^{1\times L} \ , \tag{3.1}$$

with:

- $\boldsymbol{x}_t^{(\mathrm{u})}$: time spread signal for the u^{th} user.
- $x^{(\mathrm{u})}$: modulated signal for the u^{th} user.
- $\boldsymbol{c}_t^{(\mathrm{u})}$: temporal spreading for the u^{th} user.

As it is possible to see, the temporal spreading code for the u^{th} user is c_t^{u} and it is preferably an orthogonal sequence, similar to the conventional CDMA system, for example a Walsh sequence or M-sequence [16].

Having obtained the signal, $\boldsymbol{x}_t^{(\mathrm{u})}$, it is then spatially spread. Hence, the final transmitting and spread signal is obtained through the following expression

$$\mathbf{X}^{(\mathrm{u})} = [(\boldsymbol{x}_t^{(\mathrm{u})})^T,\ (\boldsymbol{x}_t^{(\mathrm{u})})^T,\ \dots,\ (\boldsymbol{x}_t^{(\mathrm{u})})^T]^T \circ \boldsymbol{c}_s^{(\mathrm{u})}\ , \tag{3.2}$$

with:

- $\boldsymbol{x}_t^{(\mathrm{u})}$: time spreaded signal for the u^{th} user.
- $\mathbf{X}^{(\mathrm{u})}$: transmitting signal matrix for the u^{th} user.
- $\boldsymbol{c}_s^{(\mathrm{u})}$: spatial spreading for the u^{th} user.

As it is possible to see, the transmitting signal results from the Hadamard or element-wise product, represented by $\circ$, between the vector on the left and the spatial spreading code for the u^{th} user, $c_s^{(\mathrm{u})}$. This vector on the left is an array of the temporally spread signal $x_t^{(\mathrm{u})}$ repeated N_t times [16].

As mentioned before, in the transmission of the signal of each user, only one antenna is activated per instance of time.The purpose of this spatial spreading code is to decide which antenna is activated at every instance of time. So, to be able of generating such a code, it has the following structure

$$\boldsymbol{c}_s^{(\mathrm{u})} = [\boldsymbol{c}_s^{(\mathrm{u})}(1),\ \dots,\ \boldsymbol{c}_s^{(\mathrm{u})}(l),\ \dots,\ \boldsymbol{c}_s^{(\mathrm{u})}(L)]\ , \tag{3.3}$$

this way each $\boldsymbol{c}_s^{(\mathrm{u})}(l)$ sequence corresponds to the spatial spreading sequence for the l^{th} instant that chooses which antenna is activated, which means that each element $\boldsymbol{c}_s^{(\mathrm{u})}(l)$ must be expressed as

$$\boldsymbol{c}_s^{(\mathrm{u})}(l) = [0,\ \dots,\ 1,\ \dots,\ 0]^T \epsilon\ \{0,1\}^{N_t \times 1}\ , \tag{3.4}$$

with only one non-zero component and all the remaining components are all-zero. This way, the non-zero component is "1" to represent the transmit antenna that is activated at the l^{th} instant, because only one antenna can be activated according to the SM principles that support this system and its spatial spreading codes.

It is possible to see why the array of $\boldsymbol{x}_t^{(\mathrm{u})}$ is repeated N_t times, i.e., it is to match with $\boldsymbol{c}_s^{(\mathrm{u})}$ and combine the two spreading codes in order to encode the signal and obtain $\mathbf{X}^{(\mathrm{u})} \epsilon\ \mathbb{C}^{Nt \times L}$, whose dimensions show the combination of both codes.

As mentioned before, this combination also presents a trade-off between the two spreadings. On one hand there are benefits caused by the orthogonality in the temporal spreading, and on the other hand there are the benefits of transmit diversity caused by the switching between antennas, which is controlled by the spatial spreading.

Therefore, there are two situations to consider, when the system only uses one transmit antenna per user and when it uses multiple transmit antennas per user. In the case of one transmit antenna, the spatial spreading is only able to spread one antenna for all instances of time, which means that always the same transmit antenna is activated for each user. And if only one antenna is activated then there is no switching between antennas and the transmit diversity obtained is null, changing (3.4) to the following form

$$\boldsymbol{c}_s^{(\mathrm{u})}(l) = [1,\ \dots, 1]^T \epsilon\ \{+1\}^{N_t \times 1}\ . \tag{3.5}$$

This means that for one transmit antenna, spatial spreading does not influence the system and it is only spread by the temporal spreading, turning it equivalent to conventional CDMA scheme. Consequently, for a conventional CDMA scheme in this system, the system benefits from the orthogonality caused by CDMA in its spreading codes.

But as soon as the number of transmit antennas increases, the spatial spreading activates and also influences the system due to the switching between antennas. In this case, then the transmit diversity is no longer null and starts influencing system's performance. The difference is that because the two spreadings are multiplied by each other, as soon as the spatial spreading influences the system, it ends with the orthogonality of the system caused by the temporal spreading. This happens because the spreading sequences that result from the product of the two spreadings are no longer orthogonal. Hence this trade-off between orthogonality and transmit diversity exists, being observed in Chapter 4.

With this kind of multiple access scheme, it is possible to serve such a larger number of users, since the number of spreading codes generated from the combination of the temporal and spatial spreading is much higher than the ones generated from the temporal spreading alone. Given this spatial spreading that takes advantage of the antenna switching patterns of SM, the system can take full advantage of the transmit diversity generated from it.

3.1.3 Receiver

As observed in Fig. 3.1, the receiver gets all the transmitted signals of all users. Each of these transmitted signal matrices has to pass through a channel **H** specific to each user, and like in SUSM, it is important to account for the presence of noise. Therefore, in this system with N_{u} users, the received signal can be described by

$$\mathbf{Y} = \sum_{\mathrm{u}=1}^{N_{\mathrm{u}}} \mathbf{H}^{(\mathrm{u})}\mathbf{X}^{(\mathrm{u})} + \mathbf{N}\ , \tag{3.6}$$

where:

- $\mathbf{Y} \ \epsilon \ \mathbb{C}^{N_r \times L}$: received signal matrix.
- $\mathbf{H}^{(\mathrm{u})} \ \epsilon \ \mathbb{C}^{N_t \times N_r}$: channel coefficient matrix for the u^{th} user.
- $\mathbf{X}^{(\mathrm{u})} \ \epsilon \ C^{N_t \times L}$: transmitting signal matrix for the u^{th} user.
- $\mathbf{N} \ \epsilon \ \mathbb{C}^{Nr \times L}$: noise matrix.

The result, **Y**, is the sum of all users' transmitted signals $\mathbf{X}^{(\mathrm{u})}$ that passed through their respective channels $\mathbf{H}^{(\mathrm{u})}$ plus the contribution of noise **N**.

The channel, represented by the channel coefficient matrix **H**, contains N_{u} different channel matrices, each corresponding to one user. Regardless of that, the channel coefficients of $\mathbf{H}^{(\mathrm{u})}$ follow the same distribution as in the single user case, all elements being mutually uncorrelated, and each of them being a zero-mean and circularly symmetric complex Gaussian random variable with unit variance [16].

As for noise, for multiple users it cannot be described by just one sample of AWGN, but must instead be a matrix of the same dimensions as the received signal to fully describe the influence of noise on the received signal, **N**. As such, the elements of this noise matrix are Independent and Identically Distributed

(IID) and follow a zero-mean, $\mu = 0$, complex Gaussian distribution with variance σ^2 . It is important to note that in the considered scenario, the receiver has PCSI, which means that it has PCSI on all users, but the users themselves cannot use their own CSI [16]. The receiver estimates all users' data from the received signal in (3.6).

For the receiver to be able to decode each users' information, it must resort to a detector. In [16] the chosen detector was the ML decoder, which is, as previously mentioned, an optimal one. But the problem is that its computational complexity increases exponentially with the increase of some important variables of this system, like the number of users N_{u}.

As such, besides the ML decoder one considers the MF and SIC detectors, which are not optimal but are of lower complexity and can help better understanding the system. But, before looking into the detectors, there is an important scenario to analyze.

3.1.4 Channel with Correlation between Antennas

The correlation in the channel coefficients is described in [19]. The existence of correlation is considered when two antennas are separated by less than a wavelength, hence, influencing each other and becoming harder to distinguish for the detector, thus increasing the probability of a detector causing estimation errors.

This correlation can exist in both the transmit and receive antennas, representing how the antennas influence each other. Following the model in [19], the influence of this correlation in the channel matrix can be expressed by

$$\mathbf{H} = \Phi_R^{1/2}\, \mathbf{H}_w\, \Phi_T^{1/2}\ , \tag{3.7}$$

with:

- $\mathbf{H}$: correlated channel coefficient matrix.
- Φ_R : receiving correlation matrix.
- $\mathbf{H}_w \sim \mathcal{CN}(0,1)$: ideal channel coefficient matrix.
- Φ_T : transmitting correlation matrix.

The ideal channel matrix, $\mathbf{H}_w$, corresponds to the channel matrix that been considered in this work up until this point. So, to describe the correlation between antennas, the transmitting and receiving correlation matrices are needed, Φ_T and Φ_R. This gives some possible scenarios where the worst case corresponds to both the transmission antennas and the receiving antennas having correlation between each other [19]. This is the scenario explored in this work, as such, both correlation matrices are described by the Constant Correlation Model [19] in the following form

$$\Phi(\rho) = \begin{bmatrix} 1 & \rho & \dots & \rho \\ \rho & 1 & \dots & \rho \\ \vdots & \rho & \ddots & \vdots \\ \rho & \dots & \rho & 1 \end{bmatrix}\ , \tag{3.8}$$

where $\rho\,\epsilon[0,1]$ is the correlation coefficient, having a fixed value and equal for both transmission and receiving matrices. This way, it is possible to analyze the effects of the correlation between antennas, being further analyzed practically by simulating that influence.

3.1.5 Detectors

As mentioned before, three detectors are analyzed, MF, ML and SIC, which can be most distinguished by the main characteristics presented in Table 3.1 .

Table 3.1: Main characteristics of the three detectors.

Detector	Optimal	Complexity	Main Advantages
ML	Yes	High	Precise Estimations
MF	No	Low	Simple Implementation
SIC	No	Medium	Considers MAI

Starting with the highest computational complexity detector, the ML decoder is considered for a multi-user version. It is an optimal detector, being expressed as in [16],

$$\{\hat{x}^{(1)},...,\hat{x}^{(\mathrm{u})},...,\hat{x}^{(N_\mathrm{u})}\} = \underset{\forall \mathrm{u},\bar{\mathbf{X}}^{(\mathrm{u})}\epsilon\chi^{(\mathrm{u})}}{\text{arg min}} \left\| \mathbf{Y} - \sum_{\mathrm{u}=1}^{N_\mathrm{u}} \mathbf{H}^{(\mathrm{u})}\bar{\mathbf{X}}^{(\mathrm{u})} \right\|_F^2 , \tag{3.9}$$

where:

- $\hat{x}^{(\mathrm{u})}$: estimation of the transmitted signal for the u^{th} user.
- $\bar{\mathbf{X}}^{(\mathrm{u})}$: possible spatially and temporally spread signal matrix for the u^{th} user.

The result obtained from the ML decoder is the set of estimations, $\hat{x}^{(\mathrm{u})}$, of the transmitted signals from each user, $x^{(\mathrm{u})}$. This set is calculated by estimating the minimum distance between the received signal **Y** and the component of that signal without noise for the entire set $\chi^{(\mathrm{u})}$, which represents "all possible spatial-temporal spreading signals for user *u*" [16]. This means that it tests all possible combinations of signals, obtaining an optimal estimation.

But this detector's computational complexity "exponentially increases in proportion to the modulation level M, the number of users N_u and the size of the spatial-temporal spreading code " [16]. Those are variables of the utmost importance for this work, and due to that relation, alternative detectors are needed for implementation and analysis of higher order where these variables take higher values, thus, introducing the matched filter MF and successive interference cancellation (SIC).

The MF detector is the one with the lowest complexity, and consequently is also the less optimal one. It estimates the set of transmitted signals through the maximum of the cross-correlation between the received signal and the component of that signal without noise, for all users,

$$\{\hat{x}^{(1)},...,\hat{x}^{(\mathrm{u})},...,\hat{x}^{(N_\mathrm{u})}\} = \underset{\forall \mathrm{u},\bar{\mathbf{X}}^{(\mathrm{u})}\epsilon\chi^{(\mathrm{u})}}{\text{arg max}}\ \text{Re}\left\{< \mathbf{Y}, \mathbf{H}^{(\mathrm{u})}\bar{\mathbf{X}}^{(\mathrm{u})} >\right\} . \tag{3.10}$$

It calculates the cross-correlation for all possibly transmitted signals and finds the maximum for each user, estimating its transmitted signal $\hat{x}^{(\mathrm{u})}$. For simplification purposes, in this case

$$\mathbf{H}^{(\mathrm{u})}\bar{\mathbf{X}}^{(\mathrm{u})} = \bar{\mathbf{S}}^{(\mathrm{u})} \epsilon\, C^{N_r \times L} \ , \tag{3.11}$$

with:

- $\bar{\mathbf{S}}^{(\mathrm{u})}$: Possible combination for the contribution of the u^{th} user to the received signal, without the noise component.

When expanding the previous expression, it has a continuous form that is shown in [20], but its discrete form is the one able to represent this detector, being expressed as

$$< \mathbf{Y}, \bar{\mathbf{S}}^{(\mathrm{u})} >= \sum_{r}^{N_r} \sum_{l}^{L} \mathbf{Y}^{*}[r][l] \cdot \bar{\mathbf{S}}^{(\mathrm{u})}[r][l] \ . \tag{3.12}$$

Thus, for each user, the MF detector considers the contributions of all receiving antennas at all time instants for all possible transmitted signals. But the problem with MF is that it does not take into account the presence of MAI errors in the signal, and this way it may cause more errors in its estimate.

Thus, introducing the SIC detector, based on the MF detector, it takes into account the presence of MAI [21] . To understand this detector, first MAI and what it represents must be addressed. As previously mentioned, in MF and for a certain user *u*, the estimation of the signal transmitted results from the maximum of the cross-correlation of the received signal with all possible $\bar{\mathbf{S}}^{(\mathrm{u})}$ for a certain user *u*. As such, for the estimation of each user's $\hat{x}^{(\mathrm{u})}$, there is a component of these correlations that represents the other undesired users' contributions, and that may cause errors in the estimation. That is the component that represents the MAI for each user [21]. In Section 3.1.6 a deeper analysis of this component is performed.

By using MF as a basis for the estimation of the set of signals, this detector is divided into three main steps, which are repeated in an iterative way until a certain threshold is hit. The first step is to make an initial estimate of all users' signals exactly like in MF, (3.10), but this time the purpose is to sort these users by the magnitude or power of the estimated signals. After sorting them, if it is the first iteration, then the SIC detector chooses the user with the strongest signal and subtracts that user's contribution from the received signal **Y**, (3.13), which represents the third step [21].

$$\mathbf{Y}_{n+1} = \mathbf{Y}_n - \bar{\mathbf{S}}^{(\mathrm{u})} \quad , \ n = 0, 1, 2, ...N_{\mathrm{u}} \ . \tag{3.13}$$

where:

- $\mathbf{Y}_{n+1}$: received signal to use for next iteration.
- $\mathbf{Y}_n$: received signal in current iteration.

In this equation, *u* is the user selected with the strongest signal and n represents the number of the iteration, meaning that the limit of iterations is N_{u}. But if it is not the first iteration of the detector, then the detector estimates that user's signal again before subtracting it to the received signal, corresponding to the second step, because after the received signal loses one of its users' contributions, when estimating the other users' signals again that contribution no longer exists. This means that the MAI errors possibly caused by the contributions of that user *u* no longer affect the detector because they were removed. Thus, (3.12) is slightly changed to

$$< \mathbf{Y}_n, \bar{\mathbf{S}}^{(\mathsf{u})} >= \sum_{r}^{N_r} \sum_{l}^{L} \mathbf{Y}_n^*[r][l] * \bar{\mathbf{S}}^{(\mathsf{u})}[r][l] \quad , \ n = 0, 1, 2, ...N_{\mathsf{u}} \ . \tag{3.14}$$

These steps are repeated several times and each user's contribution and interference is removed until all users have been estimated again and the detector hits its threshold, when the only thing that remains in the received signal is the noise component, $\mathbf{Y} = \mathbf{N}$. This way the SIC detector is able to deal with MAI and better estimate the set of transmitted signals. But this mechanism that deals with MAI also causes a propagation of errors that may influence the detector's estimations and its performances.

