**Universidade do Minho**
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# Underwater Acoustic Communication System: Performance evaluation of digital modulation techniques

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# Underwater Acoustic Communication Systems: Performance evaluation of digital modulation techniques

Tese de Mestrado
Ciclo de Estudos Integrados Conducentes ao
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Trabalho efectuado sob a orientação de
**Professor Doutor José Cabral**
**Mestre Marcos Martins**

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*"A sabedoria da vida não está*
*em fazer aquilo de que se gosta,*
*mas gostar daquilo que se faz."*

*Leonardo da Vinci*

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# Abstract

This dissertation aims to describe all the research work performed to study binary digital modulations in the aquatic environment using acoustic waves. The underwater environment is considered an unreliable communication system due to countless factors affecting the propagation of the acoustic waves such as: high attenuation at long distances, low sound speed, existence of great noise diversity, multipath and *Doppler* effect. These features make it extremely difficult to establish any kind of underwater communication.

Thus, initially it is necessary to perform an exhaustive survey of all the research in this area in order to understand how these characteristics may affect communication in underwater environments and subsequently identify the key concepts to future specify this type of communication systems.

After that, a study about digital modulations was done in order to identify those that could be possible to conduct on this type of system. After perform an intensive research about this subject it was developed an underwater communication system using *MatLab/Simulink* tool with specific *Xilinx* blockset to verify and allow a theoretical study about the behaviour of digital modulations in underwater environment.

In order to verify the system performance and the efficiency of the performed study, a comparison between the results obtained in the theoretical system and the results obtained through practical tests was done. Through these practical tests it was possible to observe the influence of the above factors affecting the propagation of acoustic waves in underwater environments. As was initially expected, the obtained results validate and demonstrate the effectiveness of the studies that were performed.

Finally, it was still possible to identify some issues that could be addressed later, in the developing of future work in this area of research.

**- Keywords**

Digital modulations, Acoustic waves, Underwater environment, Attenuation, Noise, *Doppler* effect, Propagation delay, Underwater communication system simulation.

# Resumo

Esta dissertação tem como objetivo descrever todo o trabalho de pesquisa realizado para estudar as modulações binárias digitais em ambientes subaquáticos usando ondas acústicas. O ambiente subaquático é considerado um sistema de comunicações instável, devido a inúmeros factores que afectam a propagação das ondas acústicas tais como: alta atenuação em longas distâncias, a baixa velocidade de som, a existência de uma grande diversidade de ruído, o fenómeno de multipercurso e o efeito de *Doppler*. Estas características fazem com que seja extremamente difícil estabelecer qualquer tipo de comunicação subaquática.

Assim, inicialmente, foi necessário realizar um levantamento exaustivo de todas as pesquisas nesta área, a fim de entender como essas características podem afetar a comunicação em ambientes subaquáticos e, posteriormente, identificar os conceitos-chave para uma futura especificação deste tipo de sistemas de comunicação.

Depois disso, foi realizado um estudo sobre modulações digitais a fim de identificar as candidatas a serem usadas neste tipo de sistemas. Depois de realizar uma intensa pesquisa sobre este assunto, foi desenvolvido um sistema de comunicação subaquático usando a ferramenta *MatLab/Simulink* com blocos específicos *Xilinx* para verificar e permitir um estudo teórico sobre o comportamento das modulações digitais em ambiente subaquático.

De modo a verificar o desempenho do sistema e da eficiência da pesquisa realizada, foi feita uma comparação entre os resultados obtidos no sistema teórico e os resultados obtidos por meio de testes práticos. Através destes testes práticos, foi possível observar a influência dos fatores anteriormente mencionados que afetam a propagação de ondas acústicas em ambientes subaquáticos. Como era inicialmente esperado, os resultados obtidos validam e demonstram a eficácia dos estudos que foram realizados anteriormente.

Finalmente, foi ainda possível identificar algumas questões que podem ser abordadas mais tarde, no desenvolvimento de trabalhos futuros nesta área de pesquisa.

**- Palavras-Chave**

Modulações digitais, Ondas acústicas, Ambiente subaquático, Atenuação, Ruído, Efeito de *Doppler*, Atraso de propagação, Simulação do sistema de comunicação subaquático.

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# List of Acronyms

| | |
|---|---|
| **ACOM** | **A**coustic **COM**munications |
| **ADC** | **A**nalog to **D**igital **C**onverter |
| **AGC** | **A**utomatic **G**ain **C**ontrol |
| **AM** | **A**mplitude **M**odulation |
| **AMI** | **A**lternate **M**ark **I**nversion |
| **ASK** | **A**mplitude **S**hift **K**eying |
| **APK** | **A**mplitude **P**hase **K**eying |
| **AUV** | **A**utonomous **U**nderwater **V**ehicle |
| **BASK** | **B**inary **A**mplitude **S**hift **K**eying |
| **BFSK** | **B**inary **F**requency **S**hift **K**eying |
| **BPSK** | **B**inary **P**hase **S**hift **K**eying |
| **CW** | **C**arrier **W**ave |
| **CoW** | **C**ontinuous **W**ave |
| **DAC** | **D**igital to **A**nalog **C**onverter |
| **DPSK** | **D**ifferential **P**hase **S**hift **K**eying |
| **DSP** | **D**igital **S**ignal **P**rocessing |
| **EM** | **E**lectro**M**agnetic |
| **EMCOM** | **E**lectro**M**agnetic **COM**munications |
| **ELF** | **E**xtremely **L**ow **F**requency |
| **FDM** | **F**requency **D**ivision **M**ultiplexing |
| **FFT** | **F**ast **F**ourier **T**ransform |
| **FM** | **F**requency **M**odulation |
| **FSK** | **F**requency **S**hift **K**eying |
| **FPGA** | **F**ield **P**rogrammable **G**ate **A**rray |
| **HDL** | **H**ardware **D**escription **L**anguage |
| **ISI** | **I**nter **S**ymbol **I**nterference |
| **LDs** | **L**aser **D**iodes |

| | |
|---|---|
| **LEDs** | **L**ight **E**mitting **D**iodes |
| **LOS** | **L**ine-**O**f-**S**ight link |
| **MA** | **M**ultiple **A**cess |
| **MRL** | **M**odulating **R**etroreflector **L**ink |
| **NRZ** | **N**on **R**eturn to **Z**ero |
| **OCOM** | **O**ptical **COM**munications |
| **OFDM** | **O**rthogonal **F**requency **D**ivision **M**ultiplexing |
| **OOK** | **O**n **O**ff **K**eying |
| **PM** | **P**hase **M**odulation |
| **PLL** | **P**hase **L**ocked **L**oop |
| **PSK** | **P**hase **S**hift **K**eying |
| **PVDF** | **P**olyvinylidene **F**luoride |
| **QAM** | **Q**uadrature **A**mplitude **M**odulation |
| **QPSK** | **Q**uadrature **P**hase **S**hift **K**eying |
| **RF** | **R**adio **F**requency |
| **RL** | **R**eflective **L**ink |
| **RTL** | **R**egister **T**ransfer **L**evel |
| **SNR** | **S**ignal **N**oise **R**atio |
| **SONAR** | **SO**und **N**avigation and **R**anging |
| **SVP** | **S**ound **V**elocity **P**rofile |
| **TDM** | **T**ime **D**ivision **M**ultiplexing |
| **UUV** | **U**nmanned **U**nderwater **V**ehicle |

# 1

# Introduction

Along the human history, communications using sounds had played an important role in development of society, providing a means of communication between humanity. Through this, it was possible the evolution of human species up to now. So, why we do not do the same using ocean in order to acquire even more knowledge?

For several decades, electromagnetic waves, especially radio waves, had been extensively used for long range communications. However, when the propagating medium is water, electromagnetic waves have a limited use, because they suffer a very significant attenuation when travel long distances. This phenomenon can be demonstrated by observing an underwater light, and trying to understand how far the light beam travels. In some areas in the world, it is impossible to see our own outstretched hands under the water, even with intense illumination [KW05].

In the fifteenth century (XV), the first document about underwater acoustics, written by the famous Leonardo da Vinci, says: "If you stop your ship and dip one end of a long pipe in water, you will hear the noise of ships at a large distance" [KW05]. In this way, the first drafts about the underwater communications, using sound waves, began to appear. This technology had its major evolution during the $1^{st}$ World War [Bor10], used as a form of sonar detection.

It became very clear in the beginning of the $20^{th}$ century that sound waves could propagate in water much more efficiently than electromagnetic waves, because they suffer less attenuation comparatively with electromagnetic waves [KW05].

Over the times, humanity realized the importance of the oceans in our lives and through its exploitation could offer greats benefits to society.

The underwater environment, due to their particularities, can offer a wide range of interesting applications (some examples of these applications are provided in section 1.3). However to develop/implement these applications it is necessary a great effort in terms of research. Therefore, and because the wireless technology is very difficult to deploy in underwater environment it is important to continue to perform many research projects in this area and thus rendering the wireless underwater communication technology a very important scientific research field.

Nowadays, underwater communication systems involve three types of transmission: electromagnetic (EM), optical and acoustic [LZC08] [Men11].

Relatively to EM, it is advisable to use only in a specialized type of systems because this technique is limited by the high rate of absorption of electromagnetic signals in water [Rho07]. The second one, besides suffer the same limitation of EM have one more disadvantage: the high levels of ambient light and scattering due to the suspended particles [Arn10] [LG06]. Other disadvantage of this communication method lies in the fact that this technique is used only in a very short range (up 1 to 10 meters) [LG06]. Consequently, the implementation of these types of systems have limitations to some kinds of applications. In this way, the acoustic communication systems are the most versatile and largely used in underwater environments, since there is a low attenuation (signal reduction) of sound waves[1] when the communication channel is water. Today this technique is considered the most used in underwater communications, especially in deep water with a stable thermal factor. However, factors like surface ambient noise, temperature gradients and multipath propagation, due to reflection and refraction can adversely affect the use of acoustic waves in shallow water [LZC08]. In 1945, arises one of the first underwater communication system which enables the communication with submarines [Sto99].

Although acoustic communications in underwater environment has advantages comparatively with the other techniques (optical and electromagnetic), this type of communication has some significant challenges, more specifically the much slower speed of acoustic propagation in water. Since water is a denser medium than air, the acoustic (sounds) waves can propagate faster in water than in the air. The sound speed in air is around 340 $m/s$, and in underwater the sound speed reach 1500 $m/s$. However, this value is significantly lower than the speed of EM waves, but still fast enough to provide adequate responsiveness in many applications [KW05].

Today the research in acoustic communications has increased due the variety of applic-

[1] "Sound waves are defined as compressional waves that have a frequency that is within the audible spectrum. Sounds outside the human hearing range are often referred to as infrasound (below $20Hz$) and ultrasound (above $20kHz$)" [Con08]."Sound is a form of mechanical energy, a vibration that travels as a wave by causing pressure changes in a fluid" [Bar09].

ations in underwater environment. Until the beginning of the last decade, the non-coherent *Frequency Shift Keying* (FSK) modulation schemes, became very favourable to exploring underwater acoustic communication, due the challenging characteristics offered in underwater channel. This technology relies on energy detection that is a robust method for the characteristics found in underwater acoustic channel [APM05] [Hau09].

Table 1.1 shows the evolution of different modulation schemes used over the past twenty years. It is possible to observe the evolution from non-coherent modems (before 1997) to the recent coherent modems (after 1997).

| ***Type*** | ***Year*** | ***Rate[kbps]*** | ***Band[kHz]*** | ***Range[km]***[a] |
|---|---|---|---|---|
| ***FSK*** | 1984 | 1.2 | 5 | $3_s$ |
| ***PSK*** | 1989 | 500 | 125 | $0.06_d$ |
| ***FSK*** | 1991 | 1.25 | 10 | $2_d$ |
| ***PSK*** | 1993 | 0.3 - 0.5 | 0.3 - 1 | $200_d$ - $90_s$ |
| ***PSK*** | 1994 | 0.02 | 20 | $0.9_s$ |
| ***FSK*** | 1997 | 0.6 - 2.4 | 5 | $10_d$ - $5_s$ |
| ***DPSK*** | 1997 | 20 | 10 | $1_d$ |
| ***PSK*** | 1998 | 1.67 - 6.7 | 2 - 10 | $4_d$ - $2_s$ |
| ***16-QAM*** | 2001 | 40 | 10 | $0.3_s$ |

a) subscripts **d** and **s** stand for deep and shallow water

**Table 1.1:** *Evolution of modulation techniques [APM05]*

In table 1.1 we can see that the early phase-coherent (1998) systems offer higher bandwidth efficiencies (bit rate/occupied bandwidth) relatively to their incoherent counterparts. However, they can not outperform incoherent modulation schemes yet. Indeed, until Inter Symbol Interference (ISI) compensation, coherent systems had lower performance than incoherent systems for long transmissions on horizontal channels [APM05].

Although non-coherent modulation schemes, such as FSK, can be characterized by high power efficiency and their low bandwidth efficiency becomes a huge problem for high data rate sensors. In order to counteract this problem, fully coherent modulation techniques such as *Phase Shift Keying* (PSK) and *Quadrature Amplitude Modulation* (QAM) were used, due to the availability of powerful digital processing that they can provide. Thus there is an extensive research in this area [APM05] [Hau09].

*Differential Phase Shift Keying* modulation (DPSK) provided an intermediate solution between incoherent and fully coherent systems relatively of bandwidth efficiency. This kind of modulation can be referred as a partially coherent modulation because encodes information on the previous symbol instead to arbitrary fixed reference in the signal phase. This modulation can simplify the carrier phase-tracking requirements, but increase the error probability in PSK modulation using similar data rates [APM05].

The *Orthogonal Frequency Division Multiplexing* (OFDM) spread spectrum technique became a promising solution for underwater communications. This technique consist in a *Frequency Division Multiplexing* (FDM) scheme that use a digital multi carrier modulation method. To transmit data, a set of independent orthogonal sub carriers are used and the total bandwidth is divided into a large number of narrowband channels. Each channel does not interfere with the others [Pal09].

In order to offer bandwidth more efficiently in underwater acoustic channels the spread spectrum techniques emerged. With OFDM we can transmit more data in the same amount of time by using a larger amount of bandwidth. Other advantage is that OFDM can easily adapt to the severe features found in the underwater channel without the need of complex equalization. This system is robust against narrow band co-channel interference and against ISI. Underwater communication systems poses significant challenges in wireless transmission and OFDM is equipped to handling with these problems, such as multipath transmission [KT08].

Thus, any underwater communication system depends on the characteristics of the environment. Oceans are so complex and dynamic that makes difficult to predict the behaviour of the system. So, in addiction to everything mentioned above it is necessary to require a detailed knowledge of all physical factors in underwater environment to consequently choose the wireless technology and the associated modulation techniques.

Construct a reliable system that works perfectly in a huge range of distinct environments remains a challenge [Pre06].

## 1.1 Motivation and Objectives

Why study acoustic underwater communications? What is the motivation to read this dissertation?

Throughout the human history, the communications have an important role in the interaction among people and to the development of society.

Oceans cover 70% of the earth surface and most of this part remains unexplored when compared with land areas [Men11]. So, why not study the oceans in order to acquire more knowledge? Through underwater communication systems can be explored the many mysteries that remain hidden in the oceans highlighting aspects that otherwise might never be discovered.

For the correct and efficient use of these kind of communication systems, it is necessary to understand the acoustic waves and water properties. After that we need to trace certain goals to build the communication model and identify all important aspects that are feasible within the available time.

So, the main goals of this dissertation are:

- Study and identify the important aspects required to develop an underwater communication simulation model;
- Study various modulations techniques, in order to identify those that offer better performance;
- Simulate an underwater communication channel (e.g.*MatLab/Simulink/Xilinx*), to make possible the development of an underwater communication system;
- Develop an acoustic underwater communication system using digital modulations using a FPGA (field programmable gate array) based platform;
- Perform some experimental tests to validate what was previously studied.

## 1.2 Application scenarios

Wireless transmission through the oceans is one technology that allows the development of future observing systems of aquatic environment, serving as support for the oil industry, providing monitoring tools to study and research the marine life.

Currently, applications for underwater communications are explored in military, commercial and academical areas, making there use even more wide and diverse.

Some of these applications, that can use wireless transmission, through the oceans, are: [Men11],[APM05]

1. **Environmental monitoring**
   - Pollution (chemical, biological and nuclear);
   - Monitoring of ocean currents and winds;
   - Improved weather forecast;

- Climate change;
- Predicting the effect of human activities on marine ecosystems;
- Ocean salinity and PH control.

2. **Underwater explorations**
    - Explore marine life;
    - Detecting underwater oilfields or reservoirs;
    - Assist in exploration for valuable minerals.
3. **Disaster prevention**
    - Measure seismic activity to avoid tsunamis;
    - Study the effects of submarine earthquakes;
4. **Assisted navigation**
    - Identify hazards on the seabed (dangerous rocks, submerged wrecks and shoals in shallow waters);
5. **Rescue missions**
    - Provide help in shipwrecks;
6. **Information collection**
    - Ocean mapping;
    - Study of marine life;
7. **Surveillance systems**
    - Mine reconnaissance;
    - Intrusion detection systems;
8. **Underwater communications**
    - Diver communication (diver to diver or diver to ship);
    - Underwater Internet through Underwater Sensor Nodes (USNs);
9. **Assisted or Autonomous navigation**
    - Unmanned Underwater Vehicles (UUVs);
    - Autonomous Underwater Vehicles (AUVs);

## 1.3 Dissertation structure

This document describes all the research developed to specify and develop a system to evaluate the performance of several modulations schemes in underwater acoustic environment. This document is divided in 7 chapters.

After the introduction, chapter 2 and 3, presents the main themes surrounding the subject of this dissertation. Themes like, communication systems, modulation process, underwater wireless communications, acoustic propagation properties in water were taken into account.

The general description of the aspects presented in this work were discussed in chapter 4. The support system used to perform the work was briefly described and all the decisions considered important to the realization of the project were addressed. It was conducted a brief description about some concepts presented in system components, that can indicate the best selection to perform the proposed project.

In the chapter 5 it is presented the simulation of the modulation schemes, discussed in chapter 4. These simulations are performed in order to understand the one that best fits in underwater environment. During this chapter, all modulations blocks were thoroughly described.

In the chapter 6 were described all tests performed to study modulation schemes behaviour in underwater environment. The scenario and the environment conditions were extremely important and consequently were taken into account and were covered in this chapter. It was also carried out a comparison between the results obtained in experimental tests and the results obtained through simulation, submitted in chapter 5.

Finally, chapter 7 presents the conclusions of this dissertation. This chapter include some possible modifications in modulation schemes to improve the underwater communication system (e.g. speed, efficiency) and provide some ideas to take into account in future work.

# 2

# State of the art

Before starting any implementation, it will be necessary to perform theoretical analysis on the technologies surrounding, as well as the requirements that the system is subject. In this way, this chapter is intended to gather the basic concepts presented along this dissertation.

Initially it will be presented some important concepts about communication systems, with the intention to explain how they work. Along this chapter, subjects like modulation, demodulation will be discussed in order to provide a further insight into the communication systems.

Then, it will be presented the three types of wireless underwater communication known until now, and the advantages and disadvantages of each one and their applications.

## 2.1 Communication systems

Nowadays, many communication systems are present in quotidian and in such a diversified way. Telephones at our hands, radios in our living rooms, computers with access to internet in our office, TV channels transmitted through satellite and even our speech (see figure 2.1), are examples of a communication in the present days [Hay01].

A communication system can be defined as a medium (transmission channel), through which information flows (are transmitted) from a given location (emitter) to another location (receiver) [Men11].


**Figure 2.1:** *Examples of communication systems.*

Along this transmission a sequence of specific processes are established, that are described below [Hay01], [Men11].

1. Conception of a message signal;
2. Description of that message signal, through a set of symbols, performed with some precision;
3. Coding of these symbols, with the most appropriate way according to the physical transmission medium;
4. Transmission of encoded symbols to its destination;
5. Decoding and reproduction of the original symbols;
6. Recreation of the original signal, with a deterioration (e.g. noise, interferences) in their quality according to the imperfections of the system;

Regardless of the communication process that we want to analyse, there are always three basic elements in each communication system.

These basic elements are the emitter, that has the purpose of converting the original signal that was produced by the source of information, in a suitable "format" for its propagation through the medium (channel); the transmission channel, where the signal will be transmitted and, finally, the receiver that has the task of recovering, in a "recognizable" format the original signal from the received signal to be interpreted by the target user.

The transmission channel consists in the electrical medium that bridges the distance from the source of information to the destination. It may be constituted by a par of wires, a coaxial cable, radio wave or a laser beam. This channel will be constructed according with the needs of the system. Every channel introduces some amount of transmission loss or attenuation and this way we can say that the signal power will be progressively decreased with the increasing distance. [Car86].

As previously stated, the receiver operates on the output signal and has the function to reconstruct the original signal and deliver it to destination (user of information). Receiver operations includes amplification, to compensate for transmission loss, demodulation and decoding to reverse the signal processing performed initially at the emitter [Car86].

It should be noted that, besides the distortion undergone by the signal in its propagation over the transmission channel, the signal will be further modified due to factors such as noise and interfering signals, originated in other sources, which are added to the output of the transmission channel. With this, we can say that the received signal are a corrupted version of the transmitted signal [Hay01], [Men11].

This can be observed in the block diagram of a generic communication system presented in the figure 2.2.

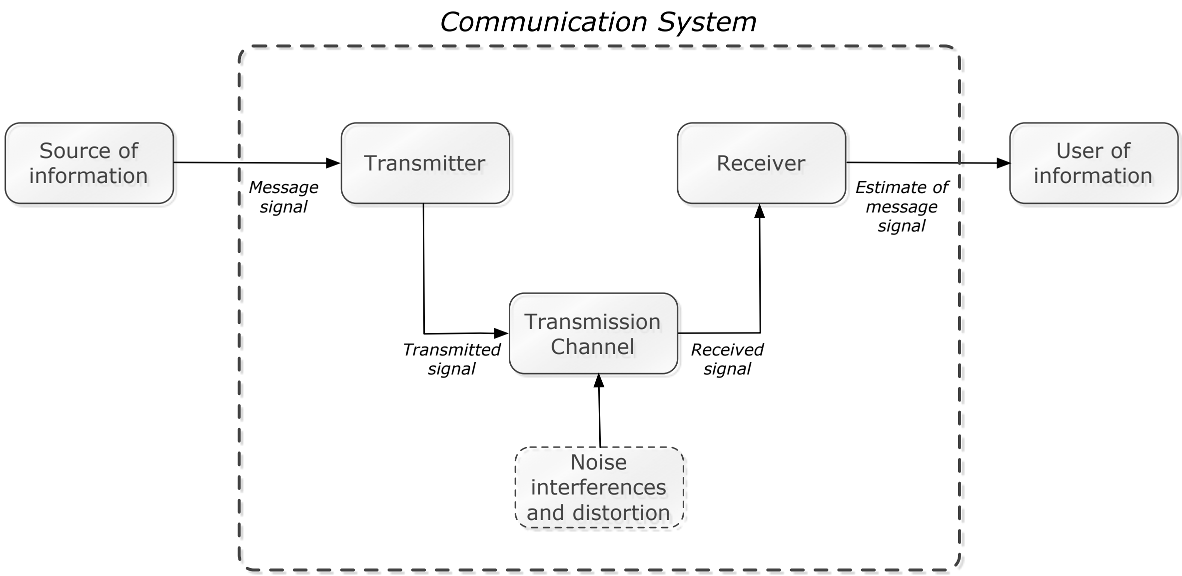


**Figure 2.2:** *Communication system block diagram.*

When we want analyse a communication system, we must always keep in mind some important aspects, namely:

- The kind of information that will be transmitted;
- How we should transmit these information;
- At which instant of time these information should be transmitted;
- Where is the destination of information that we are sending;
- From where is the information that we are expecting to receive.

As stated above, there are many kinds of communication systems. We can identify two major groups, namely wired communication systems and wireless communication systems.

Wired communication systems are constituted by: coaxial cable, telephone cable, optical fiber, among others. On the other hand, the wireless communication systems consists of communications such as: acoustic waves, optical signals, electromagnetic waves, satellite and laser beam [Men11].

In this way, the choice of communication systems types to use will be dependent on the criteria aforementioned to make the system more robust and effective as possible.

Like in every systems, we can face some limitations when designing communication systems. The fundamental limitations can be divided in two general kinds of constrains. One kind are the technological problems, including some considerations like hardware availability, economics factors, federal regulations and so on.

On the other hand we have the fundamental physical limitations, namely the laws of nature. These limitations, ultimately dictate what can or cannot be done, irrespective of technological problems that can exist. The fundamental limitations of information transmission by electrical means are bandwidth and noise [Car86].

### 2.1.1 Modulation process

As well known, signals cannot be sent directly through the transmission channels. This occurs due to its shape. This way, before the transmission, every signal suffer a process called modulation [Men11].

Limitations of the transmission channel can be overcome with the reduction of the effects of noise and interference.

Modulation is the process of varying one or more parameters of a periodic waveform, called the carrier signal, of a function of a modulating signal which contains the information that we want to transmit (original signal). On the other hand, the receiver recreate the original signal from a degraded version of a transmitted signal after its propagation by the transmission channel. The process behind the recreation of the original signal is called demodulation [Hay01].

In this way, the modulation is the process of superimposing a message signal, to a carrier signal, resulting in a modulated signal. This process can be observed in figure 2.3.

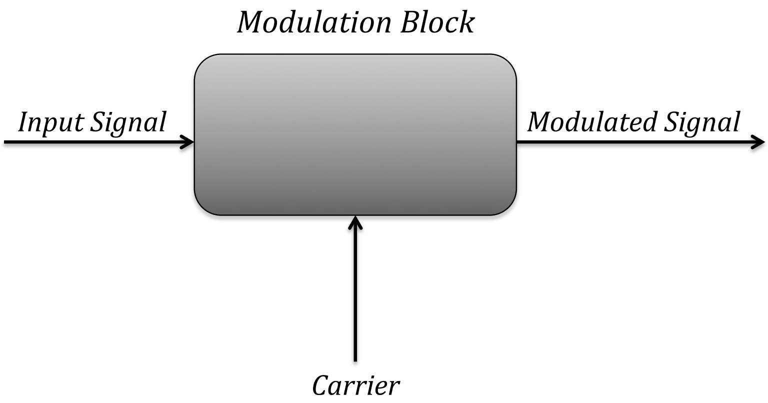


**Figure 2.3:** *Modulation Block.*

When we use a carrier wave, we can obtain properties of the signal, which are more advantageous to the transmission channels. One example of the modulation process can be observed when humans speak. The voice is transmitted through the air that, due to the high-frequency carriers present in vocal cords, are modulated by the muscular action of the oral cavity leading to the formation of the modulated signal. This way, our ears are one type of demodulator that interpret the voice like modulated acoustic waves [Men11],[Car86].

As previously stated, the process that reverse the modulation is called demodulation. However, the presence of noise and distortion in the received signal (modulated signal) is unavoidable, and makes it practically impossible to recreate exactly the original signal [Hay01].

In this way, we can conclude that the choice of modulation type is an extremely important aspect in the specification of the transmission link, because this choice affects the performance of the communication system.

We know that, some modulation schemes are less sensitive to the effects of noise and distortion than others and, due to this fact, it is necessary to analyse, in detail, the specifications and requirements of the communication system to subsequently choose the best modulation process.

The primary purpose of using modulation in a communication system is to generate a modulated signal suited to the transmission channel. Nowadays, exist several practical benefits and applications when we use modulation process, which will be briefly discussed below [Car86].

- **Modulation for efficient transmission**

  Signal transmission over a certain distance, always involves a travelling electromagnetic wave and, its efficiency depends upon the frequency of the signal being transmitted. In this way, using properties of translation frequency of carrier wave (CW) modulation, the information can be combined with a carrier, whose frequency was selected for desired transmission method.

- **Modulation to overcome hardware limitations**

  The construction of a communication system can be constrained by the high cost and availability of hardware, whose performance depends most of the times upon the frequencies involved. So, modulation process allows the designer to put the signal in some certain frequency range, and this way avoid hardware limitations.

- **Modulation to reduce noise and interference**

  To combat noise and interference a brute-force method is used that consists in increasing the signal power until it overwhelms the contaminations. However, increasing signal power is expensive and can be damage the equipment. Fortunately, some types of modulation have the valuable property, called wideband noise reduction, that suppresses the noise and interference.

- **Modulation for frequency assignment**

  When we tune a radio or a TV set to a determined station, we are selecting one of many signals being received at that time. Every stations have different assigned carrier frequency, so the desired signal can be separated from the other by filtering.

- **Modulation for multiplexing**

  Multiplexing consists in combination of several signals for simultaneous transmission on one channel. Techniques like *Frequency Division Multiplexing* (FDM) uses continuous wave (CoW) modulation to put every signal on a distinct carrier frequency, and uses a bank of filters to separates the signals at the destination. *Time Division Multiplexing* (TDM) uses pulse modulation to put samples of distinct signal in non overlapping time slots. A variation of multiplexing is called multiple access (MA). While multiplexing involves a fixed assignment of the common communication resource, at the local level, MA involves the remote sharing of the resource.

In short, we can identify two basic modulation types: Analog and digital modulation.

#### 2.1.1.1 Analog modulation

Analog modulation, also known as continuous wave (CoW) modulation, use a sinusoidal wave as the carrier and, the signal that we want transmit is analog or continuous. It should be noted that in analog modulation, the parameter that is being modulated, varies in direct proportion to the sign that we intend to transmit.

