Universidade Autónoma de Lisboa

Departamento de Ciências e Tecnologias

Licenciatura em Engenharia Eletrónica e de Telecomunicações

Digital Underwater Acoustic Communication Simulator

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Unidade Curricular: Laboratório de Projeto

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Abstract

The Underwater acoustic communication is still a relatively new term both for students and for researchers. The two thirds of water that cover our planet continuous to have much to give, and the rising interest on the oceans will continue on the future. As the interest increase, increases too the will of the researchers in use the oceans as a means, a channel of communication that can be effectively used. As we will see, this is a challenge task, fist because electromagnetic waves cannot be used in the underwater environment, so insisted of electromagnetic waves this study is turned to the study of acoustic waves and its performance on the underwater environment. As will related in this paper there are various challenges that will be explained one by one. In the first chapter there will be discussed the theories and the underwater channel properties, as well the MIMO system that implies the use of more than one antenna to transmit and receive in a way that the signal we want to send reaches de destination with substantial performance. The last chapter will be more focused on the simulation of that communication channel and its results will become clearer.

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List of Abbreviations

UWA	Underwater Acoustic
BER	Bit Error Rate
DFE	Decision Feedback Equalizer
EGC	Equal Gain Combiner
FDE	Frequency Domain Equalization
IB-DFE	Iterative-Block Decision Feedback Equalization
MFB	Matched Filter Bound
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MMSE	Minimum Mean Square Error
MRC	Maximum Ratio Combiner
OFDM	Orthogonal Frequency Division Multiplexing
PSU	Practical Salinity Unit
QPSK	Quadrature Phase Shift Keying
SC-FDE	Single-Carrier Frequency Domain Equalization
SISO	Single Input Single Output
SIMO	Single Input Multiple Output
SOFAR	Sound Fixing and Ranging
ZF	Zero Forcing
ISI	Inter Symbol Interference
EMW	electromagnetic waves
PAPR	peak-to-average power ratio
SM	spatial multiplexing
MU-MIMO	user systems
BS	base station
CSI	channel state information
DSC	Deep sound channel

FFT	Fast Fourier Transformer
IFFT	Inverse fast Fourier transformer
QPSK	Quadrature Phase Shift Keying
TDD	Time division Duplex
AGC	automatic gain controller

Project Plan

The first step in creating this project was by beginning to make the plan of the activities and to distribute the work through the 3 elements of the group like showed in Figure 1

At first there were only 2 elements of the Group. Sergio and João. This is the first MS Project plan created.

	Modo da Tarefa	Task Name	Duração	Início	Término
		Simulador de Comunicações Sub-Aquáticas Digitais(Atualizacão)	**30 dias**	**Qui 17/05/18**	**Qua 27/06/18**
		Estudo de Propagação e suas componentes (Apoio: paper UMA)	2 dias	Qui 17/05/18	Sex 18/05/18
		Analise aos diversos tipos de simulação, AWGN.	2 dias	Sex 18/05/18	Seg 21/05/18
		Analise, atrasos e ganhos médios a considerar	2 dias	Sex 18/05/18	Seg 21/05/18
		Analise e cálculo de componentes	3 dias	Seg 21/05/18	Qua 23/05/18
		Calculo Small Scale (fastFading) e long scale(slow fadding)	3 dias	Qua 23/05/18	Sex 25/05/18
		Implementação do algoritmo de simulação utilizando as formulas acima descritas para simular um canal Rayleight (e Rice)	4 dias	Sex 25/05/18	Qua 30/05/18
		Implementação do codigo em ambiente SC-FDE	3 dias	Qui 31/05/18	Seg 04/06/18
		Implementação em Matlab usando a técnica Monte-Carlo, da simulação do canal de propagação.	2 dias	Seg 04/06/18	Ter 05/06/18
		Implementação em Matlab usando a técnica Monte-Carlo, da simulação do transmissor	3 dias	Ter 05/06/18	Qui 07/06/18
		Implementação em Matlab, a simulação do transmissor, propagação, receção e medição da Probabilidade de Erro de Bit em função da Relação Sinal Ruido (Eb/N0)	7 dias	Qui 07/06/18	Sex 15/06/18
		Elaboração do relatório e Documentação	4 dias	Sex 15/06/18	Qua 20/06/18

Figure 1 MS Project Print from early planning (march)

At the beginning our main issue was to study the underwater channel impairments, study the small scale and large scale and chose the algorithm to simulate our communications channel.

	Task Name	Duração	Início	Término
	Simulador de Comunicações Sub-Aquáticas Digitais	**75 dias**	**Seg 19/03/18**	**Sex 29/06/18**
	Recolha de dados bibliográficos	5 dias	Qua 28/03/18	Ter 03/04/18
	Estudo do canal de propagação. Caracteristicas fisicas: bandas de frequências possiveis, bandas acústicas e relação profundidade salinidade e frequência	9 dias	Qua 04/04/18	Sáb 14/04/18
	Estudo do canal de propagação Caracteristicas Fisico-quimicas, velocidade de propagação, variações temporais	9 dias	Qua 04/04/18	Sáb 14/04/18
	Estudo das imparidades do canal subaquático. Influência da agua do mar na FSPL, PPL (Propagation Path Lost)	12 dias	Dom 15/04/18	Seg 30/04/18
	Estudo das imparidades do canal subaquático, Influência da agua do mar no Shadowing	12 dias	Dom 15/04/18	Seg 30/04/18
	Estudo das imparidades do canal subaquático. Influência da agua do mar no Multipath Fading	12 dias	Dom 15/04/18	Seg 30/04/18
	Analise aos diversos tipos de simulação, AWGN.	5 dias	Ter 01/05/18	Sáb 05/05/18
	Analise aos diversos tipos de simulação, Rayleight fading (Model Fading) e Model Hata Okumura (comparação de dados)	5 dias	Ter 01/05/18	Sáb 05/05/18
	Implementação em Matlab usando a técnica Monte-Carlo, da simulação do canal de propagação.	30 dias	Dom 06/05/18	Qui 14/06/18
	Implementação em Matlab usando a técnica Monte-Carlo, da simulação do transmissor	30 dias	Dom 06/05/18	Qui 14/06/18
	Implementação em Matlab, a simulação do transmissor, propagação, receção e medição da Probabilidade de Erro de Bit em função da Relação Sinal Ruido (Eb/N0)	30 dias	Dom 06/05/18	Qui 14/06/18
	Elaboração do relatório e Documentação	11 dias	Sex 15/06/18	Sex 29/06/18

Figure 2 MS Project from a planning in May

At this point David has joined our group, and there was a need to elaborate another MS Project like pictured in Figure 2. At this point the group had figured that the Small scale was the model to use, and began study on the Rice fading distribution and Rayleigh fading distribution. At this point the first part of our paper was already developed, which correspond to the chapter 2 "Underwater Acoustic Channel Characteristics". From this point (end of May) until the end of august the main focus was spent in elaborating the results section. The results section corresponds the part of choosing the algorithm and the transmission techniques, as well as making the plots, commenting the plots, analyzing the results and elaborating this paper.

Project Requirements

The basic project requirements include search for specific software. The choose was MATLAB, like pictured in Figure 3. With this software and the specific algorithm, we could simulate the channel characteristics as well design plots and more.

Search for specific literature, which was scarce since the topic underwater acoustic communications is still relatively new and unstudied.

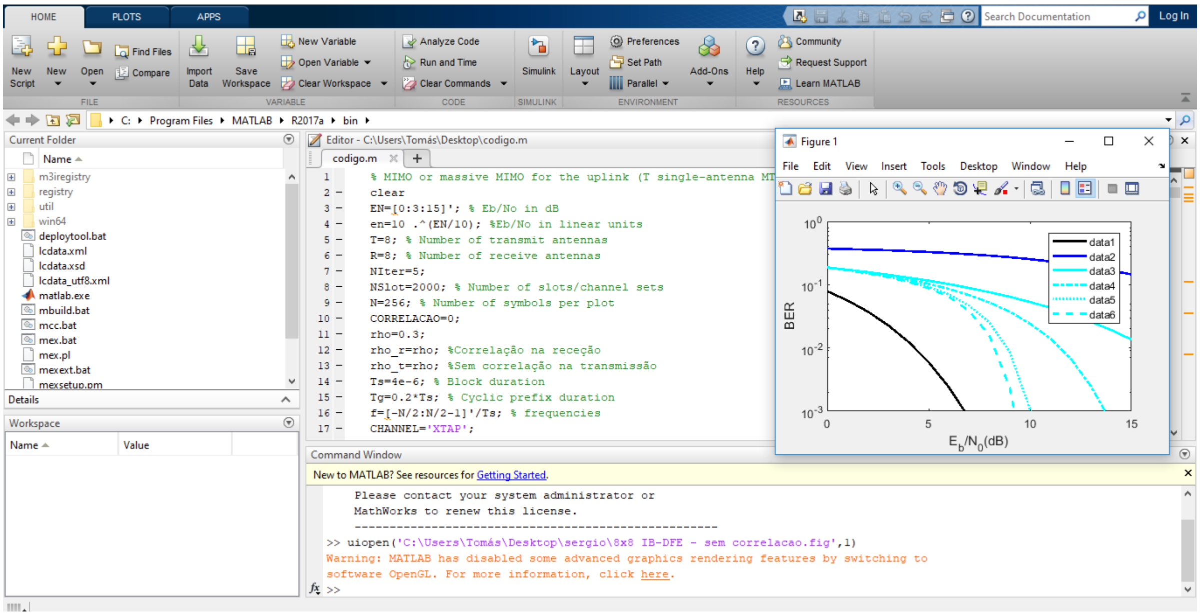

Figure 3 MATLAB creating an uncorrelated plot

Project Initiation

Like said before the project initiated by characterizing the channel impairments and choosing which system (Small or large scale) we would use.

The project initiation includes installation of MATLAB, and some specific literature that was researched in the project requirements. The book that catalyst and make the group start the project was the Book "OFDM for Underwater Acoustic Communications".

Project execution

The project execution consists mainly in running the correct algorithm and plotting the necessary results as well as commenting them. For that an exhaustive search both on online papers as well online thesis and other articles was made, that could help the group on creating this paper. The algorithm was presented us from our tutor. The group only had to alter some parts of the code in order to change some parameters that made possible the creation of the desired plots. Only after that the rest of the work could be concluded.

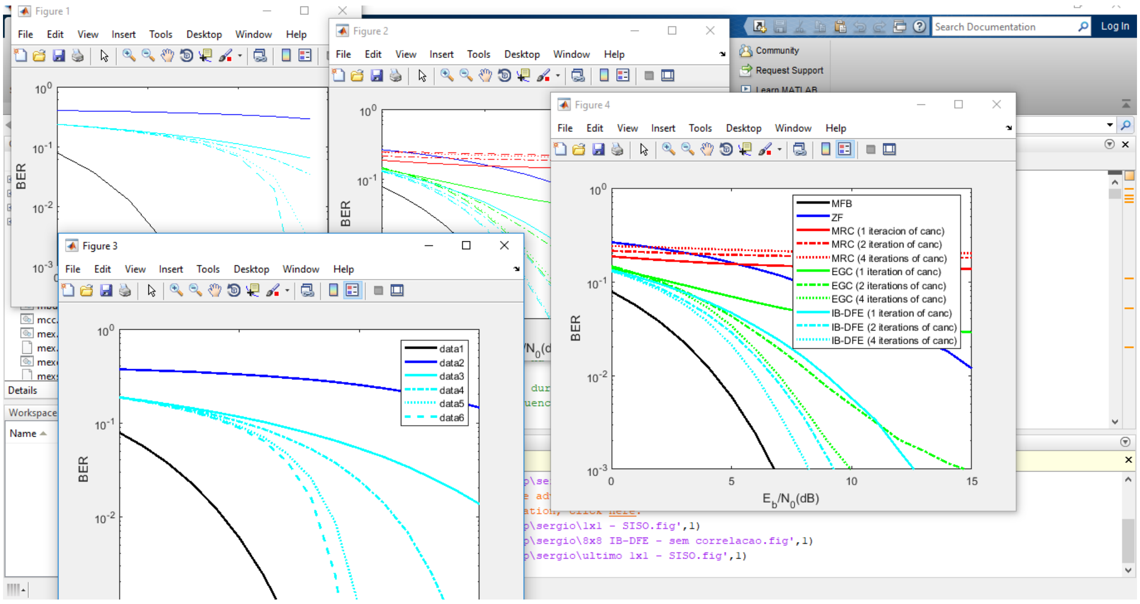

Figure 4MATLAB with 4 diverse plots

1. Introduction

The planet earth is constituted to its surface by 2/3 of water and has always been throughout the history of humanity a target of great interest and curiosity. Aristotle in 400 BC stated that the sound could be both heard underwater as well as outside. In 1490 Leonardo da Vinci wrote "If you stop a ship and put one end of a long tube in the sea water and the other end in the ear you can hear other ships that are at a long distance." In 1826 Charles Sturm and Daniel Colladon made the first reliable measure of the speed of sound in water in Lake Geneva in Switzerland. But it was not until the beginning of the 20th century that the first practical application was seen. The headlamp vessels were fitted with a sound emitter that circulated in the water. Ships battling a thunderstorm and seeing the lighthouse ship could perceive the distance to these lighthouse ships because of the difference between sound propagation by air and water. In the first great war (1914-1918) considerable progress was made in underwater acoustic communication mainly in echo "echo ranging" communication in which the sound was emitted either at extremely low frequencies or high frequencies, the sonar principle that were put into practice by Constantin and Chilowski [1] But only during World War II did the step to understand how the sound propagated in the water. At that time, it was understood that the refraction of the sound in the water occurred due to 3 properties of the aquatic environment: Temperature, salinity and pressure as shown in Figure 5

In 1945, at the end of the second major war, the North American Navy created the first underwater telephone that allowed communication between ships and submarines using Suppressed Carrier Single Side Band Amplitude Modulation also known as SSB that operated at a frequency of 8.0875 Hz. frequency because the frequency of the quartz crystal is 16,175 Hz, that is, 2x bandwidth.

There are 3 main motivations that we established before the elaborations of this paper. The first one being the intensive study of the characteristics of the underwater channel and all its elements. The second to get into a conclusion whereas is it viable or not to make an acoustic underwater communications system, and on third point if possibly create a simulation where we can compare the diverse results. That part is well explained in chapter 4 where the diversity properties of the MIMO system open doors to compare the various diversity transmission techniques. And on the conclusion, all our results, thoughts and experiences are shared.

2. Underwater Acoustic Channel Characteristics

2.1. Introduction

Given the complexity of underwater acoustic medium and the low propagation speed of sound in water, the underwater acoustic channel is commonly regarded as one of the most challenging channels for communication. As there will be shown later, the group have bet on the MIMO underwater system in an effort to have better performance results. Aldo the speed of the underwater acoustic waves reaches speeds greater than in the air, passing the speed of sound, that speed is not generally equal to all marine environments. In shallow waters the speed will have one value, and in deep waters the speed will have other value (higher in most cases)[2]. Underwater communications are getting more attention in the last years, and only when we have a fully understanding of the underwater acoustic channel characteristics, can we gradually make the underwater acoustic transmission system to match with the real marine environment, so as to achieve better performance.