3.1.6 Multiple Access Interference Analysis for the Matched Filter

MAI among users is one of the major limiting factors in SMMA systems, reducing their capacity and increasing their BER, degrading the performance of SMMA systems [22]. As such, it is very important to characterize such an influential factor in detail, to fully understand it and develop solutions that prevent MAI from causing errors and degrading the system performance of SMMA and, in this case, ST-CDMA systems.

To characterize the MAI of such a system as ST-CDMA, which is based on the CDMA approach, first the MAI of the conventional CDMA approach is analyzed and described to comprehend it in a less complex situation, and use its basic process for the more complex one, the ST-CDMA approach. Both approaches are analyzed for a receiver with a matched filter detector, the purpose being to observe the output of the detector and separate the MAI component from the signal in the output, to characterize the MAI component for each approach.

For the CDMA approach, the scenario and analysis from [22] are used, a "synchronous DS-CDMA transmitter model for the downlink of a mobile radio network with N_t transmit antennas, N_r receive antennas and a flat-fading channel" [22]. This is an AWGN channel, with Rayleigh fading, **H**. As such, the detector for the r^{th} receiver observes the signal as follows

$$w_r(t) = \sum_{m=1}^{N_t} \sum_{s=-\infty}^{+\infty} \sum_{\mathsf{u}=1}^{N_{\mathsf{u}}} A^{\mathsf{u}} b_m^{s,\mathsf{u}} k_m^{s,\mathsf{u}}(t) h_{rm}^s + n_r(t) \ , \tag{3.15}$$

with:

- $w_r(t)$: signal detected from the *u*th user.
- A^{u} : transmitted amplitude of the *u*th user.
- $b_m^{s,\mathsf{u}}$: input bit stream of the uth user.
- $k_m^{s,\mathsf{u}}(t)$: continuous spreading sequence.
- h_{rm}^s : channel coefficient for the r^{th} receive antenna and m^{th} transmit antenna.
- $n_r(t)$: continuous noise component.

The noise, n_r, in this case is also AWGN with zero mean and variance σ_v^2 at the r^{th} receiver. So, the received signal is composed of the transmitted signal, its spreading sequence, the channel and the noise components for all users N_{u}, all transmission antennas N_t and for all possible symbols s, which ends up being similar to the received signal's composition analyzed in Section 3.1.3. Before interpreting the output of the detector, first it is important to describe the cross-correlation between the signature or spreading sequences of two users, u and j, for the s^{th} symbol, which is taken from [22] as

$$\rho_s^{\mathsf{u},j} = \int_{(s-1)T_b}^{sT_b} k_m^{\mathsf{u}}(t) k_m^j(t) dt = \sum_{i=1}^{Nc} c_{s,i}^{\mathsf{u}} c_{s,i}^j \ , \tag{3.16}$$

where:

- $\rho_s^{u,j}$: cross-correlation between two spreading sequences of different users for the s^{th} symbol.
- $c_{s,i}^u$: normalized spreading sequence of the user *u* for the s^{th} symbol.

With N_c as the number of chips, $c_{s,i}^u$ represents the normalized spreading sequence, "so as to make the autocorrelations of the signature sequences unity" [22].

As mentioned before, the detector is a matched filter, and to isolate the MAI component, the detector is considered to be matched to the signature waveform of the desired user, which is user 1 in this case, for analysis purposes. As such, the output of the MF detector for the s^{th} symbol at the r^{th} receiver is

$$y_r^s = \int_{(s-1)T_b}^{sT_b} w_r(t) k_r^{s,1}(t) dt = \sum_{m=1}^{N_t} A^1 b_m^{s,1} h_{rm}^s + z_r^s + n_r \quad , \ r = 1, 2, ..., N_r \ , \tag{3.17}$$

where:

- y_r^s : detected signal for the s^{th} symbol at the r^{th} receiver.
- z_r^s : MAI component of the signal for the s^{th} symbol at the r^{th} receiver.

As such, the MAI component is represented by z_r^s and, for a certain symbol s, it is described by

$$z_r^s = \sum_{m=1}^{N_t} \sum_{\mathsf{u}=2}^{N_{\mathsf{u}}} A^{\mathsf{u}} b_m^{s,\mathsf{u}} \rho_m^{\mathsf{u},1} h_{rm}^s \quad , \ r = 1, 2, ..., N_r \ , \tag{3.18}$$

This confirms the initial definition of MAI for a specific user. It represents all the interference caused from all transmit antennas N_t by the other undesired users, and it can cause detection errors on the desired user. Hence, (3.16) describes the correlation between the desired user and the interfering users and (3.18) is still simplified into

$$z_r^s = \sum_{m=1}^{N_t} I_{rm}^s h_{rm}^s \quad , \ r = 1, 2, ..., N_r \ , \tag{3.19}$$

with:

- I_{rm}^s : MAI component in AWGN environment.

For the case of ST-CDMA, the same base steps used for the CDMA approach are applied with some changes due to the different system.

The first change is the scenario itself, i.e, the scenario that has been considered for ST-CDMA is an uplink situation of multiple users, each with multiple transmission antennas and all of them transmitting to one receiver that detects each user's information with a matched filter.

As in the previous case, the output of the matched filter is analyzed for a specific user as the one to detect, and for a certain symbol s, as such (3.10) in this case is slightly changed to

$$\rho_s^{(1)} =< \mathbf{Y}, \mathbf{H}^{(1)}\bar{\mathbf{X}}_s^{(1)} >=< \mathbf{Y}, \bar{\mathbf{S}}_s^{(1)} >= \sum_r^{N_r}\sum_l^{L} \mathbf{Y}_s^*[r][l] \cdot \bar{\mathbf{S}}_s^{(1)}[r][l] \ , \tag{3.20}$$

giving the estimation that the detector calculates for a specific user. Given this, to find the MAI component, that is the interfering users component, the element of the received signal $\mathbf{Y}_s[r][l]$ is decomposed first by considering (3.6) and (3.11) as a basis, resulting in

$$\mathbf{Y}_s[r][l] = \sum_{\mathsf{u}=1}^{N_\mathsf{u}} \mathbf{S}_s^{(\mathsf{u})}[r][l] + \mathbf{N}[r][l] \ . \tag{3.21}$$

With this element decomposed, the MAI component is found by substituting (3.21) in the matched filter output, (3.20), resulting:

$$\rho_s^{(1)} = \sum_r^{N_r}\sum_l^{L}\left(\sum_{\mathsf{u}=1}^{N_\mathsf{u}} \bar{\mathbf{S}}_s^{*(\mathsf{u})}[r][l] + N^*[r][l]\right) \cdot \bar{\mathbf{S}}_s^{(1)}[r][l] \ . \tag{3.22}$$

By simplifying this expression, the result obtained from the matched filter is divided into three components: the component that corresponds to the estimation of the signal transmitted by the user for a symbol s, the MAI component and the noise component. These three components are observed on the simplification represented in (3.23).

$$\begin{aligned}\rho_s^{(1)} = \sum_r^{N_r}\sum_l^{L}\left|\bar{\mathbf{S}}_s^{(1)}[r][l]\right|^2 + \sum_r^{N_r}\sum_l^{L}\sum_{\mathsf{u}=2}^{N_\mathsf{u}} \bar{\mathbf{S}}_s^{*(\mathsf{u})}[r][l] \cdot \bar{\mathbf{S}}_s^{(1)}[r][l] + \\ + \sum_r^{N_r}\sum_l^{L} \bar{\mathbf{S}}_s^{(1)}[r][l] \cdot \mathbf{N}^*[r][l]\end{aligned} \tag{3.23}$$

As such, the MAI component is the one that sums all undesired users' contributions as a representation of their interference in the following form:

$$z_s^1 = \sum_r^{N_r}\sum_l^{L} \bar{\mathbf{S}}_s^{(1)}[r][l] * \sum_{\mathsf{u}=2}^{N_\mathsf{u}} \bar{\mathbf{S}}_s^{*(\mathsf{u})}[r][l] =< \bar{\mathbf{S}}_s^{(1)}, \sum_{\mathsf{u}=2}^{N_\mathsf{u}} \bar{\mathbf{S}}_s^{(\mathsf{u})} > \ , \tag{3.24}$$

which is the definition of the cross-correlation between the signal transmitted from the user, without the presence of noise, and the sum of all transmitted signals from all other interfering users, also without noise, which confirms the definition of MAI. The MAI between users is described by the correlation between a certain user and all other users. The more correlated the users are, the more interference they cause to each other. As such, the MAI for a certain user and a symbol s is best described by

$$z_s^1 =< \bar{\mathbf{S}}_s^{(1)}, \sum_{\mathsf{u}=2}^{N_\mathsf{u}} \bar{\mathbf{S}}_s^{(\mathsf{u})} > \ . \tag{3.25}$$

The terms that compose MAI, more specifically the term $\bar{\mathbf{S}}_s^{(\mathsf{u})}[r][l]$, are decomposed and after some algebraic manipulation of the terms, one obtains

$$\bar{\mathbf{S}}_s^{(\mathsf{u})}[r][l] = \sum_{m=1}^{N_t} \mathbf{H}^{(\mathsf{u})}[r][m] \cdot \mathbf{C}^{(\mathsf{u})}[m][l] \cdot x_s^{(\mathsf{u})}, \tag{3.26}$$

where:

- $\mathbf{C}^{(\mathsf{u})}$: time and spatial spreading matrix for the u^{th} user.

As such, by substituting the previous expression in (3.24), an alternative and more detailed representation of the MAI can be observed,

$$z_s^1 = \sum_{r}^{N_r} \sum_{l}^{L} \sum_{\mathsf{u}=2}^{N_\mathsf{u}} \sum_{m=1}^{N_t} \left(\mathbf{H}^{*(\mathsf{u})}[r][m] \cdot \mathbf{H}^{(1)}[r][m]\right) \left(\mathbf{C}^{*(\mathsf{u})}[m][l] \cdot \mathbf{C}^{(1)}[m][l]\right) \left(x_s^{*(\mathsf{u})} \cdot x_s^{(1)}\right) \ . \tag{3.27}$$

With this version, it is easier to understand the MAI components described in (3.25) as the sum of all products between the channels, spreadings and transmitted signals of the user and each of the other interfering users. This confirms once again that MAI is the relation between a specific user and all the other interfering users, more specifically in terms of channels, spreadings and the transmitted signals themselves.

Given (3.27) it is also possible to better analyze and understand the trade-off between orthogonality and transmit diversity for this system. Considering the two situations explained in Section 3.1.2, which are a scenario with only one transmit antenna per user and a scenario with more than one transmit antenna per user, this analysis helps visualizing the effects of that trade-off in the system.

In the case of one transmit antenna, the system has a spreading equivalent to the conventional CDMA and as such, its spreading sequences are orthogonal. This means that when two orthogonal sequences are orthogonal, its product is zero, which happens in CDMA. Therefore, for a scenario with one transmit antenna per user, with a consequent spreading correspondent to conventional CDMA, the product between the spreadings of two different users is zero.

By analyzing (3.27), there is one part of MAI that is represented by the product between the spreading sequences of the desired user and other different users. For one transmit antenna per user, these two spreading sequences are orthogonal, which means that their product is zero,

$$\sum_{\mathsf{u}=2}^{N_\mathsf{u}} \sum_{m=1}^{N_t} \mathbf{C}^{*(\mathsf{u})}[m][l] \cdot \mathbf{C}^{(1)}[m][l] \underset{N_t=1}{=} \sum_{\mathsf{u}=2}^{N_\mathsf{u}} \mathbf{C}^{*(\mathsf{u})}[l] \cdot \mathbf{C}^{(1)}[l] = 0 \tag{3.28}$$

MAI as described in (3.27) is also zero, which means that for one transmit antenna per user, corresponding to a system with conventional CDMA, the system suffers no MAI between its users because of its orthogonality. Hence the estimations of the detector shown in (3.23) no longer have a MAI component, being represented by

$$\rho_s^{(1)} = \sum_{r}^{N_r} \sum_{l}^{L} \left|\bar{\mathbf{S}}_s^{(1)}[r][l]\right|^2 + \sum_{r}^{N_r} \sum_{l}^{L} \bar{\mathbf{S}}_s^{(1)}[r][l] \cdot \mathbf{N}^*[r][l] \ , \tag{3.29}$$

with only the influence of noise in its estimations. This is the advantage of having orthogonal spreading sequences in a system like this that copes with multiple users. But when the number of transmit antennas increases,transmit diversity starts to exist and MAI is no longer zero because the orthogonality in the spreading sequences is lost, hence it is described by (3.27).

As such, to see what is more valuable to the system, orthogonality or transmit diversity, simulations were done, where the effects of this trade-off are observed.

3.2 Simulator

3.2.1 Algorithm Description and Evaluation Metrics

To support and expand the first part, an extensive and detailed simulation with Python was done for the system with the ST-CDMA strategy from [16] that was previously analyzed. This simulation was done for the uplink scenario described in Section 3.1. First, one explains the base algorithm that simulates the ST-CDMA system and the metrics that are used to evaluate the results. In order to better comprehend and help explaining the base algorithm and how it works, a general diagram is presented in Fig. 3.2.

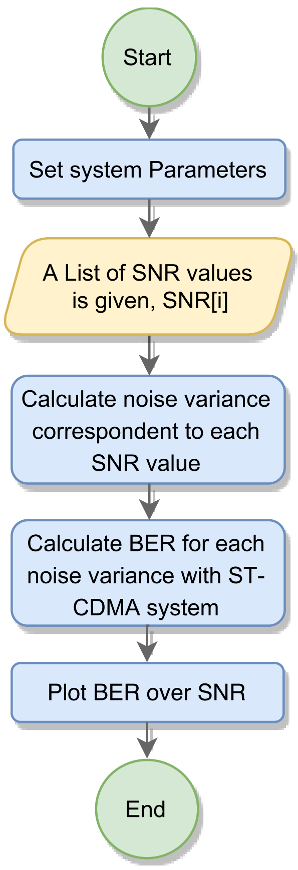

Figure 3.2: Basic functioning of the algorithm used in this work for SNR.

To evaluate such a system's performance, the chosen criterion is BER. As such, to evaluate the performance of the system in each test, BER is estimated for SNR or E_b/N_0 for a certain number of points. The latter, E_b/N_0, is a normalized SNR measure, representing the ratio of the Energy per bit, E_b, to the Spectral Noise Density, N_0. To estimate BER with accuracy, depending on the level of errors, hundreds of thousands of estimations are needed, therefore, each point is the result of the average between tens of thousands of estimations. Each estimation is the result of running the algorithm that simulates the ST-CDMA system one time. This can be seen in Fig. 3.3, where a diagram is presented to demonstrate the basic functioning of the ST-CDMA algorithm and what is realized to calculate each point of the final BER curve.

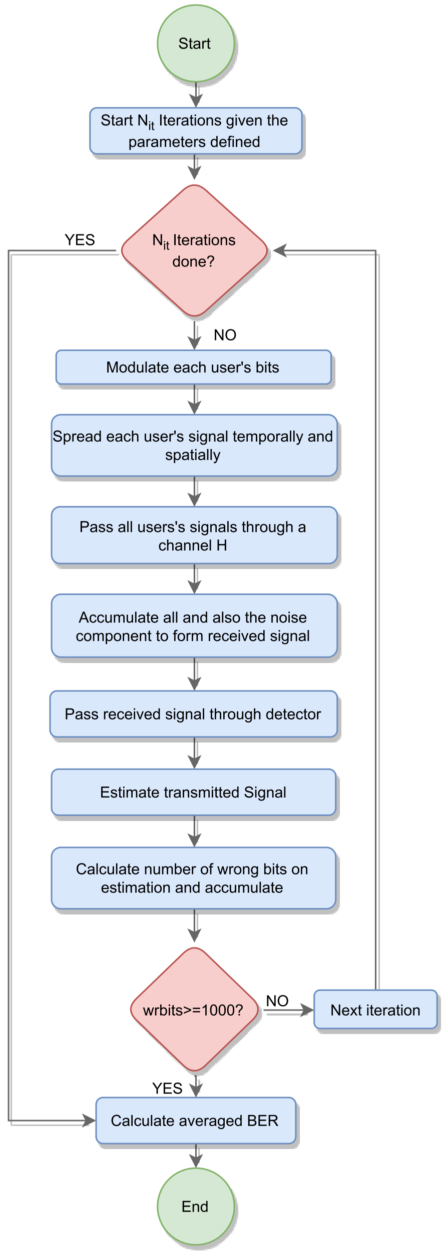

Figure 3.3: Basic Functioning of the ST-CDMA Algorithm.