In this kind of modulation, the carrier will have a much higher frequency than any frequency components, which are contained in the signal to be modulated [Men11].

The modulation process consist in the displacement of the frequency spectrum of the message that we want transmit (original message) to a new and higher frequency band.

The modulation techniques most used in analog signals are the *Amplitude Modulation* (AM) and *angle modulation*, whereas the last mentioned can be divided in *Frequency Modulation* (FM) and *Phase Modulation* (PM).

***Amplitude Modulation:***

AM, consist in variation of the amplitude of the carrier in accordance with the amplitude of the original message that we want transmit [Hay01].

This can be observed in the figure 2.4.

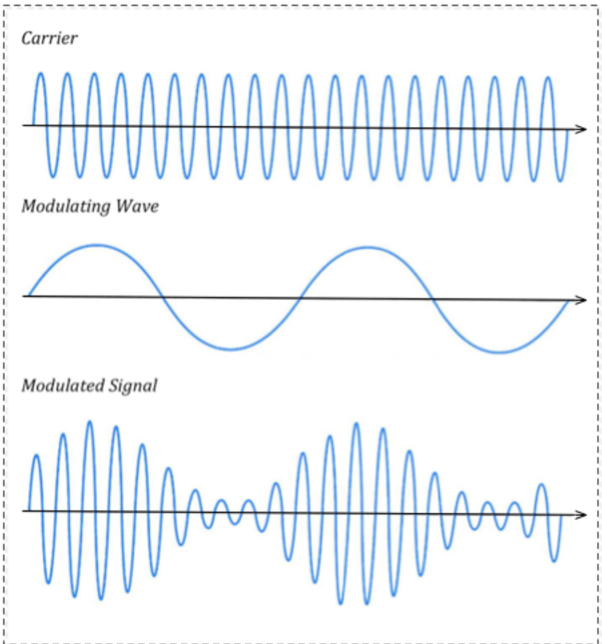


**Figure 2.4:** *Amplitude Modulation (AM)*

## ***Angle Modulation:***

As previously mentioned, *angle modulation* is an analog modulation technique. This technique consist in the variation/modification of the angle of the carrier.

However, this modulation can be further subdivided in FM and PM, which can be characterized with the variation of the frequency and phase respectively in accordance with the message signal [Hay01].

## ***Frequency Modulation:***

FM can be characterized with the variation of the frequency of the carrier in accordance with the amplitude of the message signal. The frequency carrier will change based on the amplitude of the signal that we intend to transmit (the carrier frequency varies linearly with the amplitude of this signal), and which varies with time, while the carrier amplitude is unchanged (fixed). This can be observe in the figure 2.5.

The greater the amplitude of the message signal, greater will be the frequency produced.

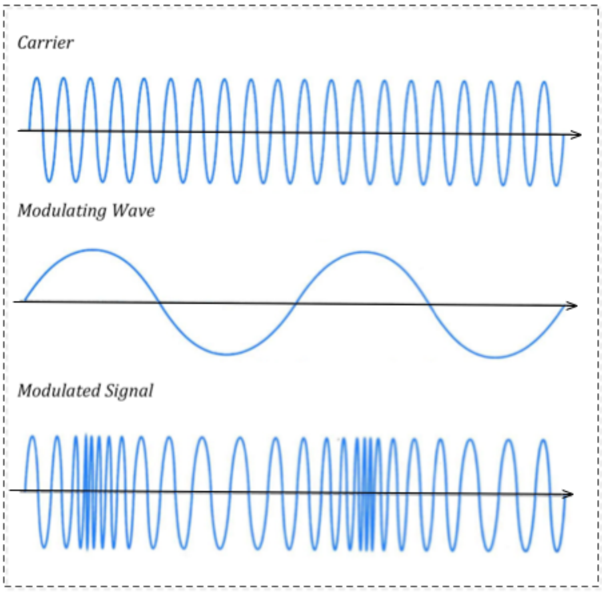


**Figure 2.5:** *Frequency Modulation (FM)*

## ***Phase Modulation:***

In PM, the phase of the carrier signal will be directly modified by the signal that we intend to transmit, that is, in PM the carrier phase varies according with the amplitude of the signal that we want to transmit.

As we can see in figure 2.6, the angle of the carrier wave changes consonant the characteristics of the signal that we want to transmit.

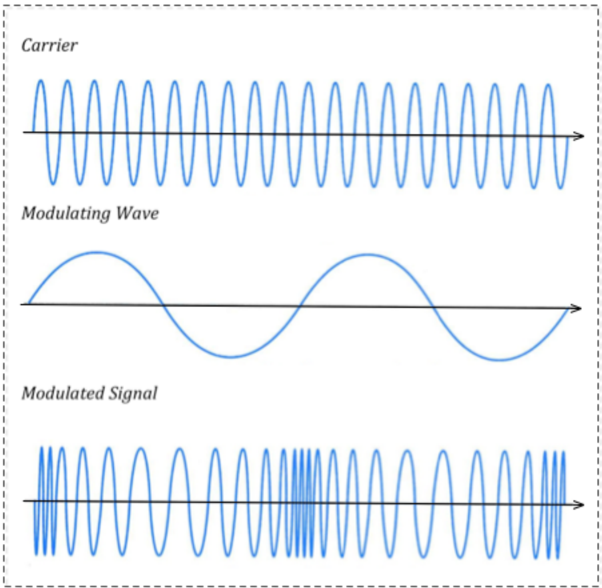


**Figure 2.6:** *Phase Modulation (PM)*

#### 2.1.1.2 Digital modulation

The transmission of data through a digital communication system can be made through two different methods: base band or channel band. In the first case, the data is encoded through the code line *NRZ (Non-Return-to-Zero)*, *AMI (Alternate Mark Inversion)*, *Manchester* or *2B1Q* and sent through the transmission channel. In the channel band data undergo a process called modulation that shifts the spectrum of the baseband signal and focuses it on a given frequency. Thus it is possible, unlike base band, send data from several different sources simultaneously, achieving a multiplexing technique. Another reason why it uses modulation, is the frequency behaviour of the transmission channel, which is not constant along the spectrum [dOF11].

In a digital communication system, digital modulation is used, also known as coded or discrete modulation, that consists in the modulation of an analog carrier signal by a discrete signal [Men11]. This modulation allows transforming digital signals in waveforms to be transmitted in the communication channel. This technique is characterized by the transmission and detection of a particular wave, through one finite set of waveforms that are known.

There are two broad categories of digital modulations: *pulse modulation* and *keying modulation*, which subsequently are divided into many other modulation techniques.

When we talk about a digital system, we find the following question: "What advantages we can have with digital system over analog ones?" This is an obvious question because, after all, an analog system requires only few components to be implemented, whereas to make an digital system it is necessary significantly more hardware.

Nonetheless, despite the increasing of hardware intricacy, we gain some advantages, namely [Car86]:

1. **Stability**

   Every digital system are inherent time invariant. To make greater accuracy in signal reproduction, are incorporated key systems parameters in algorithms, that only change if are reprogrammed. So, when is used analog hardware, its signal and its parameters can be subject to change with component ageing, external temperatures and other environmental factors.

2. **Flexibility**

   Once a digital system is finished, we have a great flexibility in changing the system. In this way, it is possible to employ a multitude of signal processing algorithms more efficiently:

   (a) Ameliorate signal fidelity;

   (b) Make error correction/detection for data precision;

   (c) Prosecute encryption for privacy and security of data;

   (d) Perform compression algorithms to remove redundancies;

   (e) Enable to do multiplexing of several types of signals (voice, pictures, video).

   Furthermore, these algorithms can be easily and remotely modified if it is necessary.

3. **Reliable Reproduction**

   As previously referred, an analog message, travelling through a channel, becomes degraded with the action of distortion and noise presented in every transmission channel. To solve this problem, we can add amplifiers to increase the signal power. However this amplification increases the noise also and, can only increases distortion. This way, the distortion becomes cumulative. One example of this phenomenon can be observed when we make a photocopy of another photocopy.

In short, when compared with the analog modulation, digital modulation provides a greater ability to transmit large amounts of information, gives a greater compatibility with the digital data services, enhances the security of the data that will be transmitted and provides a better quality of communication.

In the figure 2.7 we can observe a generic digital communication system.

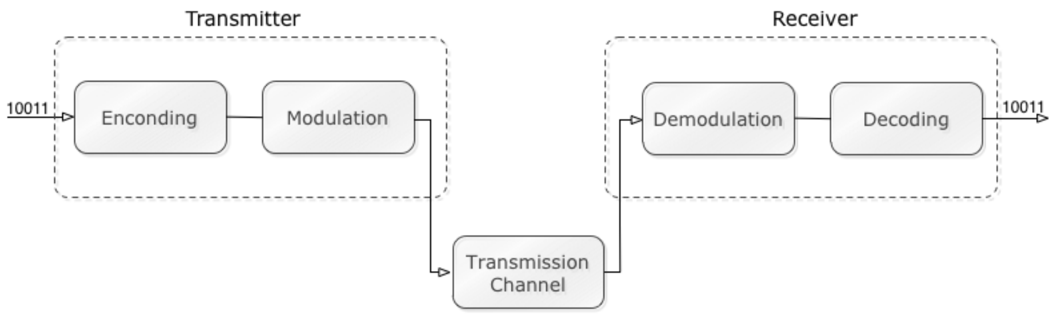


**Figure 2.7:** *Digital comunication system*

*Pulse modulation* consists in a method that "treats" (represents) the information as a sequence of pulses (pulse train), in which one or more characteristics of each pulse are modified in accordance with the variation of the input signal.

As previously mentioned, *keying modulation* are one category of digital modulation where the signal to be transmitted has a limited number of states to represent digital states that correspond to it (usually used zero or one). We can say, in a generic and simplistic way, that this type of modulation is a way to convert a digital signal in an analog signal.

The purpose of this type of modulation is allow the transmission of a digital signal through an analog communication channel. This type of modulation also have numerous techniques, which some of them will be now addressed.

### ***Phase Shift Keying (PSK):***

The PSK modulation technique consists in transmit data by changing or modulating the phase of a reference signal, which is called CW. This technique uses a finite number of phases, in which each phase assumes a unique pattern of bits. Thus, each pattern forms a symbol which are represented by the phase in question (particular phase).

Phase, in this particular context, is the starting angle at which the sinusoid begins. Depending on the start of the binary sequence, to transmit the binary symbols 0 or 1, we shift the phase of the sinusoid by 180 degrees. This modulation method is called *Binary Phase Shift Keying (BPSK)* (see equation 2.1).

$$BPSK(t) = \begin{cases} Asin(2\pi ft) & \text{if } bit = 0 \\ Asin(2\pi ft + \pi) & \text{if } bit = 1 \end{cases} \tag{2.1}$$

In the other hand, the receiver will make the determination of its phase and mapping back to the symbol it represents, to thereby retrieve the original data.

The most simplistic modulation in PSK is the BPSK, where the pair of two signals are used to represent binary symbols 1 and 0.

The result of this modulation can be observed in the figure 2.8.

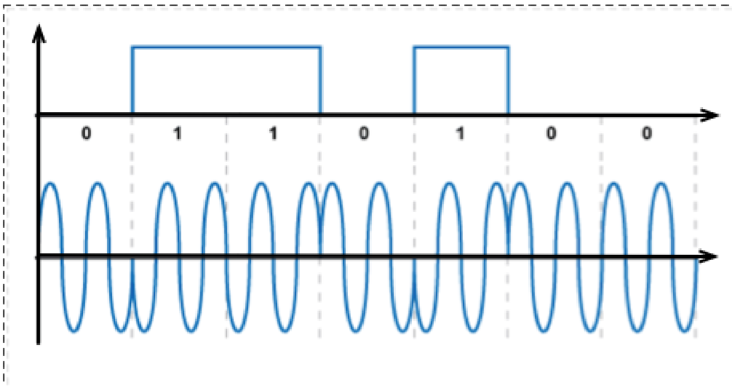


**Figure 2.8:** *Binary Phase Shift Keying (BPSK).*

As seen in figure 2.8, a pair of sinusoidal waves are used and only differ in a relative phase shift of 180 degrees, to represent binary symbols 1 and 0. However, it is possible to encode more than one bit, giving rise to multi-symbols modulations, such as *Quadrature Phase Shift Keying* (QPSK).

### ***Amplitude Shift Keying (ASK):***

ASK modulation is the change of the level of the amplitude of the carrier wave in accordance with the signal that we want transmit. So, to represent the binary symbol 1, is transmitted a signal with a particular amplitude and, to represent the binary symbol 0, we change the amplitude keeping the frequency constant (equantion 2.2).

$$BASK(t) = \begin{cases} A_1 sin(2\pi ft + \theta) & \text{if } bit = 0 \\ A_2 sin(2\pi ft + \theta) & \text{if } bit = 1 \end{cases} \tag{2.2}$$

Its operating principle can be explained through two of their particular types of modulations, the *Binary Amplitude Shift Keying* (BASK) and *On - Off Keying* (OOK).

In BASK modulation, presented in equation above, the signal that we want modulate will assume one of two possible discrete levels of the existing source of information (logic level 0 or 1). Typically, on the BASK modulation, the smaller amplitude corresponds to the logical level 0 and the largest amplitude corresponds to the logical level 1. In the other hand, the OOK modulation, the carrier assumes a certain level of voltage to the logic level 1 and zero voltage to logic level 0. Therefore, the magnitude of the modulation index is unitary [GTL06].

In the figure 2.9 we can observe the result of OOK modulation.

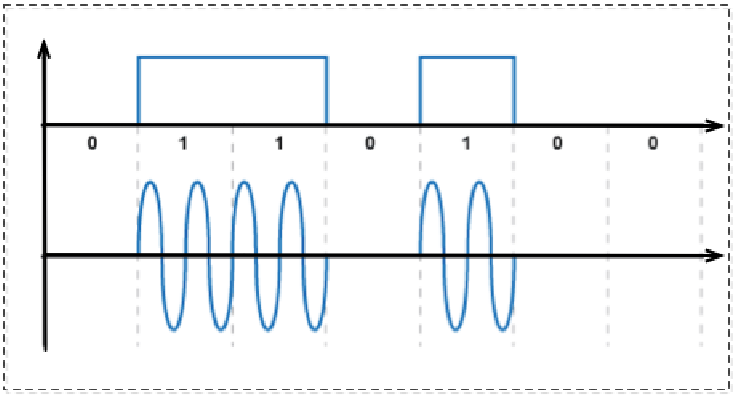


**Figure 2.9:** *Amplitude Shift Keying (ASK) OOK modulation.*

Like in other modulations, using multi-symbols is possible to increase the speed of communications, encoding this way more than one bit simultaneously. Thus, it can be used modulations like, for example, 4-ASK and 8-ASK.

## *Frequency Shift Keying (FSK):*

FSK modulation technique consists in discrete variations in frequency of the carrier wave in accordance with the signal we want to modulate. The frequency to be transmitted will be the result of the carrier frequency plus the offset for that undergoes one of the points.

In the *Binary Frequency Shift Keying* (BFSK) modulation, symbols 1 and 0 are distinguished from each other, through transmitting one of two sinusoidal waves that differ in frequency by a fixed amount [Hay01]. This can be observed in equation 2.3.

$$BFSK(t) = \begin{cases} Asin(2\pi f_1 t + \theta) & \text{if } bit = 0 \\ Asin(2\pi f_2 t + \theta) & \text{if } bit = 1 \end{cases} \tag{2.3}$$

The FSK modulator is formed by two ASK modulators, one of which produces modulated pulses in the frequency $F_1$ for each bit *1*, while the other produces modulated pulses in the frequency $F_0$ for each bit *0*. The output of the modulator is combined and transmitted [GTL06].

The result of this modulation can be observe in the figure 2.10.

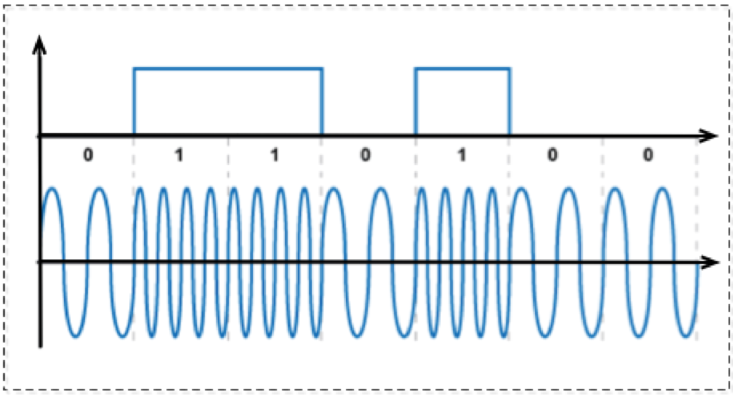


**Figure 2.10:** *Binary Frequency Shift Keying (BFSK).*

Digital modulation can be classified into *coherent* and *non-coherent* techniques, depending if the receiver is equipped with a phase recovery circuit or not. This circuit ensures that the oscillator supplying the locally generator carrier wave in the receiver is synchronized (in frequency and phase) to the oscillator supplying the CW used to modulate the incoming data stream in the emitter [Hay01].

Differently to ASK signals, PSK and FSK signals have constant envelop. Because of this property PSK and FSK signals are impervious to amplitude non-linearities, commonly encountered in micro-waves radio and satellite. In practice, through this reason, we find that PSK and FSK signals are preferred to ASK signals for passband data transmission over non-linear channels [Hay01].

All modulations described above, are called binary modulations because bits 0 and 1 are modulated in sinusoidal pulse sequences with amplitude, frequency or phase variables associated to the bit stream. However, this type of modulation is not effective when aiming at high speeds, where it is necessary to encode more than one bit simultaneously.

*M-ary* modulation is able to encode more than one bit simultaneously and, this way, it can be used when high speeds are necessary. In *M-ary* signalling scheme, we can send one of $M$ possibles signals $S_1\ (t)$, $S_2\ (t)$,...,$S_M\ (t)$ , during each signalling interval of duration $T$.

In this modulation $k$ bits are encoded that will give rise to different $M$ symbols, where $k$ is an integer [Car86],[Hay01].

This can be observe in the equation 2.4.

$$M = 2^k \qquad (Sym) \tag{2.4}$$

In turn, each symbol is represented by a sinusoidal pulse with a duration corresponding to the respective symbol. In this way it is possible to define the value of the symbol time *(Ts)*, depending on the bit time *(Tb)*. The equation that makes possible defining this value can be observed in 2.5 [Car86], [Hay01].

$$T_s = T_b \times k \qquad (Sym/s) \tag{2.5}$$

Finally, the transmission frequency or binary rhythm $R_b$, is given by equation 2.6, where the transmitted symbols rate $R_s$ is called *baud rate* and is represented by [symbols/s] [Car86].

$$R_b = R_s \times \log_2(M) = R_s \times k \qquad (Bits/s) \tag{2.6}$$

In passband data transmission the signals are generated by changing the phase, frequency or amplitude of the sinusoidal carrier in $M$ discrete steps. So, we have *M-ary* PSK, *M-ary* FSK and *M-ary* ASK digital modulation schemes.

So, we can conclude that all modulations mentioned above, can modulate more than one bit, giving rise to modulations such, for example, 4-ASK, 4-PSK, and 4-FSK.

However, with the combination of different methods of modulations into a hybrid form, we can get another way to generate *M-ary* signals. We can combine, for example, discrete changes in both the amplitude and phase of a carrier to produce modulation such *M-ary Amplitude Phase Keying* (APK).

One special kind of this hybrid modulation is the *M-ary Quadrature Amplitude Modulation* (QAM), which has some attractive properties. It transmits two digital bit streams, by modulating the amplitudes of two carrier waves, using the ASK modulation scheme where the two carrier waves, are out of phase with each other by 90 degrees. The modulated waves are summed, and the resulting waveform is a combination of both PSK and ASK modulation. We can say that *M-ary* ASK is a special case of *M-ary* QAM modulation [Hay01].

One important aspect is that binary signalling provides the greatest immunity to noise for a given $S/N$ because it has only two amplitude levels and we cannot send information with less than two levels. On the other hand, multilevel *M-ary* signalling requires more signal power but requires less transmission bandwidth. This happens because signalling rate will be smaller than bit rate of an equivalent binary signal. Therefore *M-ary* signalling can be used in applications such as digital transmission over voice channels, where the available bandwidth is limited and the signal-to-noise ratio is relative high [Car86].

Nowadays, *M-ary* modulation are often used in the construction of robust systems requiring high speeds.

Finally, in figure 2.11 we can be observe the graphic flow of modulations, where the various types of modulations are grouped, taking into account their characteristics.

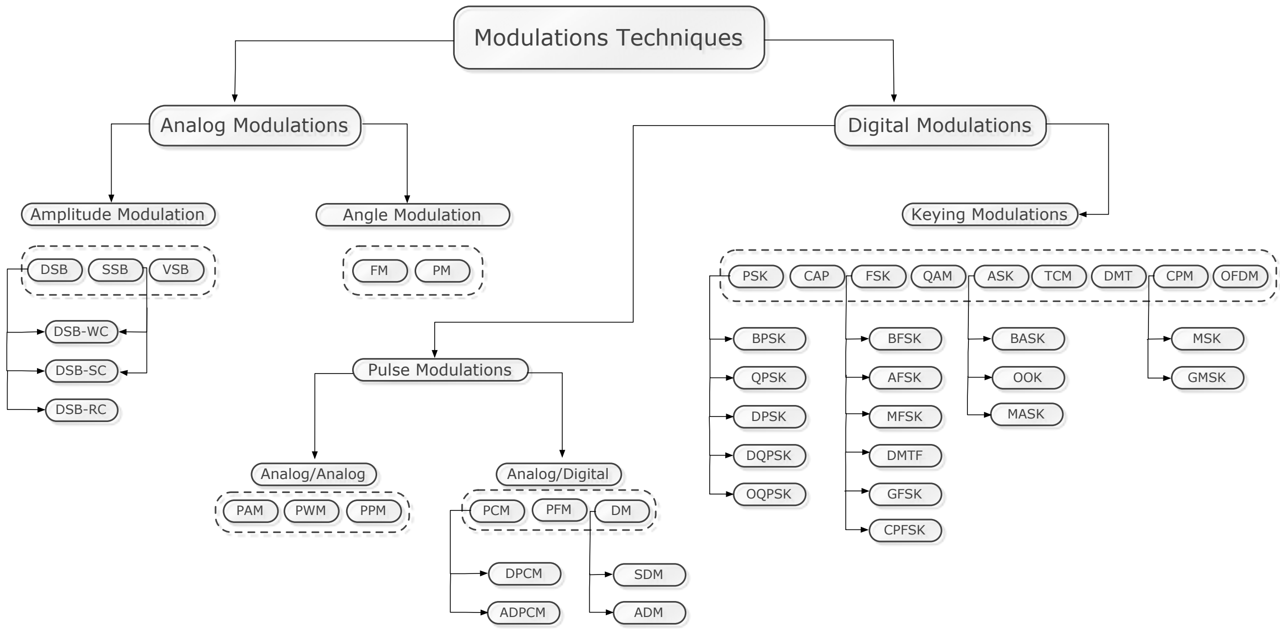


**Figure 2.11:** *General flow of modulations*

Until now, the important topics about communication systems were presented to provide the necessary background to the reader of this dissertation understand the next topics that will be presented. In the next section it will be presented, in detail, the characteristics of the underwater communication systems.

## 2.2 Underwater wireless communications

Today, wireless communication technology is presented in our lives in so many ways that it is almost indispensable for the functioning of quotidian life. However, despite the oceans cover 70% of the earth surface [Men11], underwater wireless communication continues unexplored when compared with the others wireless communications technologies. Currently, there has been an increase on the interest in the development of wireless communication systems in underwater environment. This increase has lead to intensive research on methods that allow this kind of transmission of information.

The result of this research may be organized in three big systems: Optical COMmunications (OCOM), communications using ElectroMagnetic (EM) waves and Acoustic COMmunications (ACOM).

### 2.2.1 Optical communication systems

Underwater OCOM systems arises with the emerging need to provide a high-speed communication in some applications that require a real time high-data-rate communication [Arn10]. This technology is a potential solution for high bandwidth and low latency in underwater wireless communications [CSD+08].

One example of underwater OCOM systems can be observed in figure 2.12 where an Unmanned Underwater Vehicle (UUV) or an Autonomous Underwater Vehicle (AUV) communicates with the underwater receiver using optical technology.

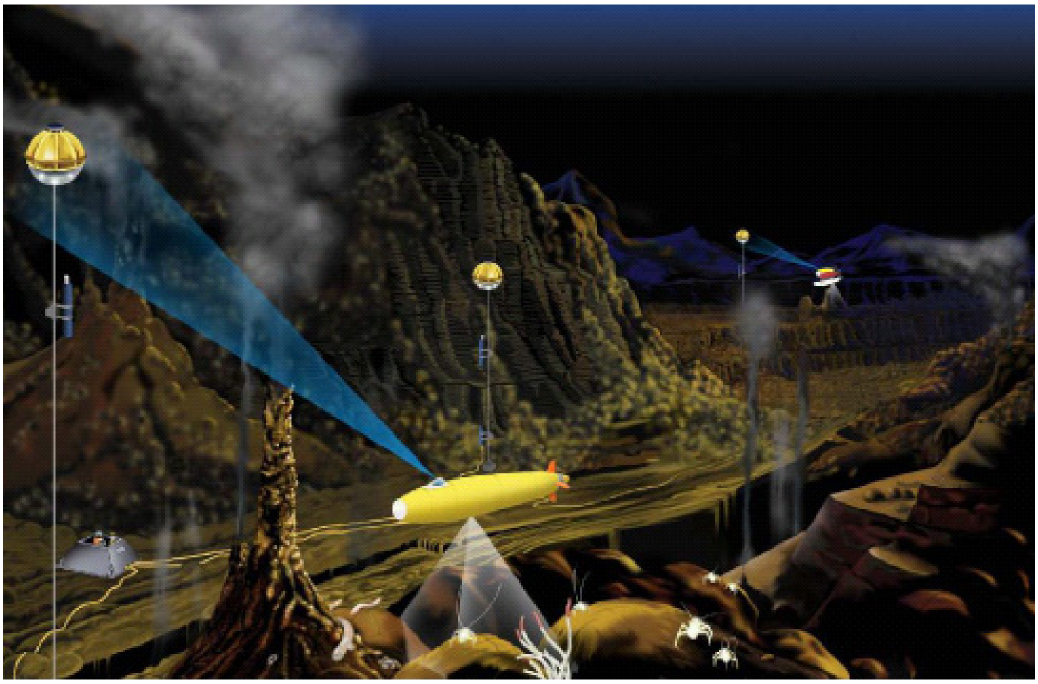

**Figure 2.12:** *Example of an underwater optical communication system [Cox07]*

This technology consists in underwater observatories that monitor some interesting resources on the seabed. These installations can be permanently fixed to the sea floor, collecting data over time. To collect the data an AUV that communicate with the observatory via an optical link is used. This kind of system is useful to various scenarios, namely can be employed for military uses to locate and disarming underwater mines or for finding enemy submarines

[Cox07]. Figure 2.13 shows several examples where underwater optical communication links are very useful.

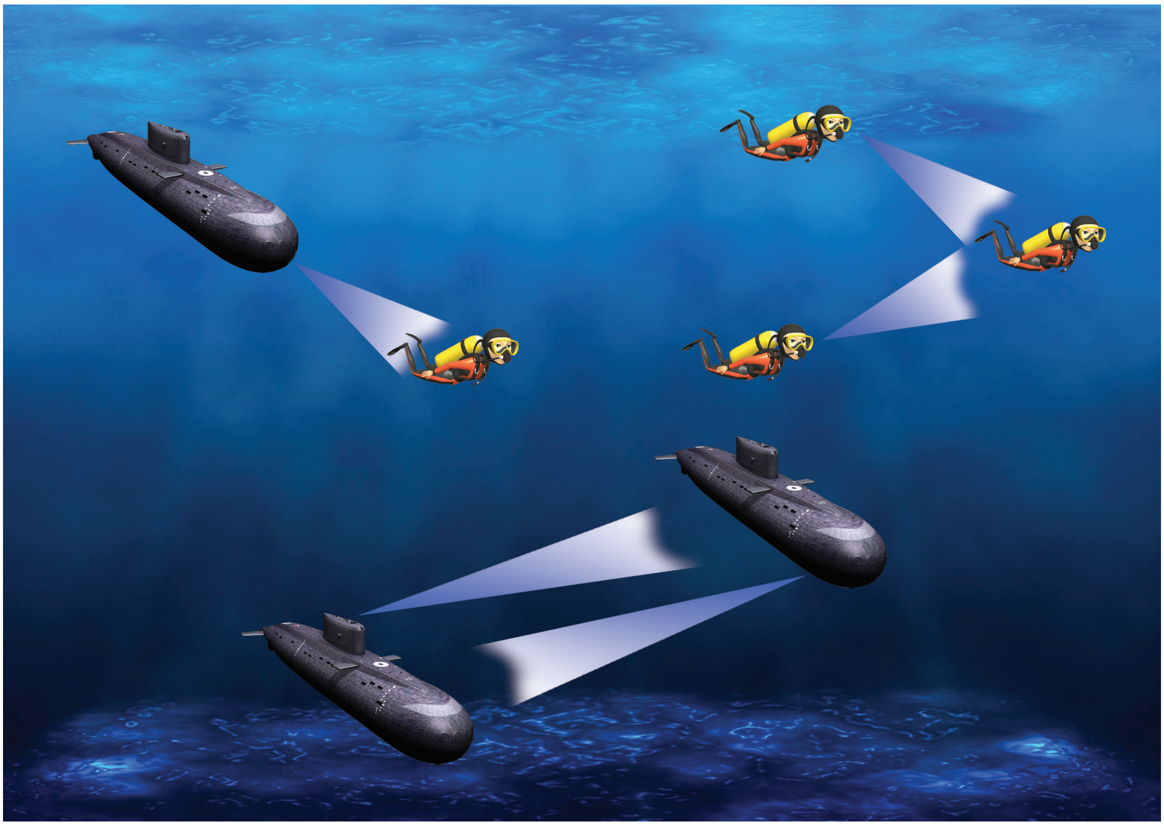

**Figure 2.13:** *Example applications of an Optical communication systems*

Using optical communications we can improve some kinds of communications (diver-to-diver and diver-to-ship). Some activities like diving becomes dangerous due to the lack of communication with other dive partners or with the surface. With an optical link it is possible to improve underwater communications, providing transfer of data, such as navigation information between divers [Cox07].