2.2. Speed of sound

The extremely slow propagation speed of sound through seawater is an important factor that differentiates it from electromagnetic propagation. The speed of sound in water depends on the water properties of temperature, salinity and pressure; illustrative plots of the three parameters as functions of water depth are shown in Figure 5. A typical speed of sound in water near the ocean surface is about $1520\ m/s$, which is more than 4 times faster than the speed of sound in air, but five orders of magnitude smaller than the speed of light.

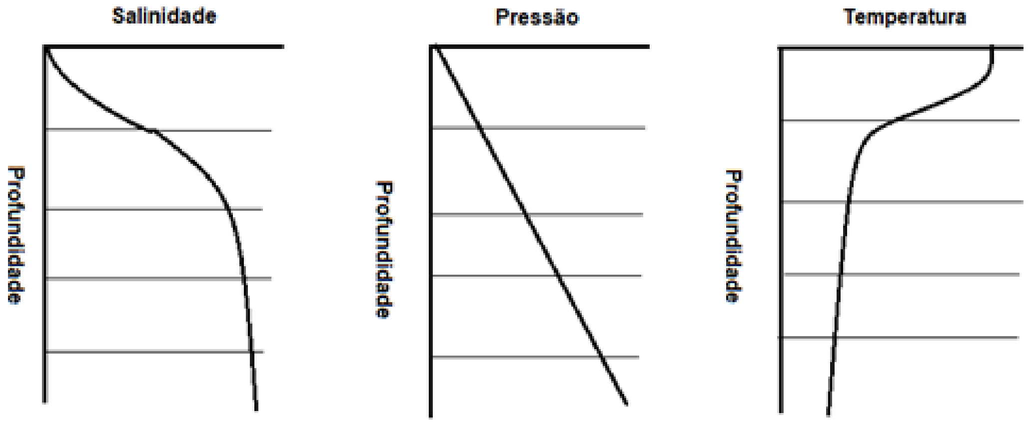

Figure 5 Shows the beave (speed) of the acoustic waves when exposed to Salinity, pressure and temperature

At the surface of the water the speed of sound travels at a speed of 1520m / s which corresponds to 5472km / h, while in air the sound travels at a speed of 331m / s corresponding to a speed of 1192 km / h, speed of the light responsible for the propagation velocity of the electromagnetic waves circulates at a 1079252848km / h. When we use acoustic waves as a means of underwater communication, we understand that propagation velocity is going to be the first dilemma we will encounter[3]

The speed of sound in water grows with increasing water temperature, increasing salinity and increasing depth. Approximately, the sound speed increases 4.0 m/s for water temperature rising $1°C$. When salinity increases one PSU, the sound speed in water increases to 1.4 m/s. As the depth of water (therefore also the pressure) increases to 1 km, the sound speed increases roughly to 17 m/s.

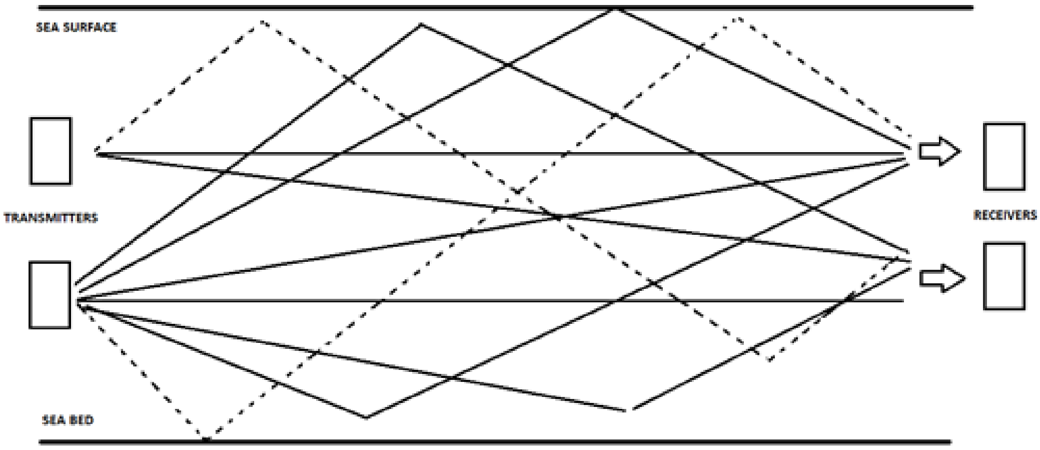

Figure 6 Multiple paths refractions behave in shallow water

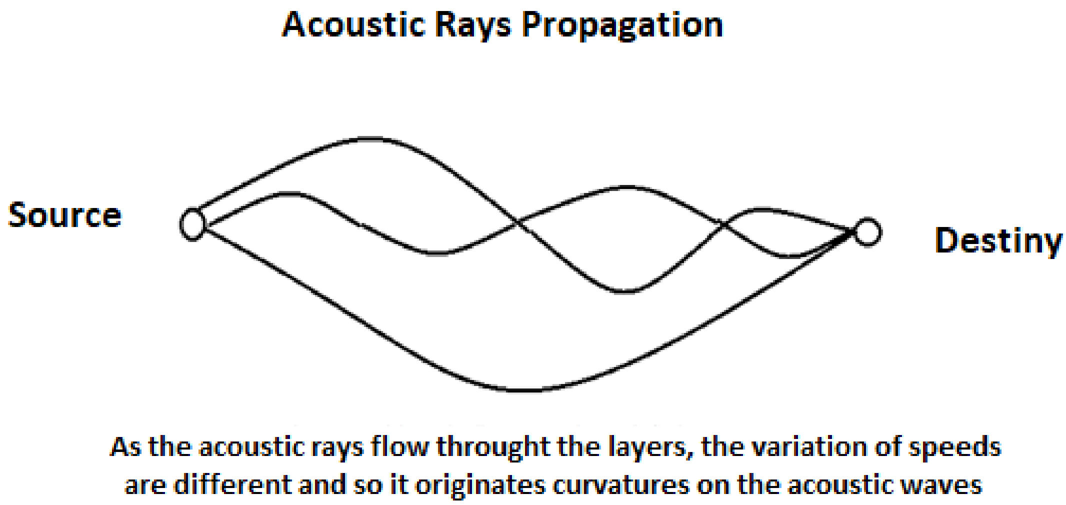

Figure 7 Multiple paths of acoustic rays in deeper water environment

According to Snell's law, a ray of sound bends toward the direction of low propagation speed. In shallow water, the sound speed is usually constant throughout the water column. The acoustic signal usually propagates along straight lines, as illustrated in Figure 6. The sound speed profile of deep-water channels diversifies the sound propagation paths. In particular, notice that there is a minimal sound speed at a particular water depth (named the channel axis) between the permanent thermocline layer and the deep isothermal layer. For an acoustic signal transmitted at the channel axis, a ray of sound will be bent downward when propagating to the permanent thermocline layer and bent upward when

propagating to the isothermal layer, thus being trapped within the two layers without interacting with the sea surface and bottom, as illustrated in Figure 7
This type of channel is called the deep sound channel (DSC), and the corresponding propagation is called SOFAR[4]. An interesting phenomenon of SOFAR propagation is that a path traveling a longer distance could have a shorter travel time. Due to the refraction caused by inhomogeneous sound speed, there exist both shadow zones and convergence zones in the acoustic field, where a shadow zone denotes an area which cannot be penetrated by direct sound paths, and a convergence zone denotes in area which is insonified intensively by a bundle of sound paths.

2.3.Attenuation

A typical characteristic on an acoustic channel is that the overall path loss depends on the frequency. In an underwater acoustic channel, the attenuation is set by the absorption loss and the spreading loss. The first one corresponds to the conversion of acoustic energy in heat, and it depends on the chemical properties of sea water. The absorption loss in sea water is frequency dependent [17].
In conclusion, the underwater absorption, when dealing with high-frequency signals has strong impact on the attenuation as they traverse the channel. The spreading loss, on other hand, refers to the spreading of energy over an expanding volume as signals propagate in the medium. It can be cylindrical, typically seen in shallow waters, or it can be spherical, mostly observed in deep waters.

2.4.Multipath

For multipath, the effects of multipath in shallow waters are mainly reflections in the surface, in the bottom and in possible objects that are in the scene. These reflections are the responsible for causing multiple arrivals to the receiver. It can be presented generally

$$h(t) = \sum_{p=0}^{P} h_p \delta(t - \tau_p)$$

Where h_p are the paths amplitudes and can be considered as a low pass filter due to channel attenuation properties. Multiple arrivals are the roots of fading since interference of different paths can be constructive or destructive. Simplified models for the fading are commonly accepted in UWA channels, like Rayleigh or Rician.

2.5.Time Varying Multipath

An acoustic wave transmission can reach a certain point through multiple paths. For shallow water transmissions, where the distance is much greater than the depth, the reflections of the wave at the bottom and at the surface generate delayed copies of the transmitted signal. For deep water transmissions, the reflections at the bottom and the surface can be disregarded, and variations in the velocity profile of the sound also produce multiple paths. In addition, multiple courses may vary over time. The two main factors that cause these variations are: changes in the environment and the Doppler effect.

2.6. Doppler Effect

The temporal variation of the multipath is a challenging problem when working with the underwater acoustic channel and the Doppler effect is its main cause in the underwater environment.

Doppler effect is of extreme importance when dealing with multicarrier communications. Little frequency variations can cause an important degradation in performance. Usually, frequency shifts are corrected with hardware via resampling due to the cost of the operation, while Doppler spectrum estimation can be done in a low-complexity manner once having the sampled signals.

Doppler shift, this effect, caused by the relative motion of two bodies, is of special importance in underwater channels. The low speed of sound, which is about $c = 1500\ m/s$ and varying slightly with the speed prole, is the principal cause of this effect. Waves and currents make both the transmitter and receiver elements to be in continuous movement even if they are still on the bottom.

Doppler spectrum, the models behind Rayleigh or Rician fading assume that many waves arrive each with its own random angle of arrival (thus with its own Doppler shift), which is uniformly distributed within $[0:::2\pi]$, independently of other waves. This allows to compute a probability density function of the frequency of incoming waves. If we look at the Rayleigh fading channel in the time domain we find that the autocorrelation function of a specific tap (single arrival) is a first order Bessel function which depends of the maximum Doppler spread.

2.7. Propagation Loss

There are three primary mechanisms of energy loss during the propagation of acoustic waves in: absorptive loss, geometric spreading and scattering loss.

2.7.1. Frequency-Dependent Absorption

During propagation, wave energy may be converted to other forms and absorbed by the medium. The absorptive energy loss is directly controlled by the material imperfection for the type of physical wave propagating through it. For EM waves, the imperfection is the electric conductivity of seawater. For acoustic waves, this material imperfection is the inelasticity, which converts the wave energy into heat.

2.7.2. Geometric Spreading Loss

Geometric spreading is the local power loss of a propagating acoustic wave due to energy conservation. When an acoustic impulse propagates away from its source with longer and longer distance, the wave front occupies larger and larger surface area. Hence, the wave energy in each unit surface (also called energy flow) becomes less and less. For the spherical wave generated by a point source, the power loss caused by geometric spreading is proportional to the square of the distance. On the other hand, the cylindrical waves generated by a very long line source, the power loss caused by geometric spreading is proportional to the distance.

2.7.3. Scattering Loss

Scattering is a general physical process in which the incident wave is reflected by irregular surfaces in many different directions. The sound scattering in underwater environments can be attributed to the nonuniformities in the water column and interactions of acoustic waves with nonideal sea surfaces and bottoms. Obstacles in the water column include point targets such as fish and plankton, and scattering volumes such as fish bubble clouds. The corresponding scattering loss depends on the acoustic wavelength and target size. In particular, the scattering loss increases as the acoustic wavelength decreases. The scattering property of sea surface and bottom is mainly determined by the interface roughness. High interface roughness induces large spatial energy dispersion. The roughness of sea surface is due to the capillary waves caused by wind, the amplitude of which ranges from centimeters to meters (e.g., swells).

In real scenarios, the two types of spreading processes coexist. The types of spreading losses occur when the acoustic wave interacts with the surface of the sea and the clouds of bubbles. In addition, wind-generated waves become mobile reflectors of the acoustic waves, thus introducing energy dispersion not only in the spatial domain, but also in the frequency domain.

2.8. Noise and External Interference

Noise is used to denote a signal that distorts the desired ones. Depending on applications, underwater acoustic noise consists of different components. Specific to the underwater acoustic communication system, the acoustic noise can be grouped into two categories: ambient noise and external interference.

Ambient noise is one kind of background noise which comes from a myriad of sources. The common sources of ambient noise in water include volcanic and seismic activities, turbulence, surface shipping and industrial activities, weather processes such as wind-generated waves and rain, and thermal noise [266]. Due to the multiple sources, ambient noise can be approximated, as Gaussian, but it is not white. The level of underwater ambient noise may have large fluctuations upon a change with time, location or depth. For short-range acoustic communication, the level of ambient noise may be well below the desired signal. For long-range or covert acoustic communication, the noise level would be a limiting factor for communication performance.

External interference is an interfering signal which is recognizable in the received signal. Corresponding sources include marine animals, ice cracking, and acoustic systems working in the same environment. Sonar operations could occasionally happen at the same time with communications, creating an external interference which is highly structured [422]. Relative to ambient noise, external interferences are neither Gaussian nor white. The presence of this kind of noises may cause highly dynamic link error rate or even link outage.

3. Underwater Acoustic Communication System

3.1. Introduction

The ever-increasing demand for bandwidth, efficiency, spatial diversity and performance of underwater acoustic (UWA) communication has opened doors for the use of Multi-Input Multi-Output (MIMO) as will be referred in the next chapter.

Underwater communication is predominantly by acoustic waves and characterized as time-varying, multipath environment. However, the attenuation and delay associated with the acoustic channel mitigates the range and data rate available. A Channel simulator were required to support the deployment of these study which relies on the characterization of the underwater acoustic channel. Acoustic communication is suitable at low frequency. Thus, modeling of multipath propagation especially Doppler Effect plays an important role. In this chapter there will be discussed some important questions that must be answered to develop a reliable underwater acoustic communication system, such as the choose between small scale and large scale, a briefly definition of the various types of fading and the reflections and refractions of the underwater acoustic rays behave, block transmission techniques (SC-FDE and OFDM) [5] and a briefly explanation of the QPSK that have been used in this study to simulate the characterization of the communication channel. Finally, there will be presented an example of a MIMO system where will be calculated the number on antennas and deduced the space between them.

3.2. Small Scale and Large Scale

Based on estimations and studies there was a need to choose between the use of a Small Scale or a Large-Scale fading model on underwater acoustic communications. Large scale fading or as sometimes referred “Shadowing” are related to large distances effects so, its affect appears clearly in case of the displacement of either the Transmitter or the Receiver. The clearest example for this case is the RF reception for a Car or a moving vehicle where the signal is influenced by Multipath phenomena where the transmitted signal is received from more than one path, and so the Large-scale fading uses a normal log distribution to calculate the fading of the ray elements. However Small-scale fading is concerned about very small changes in the position of Transmitter or receiver in order of the wavelength as this affect greatly the received frequency thanks to the doppler effect. Therefore, the small-scale fading uses a rice distribution.

Rice Distribution is a model for radio propagation anomaly or interference caused by partial cancellation of a radio signal by itself. The signal arrives at the receiver by different paths, and we can assume that it suffers of multipath interference), and at least one of the paths is changing, lengthening or shortening. Rice fading happens when one of the paths, typically a line of sight signal or some strong reflection signals, is much stronger than the others and the amplitude gains are characterized by a Rician distribution. In the rice Model when there is no possibility of a line-of-sight signal, there is a need to use the Rayleigh fading. Basically, the Rician distribution degenerates to a Rayleigh distribution when the dominant component fades away[6].