When one of the thousands of estimations is made, the ST-CDMA algorithm is run, and it starts with the transmission of the users' signals. This algorithm follows the model explained in Section 3.1, as such, each user has its information bits modulated and then spread by the temporal and spatial spreadings of the system, resulting in the final transmitting signal matrix for each user. These signal matrices are then multiplied by the channel, for each user, to account for the presence of the channel and its influence. Then the results of these multiplications are all accumulated into one final matrix that represents the information part of the signal the receiver will detect, to which a noise component is added to form the complete received signal and account for the presence of noise. Having received the signal, the algorithm uses the three different detectors described in Section 3.1.5, MF, ML and SIC to estimate in three different ways the signal each user transmitted initially. Each wrong bit on the estimation performed by each detector is accumulated to count the number of errors occurred through all the estimations that are done to accurately estimate one BER point. To finish the complete and accurate averaging of all estimations done for a BER point, the ST-CDMA algorithm has two ways of reaching the end, one is to perform the maximum number of iterations defined for the algorithm (explained further ahead in this section) and the other is to fulfill a stopping condition that exists to prevent the algorithm from estimating endlessly and to become more efficient (explained further ahead in this section).

Each BER point corresponds to a certain SNR or E_b/N_0 and those are the connection to the algorithm of the ST-CDMA system. In this work, for M-PSK modulators, their resulting constellations are normalized in order to have the power of the signal equal to one. As such, SNR depends only on the power of the noise. In this case, the power of noise is equal to its variance, because the simulated noise in this work is AWGN. Assuming the SNR is chosen, the variance of the noise is given by:

$$\sigma^2 = 10^{\frac{-SNR}{10}} \tag{3.30}$$

This equation connects the BER evaluation to the algorithm of the system, because for each point, each SNR chosen, there is a corresponding variance of noise calculated through (3.30), hence, a new estimation of the noise variable to use in the ST-CDMA system. This can be observed in the algorithm from Fig. 3.4 that is used for the simulation of the system.

```
variance ← noise power equal to variance of noise
ber ← List of BER estimations of the system for a certain number of points
x ← List of SNR points to test the system

x ← [0, 2, 4, 6, 8, 10, 12, 14, 16, 18]
for i ← range(0, 9) do
    snr = x[i]
    variance ← pow(10, −snr/10)          ▷ Calculate noise variance from SNR
    ber[i] ← ts_cdma(variance)           ▷ Estimate point for specific variance
end for
plot(ber, x)
```

Figure 3.4: BER evaluation of the system.

For each new noise variable estimated, the algorithm is run the amount of times necessary to estimate accurately the BER for that noise variable, consequently for that chosen SNR, Fig. 3.3.

But, there are some cases that must be evaluated according to the normalized ratio, E_b/N_0, instead of SNR, because they depend on more parameters and the SNR alone cannot provide a good and fair basis for evaluating these cases. These are specifically the situations that vary the modulation coefficient and the temporal spreading size. These parameters influence the signal and must be evaluated differently. Assuming the same SNR points used for the other situations, to convert it to E_b/N_0, (3.31) is used,

$$\frac{E_b}{N_0} = \frac{(\mathrm{snr})_{\mathrm{lin}} \cdot L}{N_b} <=> N_0 = \sigma^2 = \frac{N_b}{(\mathrm{snr})_{\mathrm{lin}} \cdot L} , \quad (3.31)$$

with:

- E_b : energy per bit.
- N_0 : spectral noise density.
- $(\mathrm{snr})_{\mathrm{lin}}$: SNR in linear units.
- N_b : number of bits.
- L : length of temporal spreading.
- σ^2 : variance of noise.

Regarding N_b, it is the number of bits used for the modulation, for example $N_b = 1$ for Binary Phase Shift Keying (BPSK), hence, the SNR in linear units, $(snr)_{lin}$, is divided by it, to consider the correspondent energy per bit. Then that result is multiplied by the length of the temporal spreading sequences, L, to increase the energy invested into each single bit. And as mentioned before, the constellations are normalized, therefore the energy is equal to 1, hence, it results on obtaining the noise variance for the estimations of the main algorithm of this system, like in the SNR case.

Regarding the maximum number of iterations considered to estimate with accuracy all the points of the BER performances of the system for these tests, the number considered is max $= 10^5$, which means that each point is averaged over a maximum of 10^5 estimations, Fig. 3.3. But, this only happens if the algorithm does not stop before that limit, because, as previously explained, a point is only estimated the necessary number of times to have an accurate estimate of that point. And that number of times is described in the algorithm by two conditions that stop the algorithm when one of them is fulfilled. The first one, and most important, is to stop when a certain number of errors is achieved, which in this work corresponds to 1000 errors per point. Fulfilling this condition means that the point can be accurately estimated, Fig. 3.3. The second one is a condition that keeps the algorithm from running ”forever”, when the BER is already so low that more estimations do not make a difference in the accuracy of estimating one point. These two conditions can be observed on the algorithm from Fig. 3.5 to show how they work and influence the system. The only situation where this second condition is not used is when the algorithm cannot detect even one error in the estimations for the precision chosen and it needs indeed to do the maximum number of estimations in order to detect with more accuracy.

$wrbits \leftarrow$ current number of errors in estimations
$count \leftarrow$ current number of iterations to estimate one SNR point

if $wrbits \geq 1000$ **then**
    $break$
end if
if $wrbits \geq 50$ **and** $count >$ **pow**$(10, 4)$ **then**
    $break$
end if

Figure 3.5: Stopping conditions of the system.

In these simulations, 10 points were estimated in order to create each curve simulated. From a simulation point of view, the higher the SNR, the lower the BER calculated is, and for SNR $\geq 20\,\mathrm{dB}$, the values of BER calculated require a number of iterations larger than 10^6 to maintain the precision in each point, which increases significantly the computational complexity for the simulations. Furthermore, from a certain point the SNR arrives to a saturation point, where increasing it will no longer help simulations. Therefore, a list of 10 values, SNR ϵ[0,18] dB, and 10^5 iterations are defined with these considerations, as seen in Fig. 3.4.

To obtain smooth curves with good accuracy, the estimated points must be close to each other, with an interval of [1,2] dB between each 2 points. Therefore, the chosen step was of $2\,\mathrm{dB}$, in terms of SNR. This can be seen in Fig. 3.4, where the list of SNR values used has 10 values and a step of $2\,\mathrm{dB}$ between them. This step was chosen because having a step of just $1\,\mathrm{dB}$ would show points closer to each other and prevent from seeing a longer curve for the same number of points, losing valuable information.

3.2.2 Assessement

As stated before, this ST-CDMA system already exists, this work being a theoretical and practical expansion of the work in [16]. As such, the models used here are validated by [16]. As for the practical work, the algorithm developed here is based on these theoretical models and equivalent to the one simulated in [16], with some additions. Therefore, to confirm the validity of the results presented in this work, first a comparison is done between the results obtained from the algorithm simulated in [16] and the results obtained with the algorithm developed and simulated in this work , for the exact same scenarios. This way, the validity of the algorithm developed here is confirmed if the results from both algorithms prove to have a very high and defined degree of similarity.

The scenario used for comparison between the two algorithms is taken from [16] and is characterized by $(N_\mathrm{u}, N_r, L, M) = (3, 1, 4, 2)$, with a BPSK modulator. In [16] the influence of the number of transmit antennas is tested by variating $N_t = 2, 3, 4$, thus the results obtained in [16] and in this work for such scenario can be observed in Fig. 3.6 for comparison effects.

The curves of subtitle ”Prat...” correspond to the practical results obtained from this work's algorithm and the curves of subtitle ”Teo...” correspond to the results extracted from [16]. By comparing curves of the same color between the results from this work's algorithm and from the algorithm of the paper [16] in Fig. 3.6, it is possible to observe the similarity between the algorithms' BER performance and consequently the high degree of similarity between the behaviors of both algorithms for each pair of curves. So from a behavioral and visual point of view, one can see that this algorithm is performing correctly and consequently obtaining valid results for this work. But a more statistical analysis is also needed in order to evaluate the values obtained and compare them with the ones from [16]. This allows for a better and more complete assessment to confirm indeed the validity of this work's algorithm. Thus, an analysis of the relative error, Δ, was done in order to statistically compare the values obtained in both results from Fig. 3.6. In order to calculate the relative error, Δ, the expression from (3.32) is used.

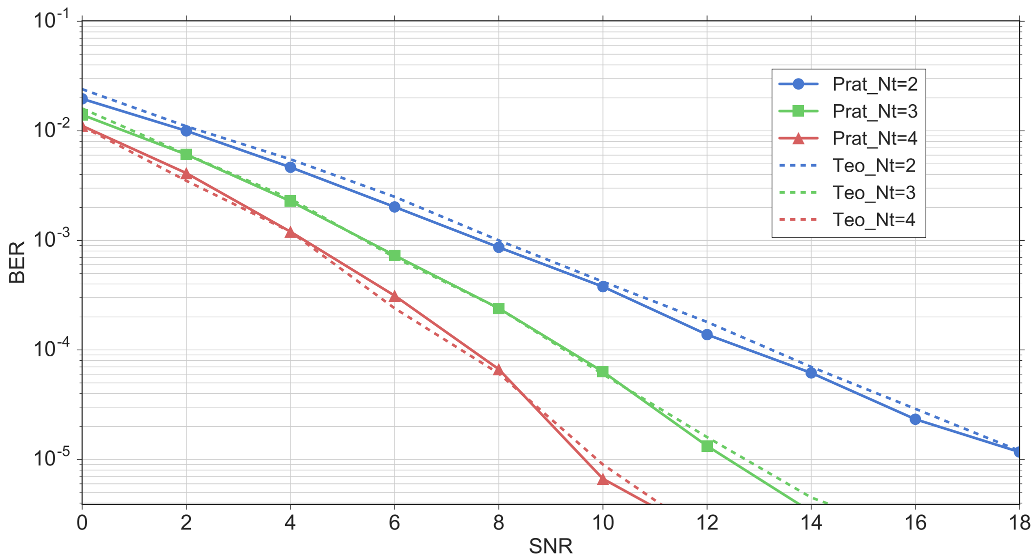

Figure 3.6: Comparison between results of the two Algorithms for Scenario with variable N_t.

$$\Delta[\%] = \frac{V_{teo} - V_{prat}}{V_{teo}} \cdot 100 \tag{3.32}$$

By using this expression, the relative error was calculated for several SNR points chosen from Fig. 3.6 and the results of these calculations are in Table 3.2.

Table 3.2: Relative Error analysis of BER for validation of the implemented algorithm.

SNR	**BER**						**VT-VP**			**Δ(%)**		
	Theoretical			**Practical**								
	Nt=2	Nt=3	Nt=4	Nt=2	Nt=3	Nt=4	Nt=2	Nt=3	Nt=4	Nt=2	Nt=3	Nt=4
0	2.40E-02	1.60E-02	1.10E-02	1.96E-02	1.40E-02	1.11E-02	4.42E-03	1.98E-03	-1.49E-04	18.43	12.36	1.35
2	1.10E-02	6.10E-03	3.50E-03	1.00E-02	6.08E-03	4.11E-03	9.80E-04	1.99E-05	-6.10E-04	8.91	0.33	17.43
4	5.50E-03	2.40E-03	1.20E-03	4.65E-03	2.28E-03	1.20E-03	8.53E-04	1.22E-04	1.65E-06	15.51	5.07	0.14
8	1.00E-03	2.40E-04	6.10E-05	8.65E-04	2.40E-04	6.67E-05	1.35E-04	-2.40E-09	-5.67E-06	13.50	0.00	9.29
12	1.80E-04	1.60E-05	NA	1.38E-04	1.33E-05	NA	4.17E-05	2.67E-06	NA	23.15	16.67	NA
16	2.90E-05	NA	NA	2.33E-05	NA	NA	5.67E-06	NA	NA	19.54	NA	NA
18	1.20E-05	NA	NA	1.17E-05	NA	NA	3.33E-07	NA	NA	2.78	NA	NA

As it is possible to observe from Table 3.2, the relative error, Δ, between the results shown in Fig. 3.6 takes values predominantly below 20% except for two specific cases. It is important to point out that in terms of precision, each point from the curves of this work's algorithm in Fig. 3.6 was estimated with the average of 10^5 iterations. As such, considering this precision of estimation the relative error obtained was no higher than 23%. This means that most of the results from this work's algorithm achieved a proximity of more than 80% with the algorithm from [16] for a precision of 10^5. Some results achieved a relative error very close to zero, or even achieved 0%, specially for the cases of $N_t = 3, 4$, possibly due to the BER values and consequently the amount of errors in those cases being increasingly lower for lower N_t.

Considering that these values are of orders between 10^{-2} and 10^{-6}, the algorithm must be very precise in order to estimate accurately the points and to have a low Δ because of such low order results that are sensitive to all the conditions of the ST-CDMA system. As such, for a more precise system, with for example 10^6 or even 10^7 iterations per SNR point, the relative error is expected to be even lower due to the increase of precision in the estimations of the BER performance. As such, considering such a relative error, it can be concluded from both perspectives, behavioral and statistical, that this algorithm and its results are validated by [16].

4

Results Analysis

In this chapter, the results of this work are presented and analyzed. First, all scenarios are defined and described. Then, the results obtained from simulations are shown, as well as the consequent analysis and discussion of results.

4.1 Scenario Description

4.1.1 Procedure for Scenarios' Simulation

The scenarios explored and simulated for this work are divided into four parts. First, the ST-CDMA system is tested by varying its main parameters and analyzing their influence, like for example the number of users, N_{u} and the number of receiving antennas, N_r. This way, it is possible to see which parameters help with system performance and which ones degrade it, getting a better understanding of the ST-CDMA system and how it works.

The second part is to test the spreading used in transmission, both temporal and spatial ones, but with emphasis on the spatial spreading.

Then comes the third part of testing. This one is specially important in a practical point of view, because it tests a more realistic scenario, compared to the tests of the other two phases of simulation. It explores a scenario of a channel that is no longer ideal, but instead has correlation between its antennas.

Another important detail is that the entire simulation of the ST-CDMA system for these three parts was made for the three different detectors previously explored in Section 3.1.5. So each test is done for all three detectors, so that the results can be compared and the difference between the detectors' performance can be observed and interpreted.

The last part is directly connected to Section 2.1.3, being the simulation of a 5G scenario taken from a 5G project, Flex5Gware, in order to simulate and observe the performance of the ST-CDMA in one of the current projects that are being developed for 5G and see how well it can fit the needs of that project.

4.1.2 Analysis of Parameters' Influence

The first phase of testing serves the purpose of analyzing the main parameters or characteristics of the ST-CDMA, what can be changed to improve performance, what can be increased or decreased. The main point here is to understand how flexible and adaptive the system is to each of the variables that help form the system, how much they can be changed to improve the system. As such, this ultimately serves the purpose of seeing what the ST-CDMA system is really capable of doing.

There are multiple scenarios tested in this part and each scenario focuses on a different parameter of the system. The parameters are components of the system and the ones analyzed are the number of receiving antennas N_r, the number of users N_{u}, the number of transmission antennas N_t, the modulation coefficient M, and the size of the temporal spreading sequences L. Special emphasis is given to the number of users since its effects are one of the main focus of this work. As previously mentioned, these tests are done using an ideal channel and the temporal spreading is an orthogonal sequence with the form $\boldsymbol{c}_t^{(\mathsf{u})} \epsilon \{+1, -1\}^{1\times L}$.

Starting with the number of receive antennas, N_r, to test its influence the considered uplink scenario was a system with the following fixed conditions from Fig. 4.1.

This scenario considers three users $N_{\mathsf{u}} = 3$, each with two transmission antennas $N_t = 2$ and BPSK modulation, $M = 2$. And also the size of the temporal spreading sequence $L = 4$, which means that 4

$N_{\text{u}} \leftarrow 3$
$M \leftarrow 2$
$L \leftarrow 4$
$N_t \leftarrow 2$

Figure 4.1: Setup for testing of Receive Antennas.

different instants of time are considered to spread the antennas in each instant. The spatial spreading is also fixed, hence the only parameter that varies is N_r and its effect is clearly seen in the tests without the effects of the other mentioned parameters. As such, this test consists of simulating the system for the cases $N_r = 1, 2, 3$ and observing the influence of N_r in these three BER performances shown in Fig. 4.11 and Fig. 4.12 . Each of these cases is tested for the three detectors, MF, ML and SIC. In Section 4.2.1 , one shows the results and analysis of the performance of ST-CDMA for this scenario.