In short, the underwater OCOM systems consists in a small group of components, where the transmitter converts received information in an optical signal and send it through the transmission medium (water). In the other hand, the receiver detects the optical signal and converts it back into an electrical signal which, subsequently, is sent to the data destination [Men11].

The OCOM systems become quite popular in the last years with the creation of reliable, low-cost light sources, such Light Emitting Diodes (LEDs) and Laser Diodes (LDs), that take advantage of the comparatively low attenuation of light in the 400$nm$ - 550$nm$ range in seawater [CSD$^+$08]. There are several types of light sources but, because of the environment in which they are placed and their characteristics, the choice falls between the two types mentioned above. Like in other systems, both the LEDs and LDs technologies have some advantages and disadvantages which makes difficult to choose the technology to use [Bru10]. After identified the appropriate technology (source of light) for the proposed system it is necessary to take into account the choice of light color.

In figure 2.14 we can observe the attenuation of electromagnetic radiation and we can concluded that blue/green wavelength are the best option for underwater environments [Cox07].

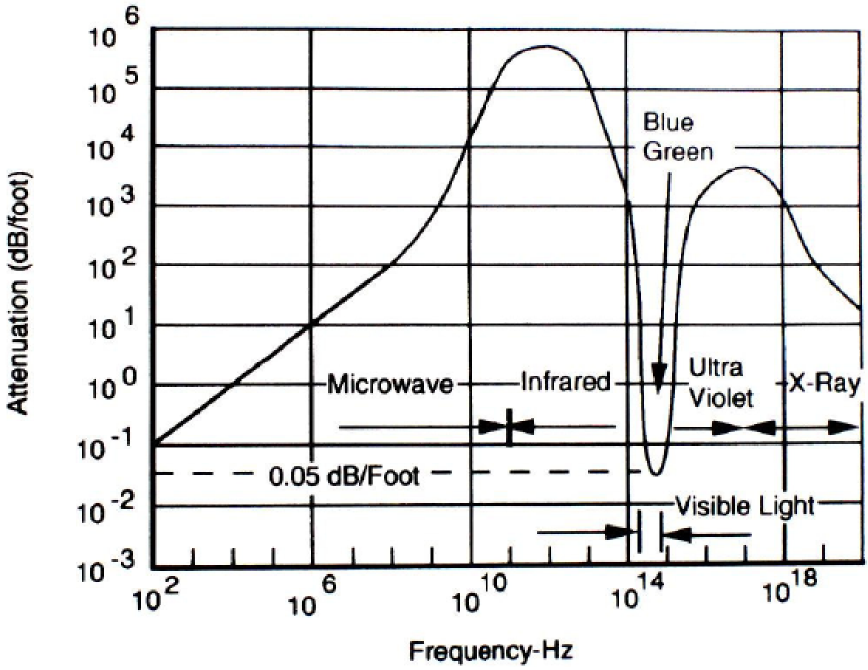


**Figure 2.14:** *Attenuation of electromagnetic radiation in water [Cox07].*

Underwater OCOM system has three types of communication links: Line-Of-Sight link (LOS), Modulating Retroreflector Link (MRL) and Reflective Link (RL) [Arn10].

LOS is the most common model communication link, where a connection between two points in wireless OCOM system is required (figure 2.15 A). In this scenario the transmitter (Submarine) directs the light beam in the direction of the receiver (diver). In this kind of technology the transmitter must be located in the line of sight of the receiver [Arn10].

MRL is an optical model used when one part of the transmission (for example the submarine) system has more resources than the other (diver). In the figure 2.15 B it is possible to observe that the submarine (interrogator) has more energy, while a small modulating optical retro reflector is installed on the remote end (diver). The submarine illuminates the retro reflector of diver with a beam of continuous waves. On the other hand, the diver reflects this beam back to the submarine while modulates the information on it [Arn10].

In some communication scenarios the types aforementioned are not available due to obstructions or misalignment of the transceivers. This way, the RL can be used. Thus, the transmitter emits a beam of light toward the surface. When the beam reaches the water-air surface is partially reflected to the receiver (see figure 2.15 C) [Arn10].

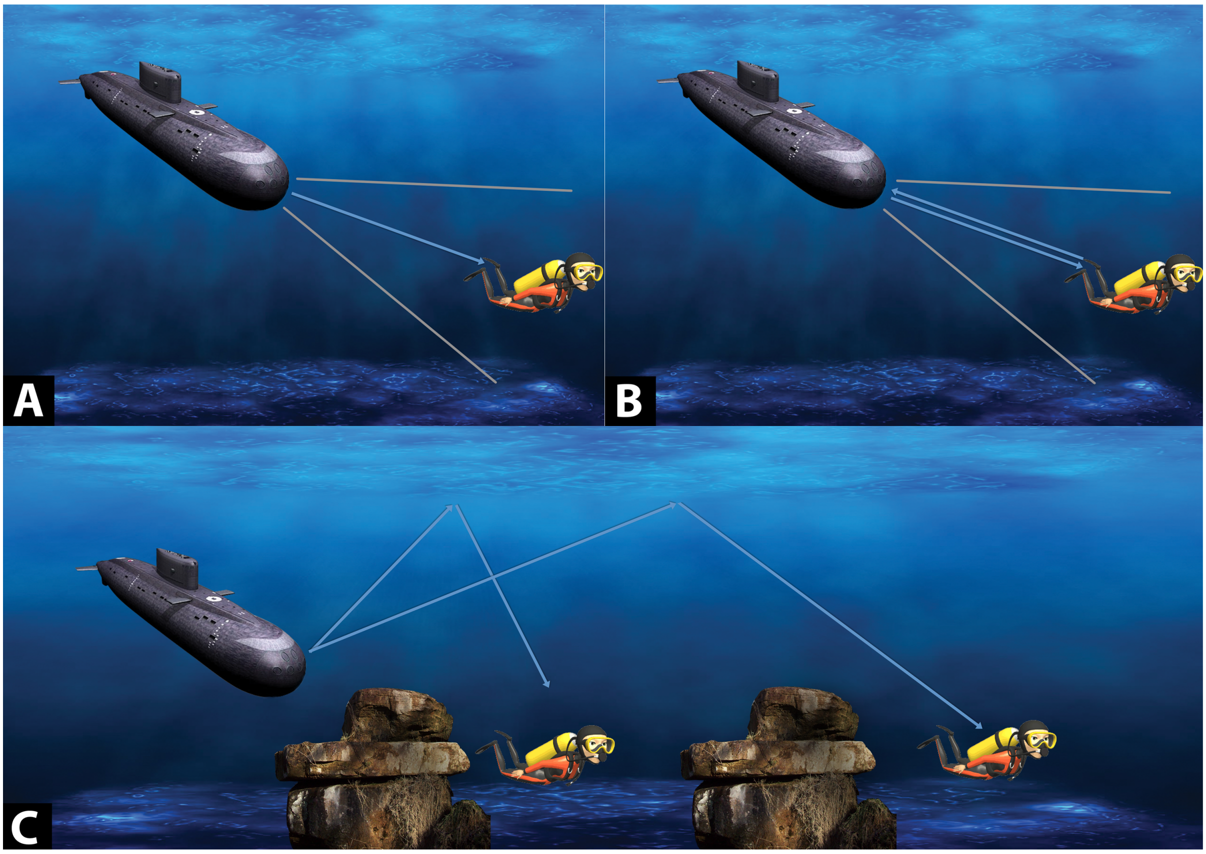


**Figure 2.15:** *Types of communication links in Optical Communication Systems*

### 2.2.2 Electromagnetic communication systems

Wireless communication systems that use EM waves, in particular Radio Frequency (RF) systems, are very used today. However, this kind of technology becomes very limited in aquatic environment because of the factors inherent to this medium, especially in the case of sea water [Lov06] [She05].

In figure 2.16, it is possible to observe the only underwater application successfully implemented that use EM waves technology. This application is Extremely Low Frequency (ELF) and consists in a bell that calls a submarine or a diver to the surface [Rho07]. This system is not very efficient because do not allow the realization of a data exchange between the entities; it only allows to call the receiver of information (submarine or diver for example) to the surface. Once on the surface, the entities will communicate using terrestrial radio to data exchange.

One of the pioneer, in radio communications to submarines underwater was Germany during World War II with the construction of "Goliath" in 1941 [She05].

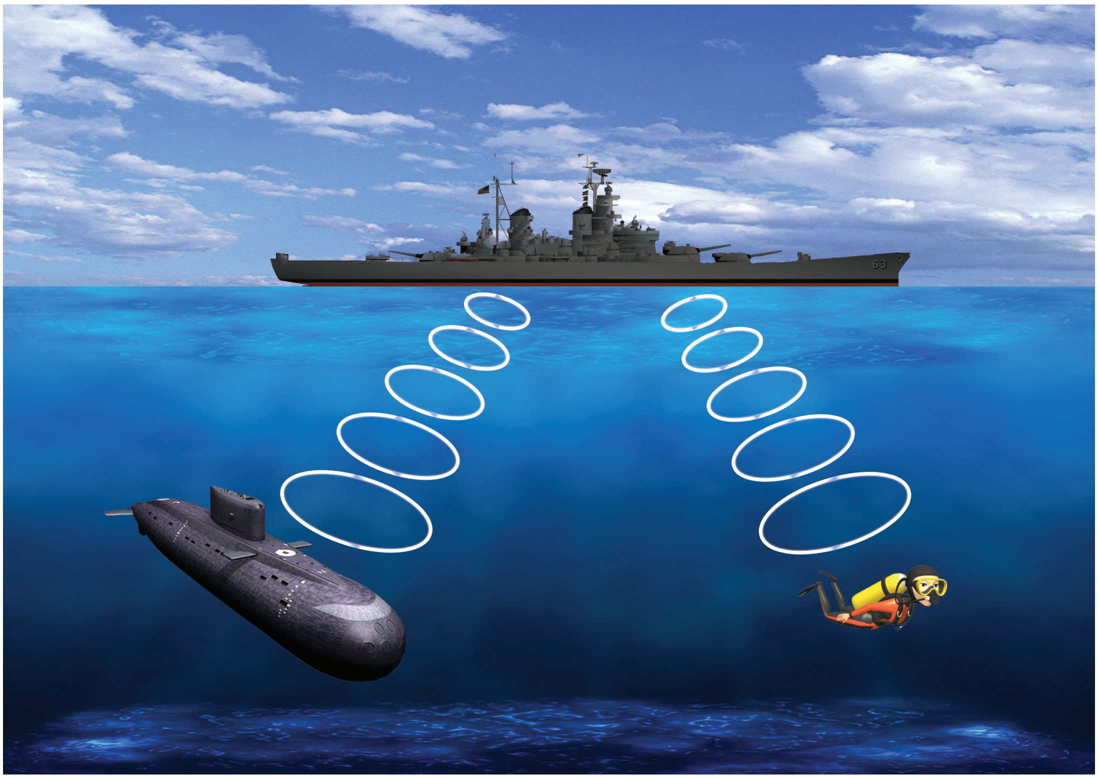

**Figure 2.16:** *Boat calling a submarine and a diver using electromagnetic waves*

EM propagation through water is very different from the propagation through the air. This difference can be explained by high permittivity and electrical conductivity. When compared with the air, the plane wave attenuation is high and increases rapidly with frequency. The water is the material that have one of the highest permittivity and causes significant impact on the refraction angle at the air/water interface [Rho06]. Due to these properties, an EM signal has a different propagation in seawater or freshwater.

Figure 2.17 shows the effect of increasing frequency in propagation velocity of EM waves for sea water, freshwater and free space, comparatively to the acoustic propagation velocity. It is possible to observe the increase of propagation velocity with the augmentation of frequency and its difference of propagation between seawater and freshwater.

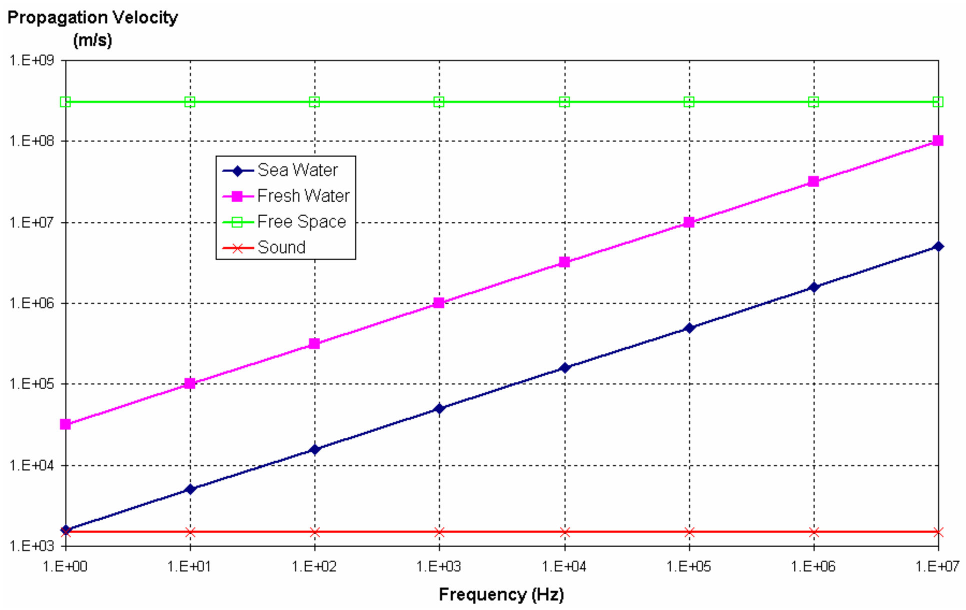


**Figure 2.17:** *Propagation velocity of acoustic and EM waves in underwater environment [Rho07].*

In Table 2.1, it is possible to observe the propagation of EM signal in seawater and freshwater. This table shows the relation of distances and bit rates for systems using EM waves [Rho07] [Men11].

| ***Range*** | *<1m* | *10m* | *50m* | *200m* | *2km* | *10km* |
|---|---|---|---|---|---|---|
| ***RF in seawater*** | Up to 100Mbps | 100Kbps | 5Kbps | 100bps | 10bps | 1bps |
| ***RF in freshwater*** | Up to 100Mbps | 1Mbps | 100Kbps | 1Kbps | 10bps | 1bps |

**Table 2.1:** *Expected data rate for EM communication systems [Men11] [Rho07].*

One important fact, when we refer to underwater communication, is to ensure that information flows by various "environments", that is ensure that communication systems work outside water. So, underwater communications includes communication that crosses the water-/air boundary. As mentioned above, due to the refraction angle, that is produced by the high permittivity of water, the EM signals become the best option for this type of communication, either in seawater or freshwater [Rho06].

Figure 2.18 illustrates the phenomenon when the EM signal cross the water/air boundary to the surface in a direction almost parallel.

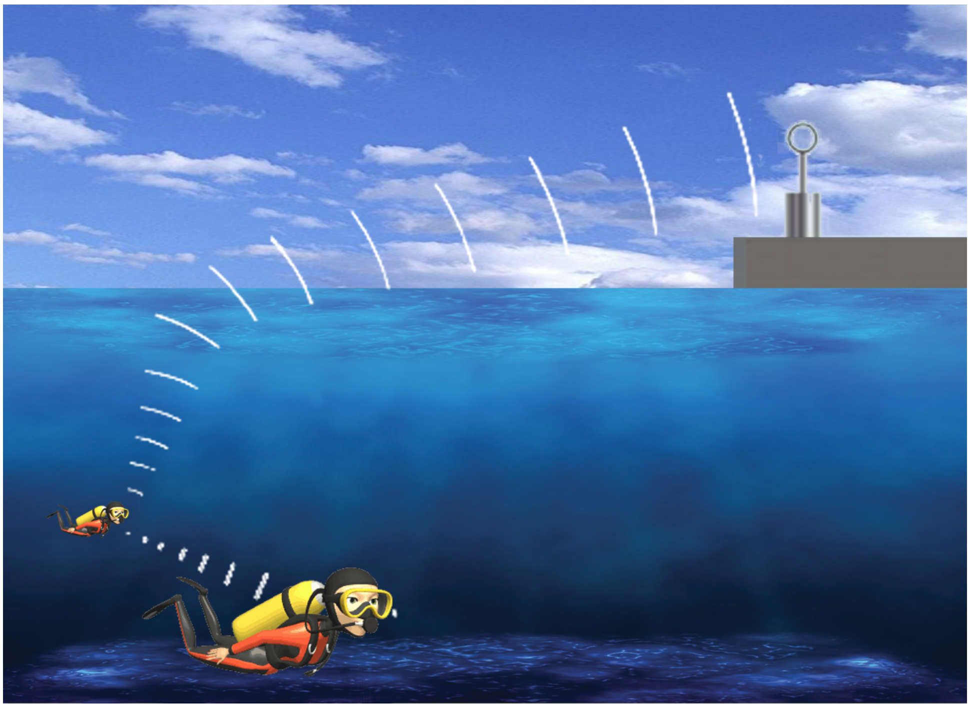

**Figure 2.18:** *Example of an EM communication system*

There are three types of antennas commonly used in EM COMunication (EMCOM) systems, such as: line antennas, magnetic coupled loop antennas and omni-directional antennas [Rho06].

Finally, we can classify underwater EMCOM systems according to its system design architecture: buoyant EMCOM system and direct linkage EMCOM system [YK11]. However, it is import to say that the buoyant EMCOM system uses wire during all underwater process and cannot be considered a purely wireless communication system.

### 2.2.3 Acoustic communication systems

ACOM is the technology most used for underwater communications (especially in long distance communications), with a significant increasing research over the last decades. However, this area of study started many years ago, when Leonardo da Vinci in 1490 proposed detecting ships by listening to the noise they radiate into water. With this theory he had demonstrated that it is possible to do the detection or tracking of objects in water using sound propagation [Vos10].

Later, in 1826 Jean Daniel Colladon, a physicist/engineer, and Charles-Francois Sturn, a mathematician, realized an experiment when recorded the underwater sound speed in Lake Geneva, Switzerland (See figure 2.19) [Vos10]. To perform this experiment, they used a church bell and a gunpowder flash. The church bell was struck underwater simultaneously with a gunpowder flash. By timing the interval between gunpowder flash and the arrival of sound (to hear the sound they used a trumpet) it was possible to calculate the sound speed. Despite the instruments used, they come to the conclusion that the velocity of sound in water was $1435 m/s$. The value determined was not too different from currently known values, making this measurement remarkably accurate [Vos10]. With this experiment it was possible to prove that sound travels faster in water than in air.

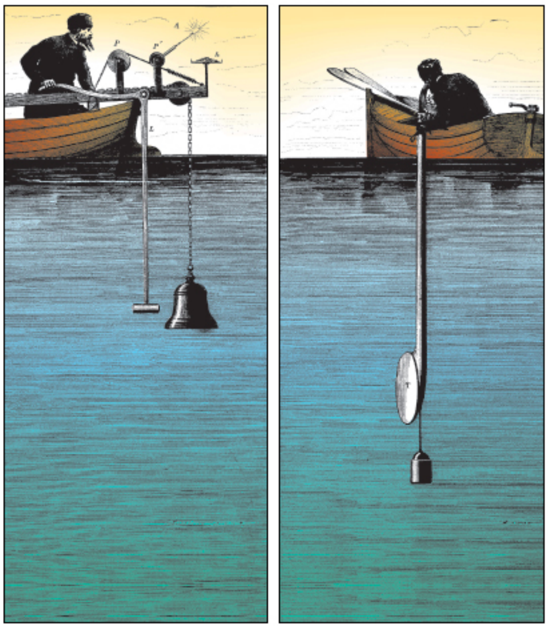

**Figure 2.19:** *First measurement of sound speed on water in 1826 [Vos10].*

The use of sound to detect objects in the water aroused enough interest following the Titanic accident. Could the accident be avoided with the use of this technology? [Vos10]

The ACOM systems were gradually growing and today is the technology mostly used for underwater communications when long distance communications is required. Today, this technology is used to detect and locate underwater objects, to measure the characteristics of the environment and to measure the location and velocity of underwater objects [Vos10]. In fact, due to many factors such as the low attenuation of sound in water, especially in deep waters with a stable thermal factor, the ACOM system is the primary form of wireless underwater communications today [LZC08].

We already know that the propagation of acoustic waves (sound waves), when the transmission channel is water, are significantly different when the transmission channel is the air. This fact can be confirmed if we keep in mind that the sound speed in water is around $1500 m/s$ while, in air, is about $340 m/s$.

An ACOM system is composed by several components. First, the information source will send digital data to the acoustic modem (modulator). This acoustic modem converts the information (electrical signal) into acoustic waves through an electronic transducer. These acoustic waves will be propagated in the underwater channel where they will reach the receiver of information that converts these acoustic waves into to an electrical signal again. Finally, this signal is sent to the acoustic modem (demodulator), that converts the signal into digital data [DKL+07].

The most important concept in underwater ACOM system is the transducer that converts energy from one form to another. The emitter device converts the electrical signal to an acoustic signal to be propagated through water. On the other hand, the receiver device (often called a hydrophone), converts the acoustic signal into an electrical signal [God02]. In figure 2.20 it is possible to observe an example of an underwater acoustic system.

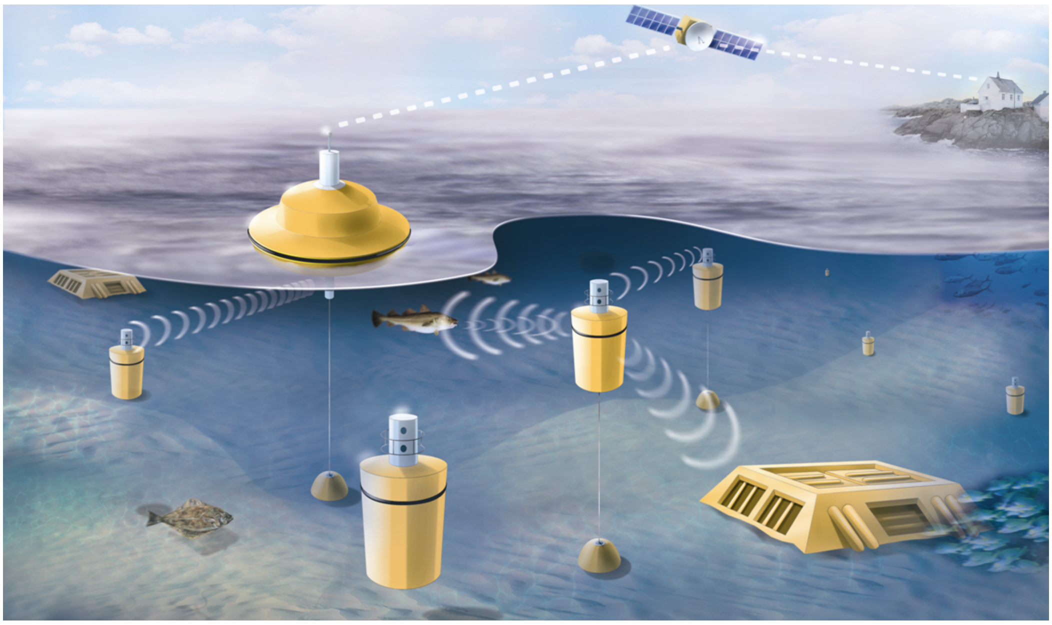

**Figure 2.20:** *Underwater Acoustic Network [Pro12].*

In accordance with the distance that can reach, underwater ACOM links can be classified as: very long, long, medium, short and very short and this can be observe in table 2.2 [APM07] [APM04].

| | ***Range (km)*** | ***Bandwidth (kHz)*** |
|---|---|---|
| ***Very long*** | 1000 | <1 |
| ***Long*** | 10-100 | 2-5 |
| ***Medium*** | 1-10 | ≈ 10 |
| ***Short*** | 0.1-1 | 20-50 |
| ***Very short*** | <0.1 | >100 |

**Table 2.2:** *Underwater Acoustic bandwidth for different ranges [APM07] [APM04].*

There are two types of ACOM systems: passive sonar and active sonar communications. The first one, as the name implies, only works to receive acoustic waves. The active sonar communication system can perform both transmission and reception [YK11].

As in other communication channels, underwater channels also has specific properties/features that influence the development of underwater ACOM systems. These properties will be discussed in more detail in chapter 3.

### 2.2.4 Summary of underwater communication systems

By the reading the previous sections it is possible to understand that underwater communication systems are significantly different. Each system have some advantages and disadvantages that are reflected in their performance in underwater environment. We can point to several factors in order to make the comparison between all communication systems and figure out what the best. Nevertheless, it is impossible to design a perfect system. Every system depends on the application scenario and can be more appropriate than the other to perform some specific task.

Table 2.3 presents a comparison between the three kinds of transmission of information in seawater environment. The major characteristics chosen to make this comparison are, nominal speed ($m/s$), power loss, bandwidth, frequency band, antenna size and effective range.

| | ***Acoustic*** | ***EM*** | ***Optical*** |
|---|---|---|---|
| ***Nominal speed (m/s)*** | $\approx 1.500$ | $\approx 1.5 \cdot 10^7_a$ | $\approx 3 \cdot 10^8$ |
| ***Power loss*** | >0.1 dB/m/Hz | $\approx 28dB/km/100MHz$ | $\propto turbidity$ |
| ***Bandwidth*** | $\approx kHz$ | $\approx MHz$ | $\approx 10 - 150MHz$ |
| ***Frequency band*** | $\approx kHz$ | $\approx MHz$ | $\approx 10^{14} - 10^{15}Hz$ |
| ***Antenna size*** | $\approx 0.1m$ | $\approx 0.5m$ | $\approx 0.1m$ |
| ***Effective range*** | $\approx km$ | $\approx 10m$ | $\approx 10 - 100m$ |

a) This value is valid for the frequency of $1MHz$

**Table 2.3:** *Comparison between acoustic waves, EM and optical waves in underwater environment [LZC08].*

It should be noted that each kind of underwater transmission of information have strengths and weaknesses and there are more comparison factors beyond those mentioned in the table 2.3. The choice of any technique depends fundamentally on the application scenario.

***Summary***

This chapter does a detailed description of the various topics that are directly related to the dissertation theme.

Initially, the concept of a communication system and everything that is connected to this was introduced, from the types of connections to its mode of operation. Then, its important concepts were presented pointing out their main features and explaining the importance of them nowadays. Subjects such as modulation and demodulation processes were described in order to provide a thorough knowledge about this subject.

After this approach, the three types of underwater wireless communication known until now were addressed: optical, EM and acoustic. Due to their unique features, ACOM systems are currently the most used and expected that this situation will remain during the next years. This idea is supported by specific characteristics presented by this type of systems, which were mentioned during the presentation of this chapter.

These concepts aims to provide the necessary background to the reader of this dissertation understand the next topics that will be presented during this document.

# 3

# Underwater acoustic channel

The underwater channel is one of the most challenging for communication purposes. When we are dealing with underwater communications, we will be faced with some problems precisely due to the use of water as a communication channel. As in other communication channels, the underwater channel has some properties/features which influence the development of Acoustic COMmunication (ACOM) systems. These problems are impossible to solve and at least they only can be minimized studying hard their behaviour. However, every problem has a different weight and importance according to the environment where is inserted and show changes from one underwater environment to another. The acoustic propagation is mostly characterized by attenuation, that increases with signal frequency, multipath, time-varying and low sound speed [Sto99].

The relevant phenomena in underwater acoustic channels are the propagation delay, attenuation, ambient noise, *Doppler* effect, multipath and bubbles. These phenomena define the conditions of underwater propagation. The above properties will now be briefly outlined.

## 3.1 Propagation delay

Every underwater ACOM system have some delays (approximately $0.67s/km$), which are much higher than the delays presented in ElectroMagnetic (EM) communications when the transmission channel is the air [APM07]. The sound speed in water is nearly $1500m/s$ and the speed of EM waves in air is $299.792.458m/s$. Due this fact, these large propagation delays, will negatively affect the communication system performance.

The sound speed in water can be affected by many properties such as temperature, salinity and depth. These phenomena can be observed in figure 3.1 and in table 3.1.