We can assume than that the Rice Model is when exists a Line-of- sight signal component and when that is not possible meaning there is no line-of-sight there is a need to add the Rayleigh fading component like is indicated in the Figure 8

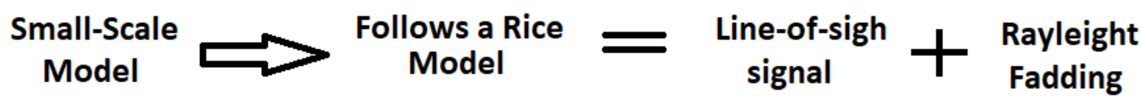

Figure 8 The components of the Rice Model

Rayleigh fading is the specialized model for fading when there is no line-of-sight signal, and is sometimes considered as a special case of the more generalized concept of Rician fading. In Rayleigh fading, the amplitude gain is characterized by a Rayleigh distribution. The requirement that there be many scatters present means that Rayleigh fading can be a useful model in heavily built-up city centers where there is no line of sight between the transmitter and receiver and many buildings and other objects attenuate, reflect, refract, and diffract the signal.

The study presented here focus in acoustic underwater communications and after this small introduction of the small scale and large-scale systems there is a sense to use the small scale, first because the small scale is a model where there is a Line-of-sight signal, and there are not large variations or large objects in the line of sight path, and it is more indicated to large areas where there are not obstacles between the transmitter and the receiver, and that is exactly what happens in the underwater environment. When the dominant component fades away thanks to the reflect, refract, and diffract of the acoustic waves, Rician distribution degenerates to a Rayleigh fading distribution.[7]

3.3. The different components of the Fading

Fading is generally a signal loss either in amplitude or phase due to sudden changes in Channel response. The time variation of received signal power due to changes in transmission medium or paths is known as fading. fading depends on atmospheric conditions such as rainfall, lightening etc. In the underwater environments fading can be worsen if meteorological conditions such as storms, thunderstorms or waves. Generally fading depends on obstacles over the path which are varying with respect to time. These obstacles create complex transmission effects to the transmitted signal. Figure 9 shows all types of fading possible that will be explained latter.

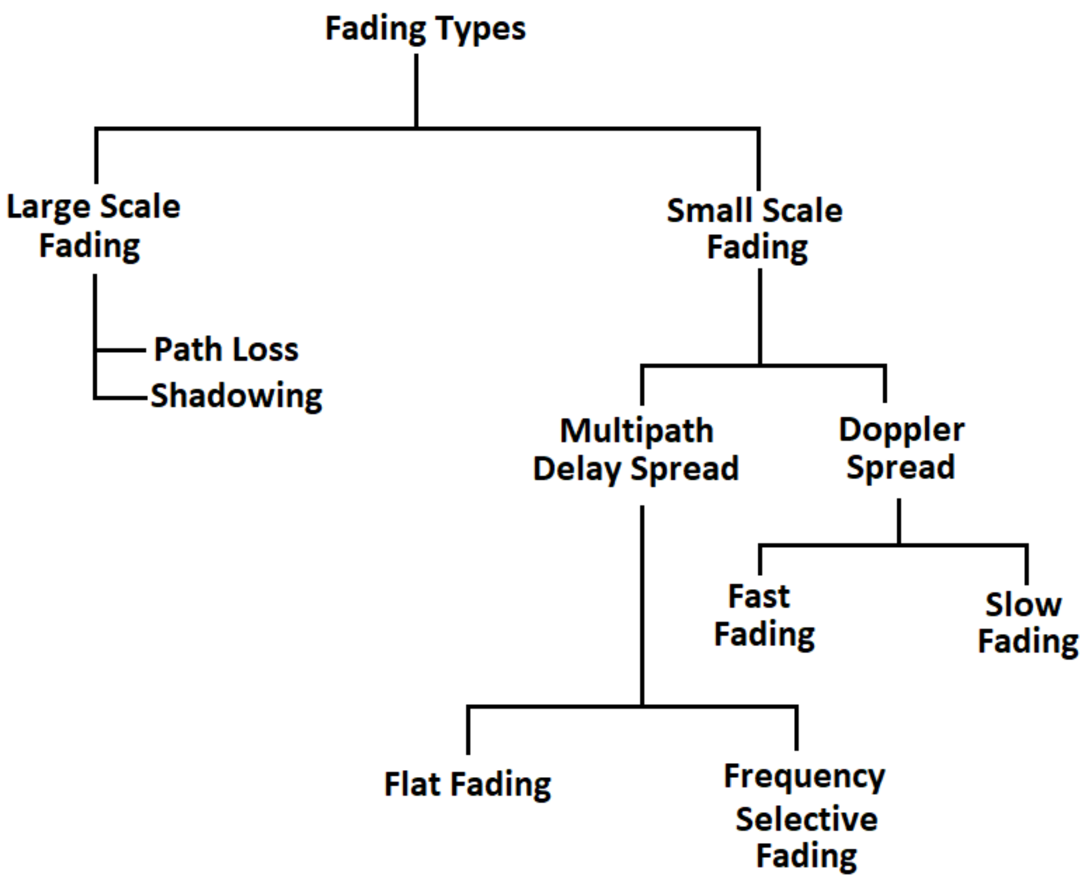

Figure 9 A scheme that collects all the existing types of fading

Fading signals occur due to reflections from ground and surrounding buildings as well as scattered signals from trees, people and towers present in the large area. In the underwater environment, algae fish, the sand plankton and others may create scattering in the acoustic signals.

There exist different channel impairments and position of transmitter/receiver and therefore there are 2 types of fading in wireless communication system. Large Scale Fading: Includes path loss and shadowing effects. Small Scale Fading: is divided into two categories. multipath delay spread and doppler spread. The multipath delay spread is further divided into flat fading and frequency selective fading. Doppler spread is divided into fast fading and slow fading.

3.3.1. Large Scale

Large scale fading happens when an obstacle comes in between transmitter and receiver. This interference causes sa large amount of signal strength reduction.

3.3.2. Path Loss

The free space path loss can be expressed as follows.

$$P\_t/P\_r = \{(4 \times \pi \times d)^\wedge 2/\lambda^\wedge 2\} = (4 \times \pi \times f \times d)^\wedge 2/c^\wedge 2$$

Where,

Pt = Transmit power

Pr = Receive power

λ = wavelength

d = distance between transmitting and receiving antenna

c = speed of light i.e. 3×10^8

From the equation it implies that transmitted signal attenuates over distance as the signal is being spread over larger and larger area from transmit end towards receive end.

3.3.3. Shadowing effect

Shadowing is the effect that the received signal power fluctuates due to objects obstructing the propagation path between transmitter and receiver. These fluctuations are experienced on local-mean powers, that is, short-term averages to remove fluctuations due to multipath fading.

3.3.4. Small Scale Fading

Small scale fading is when rapid fluctuations of received signal strength over very short distance and short time period.

Based on multipath delay spread there are two types of small scale fading Flat fading and frequency selective fading. These multipath fading types depend on propagation environment.

3.3.5. Flat Fading

The wireless channel is said to be flat fading if it has constant gain and linear phase response over a bandwidth which is greater than the bandwidth of the transmitted signal. In this type of fading all the frequency components of the received signal fluctuate in same proportions simultaneously. It is also known as non-selective fading.

The effect of flat fading is seen as decrease in SNR. These flat fading channels are known as amplitude varying channels or narrowband channels. [8]

3.3.6. Frequency Selective Fading

It affects different spectral components of a radio signal with different amplitudes. Hence the name selective fading.

Based on doppler spread there are two types of fading: fast fading and slow fading. These doppler spread fading types depend on mobile speed i.e. speed of receiver with respect to transmitter.

3.3.7. Fast fading

Fast fading is represented by rapid fluctuations of signal over small areas. When the signals arrive from all the directions in the plane, fast fading will be observed for all directions of motion. Fast fading occurs when channel impulse response changes very rapidly within the symbol duration, and have the following characteristics

-High doppler spread

-Symbol period > Coherence time

-Signal Variation < Channel variation

This parameter results into frequency dispersion or time selective fading due to doppler spreading. Fast fading is result of reflections of local objects and motion of objects relative to those objects. The received signal in fast fading, is the sum of numerous signals which are reflected from various surfaces. This signal is the sum or difference of multiple signals which can be

constructive or destructive based on relative phase shift between them. Phase relationships depend on speed of motion, frequency of transmission and relative path lengths.

Fast fading distorts the shape of the baseband pulse. This distortion is linear and creates ISI (Inter Symbol Interference). Adaptive equalization reduces ISI by removing linear distortion induced by channel.

3.3.8. Slow Fading

Slow fading is result of shadowing by buildings, hills, mountains and other objects over the path. And is characterized by the following details.

-Low Doppler Spread

-Symbol period <<Coherence Time

-Signal Variation >> Channel Variation

Slow fading results in a loss of SNR. Error correction coding and receiver diversity techniques are used to overcome effects of slow fading.

3.4.Waves behave, Refractions and reflections in the (UWA)

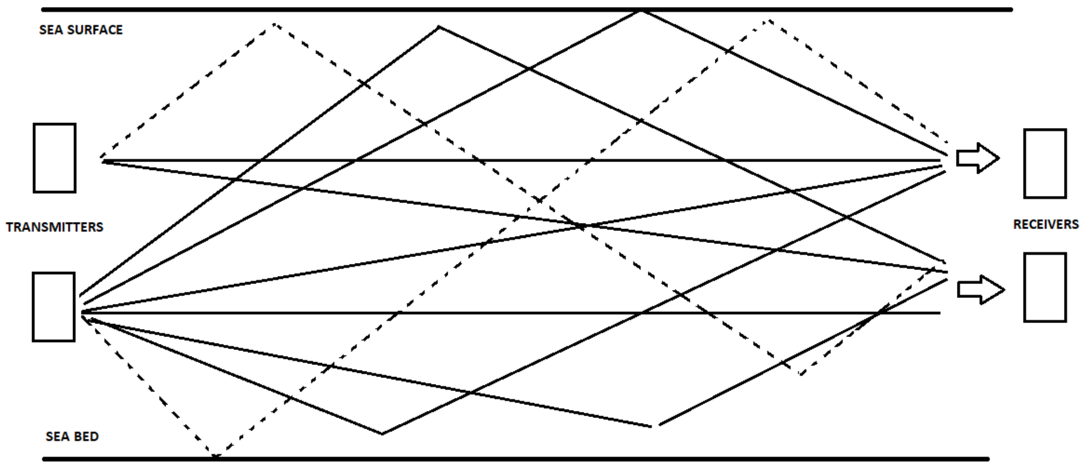

Figure 10: Acoustic wave dispersion scheme in a not deeper water

Different than the electromagnetic waves (EMW) the acoustic waves have a different behavior in un underwater environments, and can even change as deeper they go. On surface water with low temperature, the behavior of the rays of sound, usually follows a pattern of constant propagation as if it were of refractions as shown in Figure 10. But as the depth increases and the sounds propagate in the several layers rays of sound follow a behavior described according to the Law of Snell's, in which a ray of sound curves in the direction of the low speed of propagation, the lower the speed of propagation of the sound, the greater curvature will have the radius of sound. As the variation of the speed of sound also varies the curvature of the sound ray. In an acoustic sound signal, transmitted at 1000 meters depth, where the velocity is smaller, will make a downward curvature when transmitted to the Permanent thermocline layer and curvature upwards when transmitted to the Deep isothermal layer as is shown Figure 11.

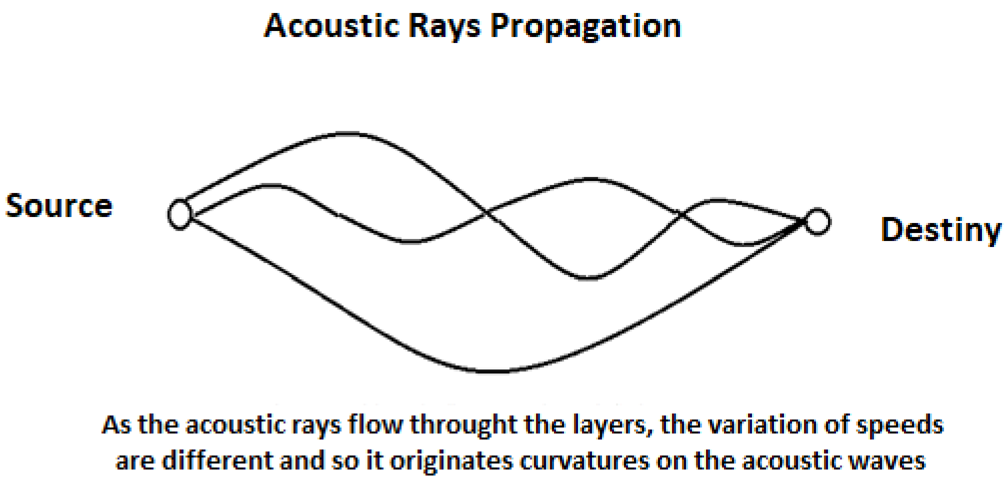

Figure 11 Multiple paths of acoustic rays in deeper water environment

3.5.Multipath rays choose

After figuring out which model should be used (in this study Small Scale) and its details, there was much debate at how much rays should be simulated. The authors started using a small number of rays in the beginning of the work, but the results were ambiguous, and so there was urge to increase the number of rays. The authors opted later to use 20 rays with uncorrelated and correlated Rice fading on the simulation to be able to make a channel more pessimist in rays path and between the transmitter and receiver and also in post processing of the data. The channel is considered invariant throughout the transmission period of a block, although it varies from block to block. The duration of the useful part of the blocks (N symbols) is 1 μs and the cyclic prefix has a duration of 0.125 μs

3.6.OFDM and SC-FDE

Orthogonal frequency-division multiplexing (OFDM) is a frequency-division multiplexing (FDM) scheme utilized as a digital multi-carrier modulation method. A large number of closely-spaced orthogonal sub-carriers are used to carry data. The data is divided into several parallel data streams or channels, one for each sub-carrier. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation or phase shift keying) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

OFDM has developed into a popular scheme for wideband digital communication, whether wireless or over copper wires, used in applications such as digital television and audio broadcasting, wireless networking and broadband internet access.

The primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions for example, attenuation of high frequencies in a long copper wire, narrowband interference and frequency-selective fading due to multipath without complex equalization filters. Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal. The low symbol rate makes the use of a guard interval between symbols affordable, making it possible to handle time-spreading and eliminate intersymbolic interference (ISI). This mechanism also facilitates the design of single-frequency networks, where several adjacent transmitters send the same signal simultaneously at the same frequency, as the signals from multiple distant transmitters may be combined constructively, rather than interfering as would typically occur in a traditional single-carrier system.

SC-FDE can be viewed as a linearly pre-coded OFDM scheme, and SC-FDMA can as a linearly pre-coded OFDMA scheme, henceforth LP-OFDMA. Or, it can be viewed as a single carrier multiple access scheme. One prominent advantage over conventional OFDM and OFDMA is that the SC-FDE and LP-OFDMA/SC-FDMA signals have lower peak-to-average power ratio (PAPR) because of its inherent single carrier structure. It has been proven that perfect constant modulus transmission is achievable.