The second parameter to have its influence tested was the number of users, N_{u}. As mentioned before, the purpose in this work is to find a multiple access strategy for spatial modulation that can cope with multiple users and perform with negligible degradation caused by users. As such, this test is of special importance to verify exactly what this system is capable of and if it can meet the requirements.

In this case, instead of varying N_r, the test consists in varying N_{u} and fixing all the other parameters, using the conditions shown in Fig. 4.2.

$N_r \leftarrow 1$
$M \leftarrow 2$
$L \leftarrow 4$
$N_t \leftarrow 2$

Figure 4.2: Setup for testing of Number of Users.

The spatial spreading is also fixed in order to focus the performance results on the effects of N_{u}. To simulate this scenario, the system was tested for the values $N_{\text{u}} = 1, 3, 4$ to analyze the BER performances in the scenarios of single user and multi user and compare them, for all three detectors as shown in Section 4.2.2.

The number of transmission antennas N_t defines how many antennas each user uses to transmit their information to the receiver and it also has an important role in the spatial spreading of the system. Theoretically, the more transmit antennas each user has the better, because it helps transmitting the information more efficiently, thanks to the transmit diversity. The spatial spreading of the ST-CDMA has the objective of choosing which transmission antenna is activated for each instance of time and for each user. Thus, if N_t increases, the spatial spreading codes also become bigger, because there are more antennas from which to choose. This means that the amount of possible spatial spreading codes increases significantly for each added transmit antenna, increasing also significantly the possible combinations of temporal and spatial spreading codes, ultimately increasing significantly the number of users that the ST-CDMA is capable of supporting. This is one of the reasons why this solution can achieve a higher number of users than the conventional CDMA approach, as explained in Chapter 3.

The second advantage of increasing N_t is also related to the spatial spreading, which is based on SM. One of the characteristics of SM is the switching between antennas and the diversity gain that results from it. This is explained in more detail in Section 4.3 but by increasing N_t, the switching is done between more antennas and the potential diversity gain that can be achieved by the system is also increased. As such, the performance of the system is expected to improve with the increase of the number of transmission antennas, N_t.

But the role of orthogonality in this system is also important for the system. As previously seen, for $N_t = 1$ the system is orthogonal and equivalent to conventional CDMA, which means the MAI in that case is null (see Section 3.1.6). But for N_t higher than 1, the MAI is not zero and the system is no longer orthogonal, hence there is this important comparison to make between the two situations in order to see which is more important to improve the system, orthogonality or transmit diversity. So in this scenario, the trade-off between orthogonality and transmit diversity is simulated and observed in order to clarify which of them can better improve the system and if the increase of N_t will indeed improve the system. In Section 4.2.3, the answers to these questions are shown.

To test then the influence of N_t, a scenario with the setup of Fig. 4.3 is simulated.

$N_{\mathsf{u}} \leftarrow 3$
$M \leftarrow 2$
$L \leftarrow 4$
$N_r \leftarrow 1$

Figure 4.3: Setup for testing of Transmit Antennas.

Fixed spatial spreading is considered while varying the number of transmission antennas for the cases $N_t = 1, 2, 3$ and for all three detectors, as shown in Section 4.2.3.

As for the modulation coefficient, M, it is what defines the size of the signal constellations created for each user. Therefore, it defines how many possible symbols can be transmitted by each user, considering that each one transmits one symbol from that constellation. This means that to simulate the influence of the Modulation Coefficient, the SNR is not enough to provide a good and fair simulation of it, because the energy of the signal is not the same when varying the Modulation Coefficient. In this case, E_b/N_0 is used with (3.31) to be able to obtain valid and fair estimations of the BER performances. In (3.31), N_b is the number of bits that are used per symbol for the modulation, hence, the SNR is not enough and E_b/N_0 is needed to account for that number of bits, which controls the size of the constellation and the modulation used. Following the work of [16], only M-PSK modulations were simulated to comprehend its influence in the performance of the system and the detectors. More specifically three different Phase Shift Keying (BPSK) modulations were simulated, for $N_b = 1, 2, 3$ which correspond respectively to BPSK with $M = 2$, 4-PSK or Quadrature Phase Shift Keying (QPSK) with $M = 4$ and 8-PSK with $M = 8$.

Each of these modulations was simulated in a scenario with the setup from Fig. 4.4 and fixed spatial spreading.

Besides these parameters, there is also the temporal spreading, where different sized temporal spreading sequences are used to test the system and see how the size of the temporal sequence,

$N_\mathsf{u} \leftarrow 3$
$N_t \leftarrow 2$
$L \leftarrow 4$
$N_r \leftarrow 1$

Figure 4.4: Setup for testing of the Modulation Coefficient.

L, influences the performance of the system, for both high and low L.

This scenario is simulated with the setup shown in Fig. 4.5 and a fixed spatial spreading.

$N_\mathsf{u} \leftarrow 3$
$N_t \leftarrow 2$
$M \leftarrow 8$
$N_r \leftarrow 1$

Figure 4.5: Setup for testing of the Temporal Spreading Size.

In this case, because the length of the temporal spreading affects the signals' energy, E_b/N_0 is used instead of the SNR to provide fair estimations and a fair simulation of the effect of the size of the temporal spreading sequence. By varying the size of the temporal spreading sequence, it is possible to observe how it affects the BER performance of the three detectors. Therefore, two situations are tested, when the temporal spreading has a small size, $L = 4$ and when it has a big size $L = 32$. The results of these two situations are shown in Section 4.2.5.

To take advantage of this scenario with longer temporal sequences, $L = 32$, the influence of N_r and N_t is once again tested in order to see if there is any difference in performance for a higher size of temporal spreading.

Starting with the influence of N_t, the same setup as before, from Fig. 4.5, is used but fixing $L = 32$ and varying N_t. The number of transmit antennas was simulated for $N_t = 2, 3$, in order to see how the system and its detectors behave with this variation when longer spreading sequences are used, and if the conclusions from Section 4.2.3 still apply in this scenario.

As for the new influence of N_r, using the same setup that was just mentioned for N_t, the number of receive antennas was simulated for $N_r = 1, 2$ to see if any significant changes in performance occur compared to the scenario where the influence of N_r is analyzed for shorter temporal spreadings.

4.1.3 Scenario of Diversity between Transmission Antennas

One of the big advantages of using SM as base of the spatial spreading for the multiple access scheme considered is the diversity gain that it can give to the system by switching between transmission antennas. As explained in Section 2.2.2, for each user only one antenna is activated per instance of time and by switching transmission antennas through time, the ST-CDMA system takes advantage of the diversity between the transmission antennas. As such, this allows to create a good number of possible switching patterns or spatial spreading sequences for each user and different combinations of spatial spreading sequences for all users, thus taking advantage of that diversity gain. This is also the second situation where it is possible to evaluate the trade-off between orthogonality and transmit diversity but in this case it simulates directly the transmit diversity.

Before going through the scenarios tested in this simulation, it is important to note that all the scenarios have the following setup from Fig. 4.6 and are tested for the three detectors.

$N_{\mathsf{u}} \leftarrow 3$
$N_t \leftarrow 4$
$L \leftarrow 4$
$M \leftarrow 2$
$N_r \leftarrow 1$

Figure 4.6: Setup for testing of the Transmit Diversity.

To understand what kind of diversity gain can be obtained and how much it can improve the ST-CDMA system, three scenarios were considered to test this effect on the system. The first scenario (curves with "none" written in the legend of Figs. 4.22 and 4.23 in Section 4.3) is a situation with a spatial spreading that gives no diversity gain at all, meaning that there is no switching between antennas and the same antenna is activated for every instance of time, $\boldsymbol{c}_s^{(\mathsf{u})}(l)\epsilon\ \{1\}^{N_t\times 1}$ which is derived from (3.4). In this scenario, since there is no switching between antennas, the system will only depend on its temporal spreading, becoming equivalent to conventional CDMA spreading that benefits from its orthogonality.

The second scenario (curves with "med" written in the legend of Figs. 4.22 and 4.23 in Section 4.3) is a situation that indeed performs antenna switching and has a certain level of diversity, but it does not switch between all the transmission antennas, being unable to achieve the full diversity gain. In this case, it is a scenario with four transmission antennas and the system only switches between two of the four antennas. As soon as there is switching between transmit antennas, the system starts depending also on the spatial spreading and therefore loses its orthogonality. So from this case onwards, the system trades its orthogonality for transmit diversity.

The third and final scenario (curves with "full" written in the legend of Figs. 4.22 and 4.23 in Section 4.3) is the one that achieves full diversity gain, that is the maximum diversity gain that can be obtained for the conditions considered in this test, more specifically $N_t = 4$ and $L = 4$. Because the key to achieving full diversity here is to have a system with $N_t = L$ that switches between all antennas. Since only one antenna is activated for every instance of time, the maximum potential of diversity among transmission antennas is achieved with a spatial spreading sequence that activates a different antenna for every instance of time, which means it must have $N_t = L$ in order to be able to switch to a different antenna at each instant of time.

4.1.4 Using a Channel with Correlation between the antennas

For the first two phases, the used channel is an ideal one, with the same distribution and characteristics detailed in Section 3.1.3. But the third phase consists specifically of testing a non ideal channel for the system and comparing its performance with the case of an ideal one. Because in the real world there are no ideal channels, as such it is of great importance to see how the system performs with a channel that is influenced by the correlation between antennas.

The simulation of a channel with existent correlation between antennas is important to simulate a more realistic scenario, where the channel is not ideal. As such, it is important to test this situation to see if the system can cope with this scenario and have a good performance. To find a solution that may work in the real world is one of the objectives of this work. To add correlation between antennas in the algorithm, the knowledge from Section 3.1.4 is applied, where the correlation coefficient ρ is introduced and now used here.

$N_{\mathsf{u}} \leftarrow 3$
$N_t \leftarrow 2$
$L \leftarrow 4$
$M \leftarrow 2$
$N_r \leftarrow 1$

Figure 4.7: Setup for testing of the Channel Correlation.

Therefore, a scenario with the parameters shown in Fig. 4.7 and fixed spatial spreading is simulated by varying the correlation coefficient $\rho = 0.1, 0.5, 0.9$ for the three detectors and its results are shown in Section 4.4.

4.1.5 5G scenario from Flex5Gware project

In this section, as previously mentioned in Section 2.1.3, a 5G scenario is simulated and analyzed. The purpose of this more practical analysis is to demonstrate the performance of ST-CDMA in a 5G scenario and to show its applicability in 5G and more specifically, in the international projects that are being developed for 5G. In this case, the scenario to be simulated and analyzed is taken from Project Flex5gware [7]. As explained in Section 2.1.3, the project states the need of a Multi-chain MIMO transmitter in order to implement Massive MIMO in a way that it can support a higher number of users, while maintaining a high energy and cost efficiency. Thus, considering the advantages of ST-CDMA, some of them caused by the SM component, it may fit well to the needs of Flex5Gware.

In [7] there is a suggestion given of being able of generating 8 RF signals with a single device. This would correspond to a downlink situation where the base station transmits 8 RF signals, each one to a different user. As such, considering that this work focuses on an uplink solution, the scenarios are also tested as uplink situations of the same project, having several users transmitting RF signals to one single digital device that receives and decodes them all. In this case, only one detector is used and it is chosen depending on the performance results obtained in all the other scenarios previously explained.

Considering the needs of the project Flex5Gware, this scenario is divided in three parts.

First is the testing of this scenario for different numbers of users, $N_{\mathsf{u}} = 1, 4, 8$, to show how the system performs with the increase of the number of users, with special emphasis for the case of $N_{\mathsf{u}} = 8$, which is the specific scenario given in [7]. This shows if it suffers significant or negligible degradation with the increase of N_{u} and also if for $N_{\mathsf{u}} = 8$ the system can perform well. For this scenario the setup from Fig. 4.8 is fixed and used.

$N_t \leftarrow 2$
$L \leftarrow 4$
$M \leftarrow 2$
$N_r \leftarrow 2$

Figure 4.8: Conditions for testing N_{u} for 5G scenario.

By using this setup and variating N_{u}, the first scenario is tested and its results are analyzed in Section 4.5. There it is possible to better understand the viability of implementing Massive MIMO in the project Flex5Gware by using the ST-CDMA system presented here.

Implementing Massive MIMO requires a system with multiple antennas at both the transmitter and receiver ends, meaning that it is important to observe the performance of the ST-CDMA system in scenarios with multiple transmit and receive antennas. As such, this scenario is divided into two phases.

In the first phase, the number of transmit antennas is varied for the values $N_t = 2, 3, 4$ with the following fixed setup from Fig. 4.9.

$N_{\text{u}} \leftarrow 8$
$L \leftarrow 4$
$M \leftarrow 2$
$N_r \leftarrow 2$

Figure 4.9: Conditions for testing N_t for 5G scenario.

The second phase is to vary the number of receive antennas for the values of $N_r = 2, 3$ using the conditions shown in Fig. 4.10.

$N_t \leftarrow 2$
$L \leftarrow 4$
$M \leftarrow 2$
$N_{\text{u}} \leftarrow 8$

Figure 4.10: Conditions for testing N_r for 5G scenario.

This way, it is possible to comprehend how the increase of N_t and N_r can influence the system's performance for the scenario with $N_{\text{u}} = 8$ of the 5G project. This scenario also helps to comprehend the advantages of multiple transmit antennas in one device, and the advantages specific to the ST-CDMA system that can also become advantages of the 5G project, should the system be implemented in it. As such, due to the importance of multiple antennas in Massive MIMO, this scenario is important to be tested in order to better analyze its viability for the flex5Gware project and how well the ST-CDMA system can fit its needs.

4.2 Performance Analysis

4.2.1 Influence of the number of Receiving Antennas

The results of varying N_r in order to determine its degree of influence in the performance of the system are shown. The numbers in the legend of Fig. 4.11 and Fig. 4.12 represent the number N_r for each curve shown.

Starting with a general analysis, it is observed that regardless of the detector, BER decreases greatly with the increase of N_r, specially for the cases with the ML Decoder. This means that the number of errors on the estimations decreases greatly with the increase of the number of receiving antennas.

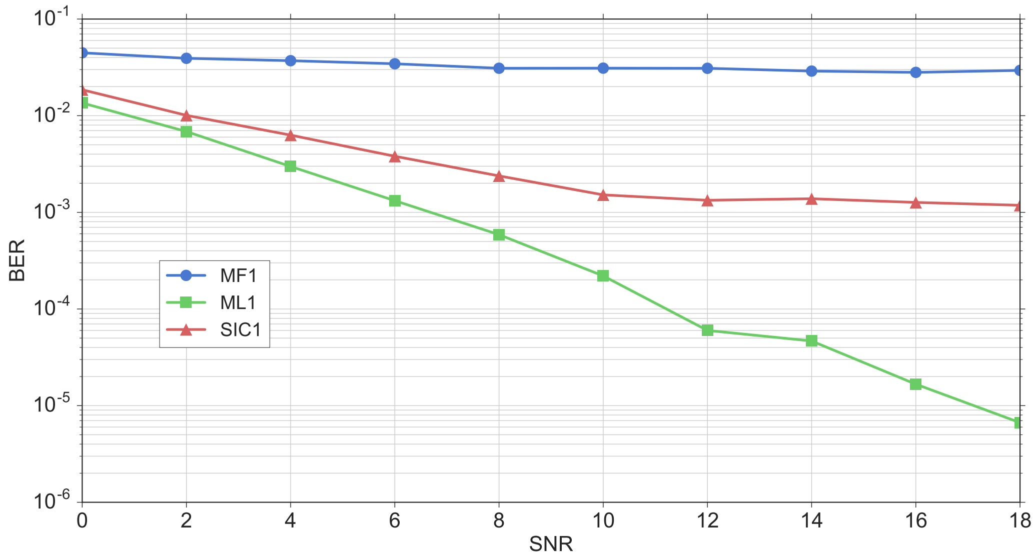

Figure 4.11: Performance of the three detectors of ST-CDMA for $N_r = 1$.