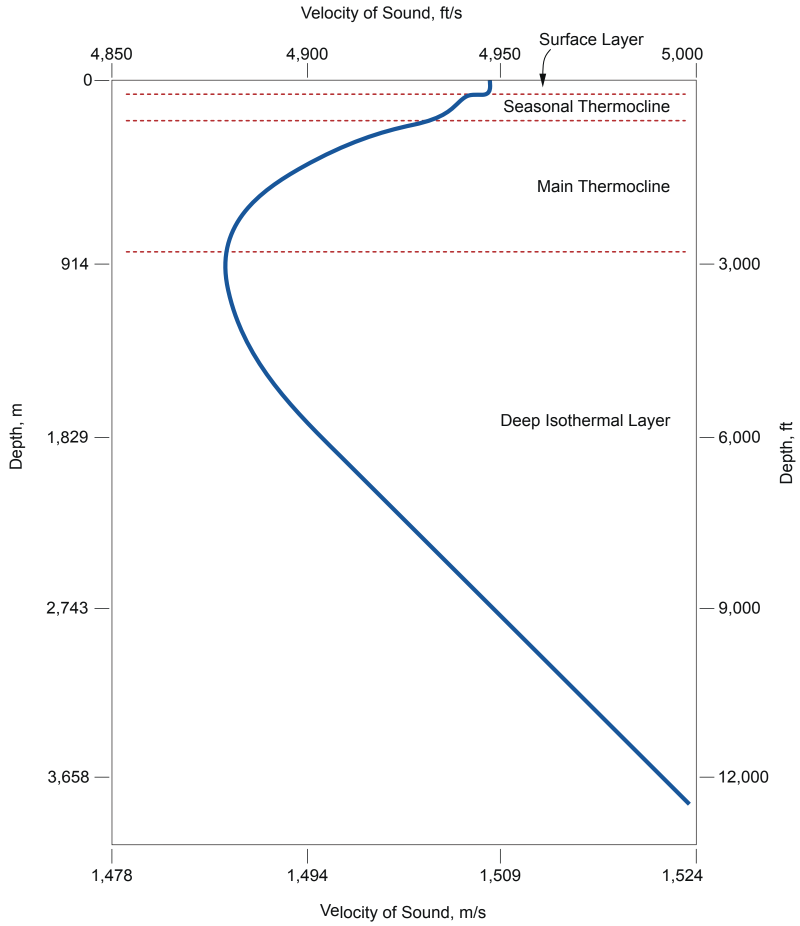


**Figure 3.1:** *Typical sound velocity profile for the deep ocean [BS08].*

The sound speed in water can be calculated through many equations, namely [IHA10] [Men11] [STS10]:

$$c = 1448,96 + 4,591T - 5,304 \cdot 10^{-2}T^2 + 2,374 \cdot 10^{-4}T^3 + 1,340(S-35) + 1,63 \cdot 10^{-2}D + 1,675 \cdot 10^{-7}D^2 - 1,02 \cdot 10^{-2}T(S-35) - 7,139 \cdot 10^{-13}TD^3 \quad (3.1)$$

Where $c$ is the sound speed in $m/s$, $T$ is the temperature in Celsius degrees (C°), $S$ is the salinity in parts per thousand ($ppt$) and $D$ is the depth in meters ($m$). This equation is known as *MacKenzie equation* that provide an error in the range of approximately $0.070 m/s$ [STS10] and is valid for the following ranges of temperature (T), depth (D) and salinity (S) [Men11]:

$$2°C \leq \text{T} \leq 30°C$$

$$0 \text{ m} \leq \text{D} \leq 8000 \text{ m}$$

$$30 \text{ ppt} \leq \text{S} \leq 40 \text{ ppt}$$

| ***Sound speed dependency*** | ***Coefficient*** |
|---|---|
| ***Temperature*** | $+4.6m/s$ per Celsius degree<br>$+5ft/s$ per Fahrenheit degree |
| ***Salinity*** | $+1.3m/s$ per ppt<br>$+4ft/s$ per ppt |
| ***Depth*** | $+0.016m/s$ per m<br>$+0.016ft/s$ per ft |

**Table 3.1:** *Sound speed variations (approximately) [BS08].*

To make a detailed and specific analysis about this parameter, we can perform a Sound Velocity Profile (SVP). It is important to refer that the SVP vary according latitude, longitude, depth and time. Thus, the SVP can only be considered valid for a certain location at a certain time. In figure 3.1 it is possible to observe a SVP example.

In short, the propagation delay consists in the relationship between the distance that one object travels between transmitter and receiver. This property is inevitably related with the object speed and consequently with the medium that it travels. This is a very important aspect in the underwater ACOM system because the transmission and reception delay (propagation delay) has to be taken into account during the signal demodulation.

The propagation delay in the aquatic environment can be calculated by the following equation [IHA10] [Men11]:

$$t = \frac{d}{c} \tag{3.2}$$

Where $t$ represents the propagation delay in seconds, $d$ is the distance between the transmitter and the receiver in meters and $c$ is the sound speed in $m/s$ which can be calculated through the equation 3.1.

## 3.2 Attenuation

The most important property, when we want to analyse an underwater acoustic channel, is the attenuation. The attenuation in water depends on two factors: distance and frequency (see figure 3.2 and 3.3) [Men11].

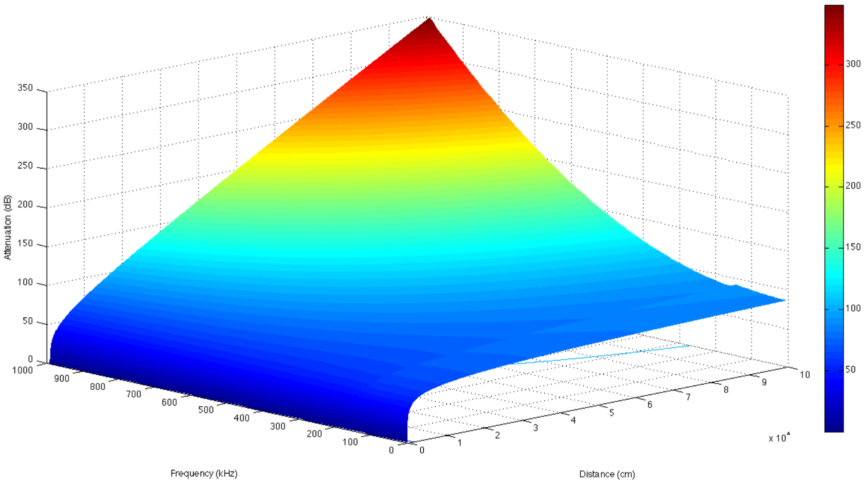


**Figure 3.2:** *Graphic of sound attenuation in water [Men11].*

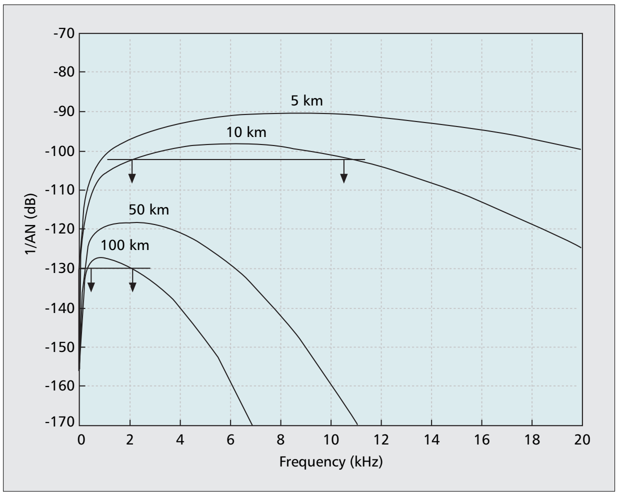


**Figure 3.3:** *Narrow-band Signal-to-noise ratio (SNR) as function of frequency for different transmission distances [SP09].*

In figure 3.3 we can observe the attenuation combined with noise in underwater acoustic communication, by plotting the quantity $[A(d, f)N(f)]^{-1}$ evaluated using the basic (ideal) propagation loss $A(d, f)$ and a typical power spectral density $N(f)$ of the background noise. It is clearly possible to observe the attenuation suffered by high frequencies at long distances. Therefore, the available bandwidth decreases with increasing distance [HSZ12].

The attenuation in underwater environment is constituted by three main components: absorption, spreading loss and scattering loss [Pre06]. The most important component of the attenuation is the absorption that consists in the transformation of acoustic energy into heat. This component is so important because its coefficient is the key factor for defining the maximum frequency that can be used in an underwater communication system (figure 3.4).

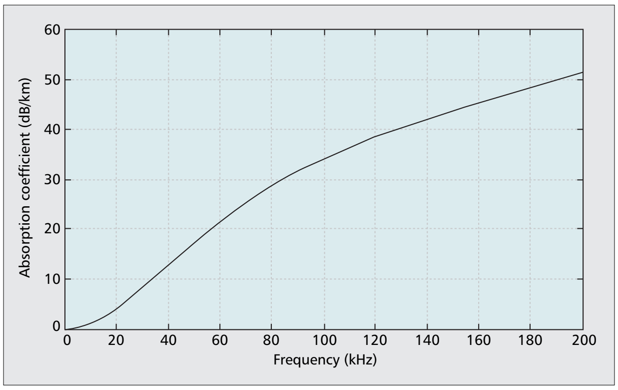


**Figure 3.4:** *Absorption coefficient [SP09].*

The spreading loss is characterized by the dispersion of the emitted energy with the increase of surface area. However, there exists many types of spreading loss, such as spreading spherical and cylindrical [Pre06].

Finally, the loss of energy suffer by the signal when it is redirected on a surface or due to inhomogeneities of the medium is the scattering loss. This phenomenon is constituted by reflection, refraction and diffraction.

The attenuation, or path loss, that occurs in a homogeneous and continuous underwater acoustic channel over a distance $d$ for a signal of frequency $f$ is given by the equation 3.3 [Sto07]:

$$A(d, f) = A_0 l^k a(f)^d \tag{3.3}$$

Where $A_0$ represents a unit-normalizing constant, $k$ is the spreading factor, and *a(f)* is the absorption coefficient.

The acoustic path loss can be expressed in *dB*, by the equation 3.4 [Sto07] [Men11] [STS09]:

$$10 \log A(d, f) = k10 \log d + l10 \log a(f) \tag{3.4}$$

The first term represents the spreading loss, and the second represents the absorption loss [Sto07], $f$ represents the frequency of the transmitted signal ($kHz$), *a(f)* is the absorption coefficient, $d$ is the transmission distance and the spreading factor is represented by $k$. The spreading factor describes the geometry of propagation and its most common values are: $k = 1$ for cylindrical spreading (shallow waters), $k = 1.5$ for practical spreading and $k = 2$ for spherical spreading (deep waters).

## 3.3 Ambient noise

In an underwater environment the presence of noise is inevitable, and this noise can be characterized by the man-made noise, site-specific noise and ambient noise. The man-made noise, as the name implies, is the noise caused by the interference of man. This can be translated by noise of machines or by shipping activity. This noise are also known by anthropogenic noise. The site-specific noise can be compared with the Gaussian noise which usually contains several non-Gaussians components and is found only in some areas. Finally, the ambient noise consists in turbulence, rain, breaking waves, maritime activity and consequently are always present in underwater environment.

In figure 3.5 it is possible to observe some sources of noise existing in the underwater environment.

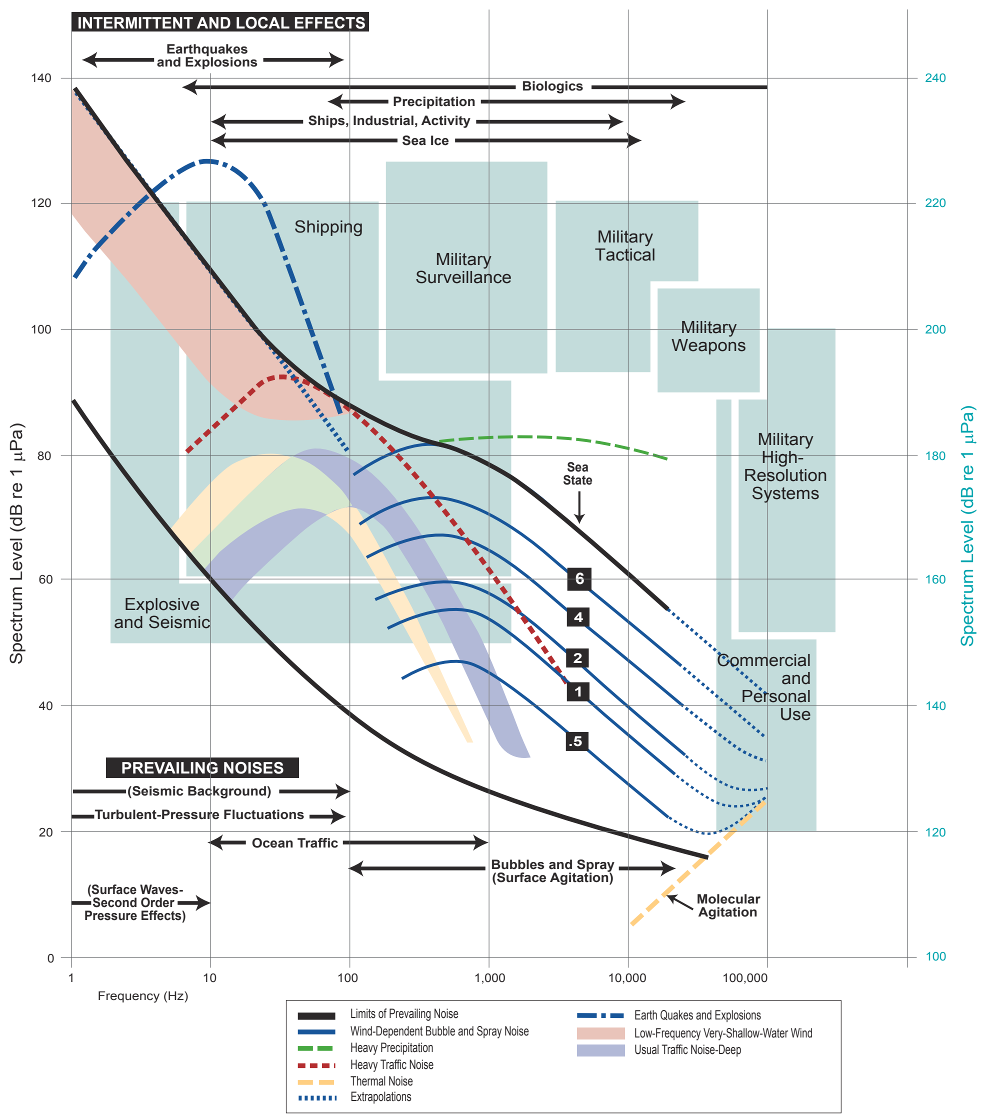


**Figure 3.5:** *Sources of noise [BS08].*

Through the important sources of noise, such turbulence, shipping, waves and thermal noise it is possible to simulate the noise present in the ocean. These types of noises can be described by Gaussian statistics and a continuous power spectral density (p.s.d.). The following equations shows the p.s.d. of the four noise sources mentioned above [Sto07] [Men11].

Turbulence Noise:

$$10 \log N_t(f) = 17 - 30 \log(f) \tag{3.5}$$

- The turbulence noise only influences a very low frequency region, $f < 10Hz$.

Shipping Noise:

$$10 \log N_s(f) = 40 + 20(s - 0.5) + 26 \log(f) - 60 \log(f + 0.03) \tag{3.6}$$

- Noise caused by distant shipping can be found in frequency region $10Hz$ - $100Hz$.

Waves Noise:

$$10 \log N_w(f) = 50 + 7.5w^{(1/2)} + 20 \log(f) - 40 \log(f + 0.4) \tag{3.7}$$

- This type of noise is the major factor contributing in the frequency region $100Hz$ - $100kHz$.

Thermal Noise:

$$10 \log N_{th}(f) = -15 + 20 \log(f) \tag{3.8}$$

- The thermal noise becomes predominant for regions $f > 100kHz$.

In the equations mentioned above, $f$ represents the signal frequency in $kHz$, $s$ is the shipping factor (varies between 0 and 1) and the wind speed, in $m/s$, is represented by $w$.

The total ambient noise power spectral density (p.s.d.) is illustrated in figure **??** and can be calculated in $\mu\, Pa$ by the sum of noise equations [Sto07] [Men11]:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{3.9}$$

## 3.4 Doppler effect

Movements caused by currents, waves and other factors affects any underwater communication system. Although transmitter and receiver are fixed, those movements give rise to the Doppler effect, leading to frequency shifting and a frequency spreading [Men11].

This phenomenon can be observed in figure 3.6, where the acoustic wave goes from point A to point B giving rise to the *Doppler* effect. Frequency shifting is represented by red and blue waves and frequency spreading is represented by black waves.

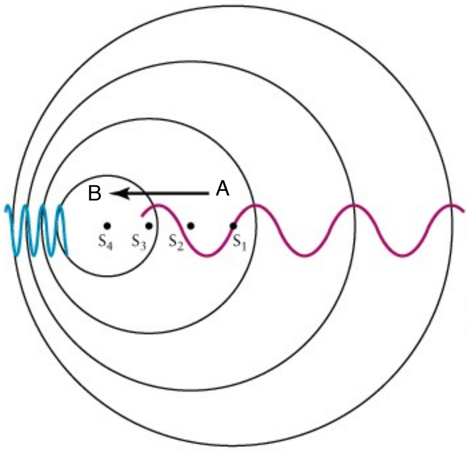


**Figure 3.6:** *Doppler effect*

*Doppler* effect is an important aspect in the design of an underwater communication system, because the system can be drastically affected by the very low sound speed and drifting.

The *Doppler* effect *($f_d$)* of a received signal is given by the equation [Pre06] [Men11]:

$$f_d = f_0 \frac{v}{c} \tag{3.10}$$

where $f_0$ is the original frequency of the signal, $v$ is the variation rate of the propagation path length (relative velocity between transmitter and receiver), and $c$ is the sound speed.

## 3.5 Multipath

One of the most common problems in underwater ACOM systems is the multipath. This problem consists in the reception by the transducer of the acoustic signals from two or more paths. This phenomenon makes the receiver to get more than one acoustic signal (figure 3.7). The multipath phenomenon causes the creation of Inter Symbol Interference (ISI) because each signal is received at different times [Men11].

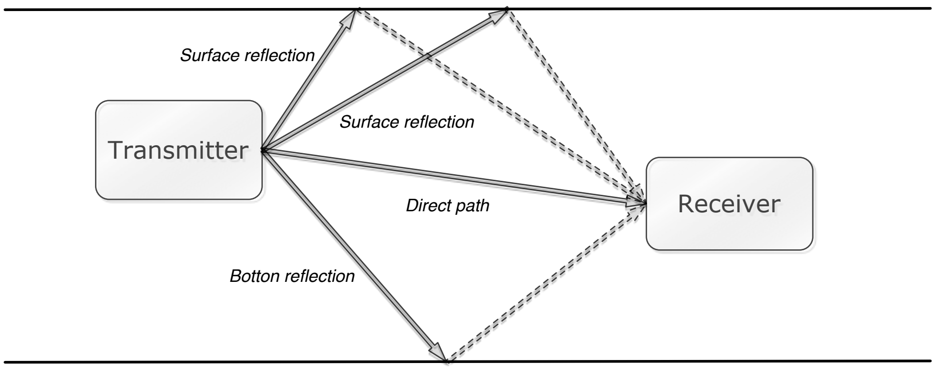


**Figure 3.7:** *Multipath effect*

Multiple path phenomenon can be caused by the occurrence of reflection or a refraction of acoustic waves. In the case of reflection, it is the result of a collision of the acoustic signal with the surface or the bottom of the sea or even with some object present in water. This phenomenon is very common in shallow water environments. On the other hand, the refraction occurs in places where the acoustic waves varies with factors such as temperature, salinity, pressure. According to these factors, this phenomenon usually occurs in deep waters [Men11].

Multiple path causes distortions in the acoustic signal and must be equalized at the receiver.

## 3.6 Bubbles

Bubbles phenomenon can cause interference in acoustic signal propagation, where high frequencies are generally most affected relatively with low frequencies. This kind of phenomenon can be created due to numerous factors, including the vibration of the transducers or even by breaking waves [Men11]. However, breaking waves bubbles can have a major influence on high frequency acoustic propagation. The presence of bubbles in a large amount can cause a significant attenuation into the signal.

Some research is being carry out in order to understand how bubbles can affect propagation of an acoustic signal in different environments and in different situations [Pre06].

***Summary***

This chapter does a detailed characterization of the underwater acoustic channel, addressing their main characteristics.

So, all phenomena present in underwater environment which influence/affect the propagation of the acoustic waves through this medium, were addressed and analysed.

Therefore, subjects such propagation delay in the acoustic waves, attenuation suffered by the acoustic signals when water is the transmission channel, noise present in this type of medium, the *Doppler* effect, multipath influence and bubbles in acoustic waves has been strongly addressed in this chapter.

All these important aspects have to be taken into account in the development of an acoustic communication system.

# 4

# System characterization

In chapter 2 and 3, it were presented all the required knowledge required in this dissertation, and now arises the need to introduce the system characterization. In this chapter, it will be performed a detailed explanation of all system components and referenced all expected and unexpected problems which were inherent in this type of design.

So, during this chapter it will be addressed the ideal characteristics for the correct system operation, and will be performed a description of how the values and system parameters were chosen.

Finally, it will be presented the support architecture used in the construction of the proposed system.

## System description

In this part of the chapter, some concepts of the system will be addressed. So, it will be described an underwater Acoustic COMmunication (ACOM) system.

This system is composed by two main components, namely:

- a communication module, a Personal Computer (PC) for example, that act as a data sender (transmitter of information), data receiver (receiver of information) or in some cases is both;
- an acoustic module, one at the transmission and other at the reception of the information. This module is composed by specific transducers and electronic blocks that will be discussed in more detail in section 4.3 of this chapter.

In figure 4.1 we can observe the architecture of the underwater ACOM system.

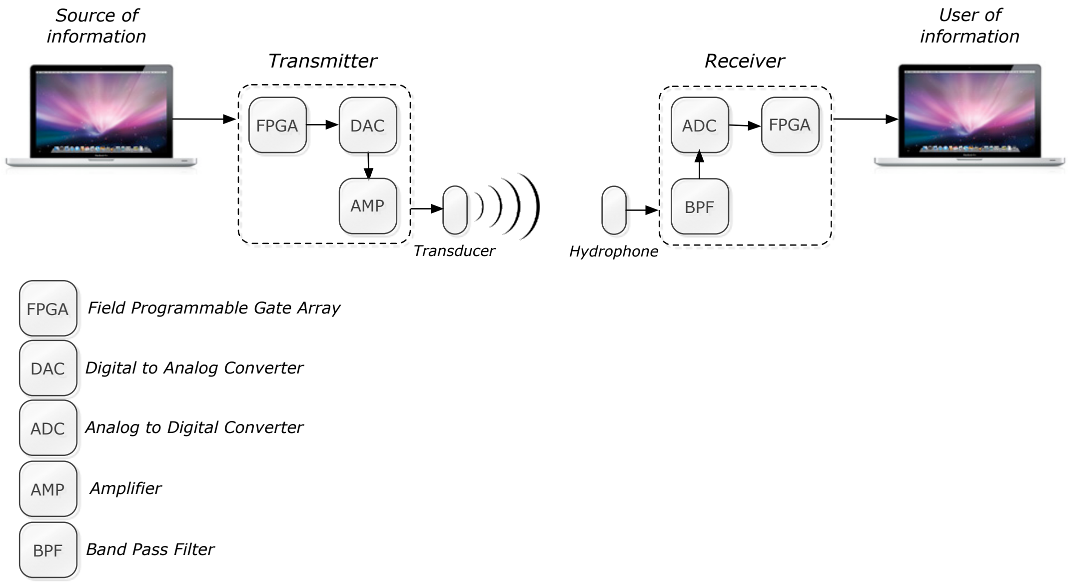


**Figure 4.1:** *Underwater communication system architecture.*

A Personal Computer was used to transmit an electrical signal that posteriorly will be converted in an acoustic signal through the acoustic module. For the acoustic module, a prototype has been developed (presented in detail later in section 4.3). Making a short description of this module we can say that it is constituted by several components. It was used a Field-Programmable Gate Array (FPGA)[1], where digital modulations were implemented, a Digital-to-Analog Converter (DAC), that makes the conversion to analogue and then be sent through the aquatic channel. The transmitter amplifier has the function of amplifying the output power, to enable the establishment of the communication within the desired distance. Due to several factors referenced in chapter 3, the signal needs to be amplified at reception. So, it was used a band pass filter with a gain associated, which in addition to filtering unwanted frequencies, acts as an amplifier. Then, it was performed the analog to digital conversion of the signal with an ADC to perform the demodulation process using FPGA.

In consideration of transducers, the choice was made according to the research work developed by PhD student Marcos Martins [MCLM+10] and the choice falls to *Polyvinylidene Fluoride* (PVDF) transducer. These components were very important to the system. The emitter (PVDF) will transform the electrical signal from the amplifier in acoustic waves. On the other hand, the receiver (hydrophone) receives the acoustic waves created by the projector (emitter) and transforms these vibrations into electrical signals again.

[1] A FPGA consists in an integrated circuit planned to be configured by a customer (client) or a designer after its manufacture. The FPGA generally uses specific hardware description language (HDL) for its configuration.

Figure 4.2 shows two of the many types of existing transducers.


**Figure 4.2:** *Types of existing transducers: a) Projectors b) Hydrophone*

Until now, all the physical components were addressed, and now arises the need to point others important aspects for the correct system operation. These aspects are essential to understand the influence that water environment has on digital modulation schemes. So the research and study of these aspects will be covered in two sections. First it will be presented the technical decisions regarding the study of water environment. In this section themes like frequency and distance will be addressed. The second section will describe the business decisions taken into account in the prototype construction.

## 4.1 Technical decisions

Technical decisions are a very important aspect in the study of aquatic environment. System operating frequency and the distance between transmitter and receiver influence the propagation of acoustic waves in water and have to be taken into account in the construction of these kind of systems.

**Frequency:**

To decide on the best frequency to use in these type of systems, we must take into account several aspects. Perceive how the frequency choice can affect the marine life, how to ensure a better information speed (data rate) possible and take into account the used hydrophone characteristics.

Underwater animals use sound with different frequencies to communicate among themselves and even to hunt. By reading [DKL+07] it was possible to verify that aquatic animals communicate using sounds of frequencies from a few hertz to about $100kHz$. It is known that with the increasing of the frequency values makes it possible to reach a higher bit rate, achieving, this way, a higher data rate. So, increasing the frequency we can send a bit in a shorter time.

Given this, and based on literature about the properties that influence the propagation of acoustic waves in water, together with the used hydrophone characteristics [Tec12a], the chosen frequency was $1MHz$. This is the frequency used in every digital modulation schemes referenced in this dissertation.

**Distance:**

The distance decision, was based on one of many possible applications that this system will be used. When the distance is too short it is possible to use a cable to communicate. So, the distance chosen is one hundred meters ($100m$), because:

- this distance makes the use of cable systems very uncomfortable and difficult;
- this distance meets best the requirements of the applications addressed in chapter 1;
- This value is between the values acceptable for a wireless underwater system and the frequency value chosen ($1MHz$).

In chapter 3 it is possible verify that with the increasing of distance obtains a reduced bandwidth and an increased attenuation suffered by the signal. So, it is important to reach a relative equilibrium among all parameters analysed.

## 4.2 Prototype decisions

In this section it will be referenced all the important aspects that influence the decision of the components to choose in the prototype construction. The criteria which were taken into account were: price, energy consumption and environmental cares.

**Price:**

The price is one of the most important criteria when we need to construct a prototype. Due the fact that this project did not have external financing, i.e., it is only financed by university funds, makes this parameter even more important, if not essential for its construction. In a final stage, this system can be commercialized and produced in a large scale, which makes the price an important factor to consider.

**Energy consumption:**

One ACOM system have energy consumption inherent with its use, what makes this a very important parameter when constructing the system. Due to the system be implemented in an underwater environments, makes the battery charging a very difficult and hard process, so it is fundamental that the system spends the minimum power as possible.

Some research in these areas, point to the possibility that the system can recharge their battery in an autonomous way, taking advantage of the movements caused by currents. Despite be a fairly innovative and effective idea, it can only be considered in the future studies.

**Environmental cares:**

Perceive if the components characteristics, used in the system, adversely affects the environment is a very important aspect that should be taken into account. So, after analysed these aspects, we can verify that all components used in this communication system will not cause any type of pollution in the environment where it will be implemented.

## 4.3 System support overview

After the presentation of the prototype decisions, it is now time to introduce the components which were chosen to make part of the support system. In the figure 4.3 it is possible to observe the block diagram of the entire communication system. The choice of the system support architecture was made taking into account the aspects mentioned in section 4.2. The support system presented was not developed in the ambit of this dissertation, but which however is indispensable to implement the binary modulation schemes developed. The study about the components that make part of the support system play an important role in the analysis of the obtained results, because it may help to understand some phenomenon that may occur in real operation, that can consequently affect these results.

It is important to note that the methodology adopted to introduce the system support architecture was not very exhaustive and unnecessarily detailed, serving this way only to contextualize the developed work in this dissertation.

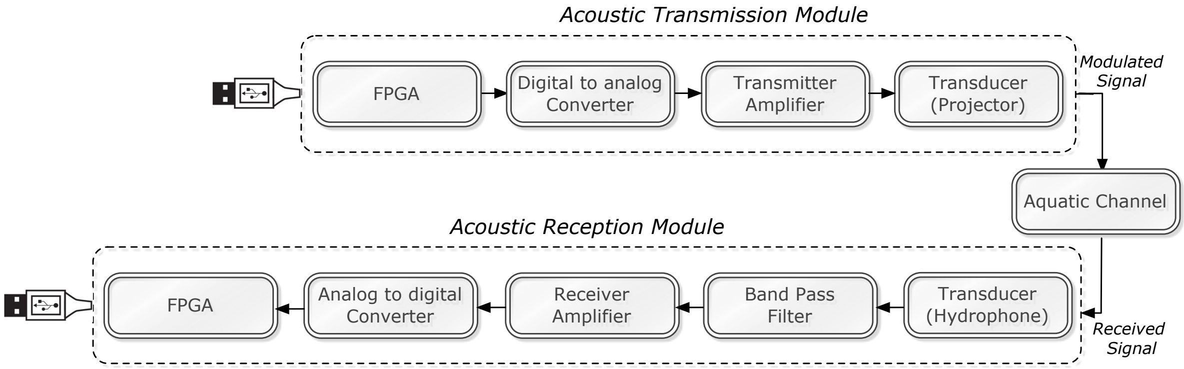


**Figure 4.3:** *Support system block diagram.*

In figure 4.3 we can observe all components of the communication system, and it is possible to identify three major blocks.