Just like in OFDM, guard intervals with cyclic repetition are introduced between blocks of symbols in view to efficiently eliminate time spreading (caused by multi-path propagation) among the blocks. In OFDM, Fast Fourier transform (FFT) is based on the receiver side on each block of symbols, inverse fast Fourier transformer (IFFT) on the transmitter side. In SC-FDE, both FFT and IFFT are applied on the receiver side, but not on the transmitter side. In SC-FDMA, both FFT and IFFT are applied on the transmitter side, and also on the receiver side.

In OFDM as well as SC-FDE and SC-FDMA, equalization is achieved on the receiver side after the FFT calculation, by multiplying each Fourier coefficient by a complex number. Thus, frequency-selective fading and phase distortion can be combated. The advantage is that FFT and frequency domain equalization requires less computation power than conventional time-domain equalization.

3.7.Digital Modulation Techniques QPSK

Digital modulations provide more information capacity, high data security, quicker system availability with great quality communication. On the other hand, digital modulation techniques have a greater demand, for their capacity to convey larger amounts of data than analog modulation techniques.

QPSK stands for Quadrature Phase Shift Keying and is a modulation used for digital signals. Modulation is a process of shifting frequencies, shifting the central frequency of a signal to a different one. Demodulation is the opposite, brings the frequency to the original frequency. There are various reasons on why shift the central frequency of a signal, for example to reduce the antenna size or eliminate bands that contain interference QPSK is one modulation technique that allows the change of central frequency of a signal.

The way we modulate is by imposing the message into one of the properties of a higher frequency signal usually called the carrier signal.

In QPSK the property that is changed is the phase, every two bits of a digital message which is transmitted is encoded in the carrier wave by changing its phase.

Any digital signal when taken as a pair of bits will have one the combination 00,01,10,11.

The phase to symbol mapping could be different, meaning one could transmit carrier with 45-degree phase shift for 00. As long as the phase between consecutive of the 4 symbols differ by 90. QPSK will modulate as followed and represented in Figure 12.

11 --> Carrier signal with a 45 degree phase shift,
00 --> Carrier signal with a 135 degree phase shift
01 --> Carrier signal with a 225 degree phase shift
10 --> Carrier signal with a 315 degree phase shift

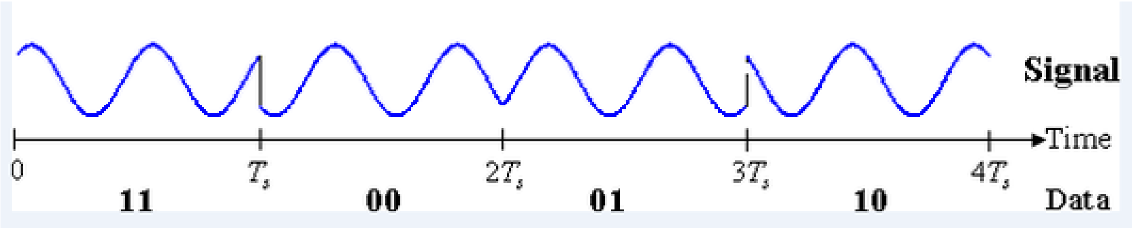

Figure 12 QPSK modulation Scheme

4. MIMO Systems

4.1. Introduction

Wireless propagation channels have been studied for several decades and are analyzed by hundreds of specialists. Thanks to that the results are a large number of channels models. The growing search for greater capacity in the wireless systems was the catalyst that resulted in various transmission techniques, including MIMO and Massive MIMO technology.

“In communications, MIMO is a technique that makes possible increase the capacity and reliability of a radio link using multiple transmit and receive antennas to exploit the spread of multiple paths. MIMO beginnings start at a 1970s research work on multichannel digital transmission systems and crosstalk between pairs of wires in a cable package”(A.R. Kaye and D.A. George, 1970).

Nowadays, it has become an essential element of wireless communication standards, including IEEE 802.11n (Wi-Fi), IEEE 802.11ac (Wi-Fi), HSPA + (3G), WiMAX (4G) and Long-Term Evolution (4G LTE).

MIMO technologies overcome the shortcomings of traditional methods through the use of spatial diversity. Data can be transmitted through N transmit antennas to N receive antennas supported by the receiving terminal. Such systems are used in wireless communication to improve capacity and bit error rate (BER). BER can be improved thanks to the spatial diversity obtained thought the large number of received antennas[9].

Significant increase is offered in data throughput and bandwidth without additional bandwidth or transmission power. These features are essential for the next generation of telecommunication systems.

Rayleigh fading was considered as the propagation channel for verification. Diversity gain and spatial multiplexing (SM) are the two main advantages of MIMO systems that are used to study the effect of bit rate increase with increasing number of transmitting and receiving antennas. In the MIMO system, we mainly need to take spatial correlation into account. The spatial correlation effect should be minimized to obtain much better system performance.

4.2.MIMO

In communications, MIMO makes possible increase the capacity and reliability of a radio link using multiple transmit and receive antennas to exploit the spread of multiple paths. The "MIMO" term, referred the mainly theoretical use of multiple antennas in both the transmitter and the receiver. In modern usage, "MIMO" refers specifically to a practical technique for sending and receiving multiple data signals on the same radio channel, at the same time via multiple-path propagation. In Figure 13, we can see what is a channel configuration of 2 transmit antennas and 2 receive antennas in a MIMO scheme. The MIMO is different from the intelligent antenna techniques developed to improve the performance of a single data signal, such as beamforming and diversity [10]. The MIMO technique applied in cellular systems brings four big improvements:

- increased data rate: due to use of more antennas, more independent data streams can be transmitted and more terminals can be attained simultaneously;

- improved reliability: increasing the number of transmit antennas creates more distinct paths for the radio signal to propagate, this is a good idea in the transmission because there are more rays of signal that will reach the receptor, and also good at the receiver because there are more rays that will reach the antennas and thus creating diversification;

-Enhanced energy efficiency: the base station can concentrate its emitted energy rays in the spatial directions, where it knows that the terminals are localized;

-Low interference: The base station may intentionally avoid transmitting to directions where scattered interference would be harmful;

MIMO wireless technology is maturing and incorporated into recent and evolving wireless broadband standards. The more antennas the base station (or terminals) are equipped with, and the more degrees of freedom the propagation channel can provide, the better the performance in all four aspects above. However, the number of antennas used today is modest. The most modern standard, the LTE-Advanced, allows up to 8 antenna ports in the base station and the handsets being built today have far fewer antennas than that []. The gains in multiuser systems (MU-MIMO) are even more impressive because such systems offer the ability to simultaneously transmit multiple users and the flexibility of selecting which users are scheduled to be received at any time[11]

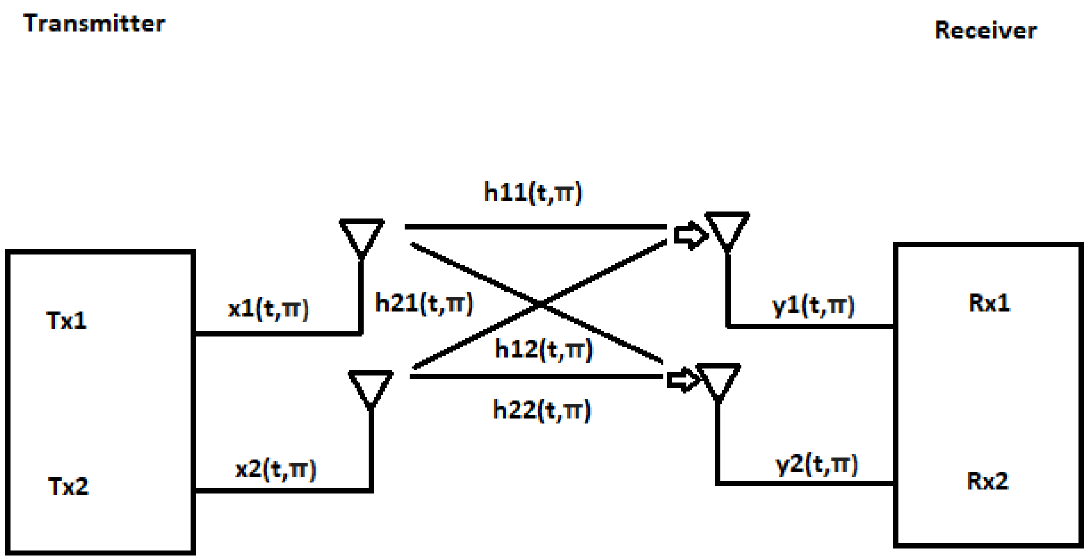

Figure 13 - A typical T=2 and R=2 MIMO system

But there are also disadvantages in the MIMO system, such as the greater complexity of the analog and digital domains. For point-to-point links, the complexity in the receiver is usually a greater concern than that of the transmitter. For example, the complexity of optimal signal detection increases exponentially with the number of transmitting antennas. In multiuser systems, transmitter complexity is also a concern, since advanced coding schemes must be used frequently to simultaneously transmit information to more than one user, while maintaining a low level of interference between users. This prohibitive complexity motivates a continuous search for computational efficiency, considering optimal or sub-optimal detectors.

4.3.Massive MIMO

The Massive MIMO is an emerging technology that increases MIMO by several orders of magnitude compared to the current MIMO system. With massive MIMO, systems can now use antenna arrays with a few hundred antennas, simultaneously serving many dozens of mobile terminals in the same time frequency resource. For example, a base station (BS) equipped with an array of active antenna elements M, using it to communicate with single antenna terminals K. The basic premise behind the massive MIMO is mimic all the benefits of conventional MIMO, but on a much larger scale. The general multiuser MIMO concept has been around for decades, but the vision of actually deploying BSs with more than a handful of service antennas is relatively new [].

By making coherent processing of the signals through the array, a transmission precoding can be used in the downlink to focus each signal at its desired terminal, and the receive combination can be used in the uplink to discriminate the signals sent from different terminals. In the downlink, this scheme would result in a set of directive bundles, as shown in Figure 14. Overall, Massive MIMO is a facilitator for the development of future (fixed and mobile) broadband networks that will be energy efficient, secure and robust and will use the spectrum efficiently. Each antenna unit would be small and active, preferably powered by an optical or electrical digital bus.

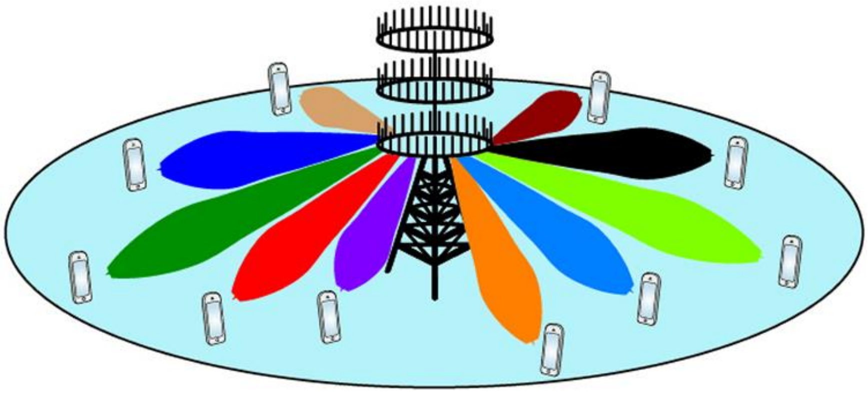

Figure 14 - Massive MIMO using beamforming credits to 5g.co.uk

Massive MIMO depends on spatial multiplexing that depends on the knowledge of the base station channel knowledge, both on the uplink and downlink. In uplink, this task can be easy to accomplish with the terminals sending pilots. Then, by combining these pilots and additional information that can be obtained from the data, the base station estimates the channel responses for each of the terminals. The downlink case turns out to be more difficult.

In conventional MIMO systems, such as the LTE standard, the base station sends pilot waveforms, on the basis of which the mobile terminals estimate the channel responses and quantify the estimates obtained and then feed them back to the base station. This will not be feasible on massive MIMO systems, at least not when operating in a high mobility environment, for two reasons:

- First, the ideal downlink pilots must be mutually orthogonal between the antennas. This means that the amount of time frequency resources needed by downlink pilots is sized as the number of antennas, so a massive MIMO system would require up to 100 times more resources than a conventional system;

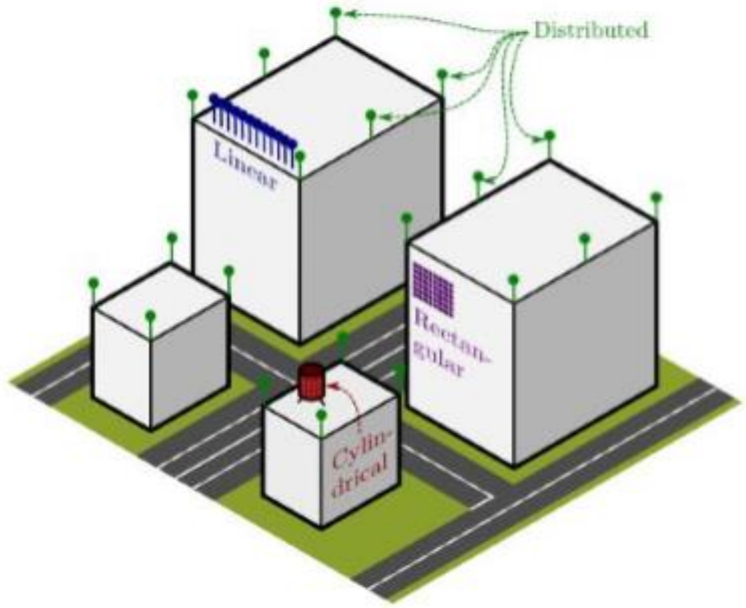

Figure 15 - Passible massive MIMO antenna configuration, credits 5g.co.uk

- Second, the number of channel responses that each terminal must estimate is also proportional to the number of base station antennas. Thus, the uplink capabilities needed to inform the base station about channel responses would be up to one hundred times greater than in conventional systems. Generally, the solution is to operate in Time division Duplex (TDD) mode and rely on reciprocity between uplink and downlink channels [14].

The massive canonical MIMO system operates in TDD mode, where uplink and downlink transmissions occur in the same frequency resource, but are separated in time. The physical propagation channels are reciprocal - which means that the channel responses are the same in both directions - that can be used in the TDD operation. In particular, massive MIMO systems exploit reciprocity to estimate uplink channel responses and then use the acquired channel state information (CSI) for the combination of uplink reception and downlink transmission pre-coding of payload data. Because transceiver hardware is generally not reciprocal, calibration is necessary to explore channel reciprocity in practice. Fortunately, uplink and downlink hardware incompatibilities change only a few degrees over a one-hour period and can be mitigated by simple relative calibration methods, even without extra reference transceivers and relying only on mutual coupling between antennas in the array [16].

There are several good reasons to operate in TDD mode. Firstly, only the BS needs to know the channels to process the antenna signals coherently. Second, the overhead of the uplink estimation is proportional to the number of terminals, but independent of M. This makes the protocol fully scalable in relation to the number of service antennas. In addition, the basic estimation theory tells us that the quality of the estimation (per antenna) is not reduced by the addition of more antennas in the BS. In fact, the quality of the estimation improves with M if there is a known correlation structure between the channel responses on the matrix [3]. As the fading causes the channel responses to vary over time and frequency, the estimate and the payload transmission must fit into a time / frequency block in which the channels are approximately static.