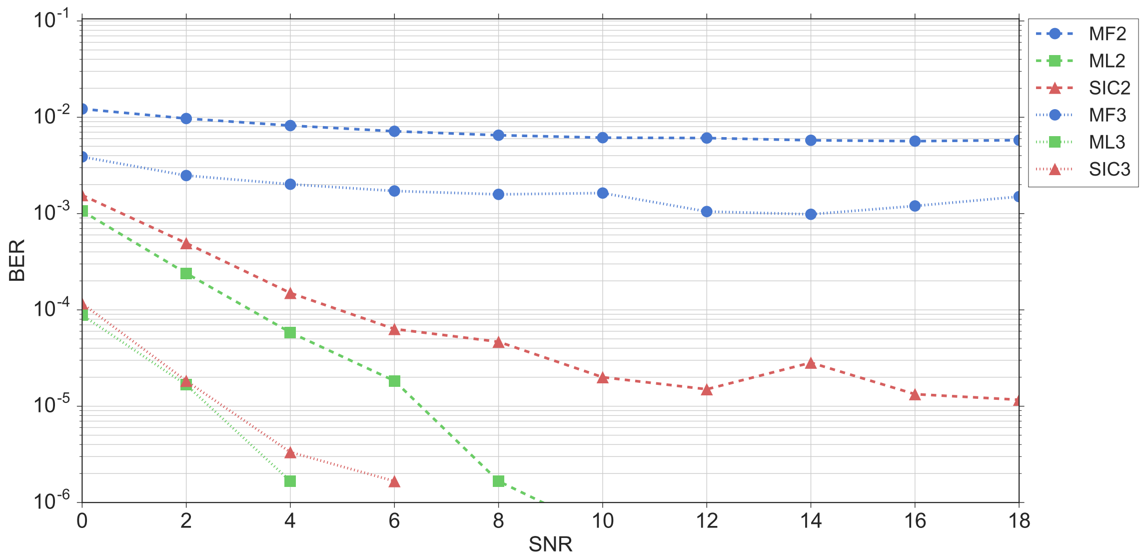

Figure 4.12: Performance of ST-CDMA for increasing N_r.

Regarding the three detectors, the MF detector is the one with most estimation errors and the ML decoder is the one with less estimation errors, hence the MF detector is the one with worst performance of the three and for the three situations it has error floor regions. As such, the most trustworthy detectors are SIC and specially the ML decoder, which has the best performance out of the three, as expected from an optimal detector. The SIC detector also has some error floor regions, but they are much smaller and this detector shows performances close to the ML decoder, which shows potential as an alternative for ML. For the specific case of $N_r = 2$, the SIC detector slightly increases its BER for an SNR of $14\,\mathrm{dB}$ but this is due to the existing error floor region, which causes the estimations to oscillate between a certain interval of points inside the error floor region. This confirms the theories explained in Section 3.1.5 and their expected results.

Focusing on N_r, independently of the error floor regions and the performance of the detectors, for the three detectors it is possible to observe how the BER performance improves with the increase of N_r. Focusing on the ML performances, when comparing BER performance with $N_r = 1$ and the one with $N_r = 2$, there is a difference of more than $7\,\mathrm{dB}$. This means that by adding just one receive antenna, the ST-CDMA has an SNR gain of more than $7\,\mathrm{dB}$, which is a significant gain in the performance of the system. This gain can also be observed but slightly smaller in the SIC curves between $N_r = 2$ and $N_r = 3$, before they enter the error floor regions.

Besides this, with just two receive antennas BER is already in the order of 10^{-6} for an SNR of $8\,\mathrm{dB}$, which is very low, hence the ML and SIC cases for $N_r = 3$ only successfully estimated until an SNR of $6\,\mathrm{dB}$, the BER was already too low to be accurately estimated with 10^6 iterations.

As such the number of receiving antennas is inversely proportional to the BER and the ST-CDMA performance improves greatly and becomes more robust with the increase of N_r.

4.2.2 Influence of the Number of Users

By varying $N_\mathrm{u} = 1, 3, 4$ as explained in 4.1.2, it is possible to observe the results from increasing the number of users in the system and also analyze the changes in performance between a single user scenario and a multiple user one, and the causes for those changes. The numbers in the legend of Figs. 4.13 and 4.14 represent the number N_u for each curve shown. From observing the resulting BER curves for the different N_u and detectors, there are some important remarks to make. First of all is that indeed the BER performance for the MF and SIC detectors decreases with the increase of the number of users as expected. But, considering only the ML curves in Fig. 4.14 (best BER performance of the three detectors), the difference between the curves is almost zero between the three curves. The fact is that according to the simulations, the ML decoder suffers almost no degradation in its performance with the increase of the number of users. This shows that the system with the ML decoder can indeed cope well with multiple users and the degradation caused by them. Expanding now the analysis to the other detectors' curves, there is another important observation for this work. The matched filter for the curve $N_\mathrm{u} = 1$ in Fig. 4.14, the single user scenario, has a BER performance as good as the ML decoder (optimal detector) and SIC, with no error floor regions.

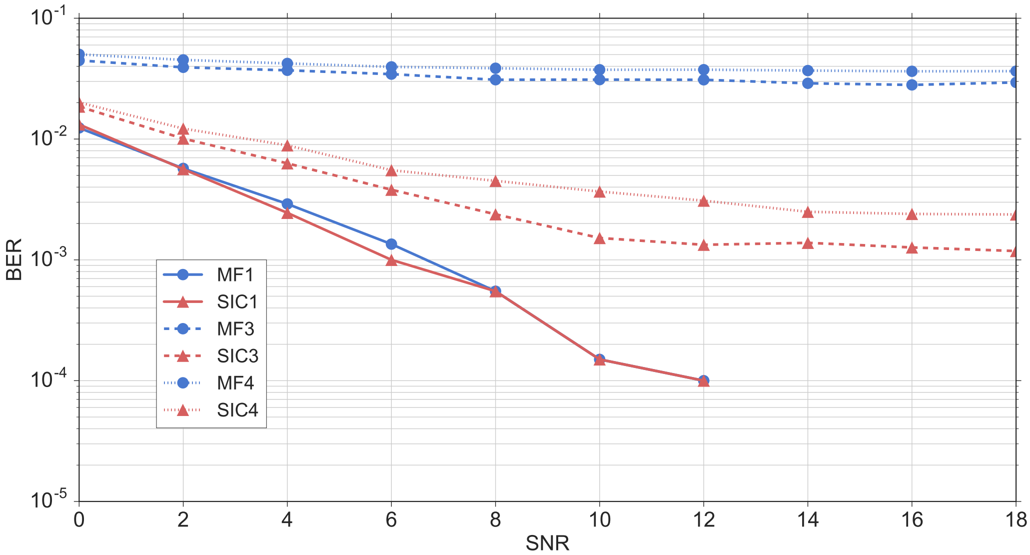

Figure 4.13: Performance of MF and SIC detectors on ST-CDMA for different N_u.

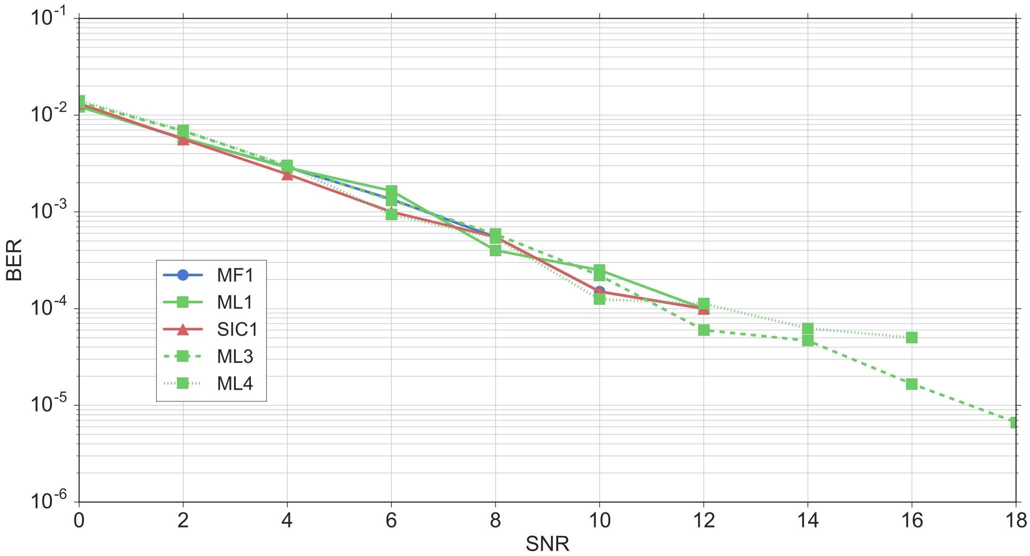

Figure 4.14: Performance of the ST-CDMA system for different N_u and different detectors.

But as soon as the matched filter tries to detect for multiple user scenarios, Fig. 4.13, the BER has a huge increase and it goes from the order of 10^{-4} for $N_\mathrm{u} = 1$ and SNR$= 12\,\mathrm{dB}$, to the order of 10^{-2} for $N_\mathrm{u} = 3, 4$ and with error floor regions. This happens because of the degradation caused by the multiple access interference between users. The matched filter does not take into account the presence of MAI between users, hence it can perform well for the single user scenario, but its performance drops drastically when it tries to detect for multiple user scenarios. This is also the reason why the SIC curves show a better BER performance than MF in Fig. 4.13, although it also shows some error floor regions and a smaller drop of its performance. As explained in Section 3.1.5, opposite to MF, SIC takes into account the presence of MAI while using the same base mechanism of MF, hence it can cope better with multiple user scenarios. As such, these results confirm the influential presence of MAI and the expected effects on the detectors' performances.

4.2.3 Influence of the Number of Transmit Antennas

By looking at Figs. 4.15 and 4.16, it is confirmed that BER performance indeed improves with the increase of N_t for the ML decoder and also for SIC, with a small issue for higher SNR, but not for MF.

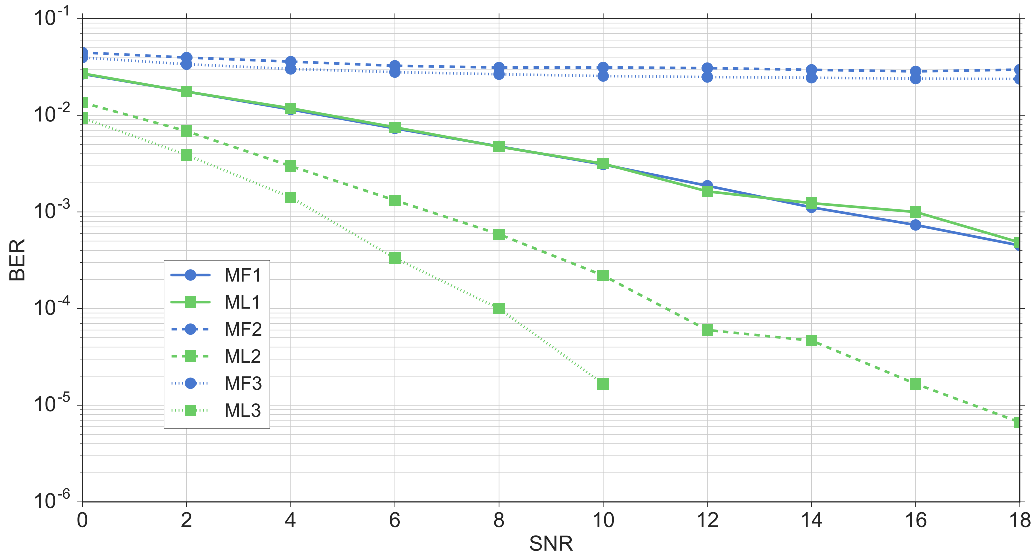

Figure 4.15: Performance and comparison of MF with ML on ST-CDMA for different N_t.

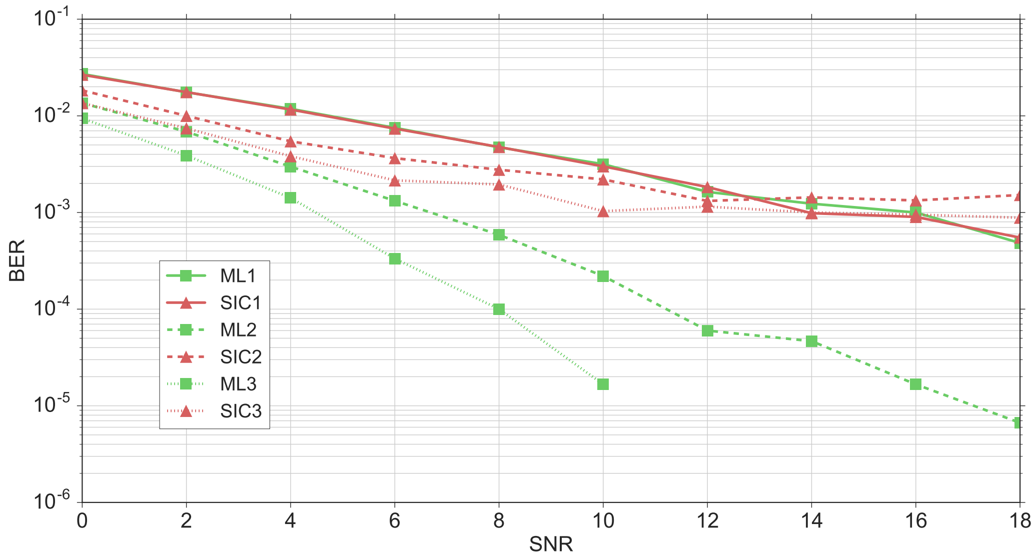

Figure 4.16: Performance and comparison of SIC with ML on ST-CDMA for different N_t.

Because ML is an optimal detector, it does not suffer the influence of MAI as much as in the case of the SIC and MF detectors. As such, when increasing the number of transmit antennas and going from an orthogonal and conventional CDMA spreading, $N_t = 1$, to a space-time spreading that has lost its orthogonality to gain transmit diversity, the system with the ML decoder takes advantage of that diversity gain and significantly improves its BER performance with a gain of approximately 4 dB per transmit antenna, despite losing orthogonality and facing MAI. This proves that with the ML decoder, trading off the orthogonality for the transmit diversity improves the system.

In the case of the MF detector, it is the opposite situation. For $N_t = 1$ with an orthogonal spreading correspondent to conventional CDMA, the MF detector can achieve an equivalent performance to both SIC and ML detectors. But as soon as the number of transmit antennas increases, the system loses its orthogonality and the performance for the MF detector degrades significantly, even with the transmit diversity gain that is obtained. This is caused exactly by the same phenomenon as in the case of the increase of the number of users, it is caused by MAI. As soon as the system loses its orthogonality, MAI is no longer zero and starts causing interference and degrading the performance of the system. Thus, the degradation observed for the MF curves is caused by the presence of MAI in scenarios with more than one transmit antenna. This means that for such a detector as MF that does not have a mechanism to deal with MAI, the orthogonality of the system is not worth losing in order to have more transmit antennas and more transmit diversity.

In the case of SIC, the curves end in error floor regions, but it is possible to see the effects of N_t. Indeed the SIC detector improves its performance with the increase of the number of transmit antennas, opposite to MF. But this improvement is not as high as for the ML decoder and for $N_t > 1$, SIC curves end up crossing each other due to the propagation of errors caused by its mechanisms. This propagation of errors increases with the increase of the number of antennas causing the improvement of BER performance to be stopped when it enters the error floor regions and for a threshold of, in this case, approximately BER $= 10^{-3}$. Despite this behavior from SIC, at most of its curves SIC is able to have a close performance to the ML decoder, proving that its orthogonality is worth losing for more transmit diversity.

As such, the performance of the system can be significantly improved for the ML decoder and SIC, but significantly degraded for MF by adding just one more transmission antenna, showing the important influence that N_t has on the performance of the ST-CDMA system and on the trade-off between orthogonality and transmit diversity.

4.2.4 Influence of the Modulation Coefficient

The results of the simulation can be observed in Figs. 4.17 and 4.18. The degradation is visible in BER performances of the three detectors, caused by the increase of M. Even though the MF and SIC detectors show some error floor regions, the degradation caused by M in their performance is also visible and considerable. In the case of SIC, it even performs close to MF for an 8-PSK modulation if one compares the values of their curves from the two graphs.