The first block represents the transmission module, the second represents the communication channel and, finally, the third represents the receiver module. Every block was constituted by several components, which it will be explained in more detail below.

### 4.3.1 Field-Programmable Gate Array (FPGA)

FPGA block consists on arrangements of several programmable blocks (logical blocks) which are interconnected between themselves with input/output cells by means of vertical and horizontal connection channels in order to implement the required functions.

FPGA is composed by three main types of resources: logic blocks, input/output blocks for connecting to the pins of the package, and interconnection wires and switches.

The first mentioned are arranged in a two dimensional array and, on the other hand, the interconnection wires are organized in horizontal and vertical routing channels between rows and columns of logic blocks [Gut09].

These logic blocks can be configured to realize complex functions, both as purely simple logic gates and, most of the time, these logic blocks include memory elements, that can be simple flip-flops or more complete blocks of memory. Typically each logic block has a small number of inputs and one output.

To implement a circuit in a FPGA, the mentioned logic blocks are programmed to perform specific function and the routing channels are programmed to make the required interconnections between logic blocks [Gut09].

The FPGA used in this project belongs to the family of Spartan-3A/3AN (see figure 4.4), and their key features can be consulted in [Xil12].

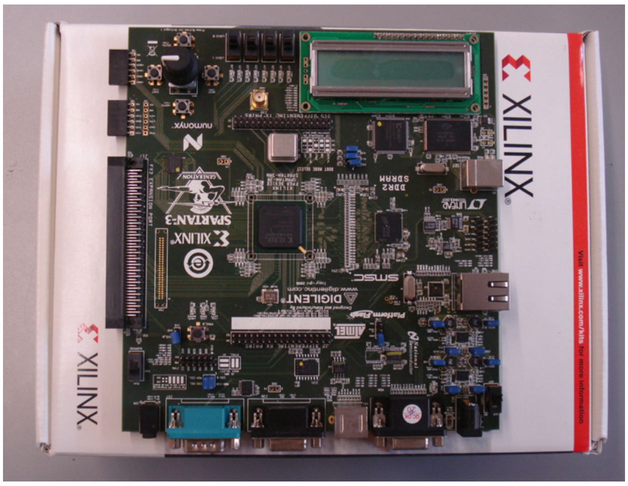

**Figure 4.4:** *FPGA used in project.*

In the proposed system the FPGA were used to support the implementation of the digital modulations and to simulate the input data. After designing the modulation scheme in the *MatLab*[2]*/Simulink* [3] environment using the *Xilinx* [4] specific blockset, it was created a bit stream file to program the FPGA device (See figure 5.1 in chapter 5).

### 4.3.2 Digital-to-Analog Converter (DAC)

A DAC is an electronic device that makes the conversion of a digital code to an analog signal. So, the DAC converts an abstract finite precision number into a physical quantity. Typically a DAC use a reconstruction filter to convert these abstract numbers into a concrete sequence of impulses, and use the *Nyquist Shannon* sampling theorem[5] to reconstruct the

[2] *MatLab* (*MATrix LABoratory*) is a programming environment that uses a high-level language for algorithm development, data analysis, visualization, and numerical computation.

[3] *Simulink* is a block diagram environment for multidomain simulation and Model-Based Design with MatLab and MathWorks.

[4] *Xilinx* is a software tool produced by *Xilinx* company for synthesis and analysis of HDL designs, which enables the developer to synthesize their designs, perform timing analysis, examine RTL diagrams and configure the target device with the programmer.

[5] According to the *Nyquist* theorem, the sampling frequency of an analog signal, that can subsequently be reconstituted with minimal information loss, should be equal to or greater than twice the highest frequency spectrum of this signal.

original signal from the sampled data. As expected, quantization errors can be introduced through digital sampling, which can be observed as low-level noise added to the reconstructed signal.

In the proposed system the DAC was used to convert the modulated signal from FPGA, into an analog signal to be transmitted through the aquatic channel. The DAC used in the system is the DAC904 [Ins12] and can be observed in figure 4.5.

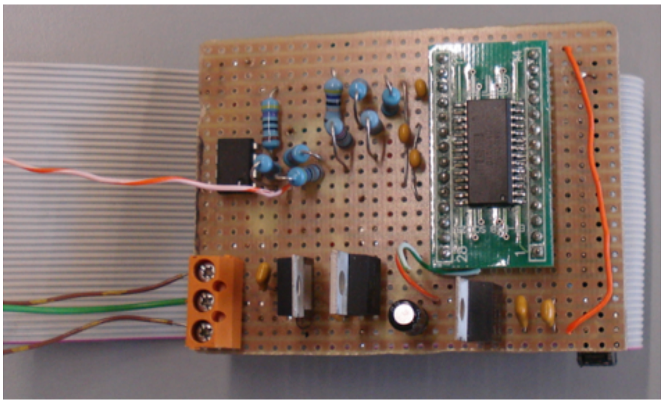

**Figure 4.5:** *DAC used in the project.*

### 4.3.3 Transmitter amplifier

An amplifier is an electronic device that increase the power of the signal. So, the transmitter amplifier receive a signal that will be amplified. The relationship between the input and output of one amplifier can be interpreted by two ways. If this relationship is expressed as a frequency function is called transfer function and, on the other hand, if is expressed in terms of magnitude we are facing to the phenomenon known as gain of the amplifier. We know that an ideal amplifier increases the power of a signal without otherwise altering it. However in real world ideal amplifiers did not exist, so the practical amplifiers presents finite distortion and noise that are invariably added to the signal.

Today exist several kinds of amplifiers that can be differentiated according to many parameters, such as: operation method, efficiency, linearity, and output power.

The amplifier used in the proposed work is presented in figure 4.6.

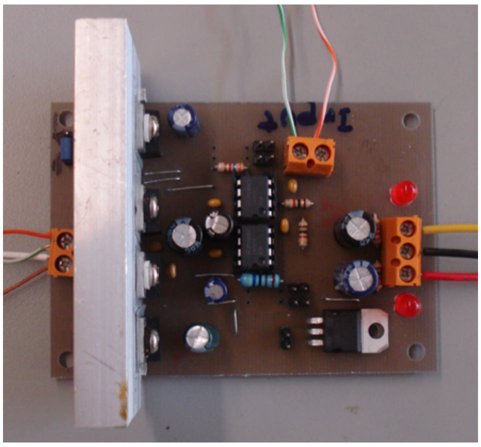

**Figure 4.6:** *Transmitter amplifier used in the project.*

### 4.3.4 Transducer (projector)

A transducer consists in a device that converts one form of energy to another. So, the signal from the amplification block causes a mechanical vibration in the transducer, that leads a creation of sound waves that will be propagated through the medium (aquatic channel). In the proposed system the type of transducer used was *Polyvinylidene Fluoride* (PDVF) that is a semi-crystalline polymer film. The PVDF transducer used has the following characteristics and is illustrated in figure 4.7.

PVDF:

- Piston (transducer type);
- $1cm$ of radius;
- $2 \times 100\mu m$ of thickness;
- Opening angle of the beam sound variable according to the frequency;

The acoustic pressure along the beam divergence angle can be calculated through the following equation [Men11]:

$$P = cp2\pi fD \tag{4.1}$$

where, $P$ is the acoustic pressure in Pascal, $c$ is the sound speed in water ($1500m/s$), $p$ is the water density, $f$ is the signal frequency in $Hz$ and $D$ is the particles dislocation in meters ($m$).

**Figure 4.7:** *PVDF projector used in the project.*

### 4.3.5 Transducer (hydrophone)

This transducer (hydrophone) has the inverse function of transmitter transducer, consisting in receive the sound waves that were created by the transmission module, and transform the vibration created into an electrical signal again. The transducer used in the project is the C304XR and can be observed in figure 4.8. Its datasheet can be consulted in [Tec12a].

**Figure 4.8:** *Hydrophone used in the project.*

### 4.3.6 Filter and receiver amplifier

Filter is an electronic circuit that performs the signal processing, where remove unwanted frequencies of this signal. So, the filter will receive the signal from the hydrophone and will remove (cut) the desired frequencies.

In this specific case it was used an active first order analog band-pass filter, with frequency band of $1kHz$ to $2MHz$. This filter has a gain associated (two), which acts as an amplifier of the reception. As the practical tests were performed at a reduced distance (in aquarium) the filter gain do not need to be very high. However, for longer distances an Automatic Gain Control [6](AGC) will be built to provide an automatic gain to the system.

The filter with gain used in the project can be observed in figure 4.9.

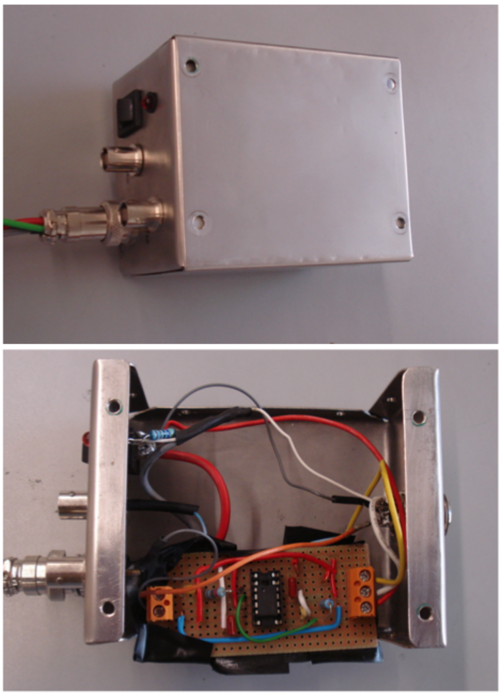

**Figure 4.9:** *Band Pass filter with gain used in the project.*

### 4.3.7 Analog-to-Digital Converter (ADC)

An ADC is an electronic device that convert continuous quantity (analog signals) to a discrete time representation in digital form. These devices can be described like a key building block in digital communication receivers employing digital signal processing techniques [Vir01].

Every ADC can be characterized by its essential parameters, such speed, power and resolution. The resolution associated to one ADC can be translated in the number of discrete values used to do the conversion. This parameter is expressed in bits, and consequently the number of discrete values available is a power of two.

In this particular system, is used a 14 bits ADC to convert the analog information (received signal) into a digital signal to be processed (demodulated) in the FPGA. The ADC used in the system is the AD9244 [Dev12] and can be observed in figure 4.10.

[6]AGC is an adaptive system. Its operation consists in refeeding of the average output signal level to adjust the gain to an appropriate level for a range of input signal levels.

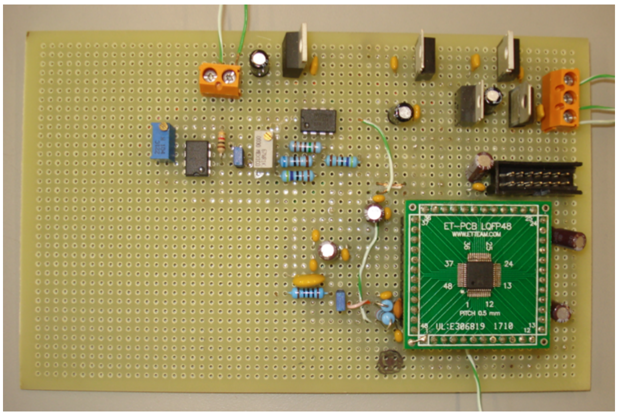

**Figure 4.10:** *ADC used in the project.*

### ***Summary***

In this chapter the description and analysis of all the system components were performed. First it were addressed all the important decisions related to the construction of the proposed system. These main decisions fall in two groups: Technical decisions and Prototype decisions.

After that, it was presented and explained all the blocks that make part of the support system, namely the FPGA, DAC, transmitter amplifier, transducer (projector), transducer (hydrophone), band pass filter with gain and ADC. Every components were briefly described to understand the important of each one in the system.

With all that has been analysed and described during the presentation of this chapter, it is possible to get a good idea of all aspects considered important for understanding the development of the acoustic communication system.

# 5

# Underwater Communication System implementation

After the presentation of the concepts contained in chapters 2, 3 and 4 it now arises the need to present the work developed with the recourse to *MatLab/Simulink* software with specific *Xilinx* blockset.

In this chapter are presented all blocks required to simulate an underwater communication system. Therefore, every modulation blocks simulated are presented separately for better understanding of the correct functioning of each one.

The specification of a modulation scheme of an underwater communication system is a difficult task and requires a detailed knowledge of all elements that influence the underwater conditions. This process can prevent unneeded expenditure on equipment and avoid the need to go to a place where the system in question can be tested.

After observing all the tests results, obtained through simulation, of several possible modulation schemes, the model must be tested in a underwater environment in order to evaluate its performance. As previously mentioned in chapter 3, the propagation of acoustic waves in underwater environment can be affected by several factors, so the results observed in experimental tests will be obviously different from those observed in the simulation model. However these results will be exhaustively detailed to understand the best model to the particular system.

This chapter starts with a brief description of the *MatLab/Simulink* tool and system generator. Then, all required steps to system implementation will be described and explained.

## 5.1 MatLab/Simulink

*MatLab* is a programming environment for algorithm development, data analysis, visualization, and numerical computation. This software can be used in a wide range of applications, including signal and image processing, communications, computational biology, control design, test and measurement, plus financial modelling and analysis.

The *MatLab* term appears from the combination of two other terms, *MATrix* and *LABoratory*. *MatLab* consists in a software that has some key features namely [Mat12a], [Men11]:

- High-level computing language;
- Data visualization via 2D and 3D graphics functions;
- Designing Graphical User Interfaces;
- Interactive tools for iterative exploration, design, and problem solving;
- Numerical computation and data analysis;
- Add-on toolboxes, which allows the use of *MatLab* in a wide range of applications;
- Offers great compatibility with other types of applications and languages.

Along this project the *MatLab/Simulink* environment in conjunction with specific *Xilinx* blockset were used as a fundamental tool to implement the *hardware* blocks on this project. *Simulink* is a software that is strongly interconnected with *MatLab* that is used in simulation, implementation, modelling and analysis of a great variety of systems, including communication systems. Besides presenting very interactive graphical environment and a very extensive set of libraries it also has an useful and efficient command prompt [Mat12b].

This software allows to simulate various types of modulations and watch the results in a graphical environment. Through *System Generator*, described below, the simulated algorithm can be implemented on Field-Programmable Gate Array (FPGA) using VHDL language on *Xilinx ISE 12.2*.

## 5.2 System Generator

*System Generator* consists in a digital signal processing design tool from *Xilinx* [PGB11]. It is based on the *MatLab/Simulink* environment used for FPGA design. Designs are made in the *Simulink* environment using a *Xilinx* specific blockset. All implementation steps, including synthesis, place and route are automatically performed to generate an FPGA programming file [PGB11] [fD08]. It also allows the inclusion of Digital Signal Processing (DSP) tools to design with FPGAs that automatic generates a HDL code starting from a *Simulink* model and allows the user to create its own libraries.

This system offers a robust *Simulink* libraries for arithmetic and logic functions, memories, and DSP functions. Due to its ability to support high level modelling and automatic code generation, *System Generator* allows to explore the interplay between mathematical abstraction and hardware-centric considerations [HB02].

The *Xilinx* DSP blockset provides over 90 DSP building blocks. Theses blocks include adders, multipliers and registers. In addition to these, a set of complex DSP building blocks are provided as forward error correction blocks, Fast Fourier Transform (FFTs), filters and memories. With these blocks it is possible to optimize the results for the selected device [fD08].

One advantage of *MatLab/Simulink* is that it can incorporate *MatLab* algorithms through *AccelDSP*[1]. The *System Generator* can also include *MCode* block to model and implement easy control operations. The System integration platform for designing DSP FPGAs are provided in the *System Generator*, that allows the Register Transfer Level (RTL)[2], *Simulink*, *MatLab* and *C/C++* components of a DSP system to come together in a single simulation and implementation environment [fD08].

Other important advantage is that the executable specification file can be created using the standard *Simulink* blocksets. So, the system generator uses the *Xilinx* DSP Blockset from *Simulink* that automatically invokes the *Xilinx* Core Generator to generate highly optimized netlists for the building blocks. Thus it is possible to execute all the downstream implementation tools to get a bit stream file for programming the FPGA device [PAT+09].

This process can be observed in figure 5.1.

[1]AccelDSP synthesis tool consists in a high-level *MatLab* language based tool for designing DSP blocks for Xilinx FPGAs.

[2]RTL consists in a design abstraction which models a synchronous digital circuit in terms of the flow of digital signals between hardware registers, and the logical operations performed on those signals.

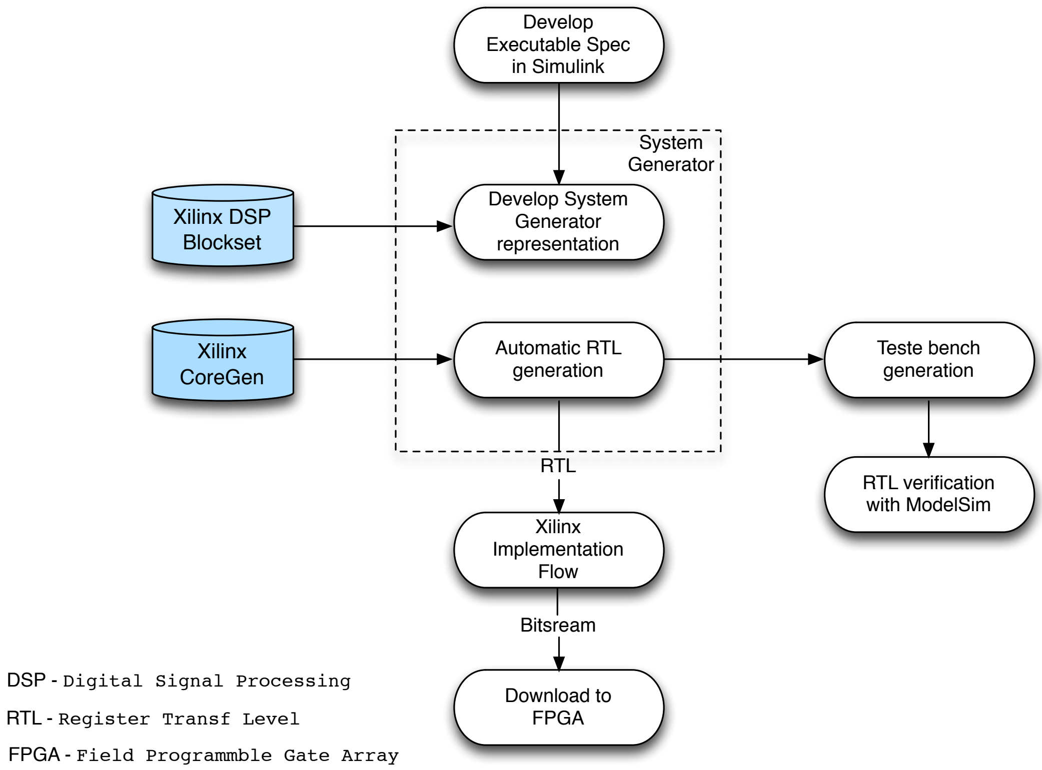


**Figure 5.1:** *System Generator design flow.*

## 5.3 Digital modulation blocks

As mentioned in chapter 2, an underwater communication system is constituted by three basic elements. These elements are the transmitter, where the original signal is converted through modulation and it is transmitted by the medium. The aquatic channel, where the signal will be transmitted and, finally, the receiver that performs demodulation of the received signal (see figure 5.2).

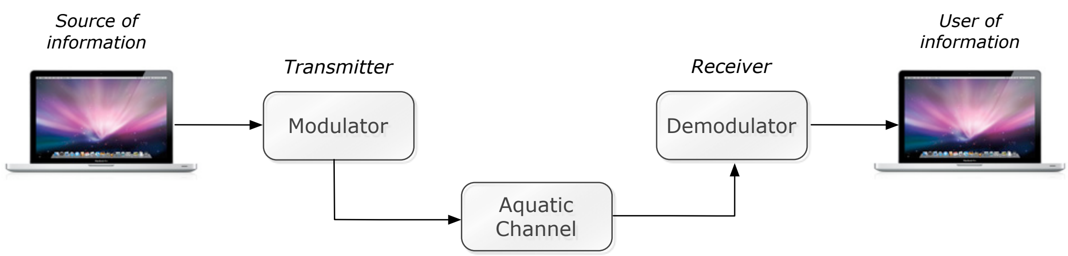


**Figure 5.2:** *Underwater communication system block diagram.*

As previously mentioned in section 1.1 the major goal of this dissertation consists in simulate binary digital modulations and try to understand which best suits to the intended system. So, along this chapter the simulation results of digital modulations will be explained and analysed in detail.

### 5.3.1 OOK modulation

*On - Off Keying* (OOK) modulation consists in a particular type of *Amplitude Shift Keying* (ASK) modulation, where the level of the amplitude of the carrier wave is modified in accordance with the digital signal to be transmitted. So, in this type of modulation the carrier assumes a certain level of voltage to the binary symbol 1 and zero voltage level to the binary symbol 0. To simulate this modulation we need to implement the modulator of the digital signal and after that proceed to the demodulation (detection) process that reconstructs the original signal.

#### OOK Modulator:

OOK modulator is constituted by several components. It was used a data stream, a carrier wave and a multiplexer. The level of amplitude of the carrier wave will be changed, in accordance with the data stream. Multiplexer was used to do this change. After this process, the modulated signal will use the interface of the Digital-to-Analog Converter (DAC) to transmit the information through the aquatic channel.

The modulation process is illustrated in figure 5.3.

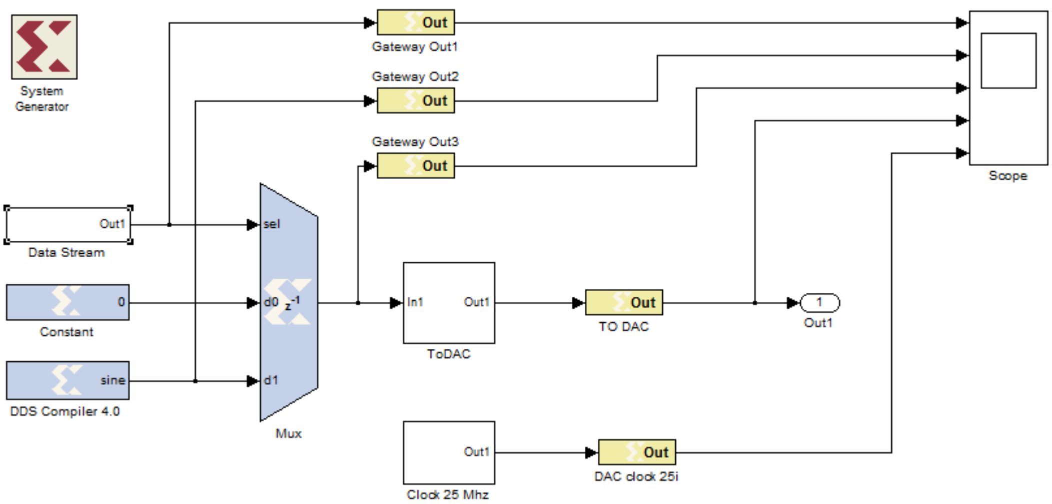


**Figure 5.3:** *OOK modulator.*

Data stream was used to simulate input data to transmit through the medium and it was generated inside the FPGA. To generate these data it was used a constant block with specific value with sample period of $256 \cdot 10^{-6}s$ followed by a register (32 bits) and a parallel to serial block (see figure 5.4) [dSF12]. Through these blocks the decimal value contained in constant block was sent in binary format to be analysed by the multiplexer. The data streaming clock was $8\mu$s. This data stream was used to simulate the input data for all modulation schemes. In a first approach it was used a *Simulink* block (*Bernoully* binary generator). However, this solution became infeasible when we performed the tests in a real system (*hardware*), because it was not possible to obtain input data on FPGA through this tool.

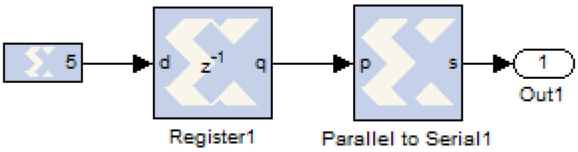


**Figure 5.4:** *Data Stream generated inside the FPGA.*

The carrier wave (CW) is a digital sinusoidal signal with the mathematical function $Asin(2\pi ft+\phi)$ where $A$ corresponds to the amplitude of the signal $(1V)$, $f$ corresponds to the frequency $(1MHz)$ and $\phi$ is the phase (0 degree). It is important to note that the sampling frequency used is $25MHz$ and the corresponding period $(4 \cdot 10^{-8}s)$ were introduced in the system generator block (see figure 5.5).

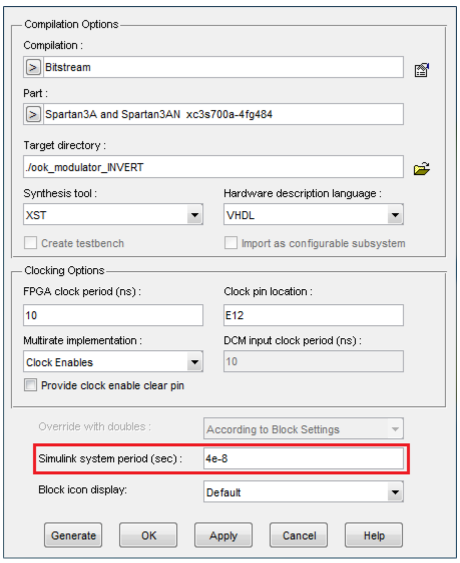


**Figure 5.5:** *System Generator block.*

The multiplexer switches between the sinusoidal signal and the constant. When the binary symbol 1 is present in data stream the sinusoidal signal is transmitted and when the data stream changes to the binary symbol 0, the multiplexer switches to another input signal (constant 0). To transmit the modulated signal through the aquatic channel, it is necessary to implement the DAC interface. This process is illustrated in figure 5.6.

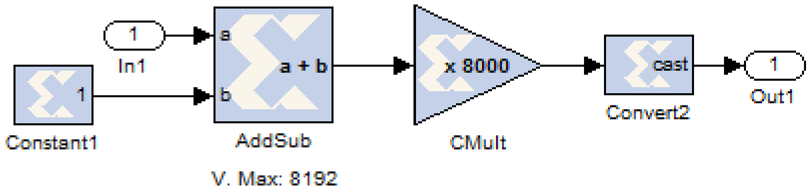


**Figure 5.6:** *DAC interface.*

The modulated signal from the multiplexer is set in a range of values between -1 and 1. However the DAC does not accept negative values, therefore it is necessary to define their scale of values between 0 and 16000 (max $2^{14}$). Thus, the constant value one (1) has been added to the modulated signal and then multiplied by 8000. In this way, the range of values for the DAC was defined between 0 and 16000. After that, was made a 14 bits cast to convert the values into the DAC data scale.

Finally it was necessary to construct the clock to the DAC. This process was done both in modulator and demodulator with a frequency of $25MHz$. The clock was implemented with the resource of various components, namely constants and counters. Their construction can be observed in figure 5.7 [dSF12].

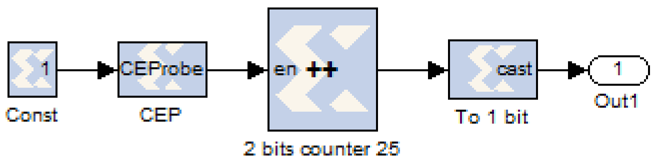


**Figure 5.7:** *DAC Clock at* $25MHz$ *in modulator.*

After concluded all the above processes, the result of OOK modulation can be observed in figure 5.8.

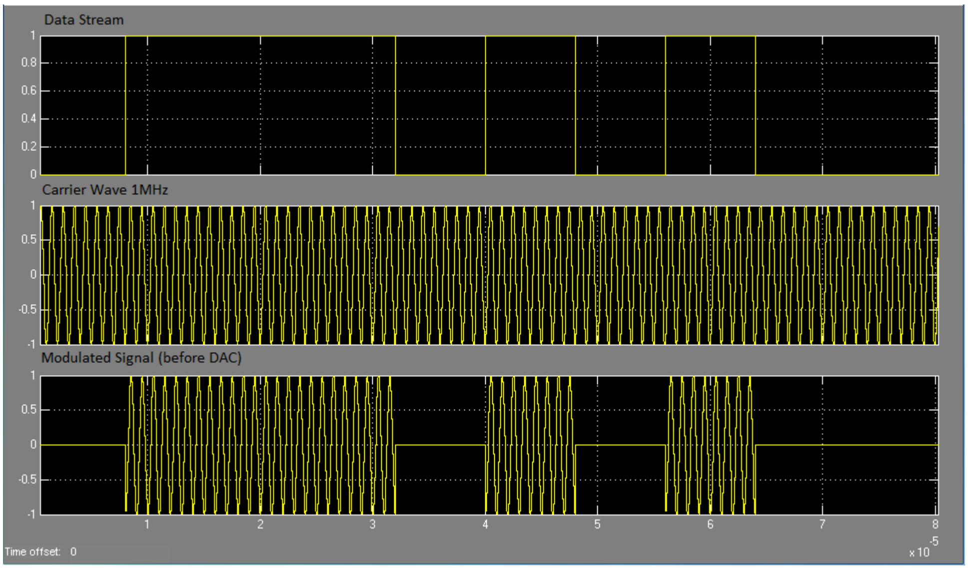


**Figure 5.8:** *Result of OOK modulation.*

## OOK Demodulator:

OOK demodulator was constituted by three fundamental blocks. It were used two Mcode blocks with different functionalities and a low pass filter. The Mcode blocks consist in a block that has an embedded *Matlab* function that may be altered according to the intended purpose. The low pass filter was constructed with the resource of Filter Design and Analysis Tool (*FDAtool*) available in *Simulink*.