The dimensions of this block are given by the coherence bandwidth Bc Hz and the coherence time Tc s, which conform to the transmission symbols τ = BcTc. Massive MIMO can be implemented using either single carrier or multiple carrier modulation.

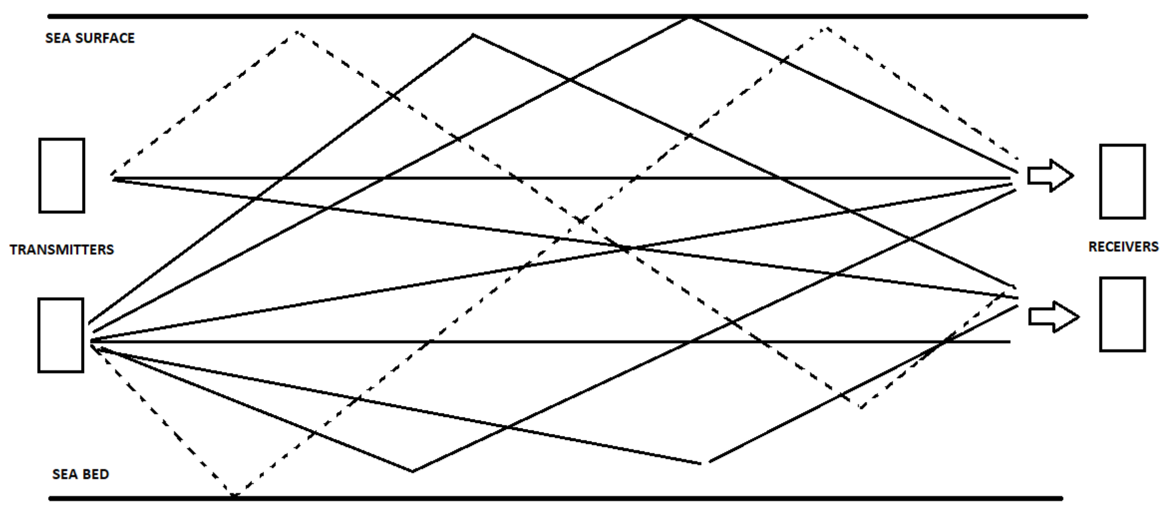

Figure 16 - Possible Massive MIMO used in underwater ambient using acoustic transmission

4.4.MIMO Systems benefices

Due to the structure of multiple antennas and the possibility of jointly manipulating data at the ends of the communications link, the use of MIMO systems provides two types of gains in wireless communications systems, which are diversity gain and multiplexing gain. The diversity gain derives from the use of the multiple paths between the transmitting and receiving antennas of the system that suffer independent fading, for the transmission of signals that carry the same information, introducing robustness to the fading. Already the spatial multiplexing gain can be exploited by the parallel transmission of different signals through the communications channel, which can be appropriately separated in the reception by the use of detectors, as uncorrelated decoder and has the objective of increasing the data transmission rate of the system. Usually these gains are antagonistic, that is, systems that maximize gains of diversity do not gain from spatial multiplexing and vice versa, but there is a possibility of establishing a balance between these two gains. In this section we will look at these gains in more detail.

4.4.1. Diversity Techniques

Classification of diversity techniques can be made by combining methods. In an effort to get the diversity gain, the signals from various channels need to be combined, and the combining method choosed affect the performance of the diversity technique used. The diversity combining methods increases the overall received power and that make a higher value of the SNR These methods are used to combine several replications of the transmitted signal, which undergo independent fading.[13] The 5 diversity techniques used and simulated in this paper are discussed below.

MFB – Matched filter bound is a model in which the Doppler normalized rate is unlimited, unrestricted. In contrast to the static channel case, the optimal matched filter receive is shown to be time varying and the probability of error is shown to depend on the transmission pulse shape. Matched filters are obtained by correlating a known signal, or template, with an unknown signal to identify the presence of the template in the unknown signal. This is the same as convolving the unknown signal with a conjugated time-reversed version of the template. The matched filter is the optimal linear filter for maximizing the signal to noise ratio (SNR) in the presence of additive stochastic noise.[14]

ZF - By employing spatial multiplexing, multiple-input multiple-output (MIMO) wireless antenna systems provide increases in capacity without the need for additional spectrum or power. Zero-forcing (ZF) detection is a simple and effective technique for retrieving multiple transmitted data streams at the receiver. If the transmitter knows the downlink channel state information (CSI) perfectly, ZF-precoding can achieve almost the system capacity when the number of users is large. On the other hand, with limited channel state information at the transmitter (CSIT) the performance of ZF-precoding decreases depending on the accuracy of CSIT. ZF-precoding requires the significant feedback overhead with respect to signal-to-noise-ratio (SNR) so as to achieve the full multiplexing gain[15]

MRC – Maximum ratio combining . the main ideia behind the MRC is the use of a linear coherent combining of branch signals so that the output SNR is maximized. In maximum ratio combining, all the branches are used at the same time. Each of the branch signals is weighted with a gain factor which is proportional to its own SNR. The co-phasing and summing is done for adding up the weighted branch signals in phase.

EGC - In Equal gain combining (EGC), the outputs of different diversity branches are first co-phased and weighted equally before being summed. (contrary to the MRC) After that the resultant output signal is connected to the demodulator. The weights are all set to one with the requirement that the channel gains are approximately flat and so constant and this is usually achieved by using an automatic gain controller (AGC) in the system.

IB DEF - it is known that nonlinear equalizers perform better than linear equalizers. iterative block decision feedback equalizer (IB-DFE) is na iterative FDE technique for SC-FDE that extended to diversity scenarios and layered space-time schemes. IB-DFE receivers can be regarded as iterative DFE receivers with the feedforward and the feedback operations implemented in the frequency domain. Because the feedback loop considers not just the hard decisions for each block, but also the overall block reliability, the result is a small error propagation. Consequently, the IB-DFE techniques offer much better performances than the noniterative methods, with performances that can be close to the matched filter bound (MFB) and have low complexity equalization schemes since the feedback loop uses the equalizer outputs instead of the channel decoder outputs.[16]

4.4.2. Gain diversity

Traditionally, schemes with multiple antennas have been used to increase the diversity of the system in order to mitigate the fading existing in the communication channel and with that, to improve its reliability. Each pair of transmitting and receiving antennas provides a different route for the signals sent from the transmitter to the receiver of the system. By sending signals that carry the same information through each of these paths, replicas are obtained in the receiving antennas of the system after suffering independent fading in the communication channel, so that, if we process them properly in the receiver, a more reliable detection of the signals will be possible transmitted.

The gain of transmission diversity can be obtained when we have the same signal being transmitted through multiple transmitting antennas of the system, generating different replicas of this signal at the reception, as shown in Figure 17 . Each of these replicas, when transmitted by the communications channel, has undergone a different fading along the channel path, and the receiver must handle these signals to obtain the estimate of the transmitted signal. In systems with gain of diversity of reception, Figure 18 we have that the signal sent by the transmitting antenna is received by multiple receiving antennas, in each one of them we will have a sample of the signal transmitted differently faded. For error to occur in reception, all paths must undergo deep fading simultaneously. However, this event occurs with small probability.

The diversity gain provides the system with an increase in the signal-to-noise ratio or a reduction in the transmission power required to obtain a given error rate. He can be defined as the slope of the error probability curve in Logarithm log scale given by:

$$d = -\lim_{\rho \to \infty} \frac{\log\big(P_e(\rho)\big)}{\log(\rho)}$$

Where Pe is the mean error probability and ρ is the signal-to-noise ratio in each of the receiving antennas of the system. In a system with N_T transmitting antennas and N_R receiving antennas.

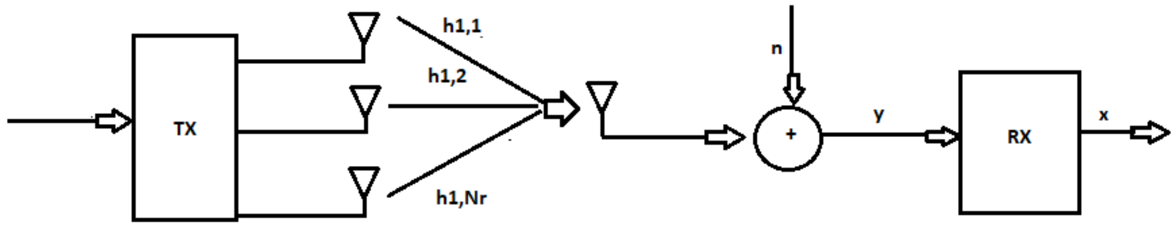

Figure 17 - Gain diversity in transmission

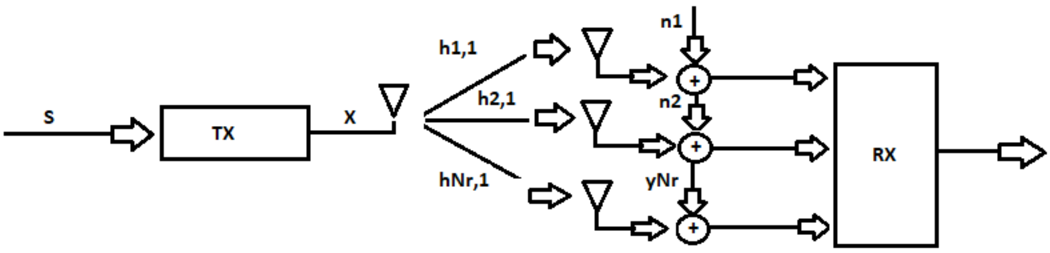

Figure 18 Gain diversity in reception

Whose channel has dimension $N_R \times N_T$, the diversity gain has maximum heat given by the channel dimension, that is, by $d_{max} = N_R \times N_T$, which is the total number of possible independent paths in the communications link.

Another interpretation for the diversity gain is that this value measures how much the MIMO transmitter can exploit the channel's multiple paths to provide robustness to fading, making the system more robust, exploiting the diversity gain decreases the probability of error of the channel. (Pe), since the probability that all the signal-only replicates undergo deep fading becomes much reduced, and this logically improves the reliability of the system and the quality of service it offers. Since the fades between the independent antenna pairs and the diversity gain obtained in the given system by d, the error probability for these systems decays in the form of (p $-d$ (raised to minus d).

For high values of p. In contrast we have that the probability of error of a system with only one transmitting antenna and one receiving antenna decays in the high ρ firm at least one.

4.4.3. Spatial multiplexing gain

In addition to gaining diversity, another way of exploiting the fading of the wireless communications channel using MIMO system is to benefit from the degrees of freedom available in this communications system due to its multiple transmitting and receiving antennas in order to increase the data transmission. The degrees of freedom of a system can be defined as the spatial dimension of the received signal, i.e. the number of different signals that can be clearly distinguished at the receiver. As we shall see, this characteristic can be verified when analyzing the capacity measures of the communications channel In an ergodic channel whose statistical properties such as its mean and variance can be deduced from a single sample sufficiently long to perform this channel or from a single sample of many embodiments whose communications system has N_T transmitting antennas, N_R antennas and path gains between each pair of Rayleigh fading antennas, represented by the channel H matrix elements and modeled as independent and identically distributed random variables, the ergodic capacity is given by:

$$C(\rho) = \mathrm{E}\left\{\log\left[det\left(\mathrm{I}_{N_R} + \frac{\rho}{N_T} HH'\right)\right]\right\}$$

Where E{} is the operator of hope and p is the signal-to-noise ratio at each receiving antenna of the system. Considering high values of P and the elements of the matrix of the independent communications channel, we can write this formula as in:

$$C(\rho) \approx min\{N_T, N_R\} \log\left(\frac{\rho}{N_T}\right) + \sum_{i=|N_T - N_R|+1}^{max\{N_T, N_R\}} \mathrm{E}\{\log X_{2i}^2\}$$

Where X_{2i}^2 is a chi-square variable with $2i$ degrees of freedom. We observed that for high values of p the channel capacity grows in the proportion of the $min\{N_T, N_R\} \times \log(\rho)$, in contrast to $\log(\rho)$ for can is with only one antenna at each end of the link. This result suggests that the channel of multiple antennas can be seen as $\mathrm{N} = min\{N_T, N_R\}$ non - interfering parallel channels, where N is the total number of degrees of freedom of the system. In the case of the path gains of the communication channel between the transmitting and receiving antennas of the system m data per h_{ij}, have independent fading, the antennas are sufficiently spaced from each other so that the signals are able to perceive as distinct points and / or signal has many reflections the matrix representing the communications channel H will be well conditioned with high probability, and thus its lines will be linearly independent of each other. The absence of these conditions implies in reducing the degrees of freedom of the system.

As the result of the spatial multiplexing gain and the fact that we can consider multiple parallel communication channels in which the independent information sequences can be transmitted simultaneously and in parallel through the system antennas as we can see in Figure 19 we have the increase of data transmission rate without there being a need to increase the frequency range used or the total power allocated to the system. The total rate transmitted by the system is therefore divided between its antennas and to this effect we call the spatial multiplexing gain. Then intuitively it is possible to simultaneously send a maximum of N different symbols of information through this channel.

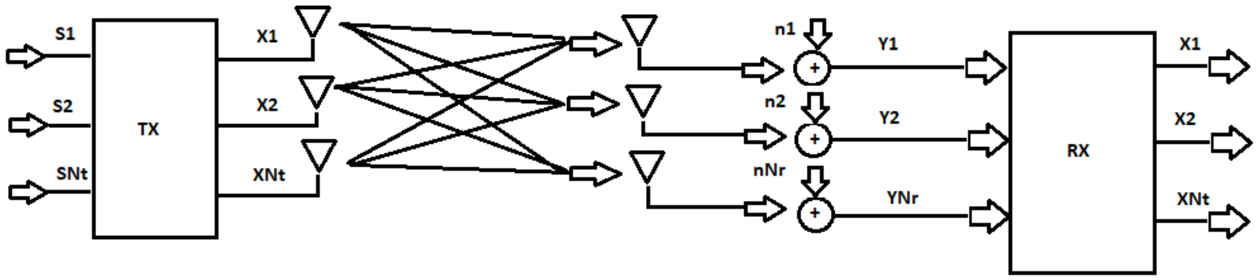

Figure 19 - Spatial Multiplexing gain system

We can say that spatial multiplexing is a simple and effective technique in increasing the capacity of the communications channel, especially at high signal-to-noise ratio at the receiver. Also, another important feature is that spatial multiplexing gain can be exploited even when the system is not aware of the transmitter's communications channel.

4.5. Distance Between MIMO Antennas

The MIMO System we present here will always have correlation because of the space between antenna's, and that is the reason why at 0.3 of correlation the System, still present good performance but beyond that value the performance drastically decreases.

In a typical MIMO scheme the λ between antenna's should be in an interval of 3 to 5. On our study we considered the maximum value and so $\lambda = 5$ as will be explained next.