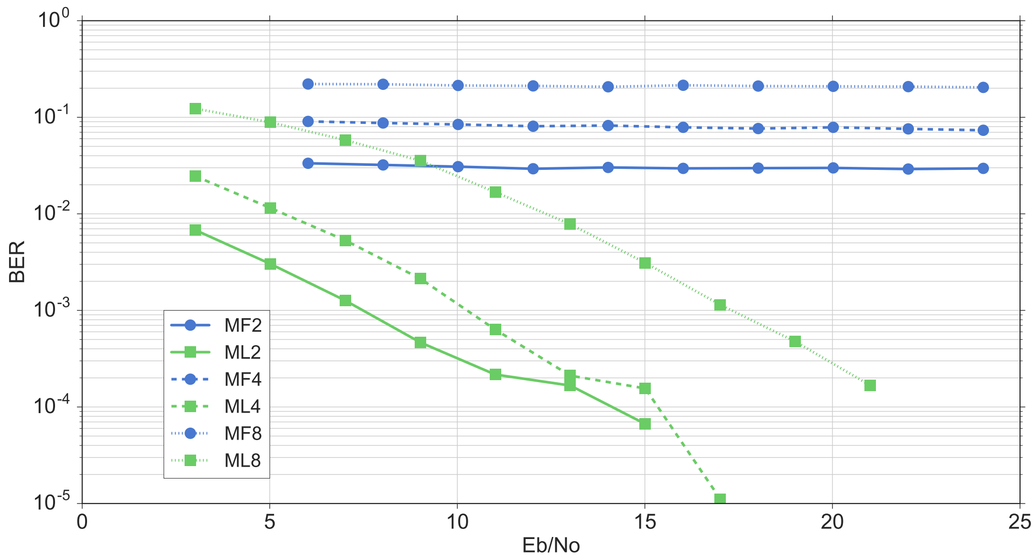

Figure 4.17: Performance and comparison of MF with ML on ST-CDMA for different M.

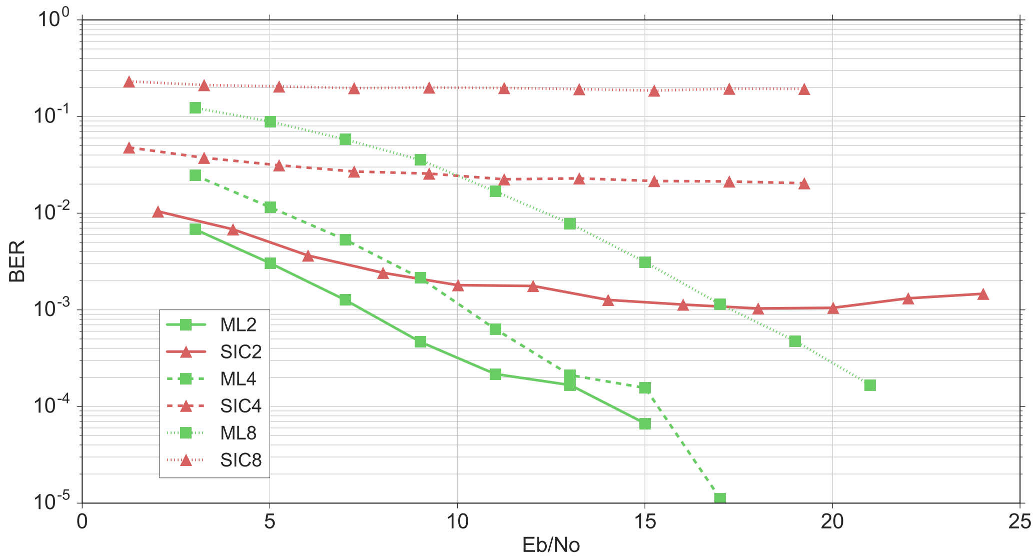

Figure 4.18: Performance and comparison of SIC with ML on ST-CDMA for different M.

Focusing more on the ML detector to better analyze the degradation, it is observed a loss of approximately 4 units from $M = 2$ to $M = 4$ and a loss of approximately 8 units, from $M = 2$ to $M = 8$, the double, for BER $= 10^{-3}$. This means that the increase of the modulation coefficient can cause a significant degradation on the performance of the ST-CDMA system, because when the modulation coefficient M is increased it means that the size of the constellation of symbols is increased. In transmission, users choose one of the symbols of the constellation and transmit it. As such, a bigger constellation means a bigger number of possible symbols for the users to choose which causes problems to detectors. All the detectors explored here have as objective to estimate the signal transmitted by each user, consequently estimating the symbol chosen from the constellation mentioned before. As such, for $M = 2$ the detectors only have to decide between two possible symbols but if $M = 8$ there are 8 possible symbols to decide from, which increases significantly the probability of estimating wrongly. As such, this causes the detectors to have more estimation errors and causes the observed degradation in the BER performances from Figs. 4.17 and 4.18.

4.2.5 Influence of the Size of Temporal Spreading Sequences

By observing Fig. 4.19, it is possible to see that there is an improvement for all detectors between the BER performances of the two sizes $L = 4$ and $L = 32$, especially significant in the case of ML.

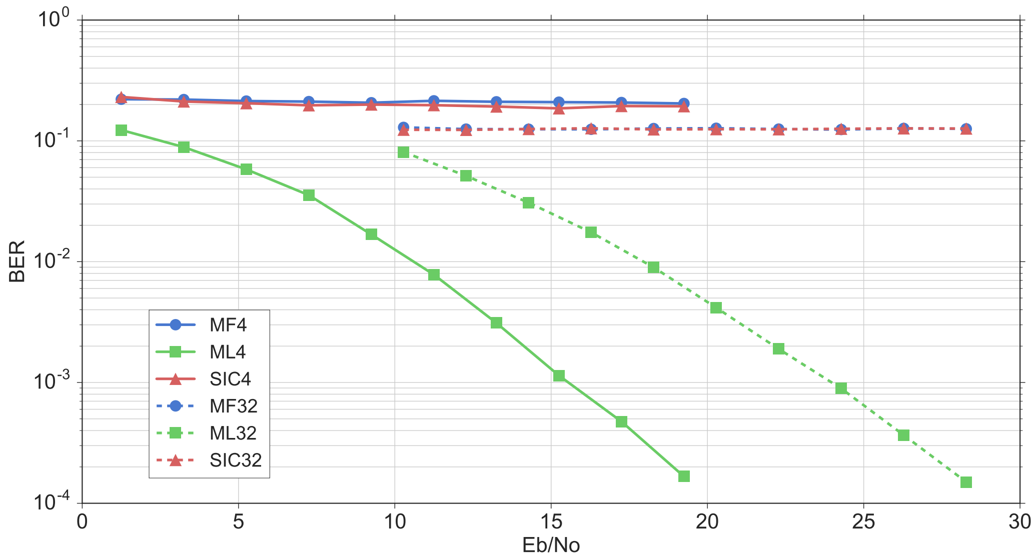

Figure 4.19: Performance of ST-CDMA for low and high L.

For ML, there is a gain of approximately 5.5 dB (after conversion to SNR) in the system, which shows how much of an influence the length of the temporal spreading is to the system and its performance. In the case of MF and SIC, due to the 8-PSK modulation, their performances are degraded and with high BER, but the improvement is still visible from the increase of temporal spreading size, and for a lower modulation, their results should prove better. This means that increasing the temporal spreading size, L, can significantly improve system's performance. Because by improving L this creates longer sequences of spreading, which allows more averaging in the estimations and therefore improving the BER performance of the detectors, improving the system.

After observing the effect of longer temporal spreading in the system, now the influence of N_t and N_r is once again simulated, but this time for $L = 32$ in order to see how those parameters influence the system performance for $L = 32$. Starting with the influence of transmit antennas, the scenario is simulated for $N_t = 2, 3$ and the results obtained are shown in Fig. 4.20.

Due to the high degradation caused by the 8-PSK Modulation, both SIC and MF detectors suffer almost no changes and their performances are too degraded to be conclusive. But in the case of the ML decoder, as expected, the performance is slightly improved by the increase of N_t, approximately 1 to 2 dB. As such, system's performance for ML improves with the increase of N_t for longer sequences.

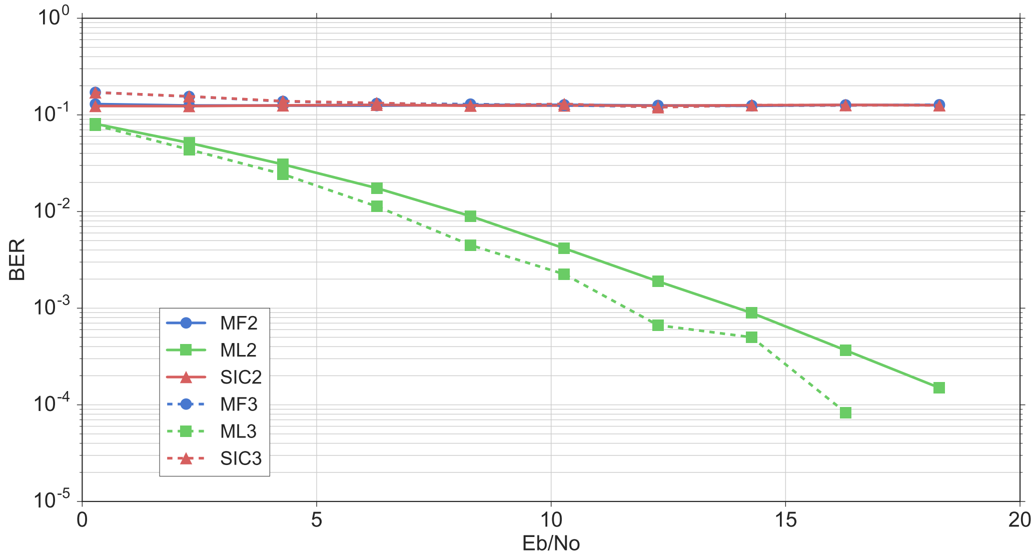

Figure 4.20: Influence of N_t in ST-CDMA for spreading sequences with higher L.

From Sections 4.2.3 and 4.2.1, it is observed that N_r is the more influential parameter and that it improves significantly the performance of the system for all three detectors. Considering this fact for the case of longer spreading cases, the number of receive antennas was simulated for $N_r = 1, 2$ to see if that significant improvement is still shown, in Fig. 4.21.

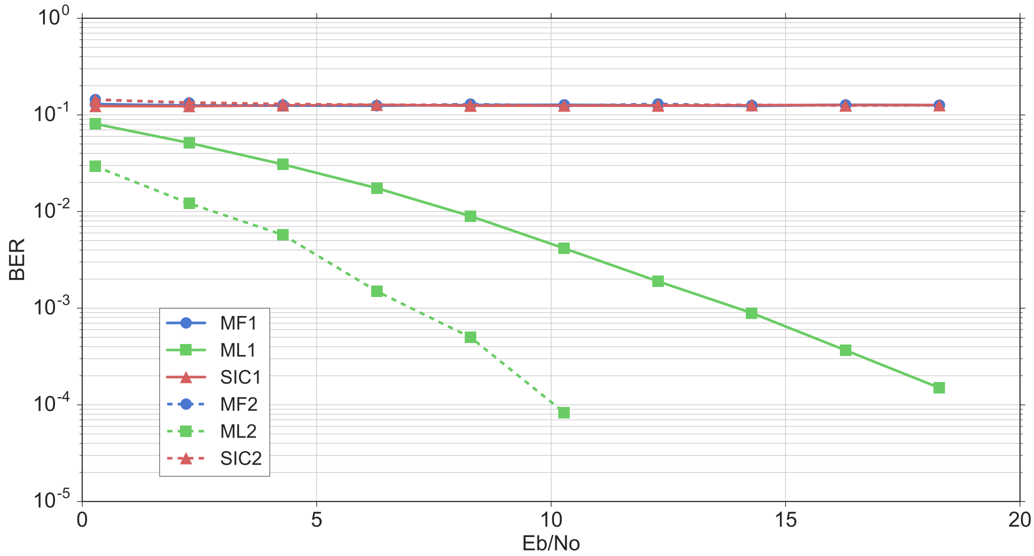

Figure 4.21: Influence of N_r in ST-CDMA for spreading sequences with higher L.

As in the previous case for N_t, it is observed that the MF and SIC performances are too degraded by the 8-PSK modulation, hence they show no conclusive results. But in the case of ML, a significant improvement when increasing the number of receive antennas, more specifically, a gain of approximately 5 dB. Comparing to the increase of the number of transmit antennas, the improvement caused by N_r is higher as expected and it confirms that N_r is an influential parameter of the ST-CDMA system independently of the size of the temporal spreading sequences.

4.3 Diversity between Transmission Antennas

Figs. 4.22 and 4.23 show BER performance of the three diversity scenarios explained in Section 4.1.3 and how they perform for each detector.

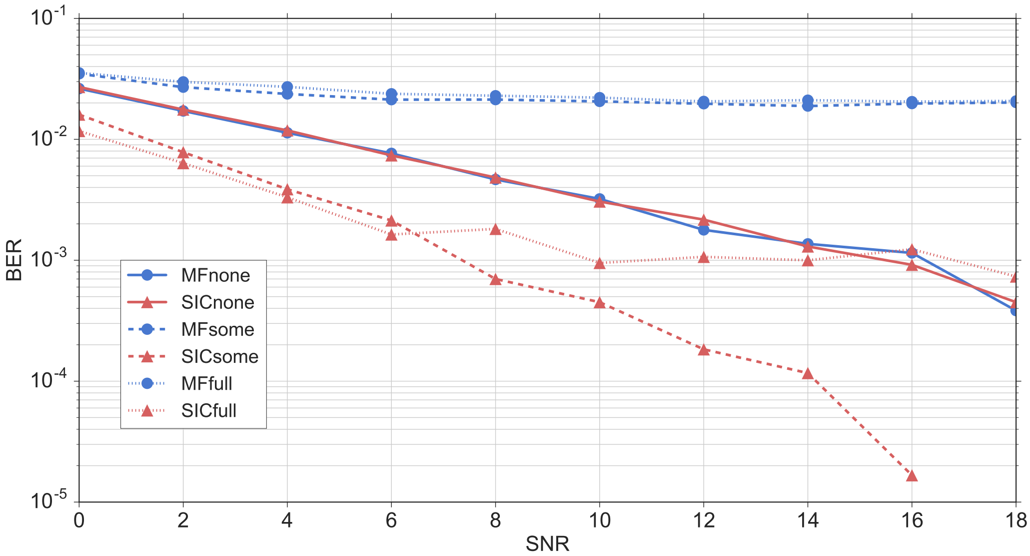

Figure 4.22: Performance and comparison of MF with SIC on ST-CDMA for different diversity gains.

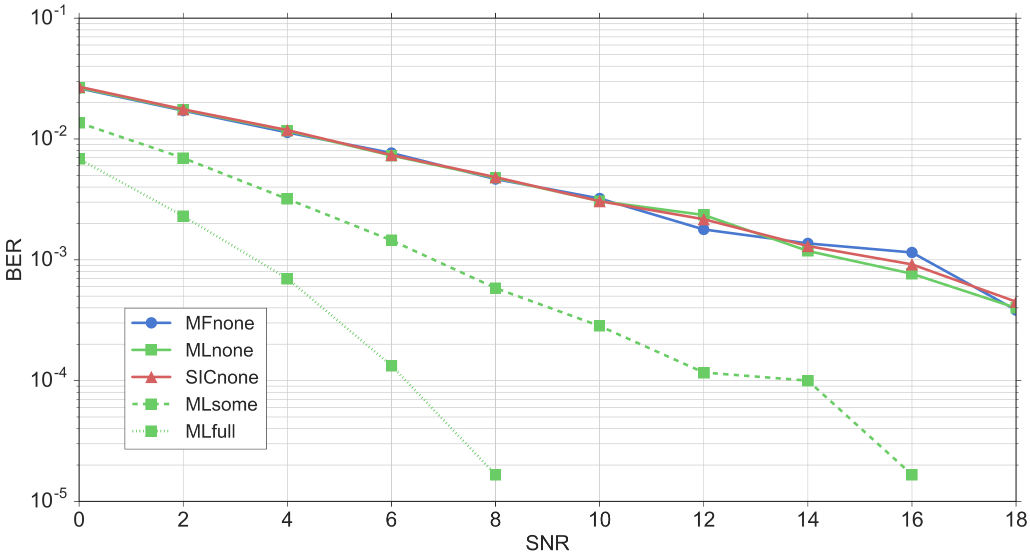

Figure 4.23: Performance of ST-CDMA for different diversity gains and detectors.