The demodulation process can be observed in figure 5.9.

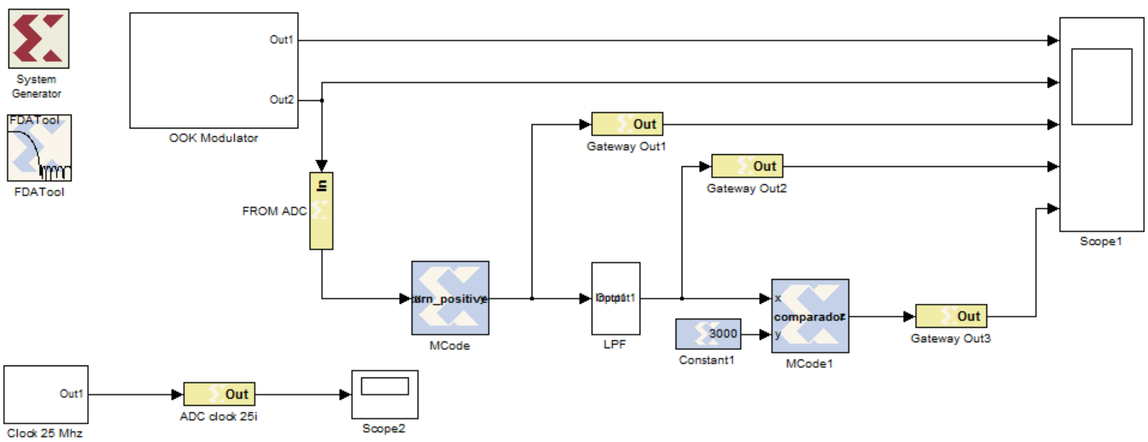


**Figure 5.9:** *OOK demodulator.*

Initially, the received (modulated) signal by the hydrophone is converted to a digital format by the Analog-to Digital Converter (ADC). Then it is used a Mcode block with a embedded *Matlab* function. Through this *Matlab* function it is possible to rectify the signal, converting the negative part into positive.

After this process, is necessary filtering the signal. This is one of the most complex block in the demodulation process. To make the OOK demodulation it was used a low pass filter with the aid of *FDAtool*. This tool provides an interface to the user, which specifies the desired parameters for the construction of the filter in question. Parameters such as response type, design method, filter order, frequency specifications and magnitude specifications are provided to the user and can be changed according to the purpose of the filter in question. This interface can be observed in figure 5.10.

*FDAtool* is a powerful tool when constructing filters, with a greatly simplified interaction interface which allows the observation of various aspects of the filter, in particular, filter specification, magnitude and phase responses. We can observe the particular aspects of the OOK demodulator low pass filter in figure 5.11.

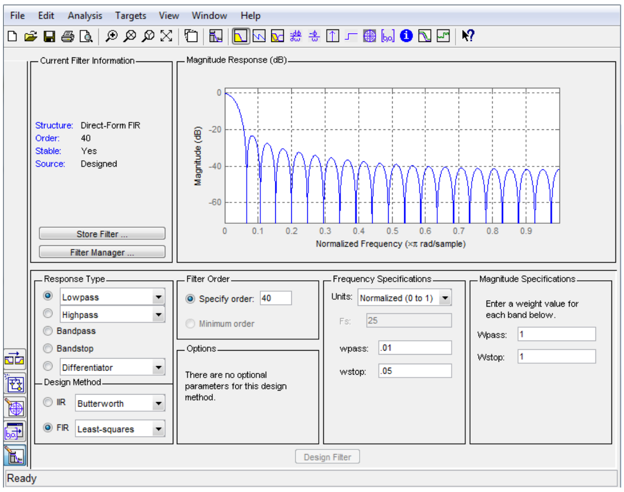


**Figure 5.10:** *Filter construction on FDAtool.*

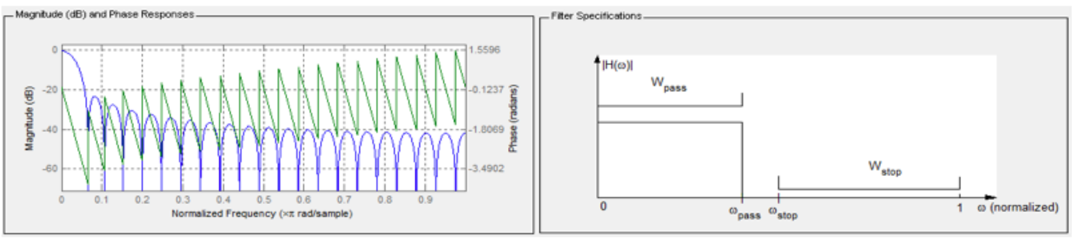


**Figure 5.11:** *Filter specification and magnitude and phase responses.*

In the figure 5.11 it is presented some specific aspects of the filter. The filter specification allows us to realize how the filter performs. Thus, it is possible to observe the band of frequencies that will be eliminated. The undesired frequencies are defined by the $W_{stop}$ while the pass band is defined by $W_{pass}$. In this particular case it is used a low pass filter and thus the pass band is concentrated between the value 0 and the value defined by $\omega_{pass}$.

One important aspect in the construction of the demodulator filter was its order. With its increase, the level of processing in the FPGA will also increase. Thus, it was necessary to reach a level where the filter order was small enough to be implemented in FPGA, but powerful enough to undertake the task for which it was designed. After analysing and perform some tests on FPGA it was possible to identify the filter order that verified these conditions of implementation (see in figure 5.10).

After the filtering process, it was necessary to analyse the signal and convert it to a binary signal again to be interpreted by the receiver. To do this, it was used another Mcode block with a *MatLab* function, where the signal that comes from the filter was compared with a constant value (3000). This constant value was selected by observing the filtering process of the signal. In figure 5.12 it is illustrated the filtering process and we can easily observe the values of amplitude in which the signal is comprised. In this way it was possible to choose one reference value to compare the signal. So, if the signal amplitude that came from the filter was greater than the constant value, the output signal would be the binary symbol 1 and if it was smaller, then the output signal would be the binary symbol 0.

In figure 5.12 it is possible to observe the result of OOK demodulation.

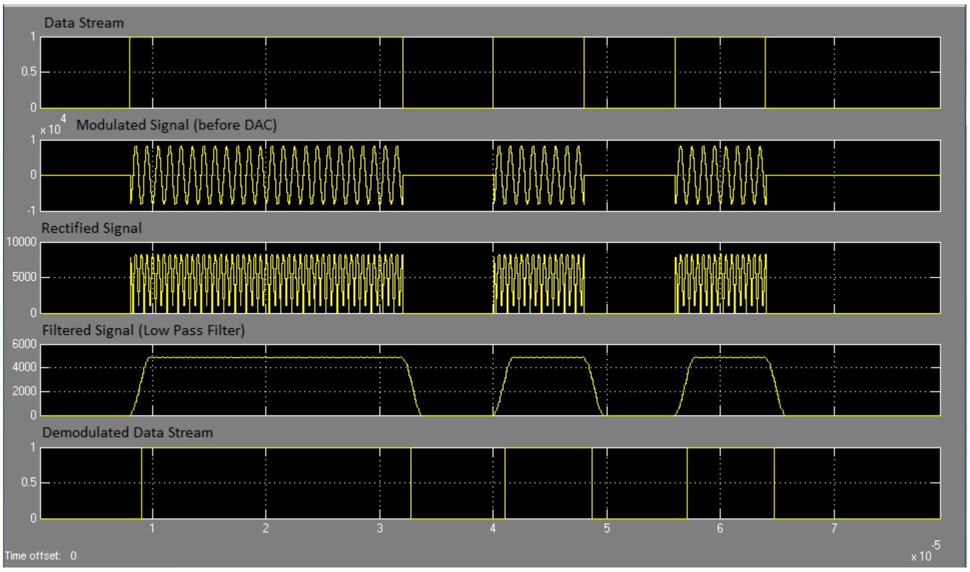


**Figure 5.12:** *Result of OOK modulation and demodulation.*

### 5.3.2 BASK modulation

*Binary Amplitude Shift Keying* (BASK) modulation is another particular type of ASK modulation, where the original signal assumes one of two levels of amplitude. The smaller amplitude is typically used to the logic level 0 and the higher amplitude to the logic level 1.

## BASK Modulator:

The construction of the BASK modulator was almost identical to the OOK modulator mentioned in section 5.3.1. The only difference resides when the binary symbol to modulate is 0. Contrary to the OOK modulation where the transmitted signal has no amplitude for this case, the BASK modulation assigns a signal with lower amplitude. It was also used in this modulation one multiplexer to make the changing of amplitude of the carrier wave in accordance with the data stream, and the DAC interface to transmit the information through the medium.

The modulation process can be observed in figure 5.13.

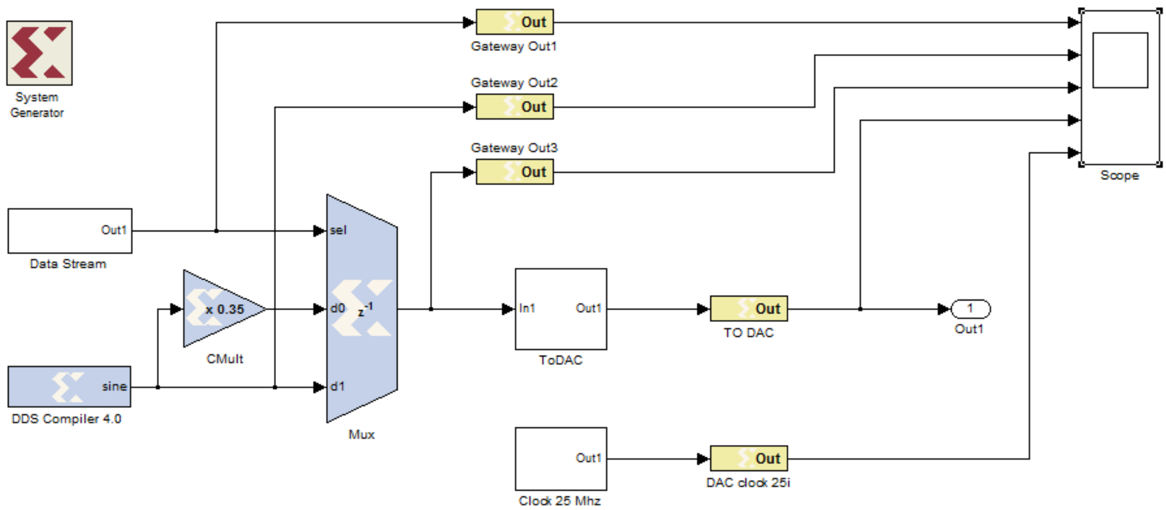


**Figure 5.13:** *BASK modulator.*

Like in OOK modulation, it was used a data stream generated inside the FPGA to simulate the input data to transmit through the medium (see figure 5.4). The carrier wave used in this modulation has the same parameters that the one used in OOK modulation described in section 5.3.1. It should be noted that the sampling frequency is exactly the same ($25MHz$).

To send the modulated signal through the medium it was necessary to perform the DAC interface, where the process is exactly the same of the modulation OOK and can be observed in figure 5.6.

Finally, it was necessary to build the DAC clock in the modulator. This process was already described and can be observed in figure 5.7. The result of BASK modulation can be observe in figure 5.14.

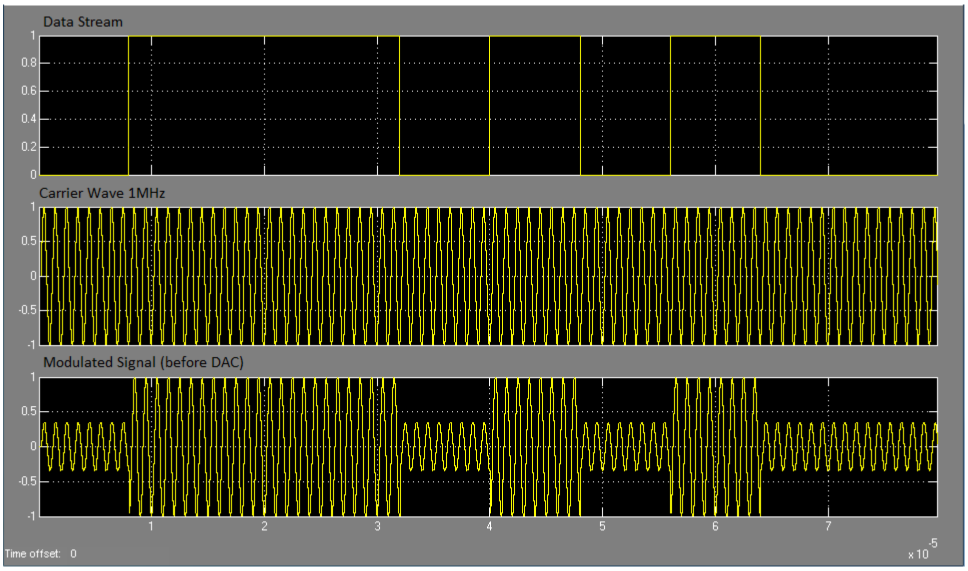


**Figure 5.14:** *Result of BASK modulation.*

## BASK Demodulator:

BASK demodulation was made exactly in the same way as the OOK demodulation. It were used two Mcode blocks, one to rectify the signal, eliminating the negative part of the signal and transforming it into positive and the other one to analyse the signal and convert it to a binary signal. In the middle of these two blocks it was used a low pass filter constructed by the *FDAtool*. The BASK demodulation process can be observed in figure 5.15.

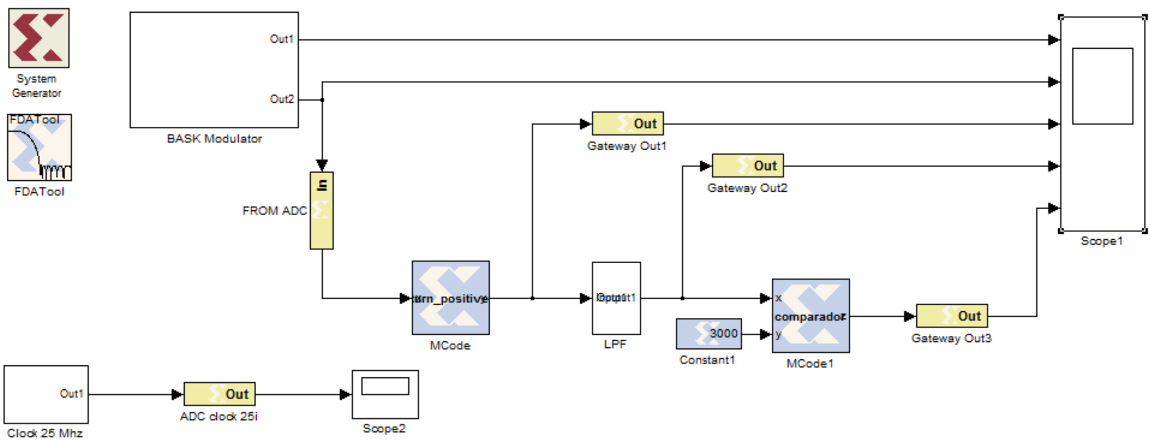


**Figure 5.15:** *BASK demodulator.*

After the received signal be converted by the ADC, it will pass through all the processes mentioned in section 5.3.1. Namely, the received signal will be rectified by the Mcode block and after filtered through a low pass filter (see figure 5.10 and figure 5.11). Finally, the signal needs to be analysed and converted into a binary signal. In figure 5.16 it is possible to observe the result of BASK demodulation.

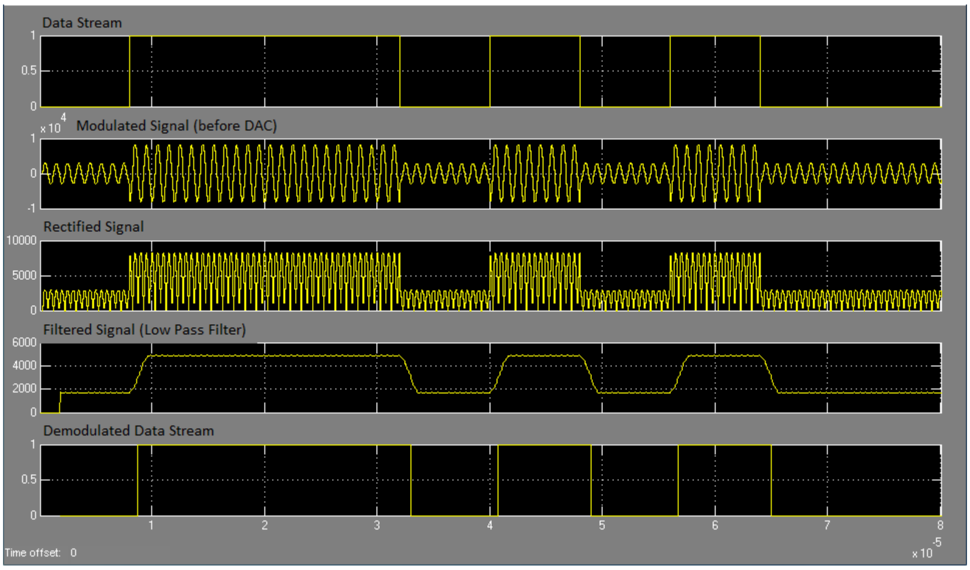


**Figure 5.16:** *Result of BASK modulation and demodulation.*

### 5.3.3 BPSK modulation

*Binary Phase Shift Keying* (BPSK) modulation consists in transmitting data by changing or modulating the phase of a carrier. To modulate the digital signal, the carrier will change between a cosine and an inverse cosine function, causing a phase shift of 180 degrees. To retrieve the original data, the receiver needs to make the determination of its phase and mapping back to the original symbol.

#### BPSK Modulator:

The BPSK modulator is constituted by a data stream, a carrier wave, an inverter block and a multiplexer. In accordance with the data stream, the phase of the carrier will be changed, or modulated causing a 180 degrees phase shift in the signal. To transmit the modulated signal through the medium it was used the DAC interface similar to the one mentioned in OOK and BASK modulation (see section 5.3.1 and 5.3.2). The modulation process can be observed in figure 5.17.

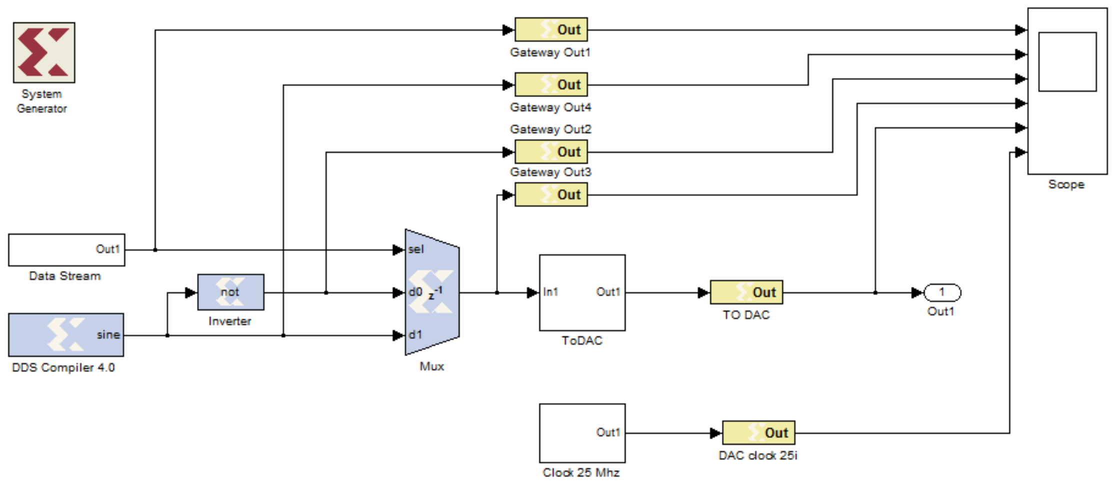


**Figure 5.17:** *BPSK modulator.*

As in modulations mentioned before, it was used a data stream on FPGA to simulate the input data (see figure 5.4). The carrier wave has the same parameters as those used in other modulations and its phase will be changed in a 180 degrees using a multiplexer and an inverter block. The multiplexer selects the carrier wave input or the inverted carrier wave in accordance with the transmitted data stream. To transmit the modulated signal through the medium it was used again the DAC interface (see figure 5.6) and the DAC clock, that can be observed in figure 5.7. The result of BPSK modulation can be observed in figure 5.18.

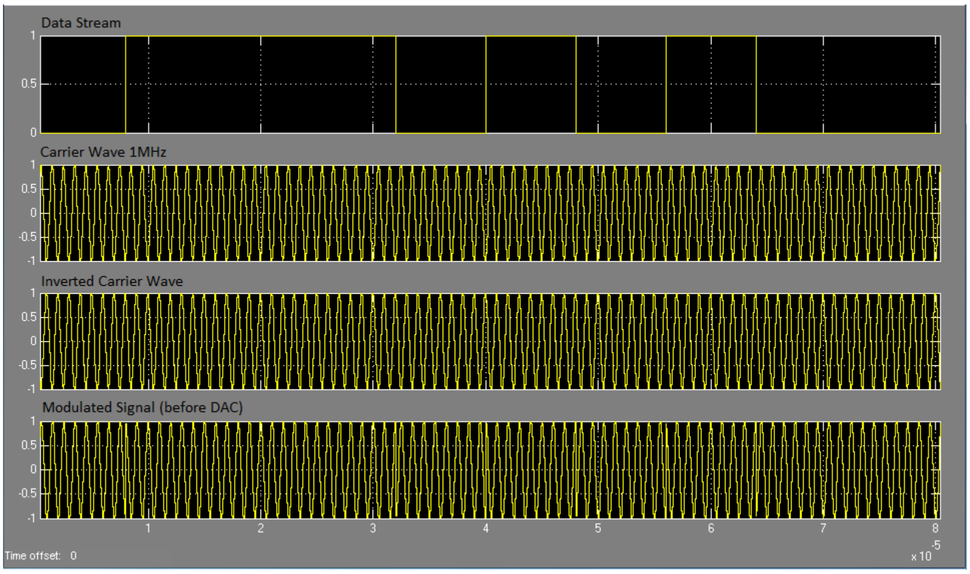


**Figure 5.18:** *Result of BPSK modulation.*

After analysing the modulated signal in scope it was possible to observe that the phase shift was not exactly 180 degrees. This was due to the small gaps between the data stream and the carrier wave. As it can be seen in figure 5.4 the data stream proceeds a parallel to series conversion which necessarily causes a delay. This delay happens in all modulation schemes but nonetheless it does not cause any type of problems. Although this gap may become negligible in terms of demodulation of the signal, the system becomes less efficient, and thus must be improved in order to overcome this fact. So, to eliminate these gaps efficiently, it was used a delay in the carrier wave before the inputs of the multiplexer. Several values of delays were tested and the value chosen was nineteen (19). Through this delay, it was possible to align the carrier wave with the data stream and thus obtaining a shift of exactly 180 degrees.

The change in BPSK modulator can be observed in figure 5.19.

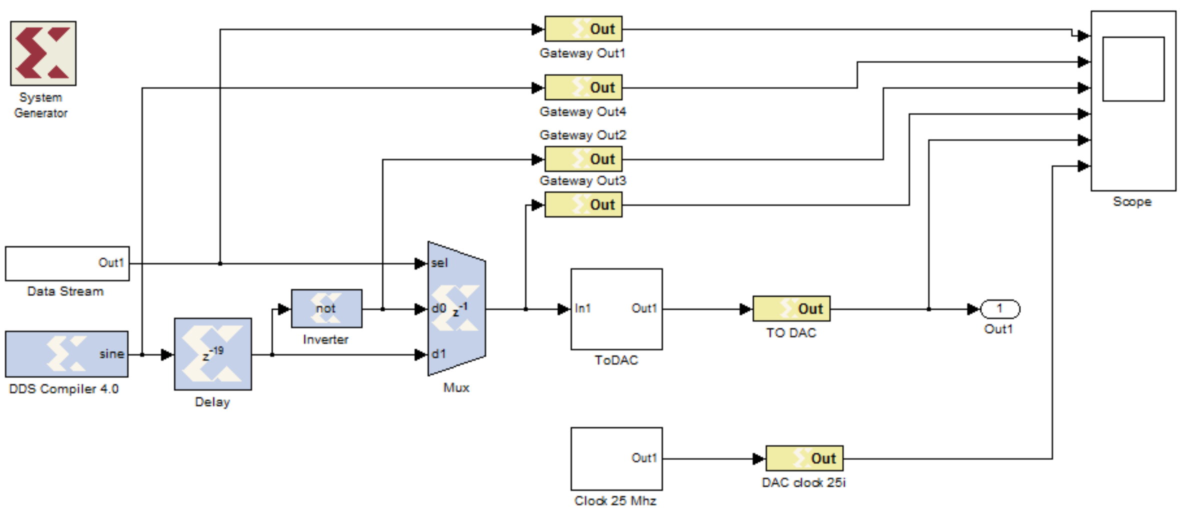


**Figure 5.19:** *BPSK modulator with delay.*

After observing the modulated signal in scope it was possible to observe that this approach improved significantly the phase shift in the modulated signal as can be observed in figure 5.20.

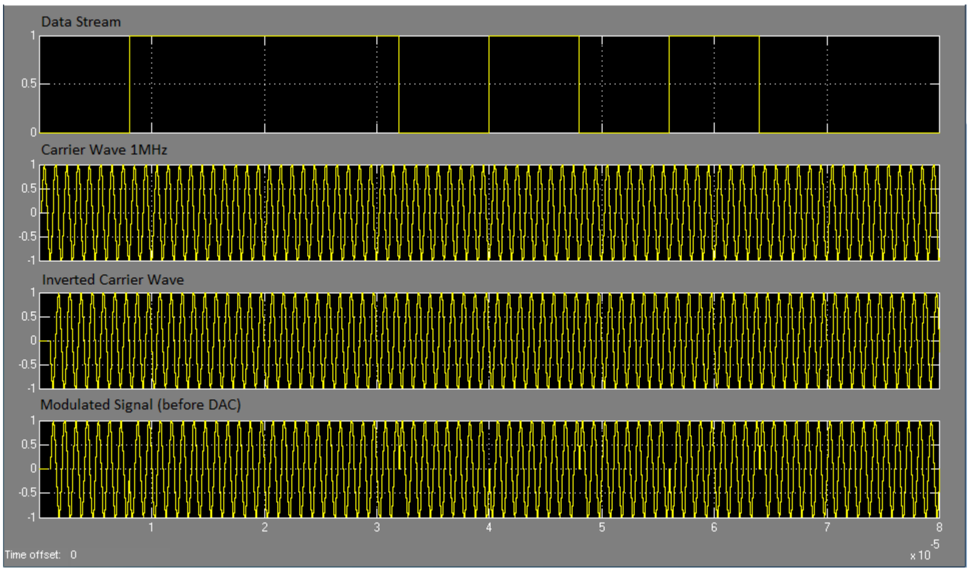


**Figure 5.20:** *Result of BPSK modulation with delay.*

## BPSK Demodulator:

BPSK demodulator was constituted by several components. It was used a carrier (CW), that was multiplied by the received signal. Then, the signal was filtrated through a low pass filter constructed in *FDAtool* and, finally, it was used a Mcode block to make the digital decision. The BPSK demodulation process can be observed in figure 5.21.

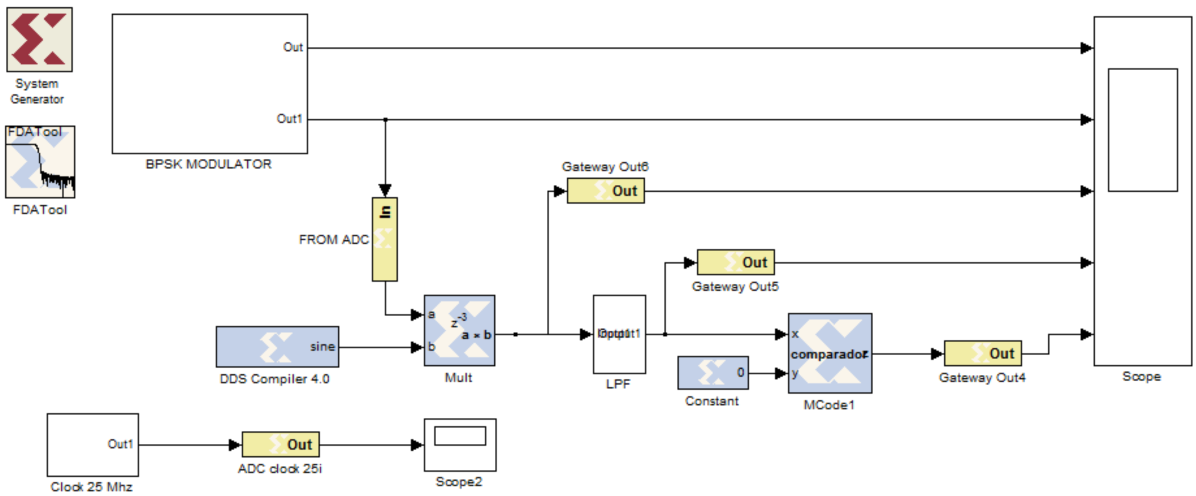


**Figure 5.21:** *BPSK demodulator.*

Initially, the received signal was converted by the ADC and it was multiplied by the carrier wave. After that, this signal was filtered through a low pass filter constructed using *FDAtool*. The parameters of the filter can be observed in figure 5.10 in section 5.3.1.