Electromagnetic waves wave length expression

$\mathcal{C} = \lambda.\mathcal{F}$

Where $\mathcal{C} = Speed\ of\ light$, $\lambda = the\ wave\ lenght$ and $\mathcal{F} = the\ frequency$

That's is true in case of the electromagnetic waves, in an acoustic underwater scheme we are dealing with waves, and therefore the $\mathcal{C} = Speed\ of\ sound$ be converted into a $\mathcal{V} = Speed\ of\ sound\ in\ watter$

That translate into the next equation

$$\mathcal{V} = \lambda.\mathcal{F}$$

Like referred in Chapter II the Speed of sound in water is $1520\ m/s$

And the $\mathcal{F}$ we will be using is $\mathcal{F} = 15Khz$

And therefore, we will have

$$\lambda = \frac{1450\ m/s}{15\ Khz}$$

$$\lambda = \frac{1450\ m/s}{15000\ hz} = 0{,}096meters$$

Approximately 10 cm of wavelength

Since the minimal wavelength between antenna's is of $\lambda = 5$, we get:

$$\lambda = 5.10 = 50\ cm$$

Therefore, 50cm between antenna's is a large value, especially if we think of a system like simulates before of T=8, R=2 like pictured below in Figure 20

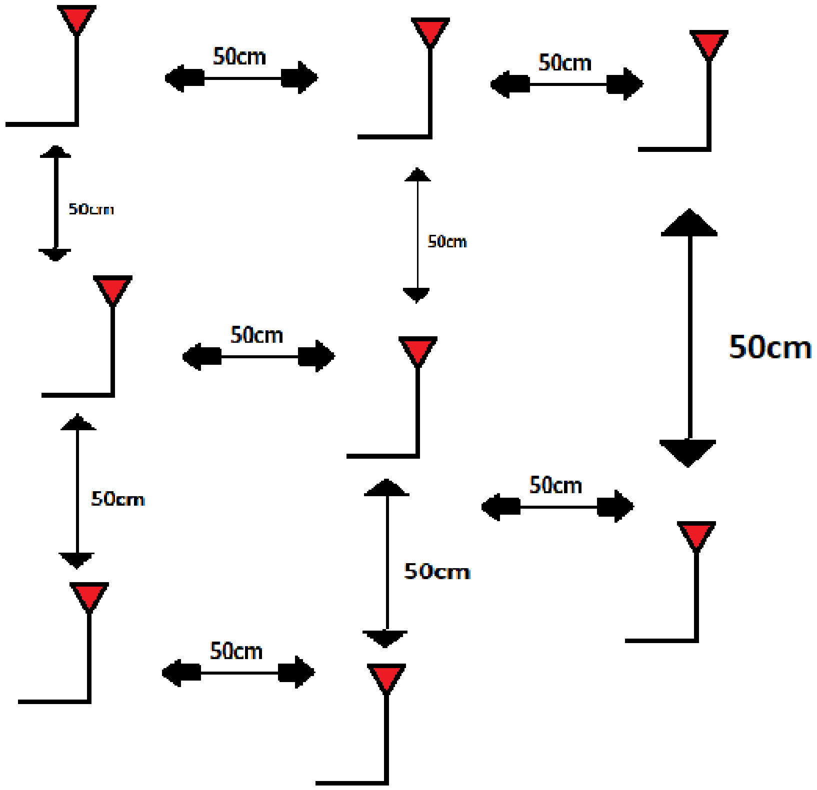

Figure 20 What is expected to be when there is a distance of 50cm between antennas.

Instead our system will have 5cm like pictured in Figure 21 of space between them and therefore there will be some level of correlation.

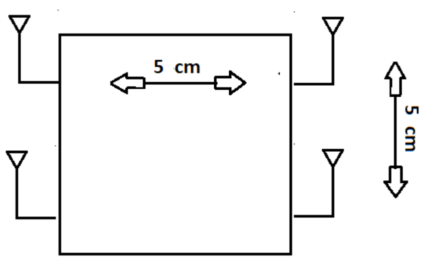

Figure 21 What we propose to be our real distance between antenas, with correlation.

5. Simulations and Analysis of Results

5.1. Performance Results

This chapter presents the performance results for the considered massive MIMO, SC-FDE scheme and a millimeter wave channel. SC-FDE is widely recognized as an excellent alternative to OFDM, especially for the uplink of broadband wireless systems. As with other block transmission techniques, SC-FDE is suitable for high data rate transmission over severely time-dispersive channels due to the frequency domain implementation of the receivers. Conventional SC-FDE schemes employ a linear FDE optimized under the MMSE criterion. However, the residual interference levels might still be too high, leading to performances which can be still substantially worse than the MFB.

Nonlinear time domain equalizers are known to outperform linear equalizers and DFE [3] are known to have good performance-complexity tradeoffs. For this reason, there has been significant interest in the design of nonlinear FDE in general and decision feedback FDE in particular, with the IB-DFE being the most promising nonlinear FDE. In this context, we present results considering both linear and nonlinear (and iterative) FDE techniques. In all simulations, a linear power amplification and a perfect synchronization are assumed at the transmitter and receiver, respectively. [12]

The BER performances are presented as a function of E_b/N_0, where N_0 is the unilateral power spectral density of the noise and E_b is the average bit transmission energy (the degradation due to useless power spent in the cyclic prefix is not included).[1] Unless otherwise stated, each SC-FDE block has $N = 256$ symbols selected from a QPSK constellation through a Gray mapping rule (similar results have been observed for other values of N provided that $N >> 1$). [2]

After several researches and studies, the authors opted for a channel with 20 equal paths of energy with uncorrelated and correlated Rice fading [4]. The channel is considered invariant throughout the transmission period of a block, although it varies from block to block. The duration of the useful part of the blocks (N symbols) is $1\ \mu s$ and the cyclic prefix has a duration of $0.125\ \mu s$ [4].

MFB is a way to measure the channel modeled by the sum of two delayed and independently Rayleigh-fading rays. Briefly, if the two rays have comparable average powers, and if the delay spread is moderate or large, then a considerable diversity gain can be obtained. It works as if the two rays could be detected separately and their results combined. Under these conditions the MFB will be included in all simulations for the sake of performance comparison, since it is a reference that points out to the best possible performance indicator.

This chapter is divided into two parts: in the first part, performance results without antennas' correlation are shown, in the second part, channels with antennas' correlation are considered.

5.2. Results without Correlation between Antenna Elements

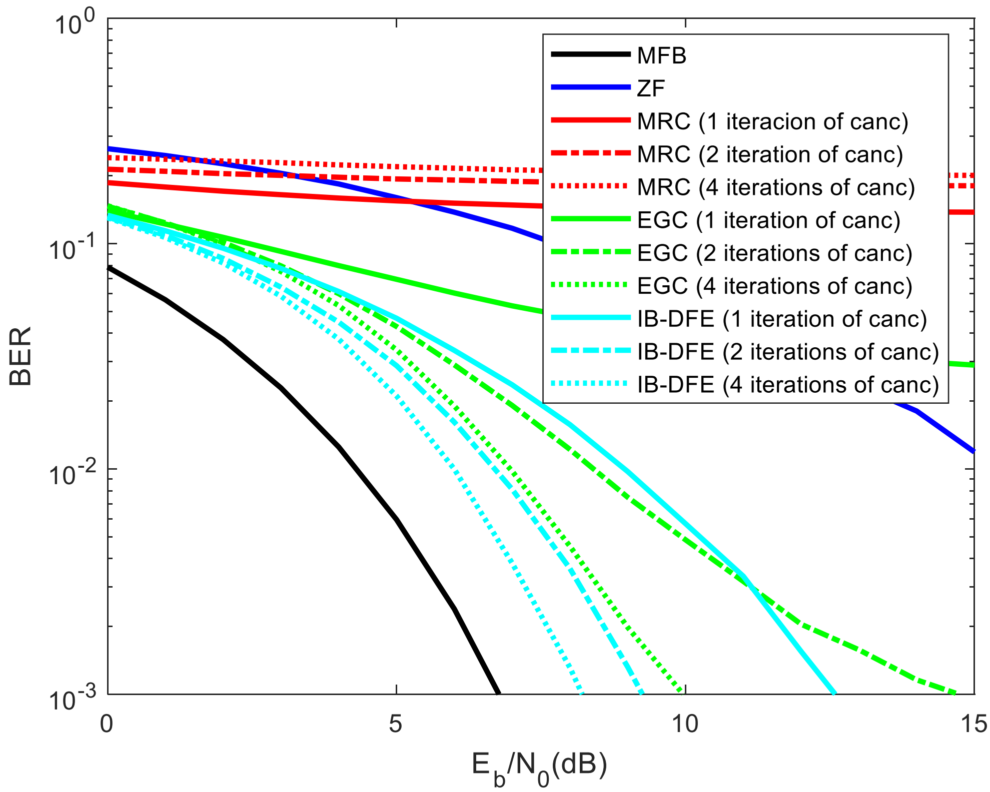

Figure 22 - BER results with one transmitting antenna and one receiving antenna (T=1, R=1) in SISO

Figure 22 shows the BER results with 1 transmitting antenna and 1 receiving antenna (T=1, R=1), i.e., for a SISO configuration, considering four types of post-processing techniques, namely: ZF, MRC, EGC and MMSE. Contrarily to the ZF receiver, where the interference is totally mitigated in one equalization step (linear FDE), the remaining receivers were employed in a nonlinear FDE fashion (with up to L=4 equalization iterations).

The IB-DFE is a transmission technique based on the equalization and post-processing technique of the MMSE. FromFigure 22 , it can be observed that IB-DFE with L=4 iterations of interference cancelation is the technique with the best performance, which demonstrates that the IB-DFE is particularly good to employ in SISO systems. With similar performance is the IB-DFE with L=2 iterations.

From Figure 22, it can be also observed that when L=4 (or even L=2) iterations are considered, the EGC out-performs the MRC. Moreover, the EGC technique is simpler to implement than the MRC since, as there is no need to estimate the channel amplitude, adaptive amplifiers/attenuators are not necessary. It can also be seen that the EGC with only one interference cancellation iteration presents a similar performance than that of ZF.

It should be noted that the ZF receiver is a regular SC-FDE receiver, without interference cancellation, because the ZF transmission technique does not generate interference. A disadvantage of the ZF technique depends on the need to calculate the pseudo-inverse channel matrix for each frequency component.

Regardless of the number of iterations, MRC performs poorly when compared to EGC, and is a little more difficult to implement and costlier in terms of energy.

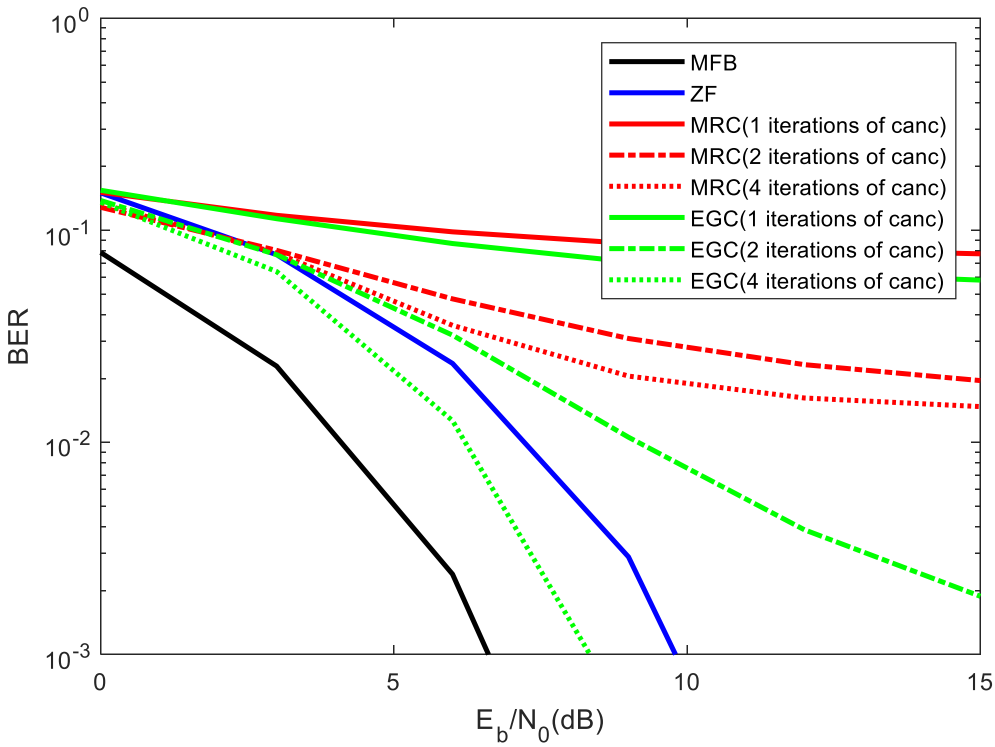

Figure 23 - BER Results with 2 antennas of transmission and 4 antennas of reception. (T=2, R=4), MIMO

Figure 23 shows the EGC with L=4 iterations of interference cancellation attained the best performance results, slightly worse than the MFB performance reference.

With worsen performance than the EGC with L=4 iterations come the Zero Forcing. As said in the last plot, as the number of receive antennas increase the ZF tends to get a better BER results, which is clearly visible in comparation with the last plot Figure 22. With a worse performance than the ZF stands the EGC with L=2 iterations of interference cancelation. The MRC with L=2 iterations shows a slight improvement in performance, opposed to this the EGC of L=2 iterations shows a much worse BER. This means that increasing the number of reception antennas, MRC of L=4 iterations tends to improve. On the other hand, the EGC of L=1 iteration greatly worsens its performance when the number of receive antennas is increased, as the Figure 23 indicates. The EGC of L=1 iteration and the MRC of L=1 iteration shows similar results and are the worse pair in terms of performance shown in this chart.

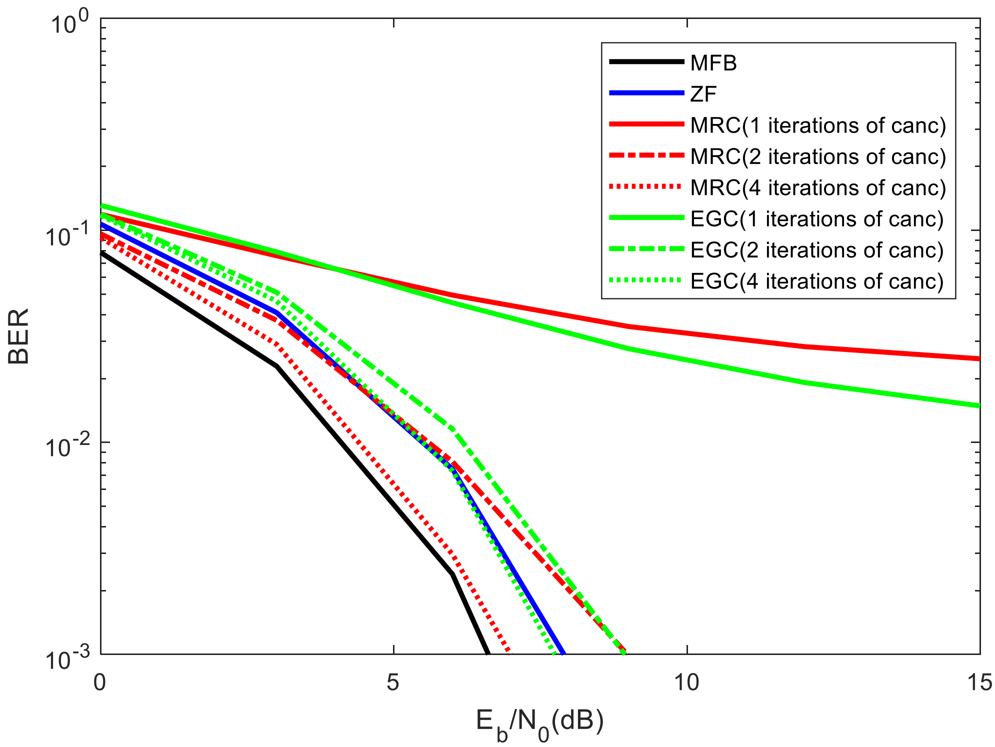

Figure 24 . BER results using 8 antennas of transmission and 2 antennas of reception (T=8, R=2), MIMO

Figure 24 shows a change of paradigm since as shown in the third plot (Figure 23) increasing the number of reception antennas would have little impact in the results and therefore it was chosen to decrease the 4 reception antennas to 2 and increase the emission antennas to 8 dealing with a system in which the number of emission antennas is 4 times bigger then the reception antennas.