As observed, the performance of ML and SIC improve with the increase of transmit diversity in the system, but in the case of MF the performance is significantly degraded. This is a similar case to the one observed in Section 4.2.3 and starting with the case of ML in Fig. 4.23, it is an optimal detector that improves significantly its performance despite the presence of MAI for the second and third scenarios.

Focusing on the ML curves from Fig. 4.23, since it achieves the best performance out of the three detectors, the difference of the performances for different diversity gains is very visible. In fact, while the curve of no diversity achieves a BER in the order of 10^{-3} for an SNR $= 8\,\mathrm{dB}$, the curve of full diversity already has a BER in the order of 10^{-5}, to show the substantial improvement caused by the increase of diversity.

Comparing the first scenario with the second one, there is an initial gain of approximately $4\,\mathrm{dB}$ and it increases with the increase of the SNR. This means that by just switching between two transmission antennas it is possible to obtain this gain in the performance of the ST-CDMA system for the ML decoder. This observation shows once again that trading off orthogonality for transmit diversity for the ML decoder is the right decision. As soon as the system starts switching between antennas and loses its orthogonality, MAI starts degrading the system, but the improvement caused by the transmit diversity is bigger in the case of ML and it is worth losing the system's orthogonality for it, as seen in Fig. 4.23. The more extreme case to compare is between the curves of full diversity and no diversity, showing an initial gain of approximately $6\,\mathrm{dB}$ in the performance of the ST-CDMA system, that gain increasing with SNR.

As for the matched filter detector, when the system has no switching between antennas (no transmit diversity) and works as conventional CDMA, it benefits from orthogonality caused by the CDMA spreading, hence it is not influenced by MAI because MAI is zero. This allows MF to have a performance equivalent to ML and SIC for the first scenario with no transmit diversity, as observed in Fig. 4.23. But as soon as the system starts switching between antennas, whether it is full diversity or just two antennas switching, it starts benefiting from transmit diversity but in exchange for losing its orthogonality. And by losing its orthogonality it becomes vulnerable to MAI, since, in this case, MAI is no longer zero. This leads to the significant degradation observed in the MF curves of Fig. 4.22, from no diversity to full diversity, because MF has no mechanism to deal with MAI, suffering the observed degradation in its performance and showing that for MF, orthogonality is worth keeping instead of trading it for transmit diversity.

As for the SIC detector, in FIg. 4.22 its performance also increases significantly with the increase of transmit diversity, despite the loss of orthogonality. This shows that by having a mechanism to deal with MAI as SIC does, it can improve its performance significantly, opposed to the MF case that cannot deal with MAI, degrading its performance. Besides this, SIC shows in general close performances to the ML decoder, showing that it can be an alternative to ML with lower complexity. But there is the specific case for the curve of full diversity, here it is possible to observe the propagation of errors caused by the mechanisms used in SIC to deal with MAI. This causes an error floor region in SIC with a threshold of BER $= 10^{-3}$, also seen in Section 4.2.3. Thus SIC shows to be a good alternative in general to ML but with some specific cases to consider.

This shows that the presence of transmit diversity in the system is an important factor and can improve or degrade greatly the performance of the system, depending on the detector.

4.4 Using a Channel with Correlation between the antennas

The performance results from testing the scenarios considered in Section 4.1.4 are presented here, Figs. 4.24 and 4.25, in order to analyze the influence of correlation between antennas in the channel and consequently in the system.

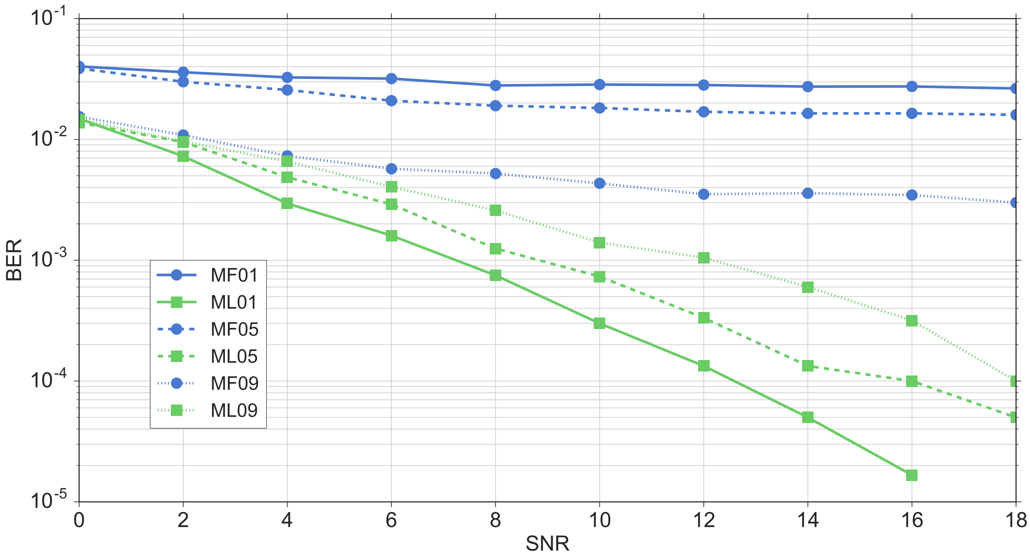

Figure 4.24: Performance and comparison of MF with ML on ST-CDMA for different correlation coefficients, ρ.

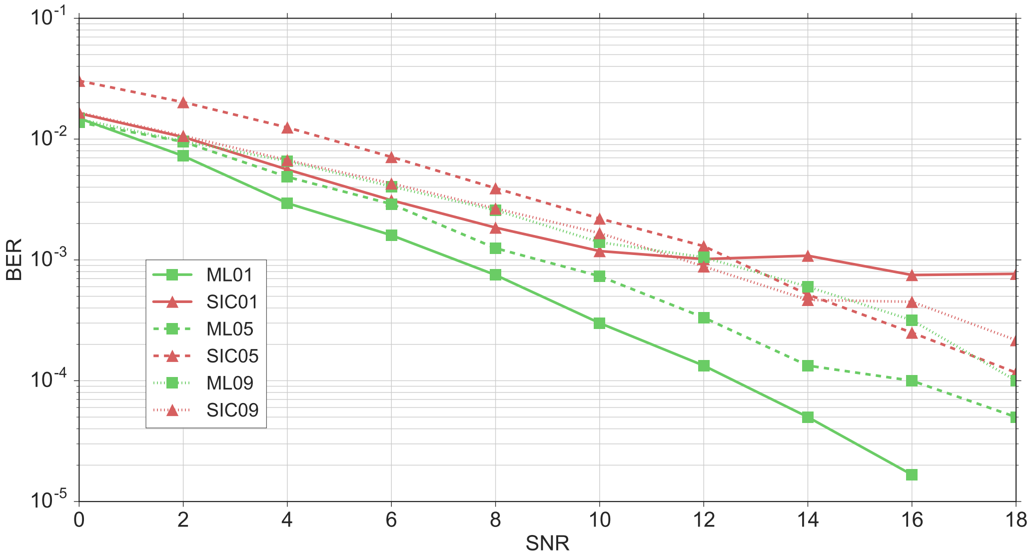

Figure 4.25: Performance and comparison of SIC with ML on ST-CDMA for different correlation coefficients, ρ.

Although the MF curves show error floor regions on most of its performance from Fig. 4.24, both figures show that, for the detectors, the BER performance of the ST-CDMA system degrades with the increase of correlation in the channel. The SIC curves in Fig. 4.25 also show the beginning of error floor regions due to its propagation of errors but can better show the behavior of channel correlation than MF, and achieves performances close to ML. But the one that best demonstrates the effects of the channel correlation is the ML decoder. Focusing on the ML curves, by increasing the correlation from $\rho = 0.1$ to $\rho = 0.5$ there is a loss of approximately $2\,\mathrm{dB}$ and from $\rho = 0.1$ to $\rho = 0.9$ there is a loss of $4\,\mathrm{dB}$ in the system. As such, the correlation in the channels has a significant influence in the system and can considerably degrade its performance.

For a small correlation like $\rho = 0.1$, the system behaves closer to the ideal channel situation that corresponds to $\rho = 0$, and that has indeed an ideal performance compared to scenarios with correlation. Comparing with that ideal scenario, the higher the correlation the higher the degradation is in the performance of the system, and farther away it gets from the performance in the ideal scenario.

This behavior is justified by looking into the meaning of existing correlation between the channel coefficients. For an ideal channel, the channel coefficients are mutually uncorrelated, which means that they are completely independent from each other, and more importantly they are therefore distinguishable between each other.This characteristic of being distinguishable helps greatly in the detectors' estimations of the transmission antennas and of the transmitted signals, because the channel coefficients are uncorrelated and completely different from each other, making it easy to distinguish them in the estimations. But if correlation between antennas is added to this scenario, and the channel coefficients become correlated between each other, then they become less distinguishable from each other [19]. And this effect causes the detectors to make more estimation errors, because it becomes harder for the detectors to distinguish between the individual channel coefficients and estimate correctly [19].

Therefore, as observed in Figs. 4.24 and 4.25, the higher the correlation, the harder it is to distinguish the individual channels and the higher is the number of errors in the detectors' estimations, causing a higher degradation in the performance of the ST-CDMA system.

This proves that the existence correlation between the antennas and its effects are an important issue and it influences significantly the ST-CDMA system. As such, in a real world implementation of this system, the channel correlation is an important factor to take into account in its performance.

4.5 Analysis of 5G scenario for Flex5Gware

Following the descriptions and scenarios given in Section 4.1.5, this section focuses on analyzing the performance results of the ST-CDMA system for the 5G scenarios considered and also on comprehending the viability of this system in a 5G system by using the example of the project flex5Gware [7].

The chosen detector for the simulations of these scenarios is the ML decoder. From observing the previous results from the other scenarios, it can be concluded that the ML decoder has a better performance than the other two detectors. Despite its high computational complexity, it is an optimal detector and consequently it can best show how well the ST-CDMA system can fit in 5G systems.

For the first scenario, the number of users was varied with the values $N_\mathrm{u} = 1, 4, 8$, obtaining three different curves, Fig. 4.26.

From Fig. 4.26, it is possible to observe one main result, i.e, the performance of the ST-CDMA

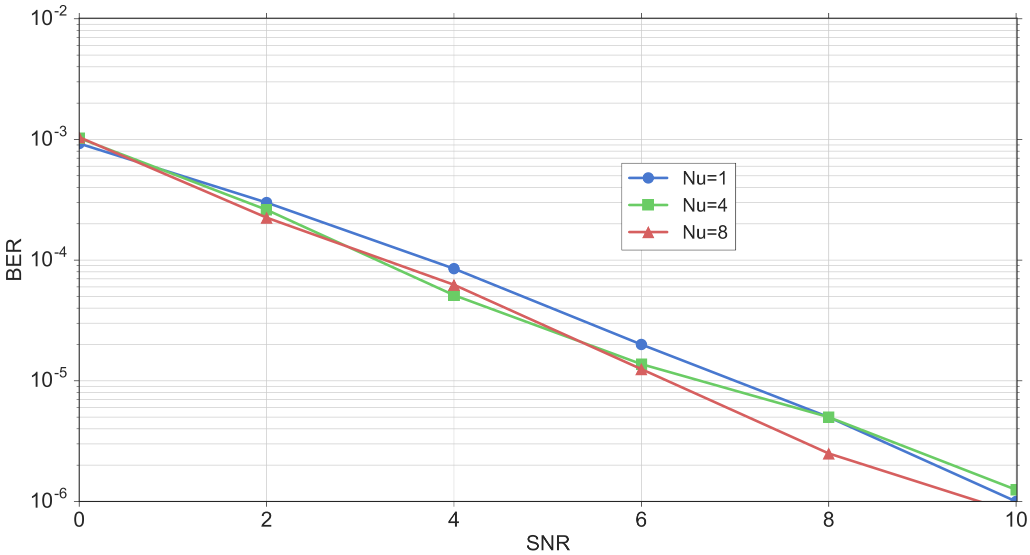

Figure 4.26: Variation of N_{u} in 5G scenario.

system is very similar between the three curves. This means that the increase of the number of users, N_{u} in the system causes almost no degradation or even negligible degradation in the performance of the ST-CDMA system, specifically for the ML decoder. This behavior is also observed in Section 4.2.2. Whether it is a single user case or a multiple user case, the performances of both are almost the same, which is also due to the fact of the ML decoder being an optimal detector. Besides this, the BER values observed are also very low and with an accentuated decrease with the increase of SNR, showing even values of the order of 10^{-6} for SNR $> 12\,\mathrm{dB}$. As such, the system shows a good performance and with negligible degradation from the increase of the number of users, which are good conditions to implement Massive MIMO. Also, for this system to be implemented in the real world, and consequently in 5G, BER performance must be comprised with values of BER$\leq 10^{-3}$ in order to have a valid and feasible performance the real world. As it is possible to observe, BER performance obeys that validation criterion and achieves an even better performance with the increase of SNR.

Massive MIMO targets a very high number of users to support, hence it needs a system that can support its user requirements and suffer negligible degradation from its increase in its performance. This ST-CDMA system shows those conditions and that it may support well Massive MIMO in a 5G system such as the one from Project flex5Gware.

Another condition that comes from implementing Massive MIMO or even MIMO in general, is the use of multiple antennas at both transmitter and receiver ends. Thus comes the second scenario described in Section 4.1.5 and divided in two phases, the variation of N_t, Fig. 4.27, and the variation of N_r, Fig. 4.28. This provides the results needed in order to analyze the system's behavior when the number of antennas increases at transmitter or receiver sides, or even both. The increase of those two parameters symbolize an increase of implementation complexity, in other words, a more complex ST-CDMA system and in this case, if implemented with this system, it will mean a more complex system of Massive MIMO to implement in 5G systems. Thus, it gives more meaning to comprehending how the number of antennas influences the performance of the system in this 5G scenario, and how well it can take advantage of those influences to improve the performance of the system.

As such, first using the scenario with the setup from Fig. 4.9 from Section 4.1.5, the system was simulated for the values $N_t = 2, 3, 4$, obtaining the results shown in Fig. 4.27.

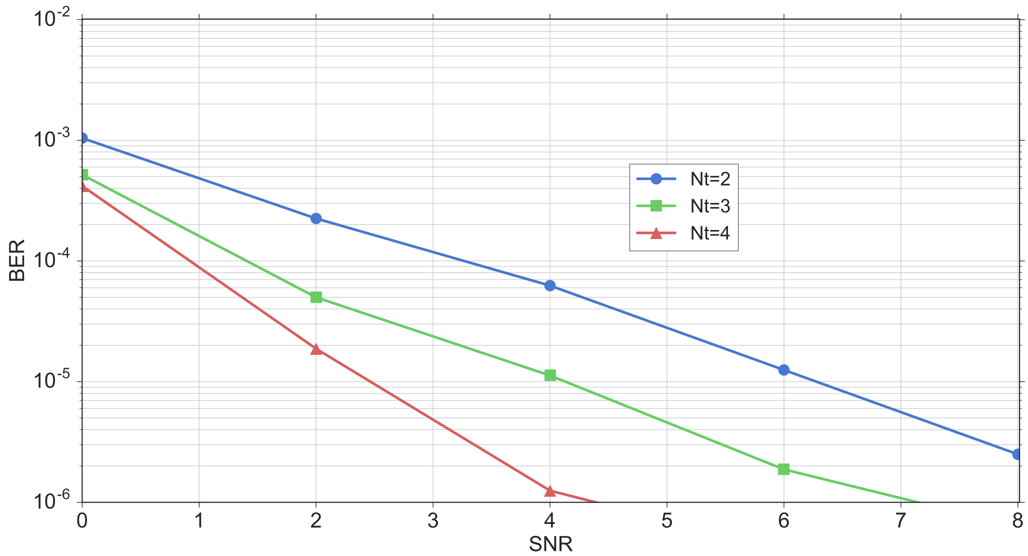

Figure 4.27: Variation of N_t in 5G scenario.

By observing Fig. 4.27, similar to the results observed in Section 4.2.3, the increase of N_t results in an increase of the BER performance of the system. By comparing each curve, it is possible to observe an increasing distance between them. For a BER close to 10^{-6}, it is possible to observe a difference of approximately $2\,\mathrm{dB}$ from $N_t = 2$ to $N_t = 3$, and a difference of $2\,\mathrm{dB}$ from $N_t = 3$ to $N_t = 4$, showing an improvement in the form of an almost constant SNR gain of approximately $2\,\mathrm{dB}$ in BER performance of the ST-CDMA system per adding of one transmit antenna. This improvement in performance is mainly due to the diversity gain obtained from increasing N_t, as explained in Section 4.2.3, which is a specific advantage of this ST-CDMA system caused by its SM component. For implementing Massive MIMO in a 5G system, this advantage can give a significant help in system's performance.