After the filtering process, it was used a Mcode block with a *MatLab* function, where the signal was compared with a reference constant. This constant value was chosen through the analysis of the amplitude values of the signal after the filtering process. So, to the specific case of BPSK demodulation the constant value chosen was zero (0).

In the figure 5.22 it is possible to observe the result of BPSK demodulation.

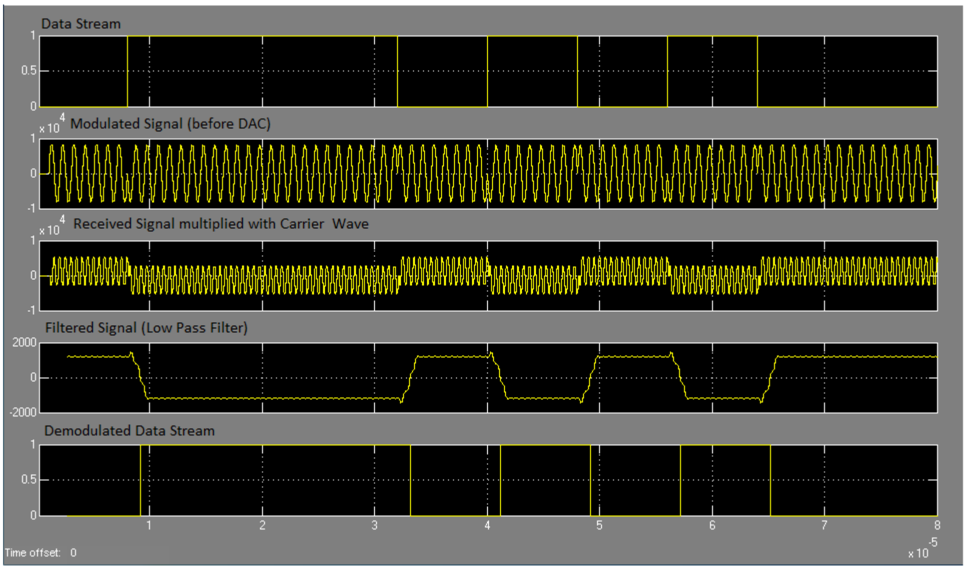


**Figure 5.22:** *Result of BPSK modulation and demodulation.*

### 5.3.4 BFSK modulation

*Frequency Shift Keying* (FSK) modulation consists in variations on the carrier wave frequency in accordance with the digital input signal. In the case of *Binary Frequency Shift Keying* (BFSK), when only one bit is encoded, symbols 1 and 0 are distinguished from each other through transmitting one of two sinusoidal waves that only differ in frequency.

## BFSK Modulator:

BFSK modulator was constituted by a data stream, two carrier waves and a multiplexer. The digital information was transmitted through frequency changes of a carrier wave. According with the data stream that we want to transmit, the multiplexer will select one from the two carrier waves. The DAC interface was used again to transmit the digital information through the medium.

The BFSK modulation process can be observed in figure 5.23.

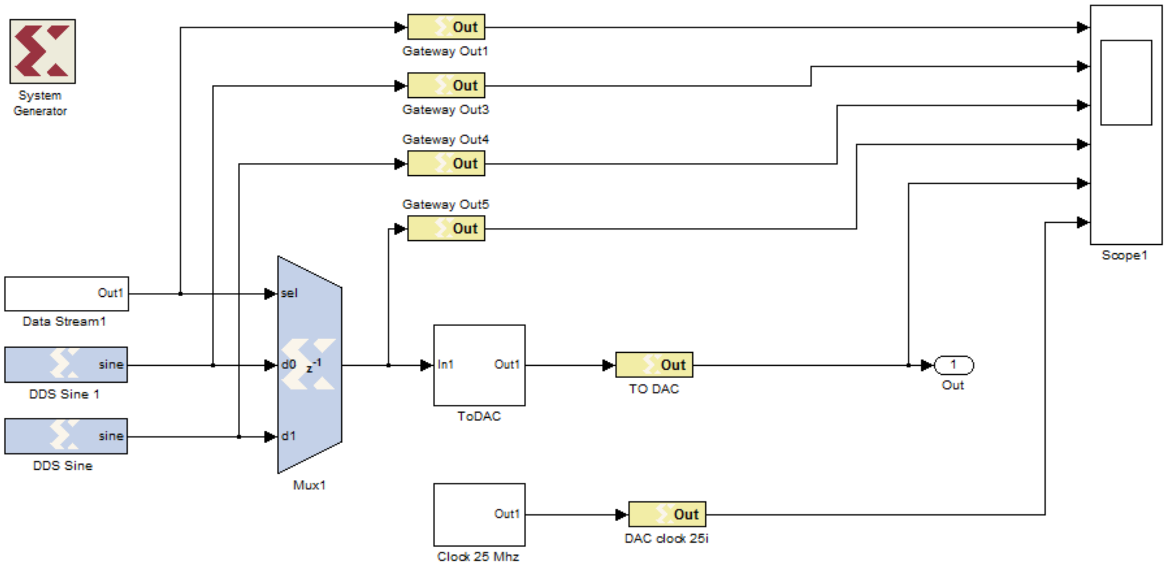


**Figure 5.23:** *BFSK modulator.*

Once again it was used a data stream generated inside the FPGA to simulate the input data where its construction process can be observed in figure 5.4. The carrier waves used in this type of modulation have the same parameters which only differ on frequency. One of them uses $1MHz$ and the other uses $500kHz$. According with the symbol that we intend to transmit in the data stream, the multiplexer will select one of these carrier waves, available in its inputs. The DAC interface and its clock were already mentioned in the above modulation schemes and its construction can be verified in the figures 5.6 and 5.7 respectively.

The result of BFSK modulation can be observed in figure 5.24.

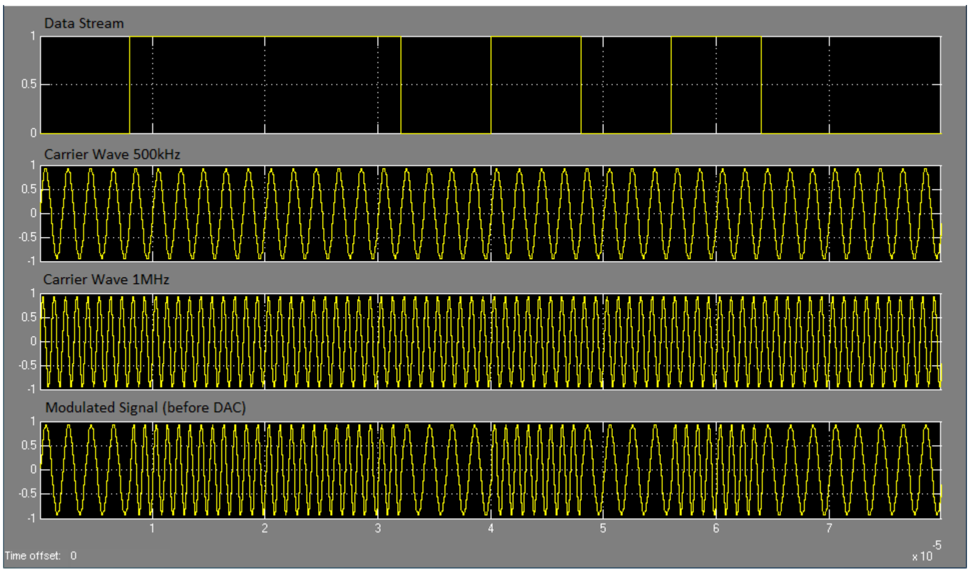


**Figure 5.24:** *Result of BFSK modulation.*

## BFSK Demodulator:

### Solution 1

The BFSK demodulation involved a large research and analysis and presented a large number of difficulties. Therefore, there were developed three different solutions in order to perceive which offers better performance during the tests in underwater environment.

The first solution designed to perform the BFSK demodulation was constituted by one of the two carrier waves, that was multiplied by the received signal. Then it was used a low pass filter constructed in *FDAtool* and finally it was made the digital decision using a Mcode block.

The BFSK demodulation process can be observed in figure 5.25.

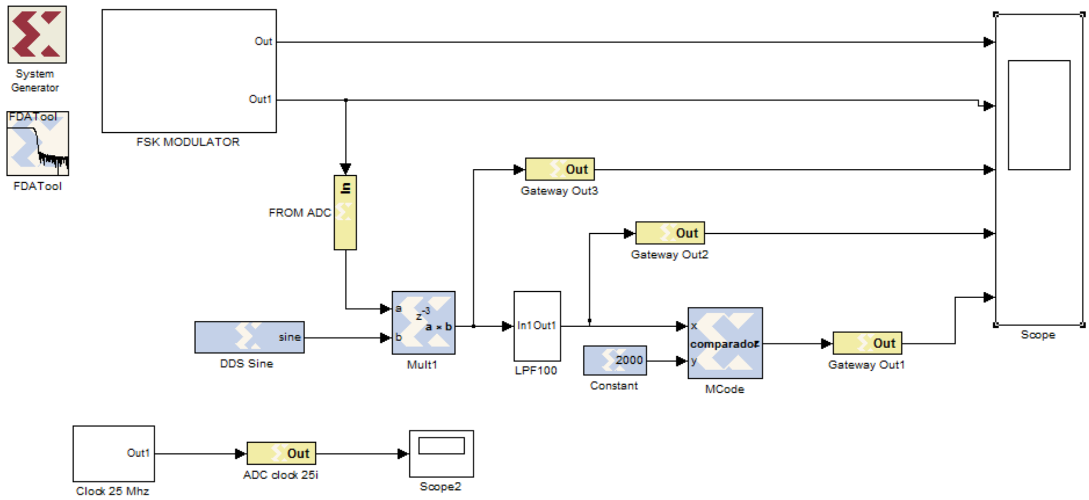


**Figure 5.25:** *BFSK demodulator solution 1.*

As in all demodulation processes, the received signal was converted by the ADC. After the conversion, the signal was multiplied with the higher carrier wave ($1MHz$). Then, it was performed the filtering process through a low pass filter constructed in *FDAtool*. The parameters of the filter can be observed in figure 5.26.

After the filtering process, it was used a Mcode block with a *MatLab* function, where the signal was compared with a reference constant. The reference value was calculated through the analysis of the amplitude range of the signal after the filtering process. In figure 5.27 we can observe the range of the signal and through the constant block we can define a value to make the digital decision.

In figure 5.27 we can observe the result of BFSK demodulation.

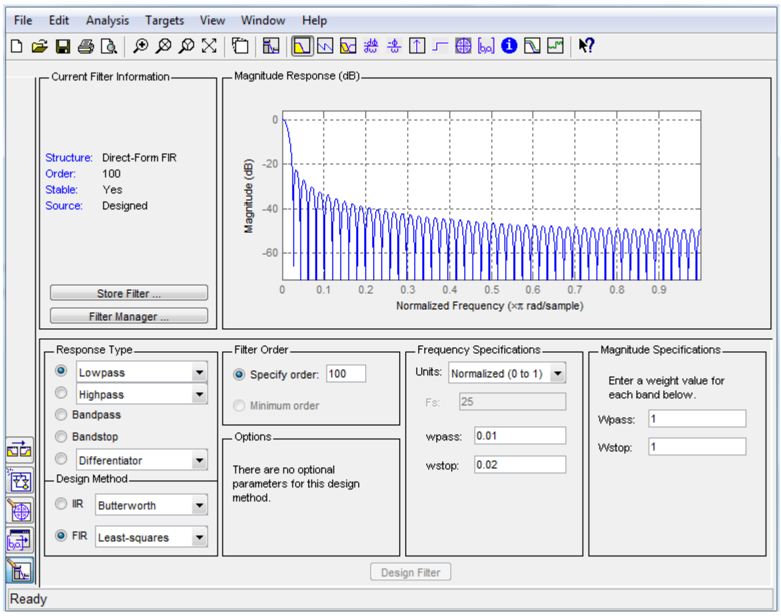


**Figure 5.26:** *Filter construction on FDAtool to BFSK demodulation.*

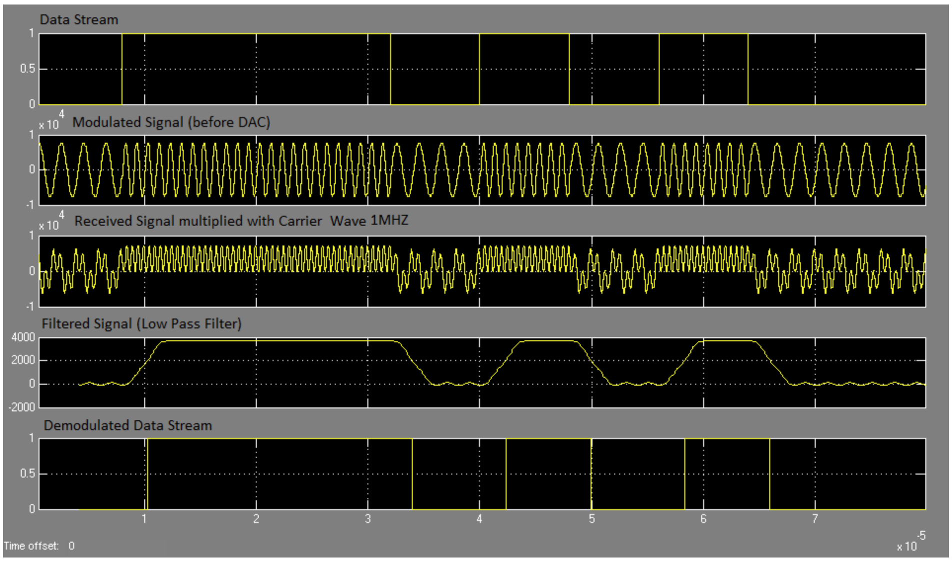


**Figure 5.27:** *Result of BFSK modulation and demodulation in solution 1.*

## BFSK Demodulator:

### Solution 2

The other solution designed to perform the BFSK demodulation was made through the multiplication of one of the carrier waves by the received signal. After this process, it was used a band pass filter, a Mcode block to rectify the signal and a low pass filter. Finally, it was used other Mcode block to recovery the original signal.

The BFSK demodulation process can be observed in figure 5.28

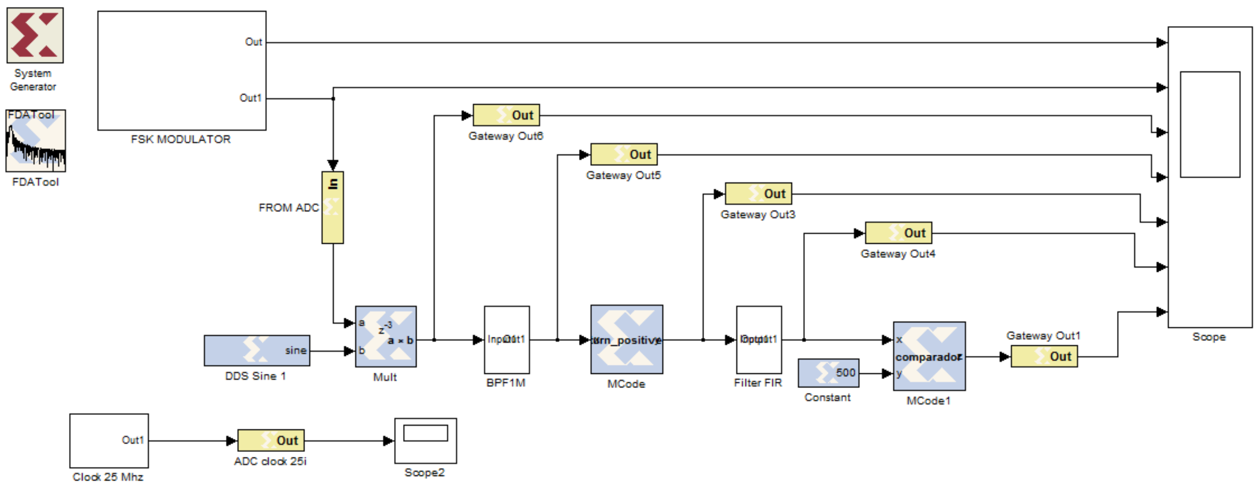


**Figure 5.28:** *BFSK demodulator solution 2.*

So, the received signal was converted to a digital signal through the ADC. Then, the signal was multiplied with the lower carrier wave in terms of frequency ($500kHz$). The next step was the filtering process using a band pass filter centred in $1MHz$. The *FDAtool* parameters of the filter can be observed in figure 5.29.

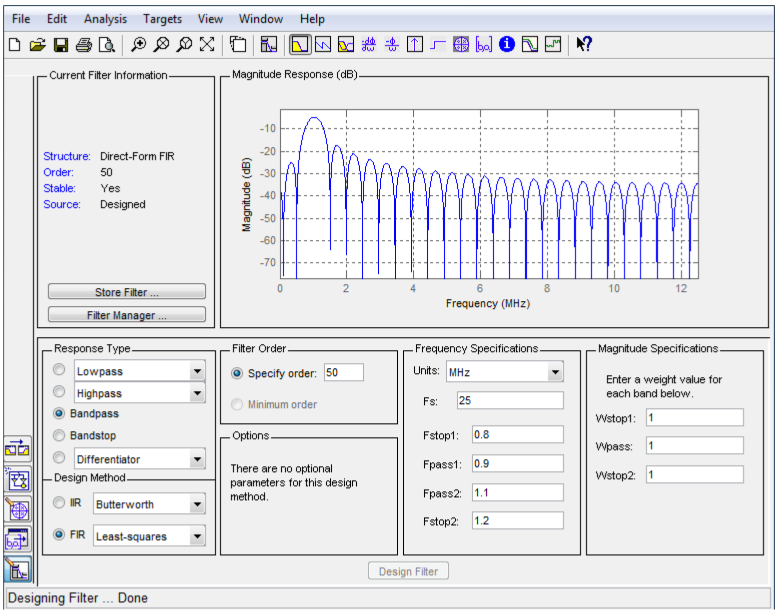


**Figure 5.29:** *Band Pass Filter constructed in FDAtool.*

After the filtering process, using the band pass filter, it was used a Mcode block to rectify the signal. Therefore it was possible to convert the negative part of the signal into positive. Then it was used a low pass filter to filter the rectified signal. The filter used has been previously presented and its parameters can be revised in the figure 5.10 in section 5.3.1.

Finally, the digital decision to reconstruct the original signal was made through a another Mcode block that compares the signal value with a constant. The Mcode block uses a *MatLab* code which compares the value of the signal from the filter with a reference value in a constant block. As in others demodulation process the value of the constant is calculated through the analysis of the range of amplitude values of the signal after the filtering process. In figure 5.30 we can observe these range of values and for this specific case of BFSK demodulation the reference value chosen is 500.

In figure 5.30 we can be observe the result of BFSK demodulation to this particular case.

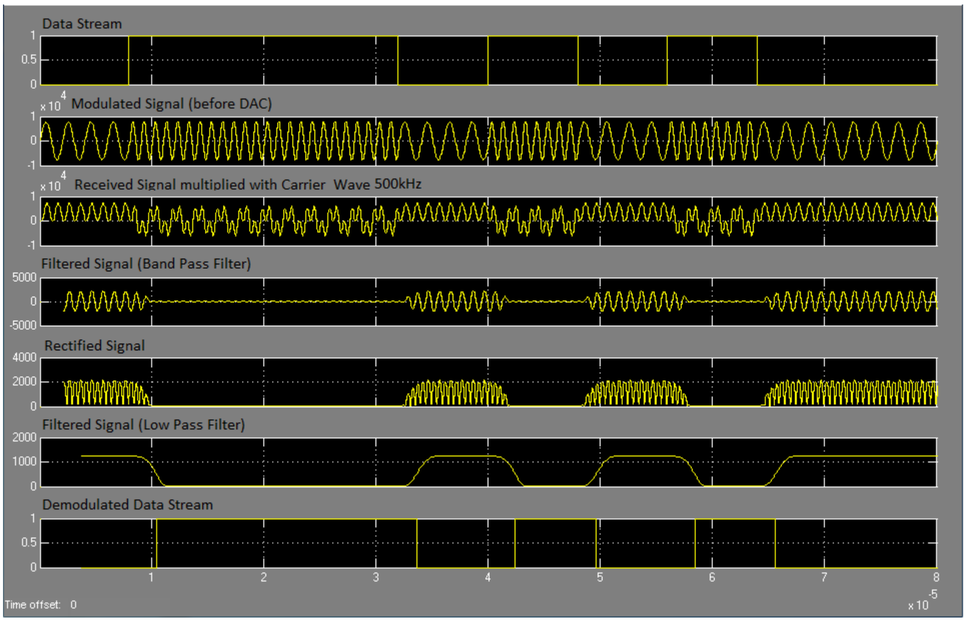


**Figure 5.30:** *Result of BFSK modulation and demodulation in solution 2.*

After a thorough analysis regarding the solutions presented above, it was possible to observe and conclude that they were not liable to implement in the FPGA used. Due to its very high order of filters it was not possible to generate the code of the bit stream file for programming the FPGA device. Thus, another solution has been proposed to try to overcome this problem.

## BFSK Demodulator:

### Solution 3

The solution developed is identical to the one previously adopted (solution 1). The only difference lies in the processing performed to reduce the order of the low pass filter used. The BFSK demodulation process adopted in this solution is illustrated in figure 5.31.

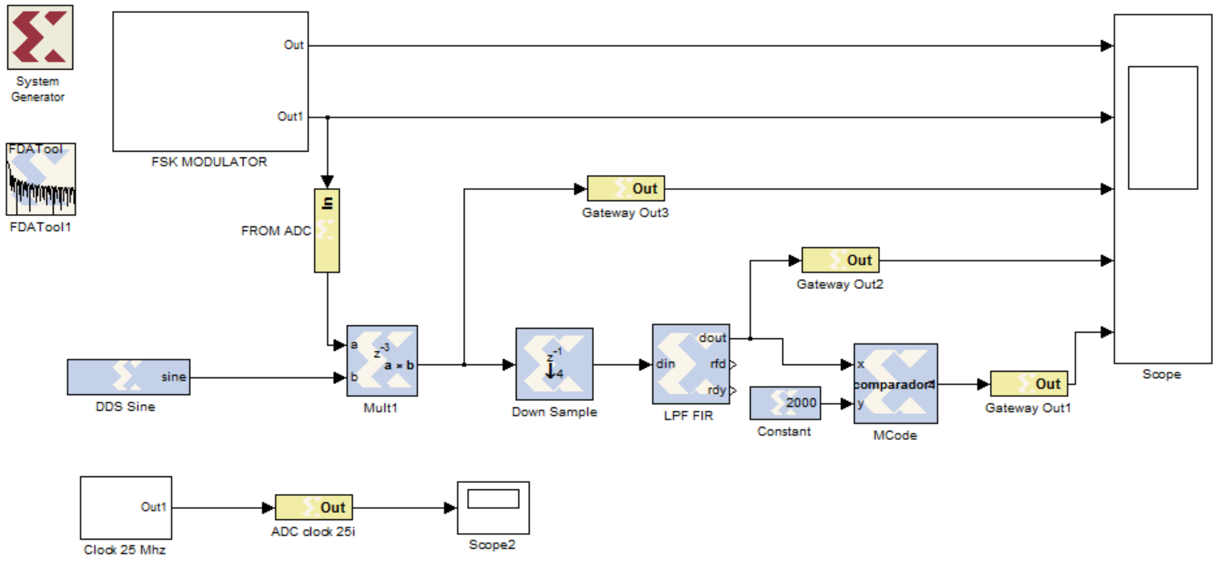


**Figure 5.31:** *BFSK demodulator solution 3.*

As can be seen, through the figure 5.31 the only difference with the approach adopted in the first instance is the use of the *Down Sample* block. This block allows to reduce the number of signal samples and consequently allow to reduce the filter order used. Thus, it was possible to use a low pass filter with an order substantially lower than the one used in the previous approach. The filter used to make the BFSK demodulation is exactly equal to the filter presented in the remaining demodulation processes (order 40) and their parameters can be reviewed in figure 5.10.

The result of BFSK demodulation in this particular case can be observed in figure 5.32.

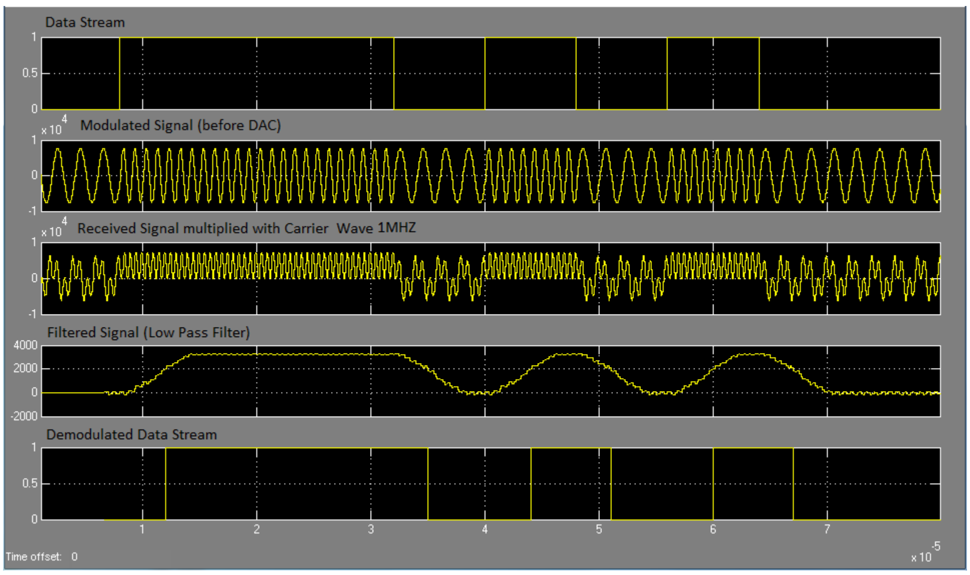


**Figure 5.32:** *Result of BFSK modulation and demodulation in solution 3.*

***System overview***

By making a system overview, we can conclude that all modulation schemes presented are binaries. In other words, it is only possible to encode one bit at each time, thus achieving a maximum speed of communication of $500kbps$. Although this type of modulation was not effective when aiming high speeds, it was necessary to perform all of them to see which one best fits the underwater environment. After simulate and test every modulation schemes presented in this chapter, we can determine which one provides better performance and then it was possible to make the next step that consists in encoding more than one bit simultaneously and consequently providing higher communications speeds.

***Summary***

In a first phase it was described the *MatlLab/Simulink* and System Generator tool. These tools are fundamental to the construction of the proposed system and this description allowed to introduce some important concepts about them and in this way to demonstrate that both are very powerful to perform analysis of these kind of systems.

Afterwards, all modulations schemes that were simulated were presented with maximum detail. In this way, every modulation type were divided in separate sections including all the steps and decisions that were taken for its construction and the results obtained after simulation. In order to complete this explanation it were used illustrative references in all sections that allowed a wider observation of everything that was presented in the chapter.

6

# Tests and Results

This chapter presents experimental results that were obtained using the support system presented in chapter 4.

So, to carry out a more precise analysis of the system, several tests were performed. Firstly, the system was tested outside the underwater environment, to realize if the results obtained were consistent with those obtained during simulation. After that, all digital modulations schemes with *Polyvinylidene Fluoride* (PVDF) transducer in underwater environment were tested and the results obtained were thoroughly analysed in order to understand its advantages and disadvantages.

Initially, it will be presented the place and the conditions where the system was tested and, posteriorly, for each case study, all the practical tests are described in detail.

## 6.1 Scenario 1

As previously mentioned, in order to understand if the simulations were consistent with the expected, all binary modulations schemes were performed outside underwater environment, that is, it was made a loop between the transmitter and the receiver. This test scenario can be observed in figure 6.1.

With this scenario it is possible to understand if the binary modulation schemes are in agreement with the simulations described in chapter 5.

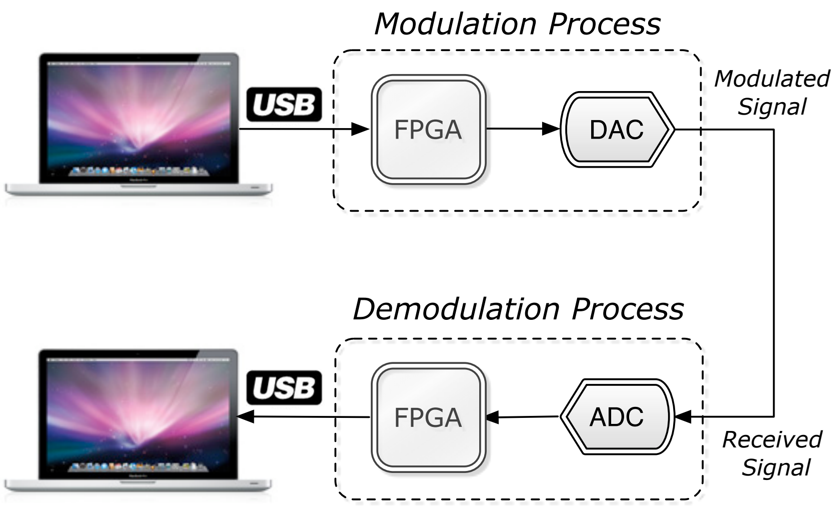


**Figure 6.1:** *System architecture used in the experimental tests.*

## 6.2 Scenario 2

The place used to perform the experimental tests was an aquarium, illustrated in figure 6.2, with 120$cm$ of length and 50$cm$ of width. Despite the fact that it is a small environment, it is sufficient enough to carry out the required tests.