However, unlike the previous 3 plots, the MRC of L=4 iterations had a significant improvement, to the point that it can be showed side by side with the MFB which has the best E_b/N_0 ratio. We can therefore assume that with the increase of the number of receive antennas and if these are higher in the order of four times more the reception antennas the MRC with L=4 iterations of interference cancellation has a significant gain in relation to the other techniques. Next and with identical performances slightly worse we have the EGC of L=4 iterations and Zero forcing.

It should be noted that the Zero forcing maintain its E_b/N_0 ratio as long as a 1x1 SISO system is not used. Slightly behind the Zero Forcing and the EGC of L=4 iterations is the pair EGC of L=2 iterations and L=2 iterations MRC. There was a significant improvement in relation to the MRC of L=2 iterations with the increase in the number of reception antennas. Finally we have the pair of MRC and EGC with L=1 iteration of interference cancellation, both kept the ratio of E_b/N_0 relatively unchanged in pair with the previous chart Figure 23

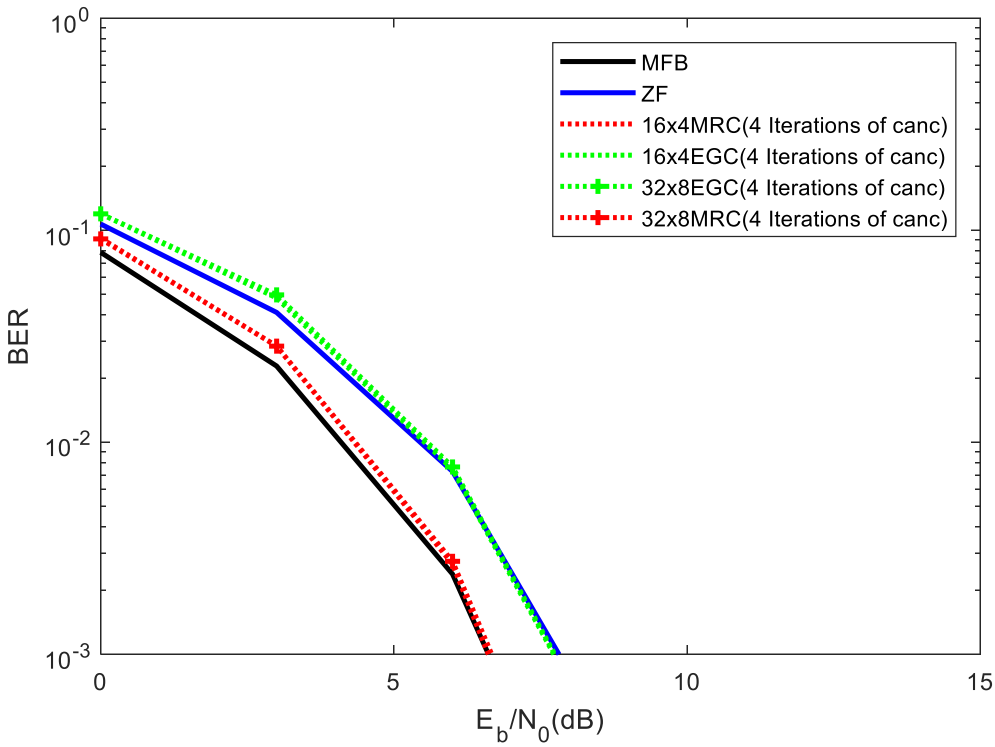

Figure 25 BER results of different antennas configurations

Figure 25 combines two plots together because the differences between 16x4 and 32x8 are insignificant, and so comment them individually would be inviable. In addition, any plot above 32x8 will have fewer differences and so the plot Figure 25 of 32x8 appears here as being the graph that shows the best performance figures.

In the Figure 25 the BER Results are shown with 4 transmit antennas and 16 receiving antennas using massive MIMO as well as a plot with 8 transmitting antennas and 32 receiving antennas.

In Figure 25 the idea that with the increase in the number of receivers, the MRC technique with L=4 iterations of interference cancellation, further improves the E_b/N_0 ratio to a point, contrary to the previous plots, performs the same as the MFB, which until now had not yet happened. This ratio is maintained since the number of transmit antennas is four times higher than the number of receiving antennas.

EGC with L=4 iterations and Zero forcing remain identical to the previous plot. Both occupy the second place with a similar E_b/N_0 ratio. We can say that Zero forcing has maintained its E_b/N_0 ratio since a 1x1 SISO system is not used. In relation to the MRC pair with L=2 iterations and CGE with L=2 iterations, it worsened the E_b/N_0 ratio of the EGC of L=2 iterations.

Finally we have the pair of MRC and EGC without interference cancellation iterations, both kept relatively unchanged the E_b/N_0 ratio in pair with the previous plots.

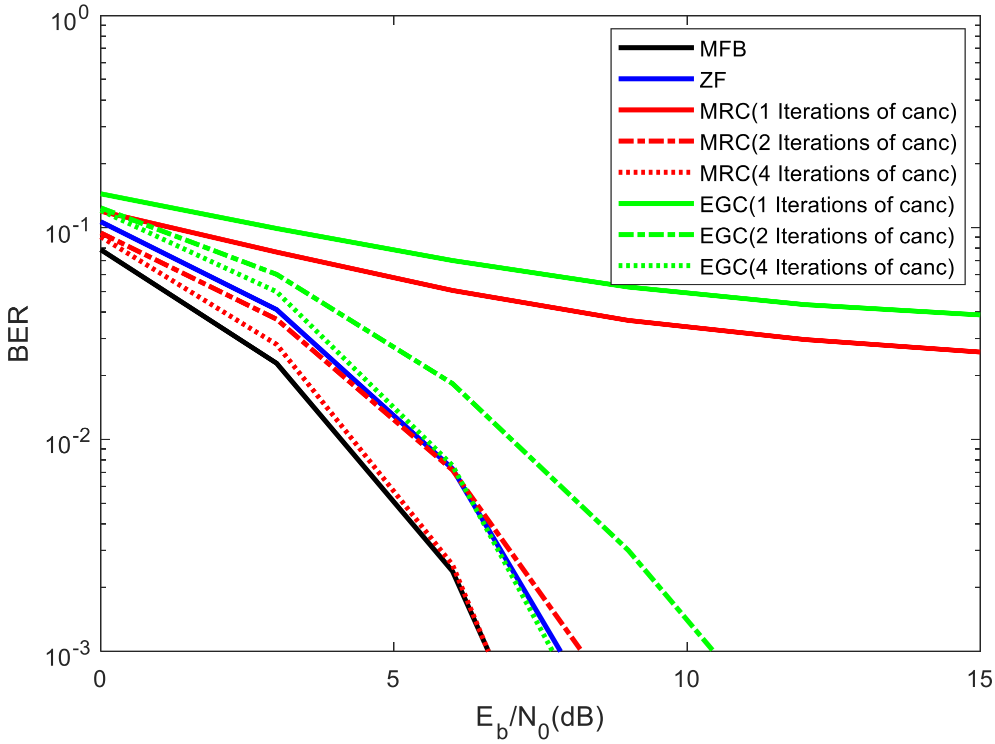

Figure 26 BER results with 16 transmitting antennas and 64 receiving antennas, (T=16, R=64), a typical m-MIMO configuration

Figure 26 was elaborated to prove the above sentence, that a higher number of transmitting and receiving antennas is unnecessary as there is not a relative gain in performance.

5.3. Results with Correlation between Antenna Elements

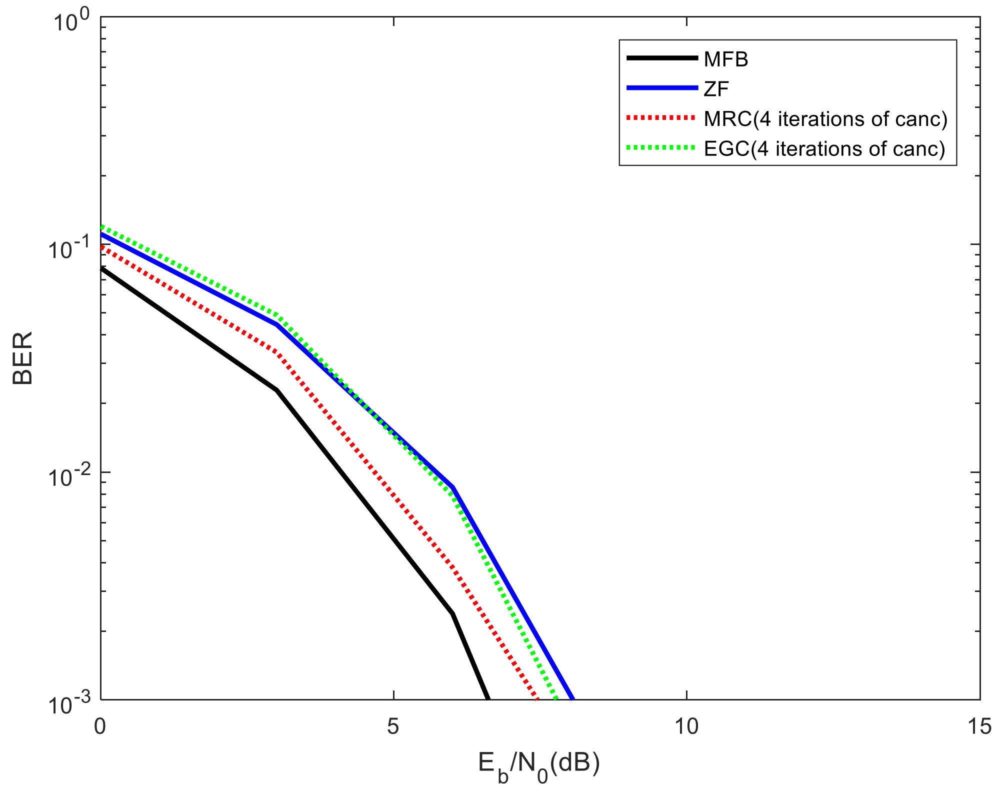

Figure 27 BER Results with 8 emission antennas and 2 receive antennas (T=8, R=2), with correlation coefficient of 0.3

Figure 27 shows the simulated results of BER in relation to EB / N0 for massive MIMO, composed of 2 antennas for transmission and 8 for receiving (T2, R2), with correlation in post-processing, the correlation coefficient (ρ) being equal to 0.3. Using algorithms referring to equalization and diversity techniques (it is with cancellation of interferences) respectively ZF, MRC and EGC.

The figure above Figure 27s hows its results with an iterative receiver with up to L=4 iterations of interference cancellation as well as a filter limit appropriate to the scenario.

The results of the graph above, shows performance results close to the plot of Figure 24 that does not make use of correlation between the antennas. In this case in post-processing the ZF appears with performances below and far from the MFB. The results obtained with the EGC and MRC techniques with the L=4 iterations of interference cancellation present a closer performance of the MFB. Note that the MRC technique performs above the EGC

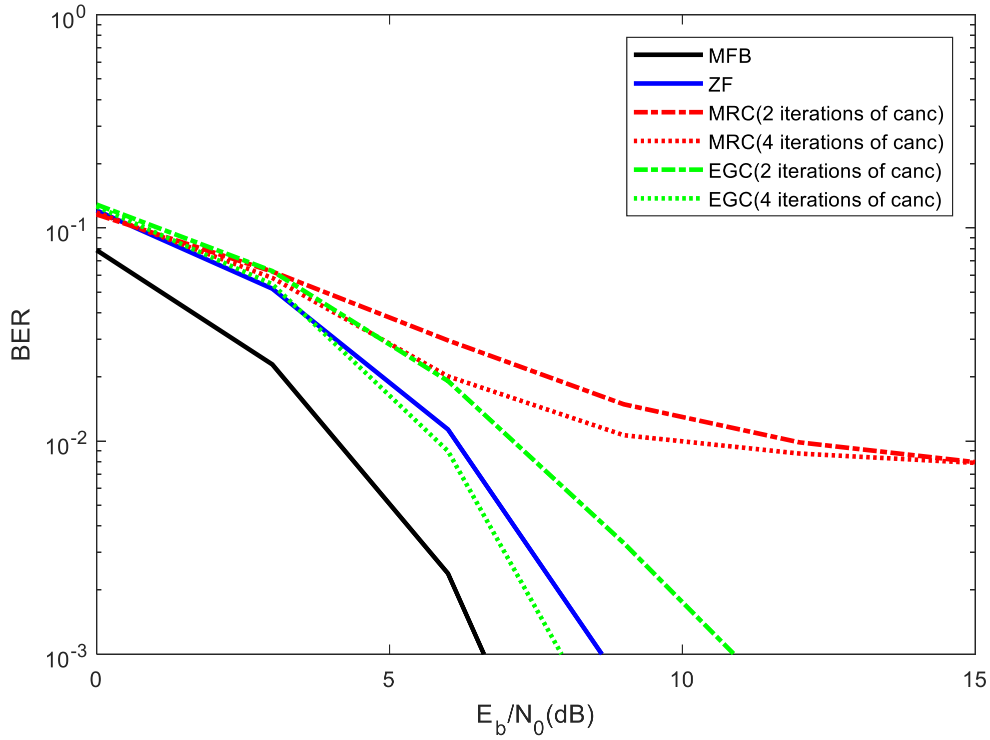

Figure 28 BER results with 8 transmitting antennas and 2 receiving antennas (T=8, R=2), in m-MIMO with a correlation coefficient of 0.5

Figure 28 indicates that with the increase of the correlation coefficient (ρ) the performance of the ZF and the other technique EGC and MRC tend to worsen.

The EGC evidences its margin of progress superior to the ZF, whereas the MRC different from the previous results presents a very bad performance and far from the acceptable even with iterations above 4, because of that the coefficient correlation equal to or greater than 5 does not present an acceptable level of performance.