Next is the variation of N_r, which follows the conditions from Fig. 4.10 of Section 4.1.5. For this case, the system was simulated for the values of $N_r = 2, 3$, resulting in Fig. 4.28. For this case, it can be seen a significant improvement caused by increasing the number of antennas just by one. In the $N_r = 2$ curve, BER is already at the order of 10^{-5} for an SNR $> 6\,\mathrm{dB}$, compared to the curve $N_r = 3$ that already achieved that order of BER values for an SNR = $2\,\mathrm{dB}$, showing an SNR gain of approximately $4\,\mathrm{dB}$ between the two curves. This shows what adding one single receive antenna can do to improve the ST-CDMA system's performance and how influent that parameter can be to Massive MIMO and 5G systems.

For a better understanding of the influence of both N_r and N_t antennas, of all antennas in the ST-CDMA system and also specifically for this 5G scenario with $N_\mathrm{u} = 8$ users, a slightly different view, in 3D, is demonstrated in Fig. 4.29 with fixed SNR $= 2\,\mathrm{dB}$. In Fig. 4.29, it is possible to observe how the

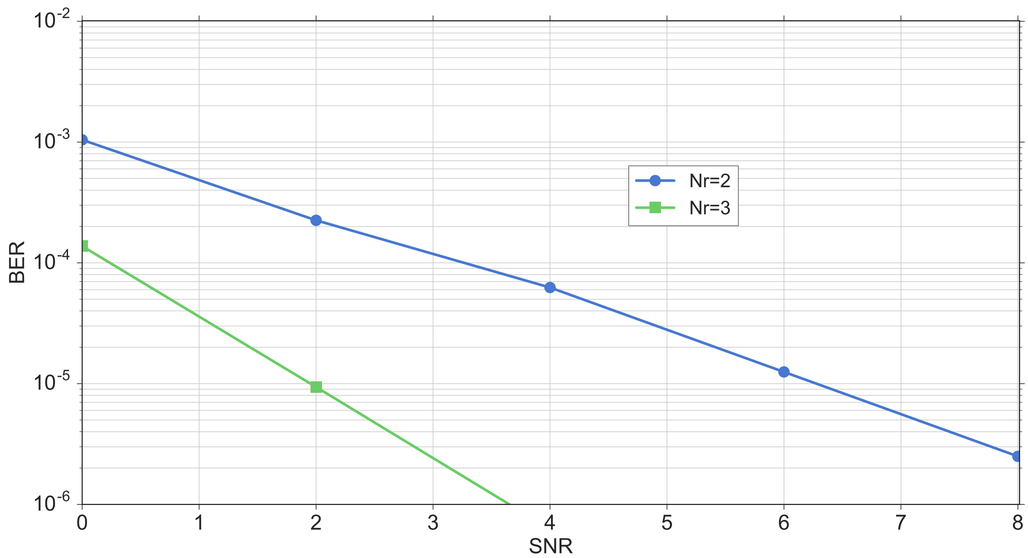

Figure 4.28: Variation of N_r in 5G scenario.

BER performance of the ST-CDMA system is influenced can vary and improve with both the antennas' influence and comparing both influences separately. The performance hits a maximum of approximately 2x10^{-2} which corresponds to the worst BER performance in the graph for a combination of just one antenna of each, $(N_r, N_t) = (1, 1)$, a scenario where the system is still an orthogonal one and does not benefit from spatial diversity due to $N_t = 1$.

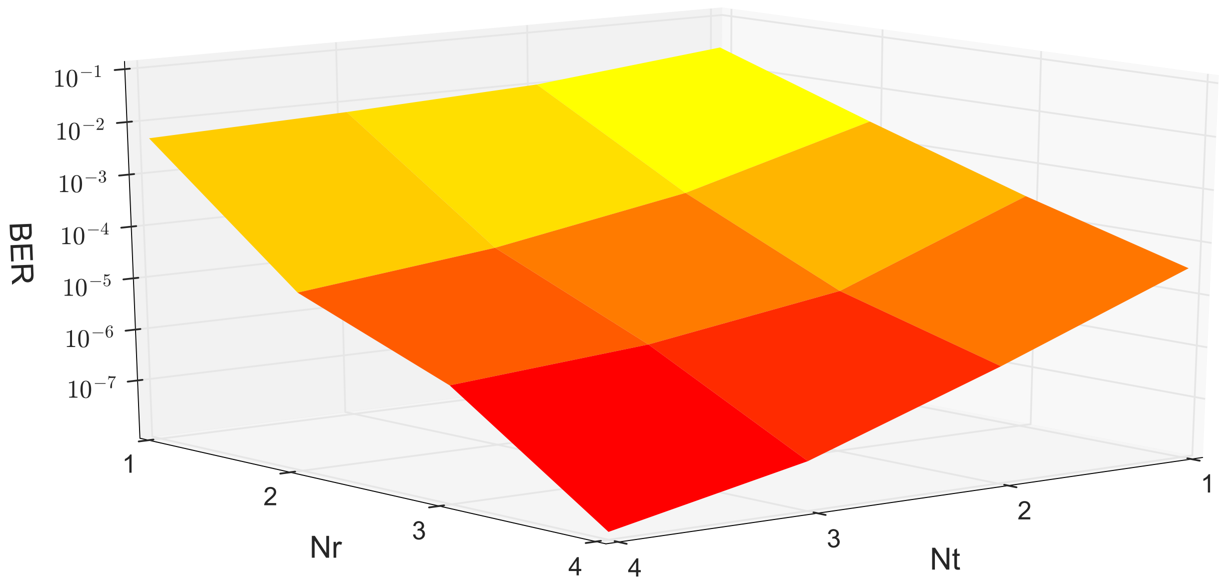

Figure 4.29: Influence of transmit and receive antennas in a 5G scenario.

Besides this, there is also only one antenna to receive the full signal and afterwards detect it. This corresponds to a non-MIMO scenario and it presents a BER too high for being feasible in the real world. As explained before, for it to be implemented in the real world and consequently in 5G, BER cannot be higher than 10^{-3}. As such, from observing the 3D graphic, one can conclude that the lowest combination of antennas for which the system is feasible and has a valid performance, is $(N_r, N_t) = (2, 2)$ which corresponds also to the minimum combination to achieve MIMO. This shows the significant improvement that a MIMO implementation can have on a system, with exception for the cases of $(N_r, N_t) = (3, 1)$ and $(4, 1)$ due to the significant influence that N_r alone has over the ST-CDMA system. This last fact and also by comparing in Fig. 4.29 the variation of N_r alone with the variation of N_t alone, show the superior influence of N_r in the ST-CDMA system compared to the influence of N_t. Another observation that is possible to make in Fig. 4.29 is the joint influence of both parameters. By increasing both N_r and N_t together, the performance improves even more significantly, reaching a maximum of approximately 10^{-8} for a combination of $(N_r, N_t) = (4, 4)$ and showing the advantages of MIMO.

These 5G scenarios that were simulated show the potential of ST-CDMA in 5G systems, the support and resources it can give to those systems, and the advantages of implementing it in 5G systems and of using ST-CDMA to implement Massive MIMO. With a negligible degradation in performance with the increase of the number users and considerable improvements in the performance caused by the increase of the number of antennas of the system, showing good performances and considerable potential since, it may fit well into 5G systems and more specifically it may be a good choice to implement Massive MIMO in the project Flex5Gware [7].

5

Conclusions

To end this work, this chapter outlines its main conclusions. It revisits the goals of this thesis and summarizes the main aspects of the problem and solution presented in this work, highlighting its main results and the conclusions drawn from them. Lastly, it points to future directions for other works to follow and further expand the subjects addressed in this work.

The main objectives of this work are to investigate a solution based on Spatial Modulation that can serve multiple users and may work in a real world implementation, while keeping system's complexity as low as possible, a solution that may have an important role in the next generation of mobile networks, 5G. Nowadays SM for multiple users is becoming a technology more and more explored, because of its advantages. SM has a low computational and implementation complexity and has only one active antenna per time instance, avoiding completely inter-channel interference and increasing spectral efficiency. But despite these advantages, there is still a need for more practical multiple access schemes for SM due to the degradation caused on systems tested in real world. As such, this work came to be in order to try and do that, investigate a solution that may show potential to be implemented the real world and cope with the correspondent degradation. Besides this, with 5G systems being currently in development, this work also sought to explore SM and its variations as a possible technology to implement and support future 5G systems. Consequently, the ST-CDMA solution is found. A theoretical and practical expansion of the work is taken, to show of what it consists and more importantly what it is capable of, especially in a practical point of view.

Chapter 2 is divided into two main parts and it gives the theoretical background to this work. The first part, Section 2.1, gives an overview of the current progress in 5G systems. It gives a detailed and fundamented description of what is required and expected from a 5G system, from both the user's and the system's viewpoint in order to see what kind of goals are to be achieved by 5G systems and how the system's explored in this work can help meeting those goals. This section also introduces the reader to some of the current technologies that are showing increasing interest and are being developed for the 5G era, mentioning for the first time in this work SM, showing its potential and justifying the focus given to it in this work. As such, to better understand the potential of SM, an overview of its current applications and future applications in 5G is done, in order to see how it can fit the current generation and the future generation of Mobile Networks, 5G, how it can fit its systems and the advantages it can bring to those systems.

The second part of this chapter, Section 2.2, consists of an introduction to the technologies explored in this work, the reasons and advantages to explore them and what has been already explored up until now in order to show the reader what can still be explored and how this work contributes to that and the world. This shows a certain evolution in technology and complexity throughout the chapter. First is SM for a single user, where the bases of SM are presented, the transmitter and receiver as well as the detector, with the help of the system model diagram to better understand it. The key concepts and advantages are explained. This chapter serves as a base of knowledge for the rest of the work, since it explains the main terms that are used. From here on, the work is dedicated to multiple user scenarios, which are introduced in Section 2.2.2. One explores some of the MA approaches and also MU-SM and SMMA to better comprehend the strategies that are already created and where they are missing or could be improved.

Then comes Chapter 3, where the ST-CDMA solution is introduced and an analysis of this strategy is realized. This chapter is also divided into two parts, first the theoretical analysis of this solution and then the description of the process of simulation of this solution. The first part starts by exploring all the mechanisms of transmission, specially the temporal and spatial spreading and then it goes through the receiver, with special attention to analyzing a more realistic scenario with a channel that has correlation between its coefficients and developing a mathematical description of this effect. Then it describes the process of decoding for the three detectors that are explored here, MF, ML and SIC, and it ends the theoretical model with a detailed analysis of one of the most important issues in the performance of an SMMA strategy, and, in this case, of the ST-CDMA system. It is a mathematical analysis of the multiple access interference between users, MAI, obtaining in the end a mathematical expression that symbolizes the MAI for a certain user, which is represented by the cross correlation between the desired user's signal to detect and the sum of all the undesired users' signals. Also thanks to this analysis of MAI, it is possible to observe the theoretical effects of the trade-off between orthogonality and transmit diversity that influence this system.

As for the second part, the whole process of simulating the ST-CDMA system is explained. The conversion from the theoretical model to the algorithm used is explained with detail and the basic functioning of the algorithm is also described. After describing the algorithm the metrics used to evaluate this work's results are outlined and an assessment of this work is done by comparing with other works their results, in order to show the validity and veracity of the practical work performed and its results.

Chapter 4 presents the practical part of this work. In this chapter, a simulation and results analysis is performed for the ST-CDMA system. All the tests performed in this chapter are performed for three different detectors, which allowed to compare their performances and methods of estimation and obtain important conclusions for this work. Only the 5G scenarios, tested last in this chapter, used just one detector that is chosen among the three according to their performance results and computation complexity.

First, the scenarios to test and analyze in this work are described in detail, their setups and conditions, their purposes and how those scenarios help this work. Then, after describing all the scenarios, the results of simulating those scenarios are demonstrated and an analysis of those results is given in order to provide a detailed analysis of the ST-CDMA system's performance and what it is capable of, as well as trying to show where and how it can fit in future 5G systems. The first group of scenarios to test are the ones that tested the system's main parameters and their influence on the system. Parameters such as the number of receiving antennas, the size of the temporal spreading sequences and the number of transmission antennas are concluded to be of significant help to improving the performance of the ST-CDMA system, depending on the detector in the case of N_t. In the case of N_t, it is possible to interpret the influence of orthogonality and transmit diversity in the system and how they affect differently each detector due to the MAI presence. And parameters such as the modulation coefficient, and most importantly the number of users, are concluded to increase the degradation of the performance of the ST-CDMA system. In the case of the number of users, although it degrades the system, that degradation in the case of ML is very small, hence the ST-CDMA solution can cope well with the increase of the number of users. But only when considering small numbers of users, in a realistic scenario there is a much larger number of users and the degradation is caused by the accumulated interference of all those users, which may be considerably higher. It is also possible to identify the degradation of MAI for the

MF detector. The degradation in its performance from a single user scenario to a multiple user scenario is big and it does not happen in the case of SIC, which has the same base estimation algorithm as MF but SIC takes into account the presence of MAI. As such, the strong presence of MAI and its issues is confirmed.

After analyzing the parameters, two specific scenarios of special importance are investigated, starting with the diversity gain that can be achieved by the ST-CDMA system due to its use of spatial modulation in the spatial spreading. The results are significantly positive for ML and SIC, with big gains in the system performance and show why spatial modulation is becoming more and more important through the years. But for MF, the loss of orthogonality and consequent presence of MAI show to be more influential to the detector, meaning that MF is better when keeping an orthogonal spreading, conventional CDMA, without transmit diversity. The second scenario is the simulation of the realistic situation described in Section 3.1.4, a channel with correlation which shows the degradation of system's performance for changing from an ideal channel to a more realistic scenario with a non-ideal and correlated channel. This demonstrates a more realistic performance to expect from the system if it is ever implemented in the real world and what levels of degradation can be expected from the channel.

The last scenarios that are explored in this work are based on situations with 5G communications, scenarios that can be applied to 5G systems and show how SM can fit the future 5G systems. One of the applications for SM in 5G is by using it to implement Massive MIMO, and this technology is required to support a very high number of users with a high level of performance and multiple antennas at both ends to support the MIMO system. And through two 5G scenarios applied to the ST-CDMA system that are tested for only one detector, the ML decoder, it is possible to observe and conclude that this system can provide and keep a high level of performance while suffering negligible degradation from increasing the number of users. Not only this but the system is also positively sensitive to increases in the number of antennas, especially on the receiver end, allowing the system to improve significantly its performance and cope even better with the increase of users. Thus the results of these 5G scenarios are positive and show the potential that SM and its variations have and the important role they can gain in future 5G systems.

In conclusion, it is shown why Spatial Modulation has such a rising interest and what advantages it brings to a system. Then its application in multiple users is explored and compared to the conventional approaches. After reviewing the existent approaches a possible solution for the requirements of this work is found and explored: ST-CDMA. The model is analyzed and its existing work is expanded by considering and analyzing several scenarios and important effects in the system, like the presence of MAI, the three detectors explored and the model of a channel with correlation. Then the ST-CDMA system is simulated for all the different scenarios described before in order to support the theoretical analysis done. The parameters that can improve the system and degrade the system are identified and their influence is explored in detail. Also the important effects on the system are tested and explored in order to describe their influence in the system, such as diversity and MAI. Then a more realistic channel is tested to give a more reliable information of its performance in a more realistic scenario and also an introduction to what kind of degradation this system may suffer in a possible real world implementation.

To end, a 5G environment is used to test this system and see how it performs and how it can fit in future 5G systems.

In future works, there is still much to explore in this subject. Starting with a possible real world implementation of the ST-CDMA system that can test everything that is tested in this work and see how this system actually behaves and how it copes with the consequent degradation. The MAI analysis can also be expanded and even possibly derive a bit error probability for the edge cases, for no spatial spreading and maximum spatial spreading by looking into a possible CDMA approach of the same. The tests can be performed for higher numbers of users and more 5G scenarios can be tested in order to complement the ones explored here and to test the system in different environments and working together with other 5G technologies. In sum, there is still much to explore in this subject and more importantly, there is a lot of potential and promise in Spatial Modulation for Multiple users, starting with the ST-CDMA solution presented here.

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