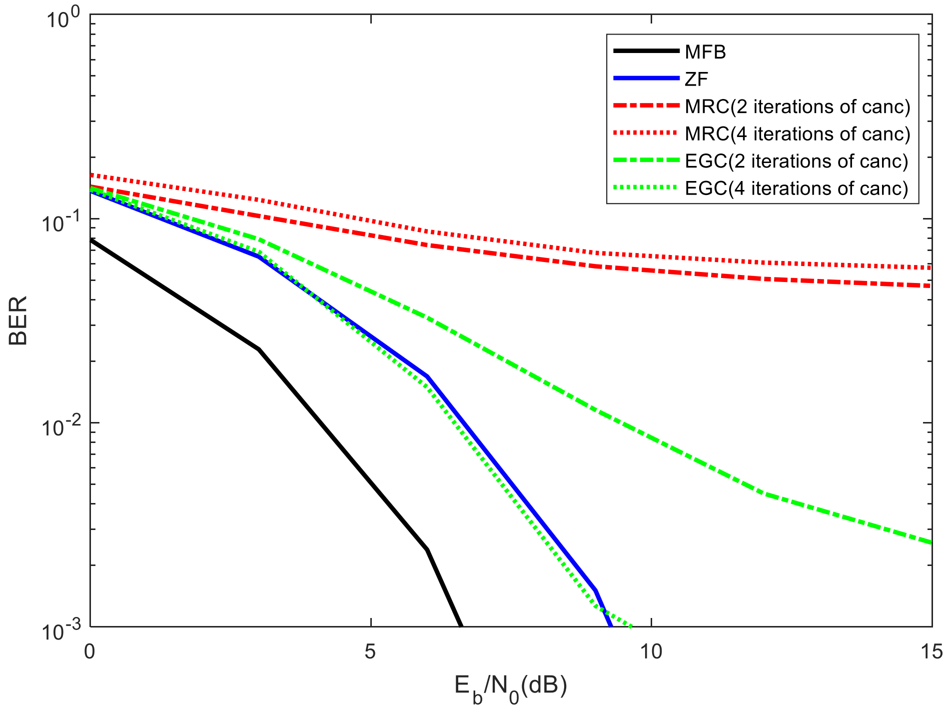

Figure 29 BER results with 8 transmitting antennas and 2 receiving antennas (T=8, R=2), in an m-MIMO typical configuration with a correlation coefficient of 0.65

It's evident on Figure 29 that a correlation coefficient equal to 0.65 and as long as these values is bigger that the performance results tend to be worse. The ZF, EGC distance themselves more from the MFB, and to note that the MRC can no longer deliver a good result.

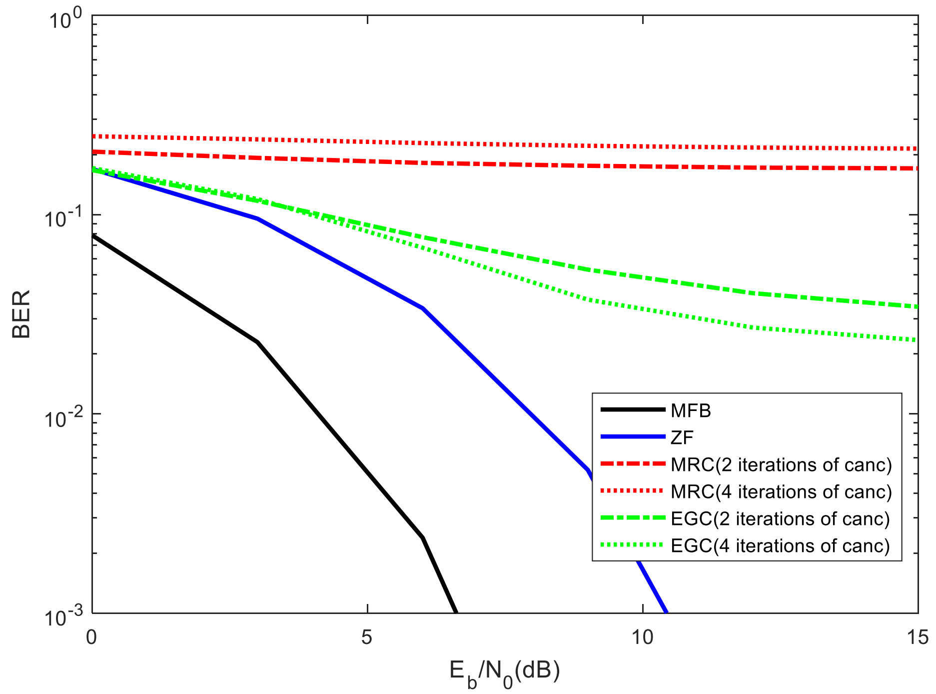

Figure 30: BER results with 8 transmitting antennas and 2 receiving antennas (T=8, R=2), in a m-MIMO configuration with a correlation coefficient of 0.8

With the coefficient of correlation at 0.8 between antennas the ZF is the technique that has a more acceptable performance as seen inFigure 30, still, it is as sawn before, getting worse as the correlation factor grows, and as compared to Figure 29. Also, the EGC and MRC techniques have very poor performance results, especially the MRC.

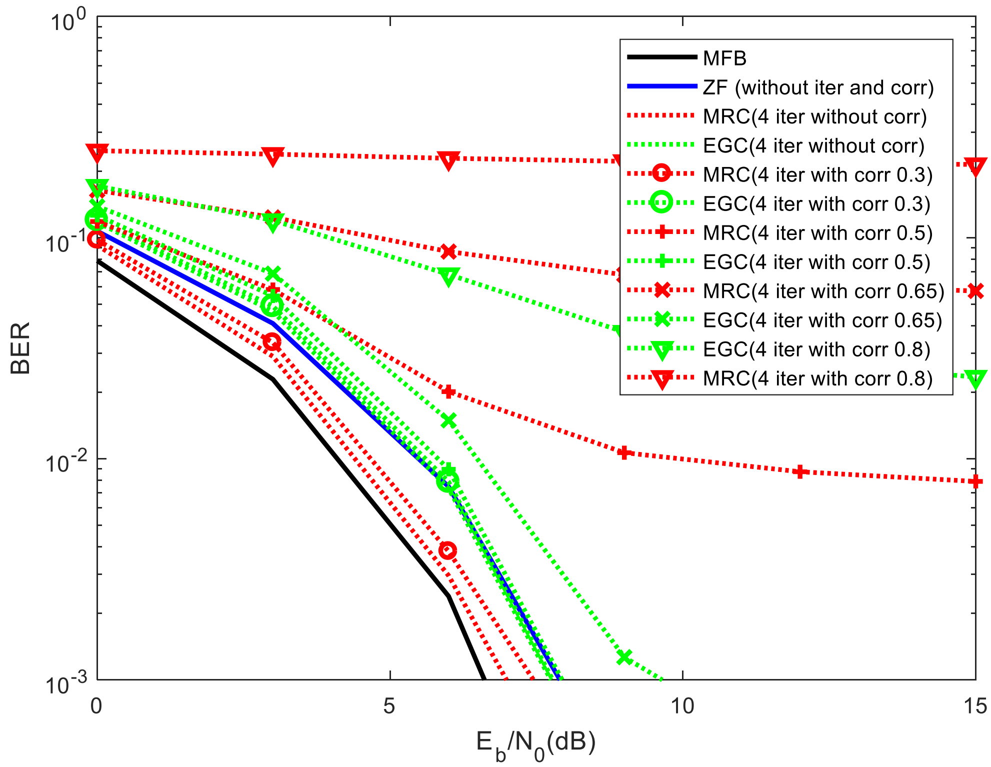

Figure 31: A plot that combines a majority of non-correlated and correlated techniques in order to have a bigger picture

The plot presented here in Figure 31 joined all the major communication techniques with and without correlation in order to make a deeper analysis and to make possible for the reader to compare the plots without turning pages. As seem in the Figure 31 a non-correlated MRC with L=4 iterations of interference canceller is side-by-side with the MFB. Slightly worse there is the correlated MRC also with L=4 iterations and with a correlation factor of 0.3. Out-performing the MRC there are 3 neck-to-neck techniques. The ZF, without correlation and iterations, the EGC with L=4 iterations and a correlation factor of 0.3 and also the EGC with a correlation of 0.5 and L=4 iterations. A little worse comes the EGC with L=4 iterations and a correlation factor of 0.65. Behind and with much worse performance appears the MRC with L=4 iterations of interference cancelling and a correlator factor of 0.5. Following the MRC is the ECG of L=4 iterations and a correlative factor of 0.8. At the same performance is the EGC with L=4 iterations and a correlative factor of 0.65, and at last there is the MRC of L=4 iterations with the correlation factor of 0.8. It’s not a linear idea but, the more the correlation value the worse performance the technique gets.

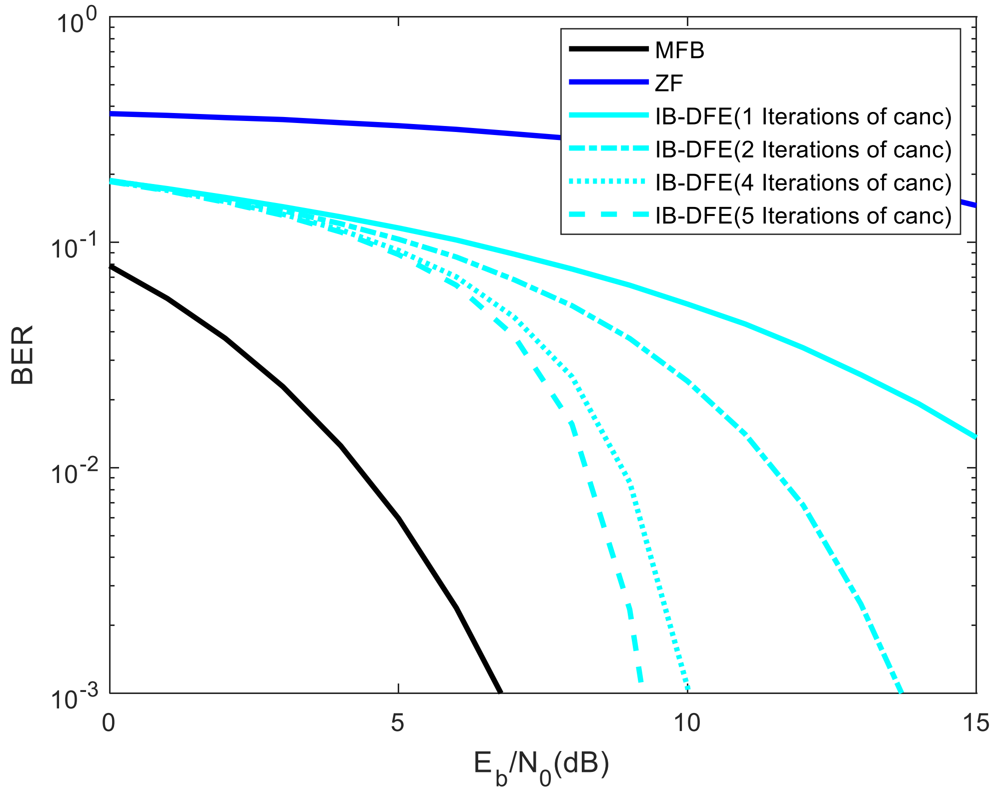

Figure 32 BER results of IB-DFE without correlation with 8 transmitting antennas and 8 receiving antennas (T=8, R=8)

Figure 32 shows the IB-DFE technique as well as the ZF and the MFB for comparative reasons. Keep in mind the IB-DFE plotted here is presented without correlation. But as far as performance goes the IB-DFE with L=5 iterations of interference cancelling attained a fair result, not good as the MFB. Followed by a slightly out-performed IB-DFE of L=4 iterations. Much further behind there is the IB-DFE of L=2 and L=1 iteration. And at last the ZF.

6. Conclusions

6.1.Conclusion

This paper development was divided into two main points. The first one being the characterization of the underwater channel and the second creating a simulation of a MIMO acoustic communications system. On the characterization of the underwater environment there was a care to study exhaustively all the major components of the underwater acoustic environment. As seen in the second chapter it was made a difference between the speed of sound in water and the speed of sound in the air, concluding that the speed of sound in the water was higher than in the air.(in water =1520 m/s in air = 343 m/s) which is almost 4 times faster, being that the reason why an acoustic communications underwater system makes sense. There was too an effort to understand the behave of this speed when pressure and temperature raised, and find out that this speed will vary Figure 5. Also understand that the deepest the acoustic waves travel the more will the waves bent, contrary on shallow waters the behave follows the snells law like showed in Figure 7 After this step off understanding was made the group progressed into other interesting questions. Choosing between Small Scale or a Large-Scale fading model to be applied on the underwater acoustic communications system. The choose was the small scale because the small scale is a model where there is a Line-of-sight (LOS) signal, and there are not large variations or large objects in the line of sight path, and it is more indicated to large areas where there are not obstacles between the transmitter and the receiver, and that is exactly what happens in the underwater environment, and when the dominant component fades away thanks to the reflect, refract, and diffract of the acoustic waves, Rician distribution degenerates to a Rayleigh fading distribution. After this decision there was an effort to make a big approach on all types of Fading as shown in Figure 9, and a more concise approach on the two types of fading the underwater acoustic system would deal, fast fading slow fading and multipath delay spread. Then on chapter 4 the MIMO systems was explained as well as the Massive MIMI and discussed some benefits of their use, being the 2 most important the diversity gain and the special multiplexing gain. After this phase one, we had begun the second phase of our project that was on simulating, but before the group needed to study the diverse diversity communications techniques that the MIMO system offered. In an effort to get the diversity gain that the multi antennas MIMO systems offered the signals from various channels need to be combined, and the combining method choose affect the performance of the diversity technique used. The diversity techniques that were used are MFB ZF MRC EGC and IB DEF. After these studies was made, the group begun the simulation part, where the group simulated various charts using those diversity techniques in an effort to get a conclusion as described in the cap 6. These part, and charts were divided in two parts being the first one without correlation and the second with correlation between antennas. Without correlation, and using a SISO type we found the diversity technique IB-DFE the better to use and as saw on the plot Figure 22 it is the ono who have a better BER performance. On a MIMO type of T=2, R=4 without correlation the EGC of D=4 iterations of interference canceling was the choice to make as visible in the plot.

We understand that if the number of transmission was 4 times higher than the number of receivers like the Figure 24 in an uncorrelated (T=8, R=2), MIMO the MRC with D=4 iterations of interference cancelations the best option to use. On a massive MIMO configuration of T=16, R=64 uncorrelated the MRC was as Good a the MFB.

On a correlated Scenario there we 4 types of plots that were made. Being 0.3, 0.5, 0.65 and 0.8 all at a MIMo type of T=8 and R=2. Of all these 4 plots as show in Figure 27, Figure 28, Figure 29 and Figure 30 the only one with a good performance is the one with 0.3 of antenna correlation as showed in figure xx. On the rest, as the correlation increases the performance gets poor. On the 0.3 correlation on T=8 and R=2 the MRC with D=4 iterations of interference canceler is the one with the best performance.

The group also find out that our distance between MIMO antenna's using $\lambda = 5$ would be given by:

$$\lambda = \frac{1450\ m/s}{15000\ hz} = 0{,}096 meters$$

Approximately 10 cm of wavelength

Since the minimal wavelength between antenna's is of $\lambda = 5$, we get:

$$\lambda = 5.10 = 50\ cm$$

Therefore, 50cm between antenna's is a large value, especially if we think of a system like simulates before of T=8, R=2 and therefore we opted to use a system, where the distance between antenna's would be 5Cm like show in pictureFigure 21

6.2.Dificulties

Being the underwater acoustics relatively new term both for students and researchers, its true that the information on certain topics are still scarce. Another difficulty that the group felted was in the direction of the paper. Creating a guideline and a guidance to this paper was extremely difficult, sometimes the group would start making a topic but found on the middle of the task that it would become inviable or not going the direction it was planned, and so there were much time wasted. There is some specific software that was used that still require power and performance Portable computers. That was specially noted when plotting some of the graphics. Especially the Figure 32 that toke approximately 1.5 days to create. All plots in exception this last referred, took in average 1 to 2 hours processing.

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