**Figure 6.2:** *Aquarium used to carry out experimental tests.*

To carry out the experimental tests, the transmitter was placed at a distance of 50$cm$ from the receiver and 10$cm$ from the bottom of the aquarium.

After describing the scenarios where experimental tests were performed, the case studies that were considered are presented in the following section.

## 6.3 Case studies

In order to facilitate the observation of the results of experimental tests, it was defined to send only a data frame (101) between the transmitter and receiver. In the interval between of two data frames the system was purposely left idle. Thus, it was sent just a burst of information, which thereby facilitated the observation of the information sent by the transducer and what was being received by the hydrophone. So, the results displayed in the figures of experimental tests the transmitted signal is plotted in red, and the blue signal identifies the signal received. To observe these results it was used a digital oscilloscope (Pico Scope 4227 [Tec12b]).

After presenting all the important background for a correct observing of the obtained results, it will be now presented the selected case studies to assess the quality of the models developed in *Matlab/Simulink* with specific *Xilinx* blockset. In any case study presented, it will be mentioned all important aspects and relevant parameters of the obtained results.

### 6.3.1 Case study 1

In this section it will be presented the results of the experimental tests of all modulations schemes through the system present in figure 6.1.

#### 6.3.1.1 OOK modulation

This section presents the OOK demodulation step by step. Thus, a signal generator was used to simulate an OOK modulation at the input of the ADC and it was used a DAC to observe the various stages of demodulation. Firstly, it is necessary to adjust the signal from the signal generator (analog) to digital values at ADC (figure 6.3)

The next step in OOK demodulation consists in the rectification of the signal, converting the negative part of the signal into positive. This process is illustrated in figure 6.4.

After this process it is necessary to filter the signal. However, after observing the result of the filtering process, using the low pass filter present in simulations, it was possible to observe too much noise present in the signal. This noise could compromise the signal analysis in the next demodulation process. Thus, it was built a band pass filter with passband between $100Hz$ and $500kHz$ to try to eliminate most part of the noise. The resulting signal can be seen in figure 6.5.

The last process in OOK demodulation consists in the conversion of the signal to digital to be interpreted by the receiver. So, the signal from the filter was compared with a constant value previously calculated. Through the observation of the filtered signal it is possible to set the reference value to be used in the comparator. This value in *volts* is converted to the value range of the ADC (-8192 to 8192) and consequently the comparison is made.

After the comparison process, it is possible to observe the result of OOK demodulation in a preselected FPGA pin. However, after observing the output of the FPGA, it was possible to see that the output was inverted. Thus, it was only necessary to invert the order of the comparison process or apply an inverter in the output of the comparator to solve the problem (see figure 6.6).

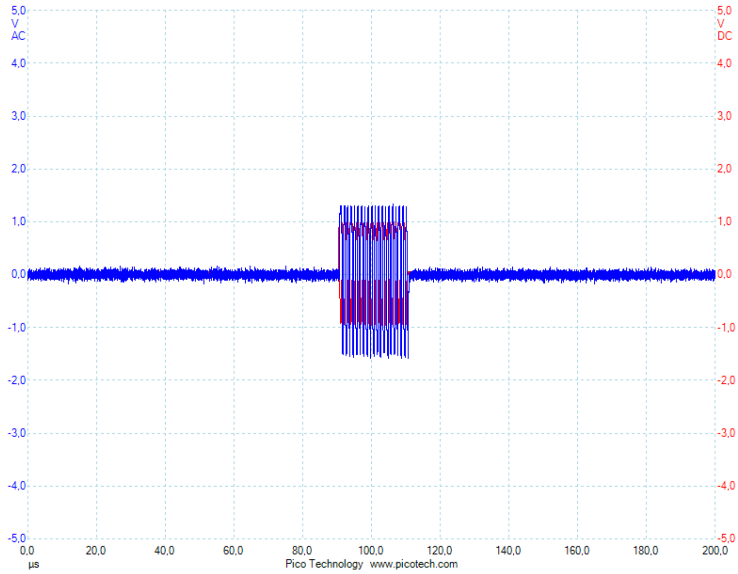


**Figure 6.3:** *Adjusting the scale values of the ADC.*

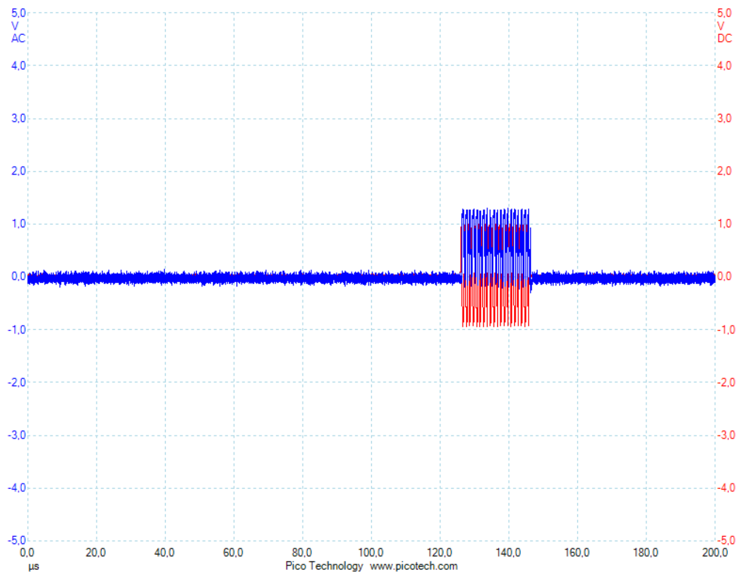


**Figure 6.4:** *Rectification of the OOK modulated signal.*

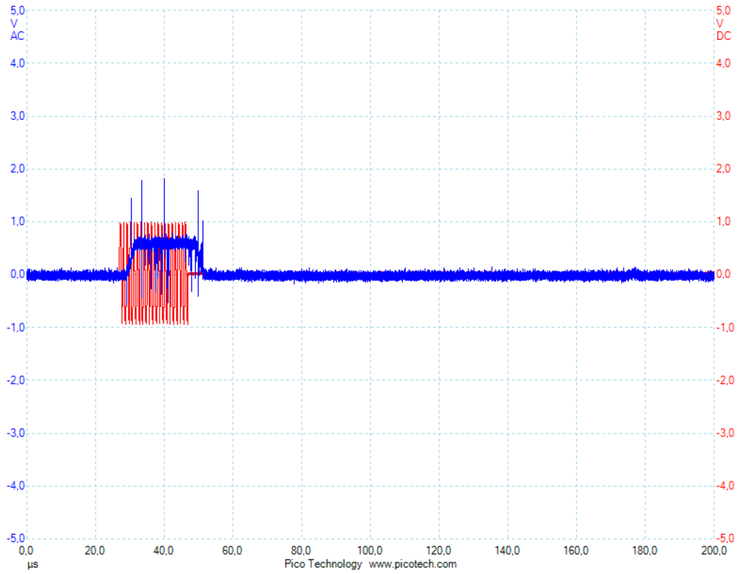


**Figure 6.5:** *Filtering process of the OOK modulated signal (low pass filter).*

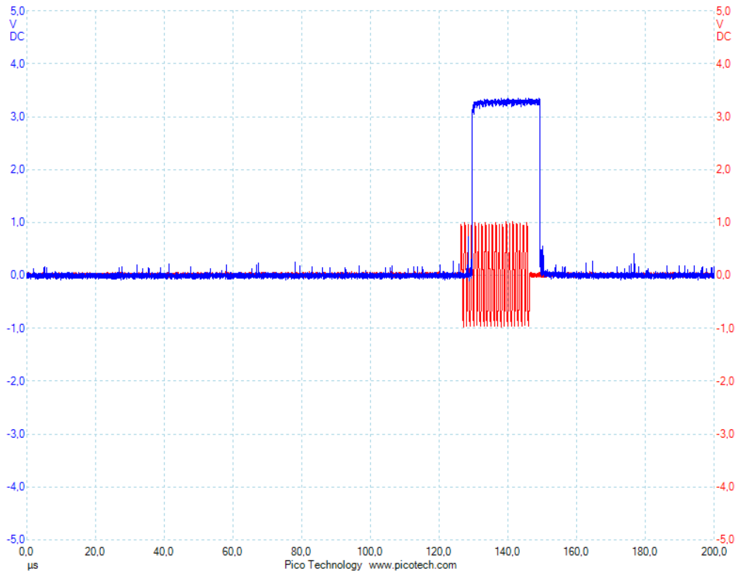


**Figure 6.6:** *Inverted OOK signal demodulated in FPGA.*

Finally the whole system was tested with the conditions mentioned in section 6.3. The result of OOK modulation and demodulation can be observed in figure 6.7.


**Figure 6.7:** *Result of demodulated OOK data stream in FPGA.*

#### 6.3.1.2 BASK modulation

This section presents the BASK demodulation process. Unfortunately, in this type of modulation it was not possible to observe all steps in the demodulation process, because the signal generator does not provide a simulation of BASK modulation, and thus the DAC had to be used to provide the modulated signal and thereby it was not possible to use it to verify the result of all stages process. The result of BASK modulation and demodulation can be observed in figure 6.8.

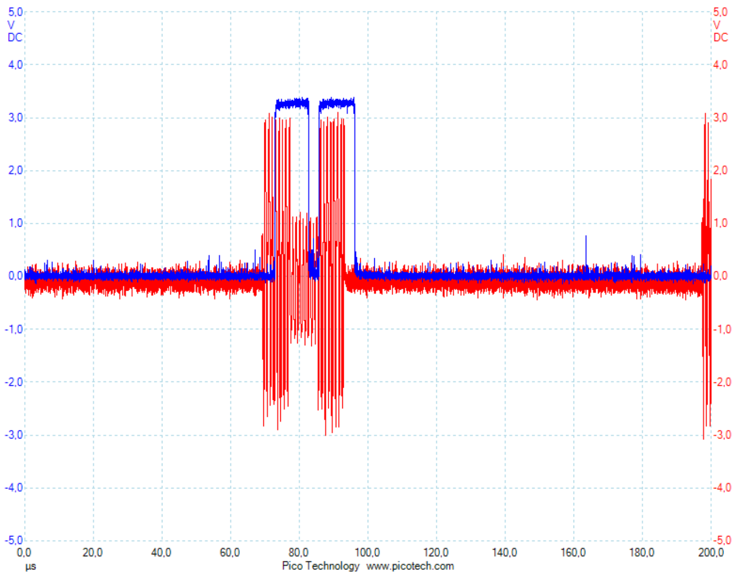


**Figure 6.8:** *Result of demodulated BASK data stream in FPGA.*

#### 6.3.1.3 BPSK modulation

In figure 6.9 it is possible to observe the result of BPSK demodulation process.

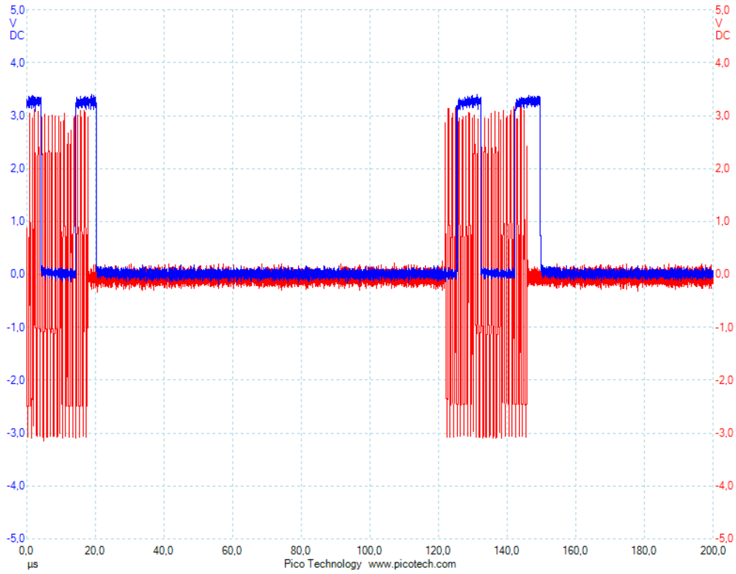


**Figure 6.9:** *Result of demodulated BPSK data stream in FPGA.*

#### 6.3.1.4 FSK modulation

Figure 6.10 presents the FSK demodulation process, where the modulated data stream is represented by the red signal and the binary result is represented by the blue signal.

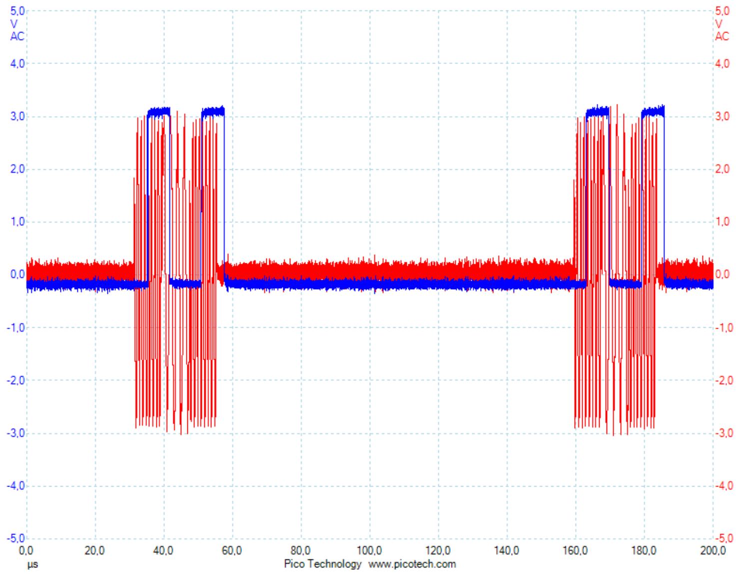


**Figure 6.10:** *Result of demodulated FSK data stream in FPGA.*

The analysis of these results will be described in section 6.4 of this chapter.

## 6.3.2 Case study 2

In this case study the results of the experimental tests of all modulations schemes will be presented, using the PVDF transducer with the conditions mentioned in the section 6.3 of this chapter.

### 6.3.2.1 OOK modulation

In figure 6.11 and 6.12 it can be observed the OOK modulation and demodulation process using PVDF transducer.

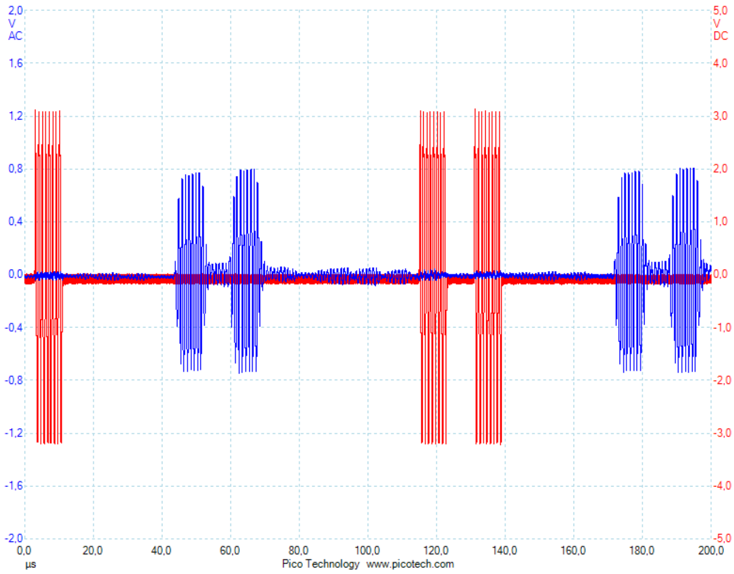


**Figure 6.11:** *Result of OOK modulation with PVDF transducer.*

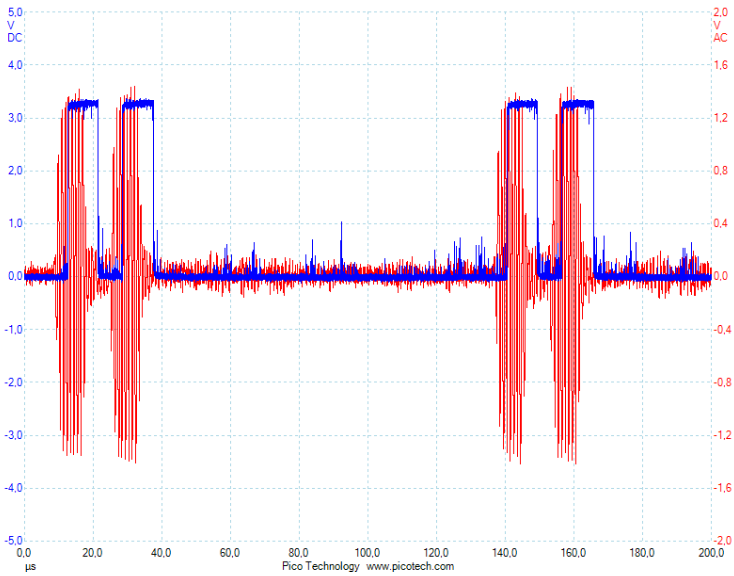


**Figure 6.12:** *Result of OOK demodulation with PVDF transducer.*

#### 6.3.2.2 BASK modulation

In figure 6.13 and 6.14 it can be observed the BASK modulation and demodulation process using PVDF transducer.

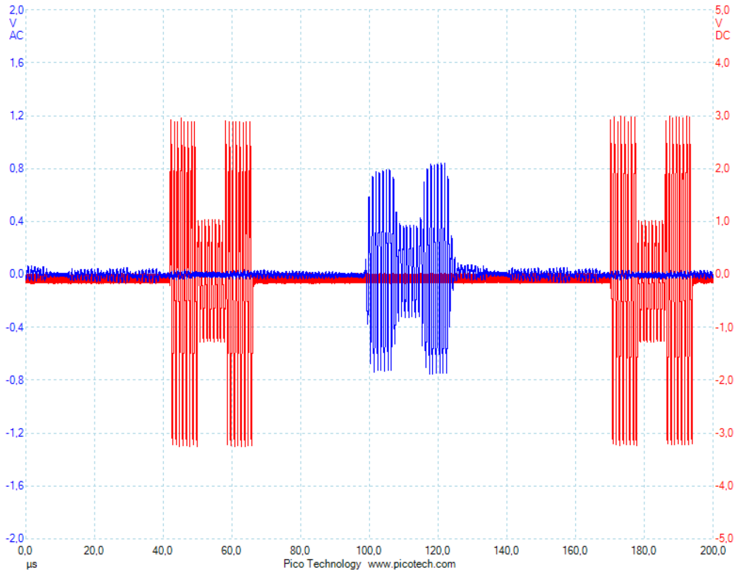


**Figure 6.13:** *Result of BASK modulation with PVDF transducer.*

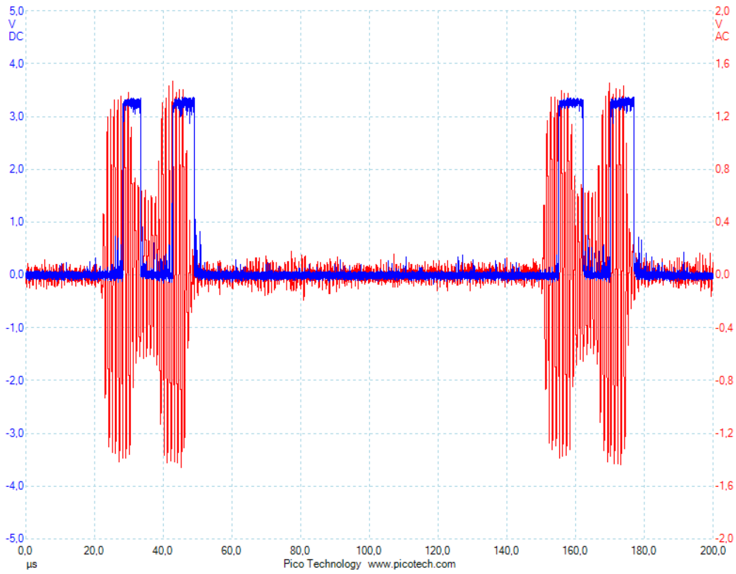


**Figure 6.14:** *Result of BASK demodulation with PVDF transducer.*

#### 6.3.2.3 BPSK modulation

In figure 6.15 and 6.16 it can be observed the BPSK modulation and demodulation process using PVDF transducer.

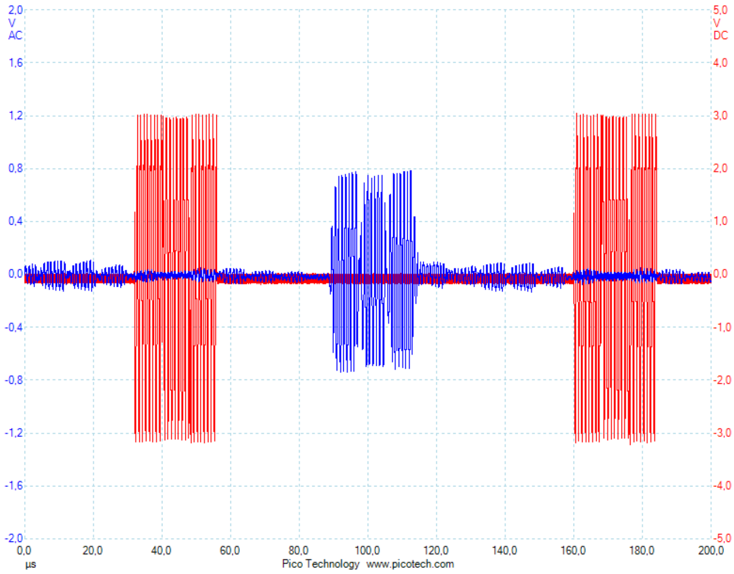


**Figure 6.15:** *Result of BPSK modulation with PVDF transducer.*

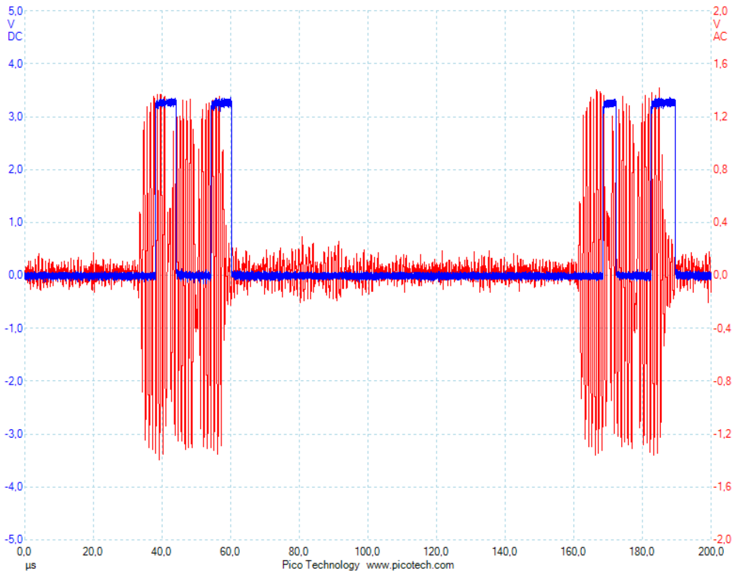


**Figure 6.16:** *Result of BPSK demodulation with PVDF transducer.*

#### 6.3.2.4 FSK modulation

In figure 6.17 and 6.18 it can be observed the FSK modulation and demodulation process using PVDF transducer.

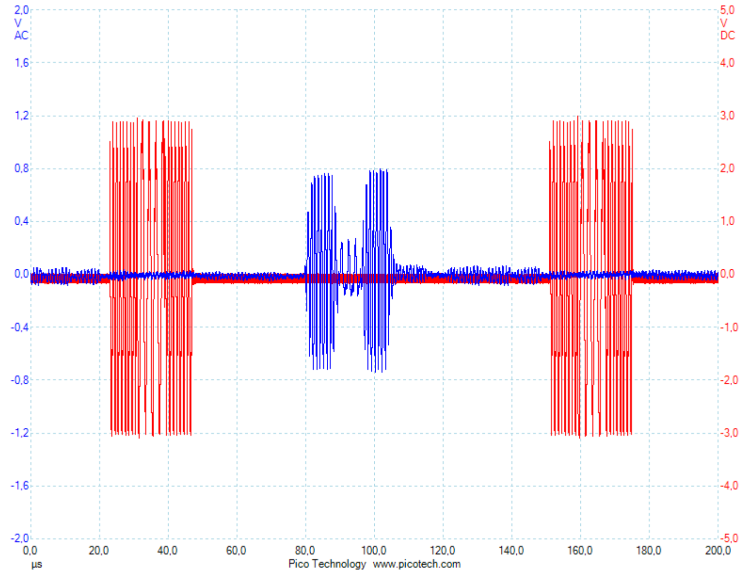


**Figure 6.17:** *Result of FSK modulation with PVDF transducer.*

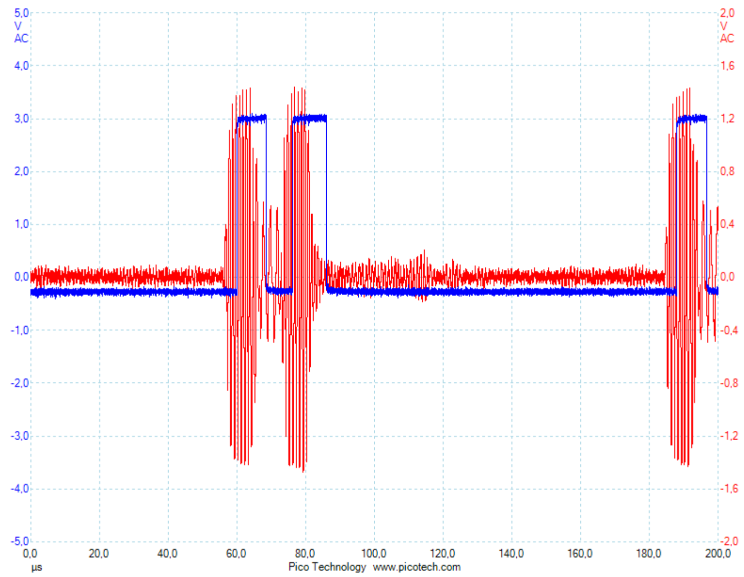


**Figure 6.18:** *Result of FSK demodulation with PVDF transducer.*

## 6.4 Comparison and Analysis of the obtained results

After the presentation of the results obtained through the experimental tests with the conditions mentioned in the section 6.3 of this chapter, it was possible to observe that the results of the various modulation schemes submitted are in agreement with the results obtained through simulation, presented in the chapter 5.

As expected, it was found some noise from the electronic embedded in the support system, that through small adjustments, which have been mentioned previously, minimized its impact on the signal.

In order to analyse the obtained results, it was decided to do it separately.

***OOK Modulation:***

Consists in a rather simplified modulation, but very effective in underwater environments. It is possible to observe in figure 6.11 that the signal received by the hydrophone has a very acceptable form (very similar to the emitted signal) to carry out the demodulation process. Thus, through the analysis of figure 6.12 it is possible to verify that the signal demodulation is carried out effectively.

Its simplicity has only one inefficient aspect, which is that it is not possible to identify, at the reception, if the system is sending the bit 0, or not transmitting any kind of information at all.

***BASK Modulation:***

As well as the OOK modulation, this particular type of *Amplitude Shift Keying* (ASK) modulation shows to be quite efficient in an underwater environment using high frequencies. It is possible to observe in figure 6.14 that the demodulation process of the signal received by the hydrophone is made effectively, therefore becoming a good choice for this kind of systems. By introducing a new status in the signal comparison, it will be possible to identify when the system is idle or sending data frames with bit 0, thereby improving its efficiency in this type of environment.

***BPSK Modulation:***

Despite the fact that BPSK modulation is a binary version and consequently a more simpler version of *Phase Shift Keying* (PSK) modulation, in figure 6.15 it is possible to observe that the phase shift of the modulated signal, received by the hydrophone, becomes quite difficult to identify. This happens due to the energy accumulated in the transducer when a phase shift occurs in the modulated signal. With this phase shift the signal vanishes, and the transducer transmits the stored energy in the form of acoustic waves to the medium. In the figure 6.16 it is possible to verify that the signal is correctly demodulated. However it was necessary to make some adjustments in the comparison process. Some errors were found in the demodulation process on recovering the binary data stream, due to some inevitable presence of noise in the support architecture. Thus, to solve the problem, two comparison points were used, avoiding reading errors in the recovering of the binary data stream.

Although this type of modulation can be effective for the proposed system, with the need to provide higher speeds of communications, by introducing more complex modulations, such as *Quadrature Phase Shift Keying* (QPSK) or even *Quadrature Amplitude* (QAM) modulation, where the number of phase shifts increases substantially, it became practically impossible to perform the demodulation process of the received signal effectively.

***FSK Modulation:***

As well as in BPSK modulation, through the observation of figure 6.17 it is possible to detect a difference between the modulated signal, sent by the transducer, and the signal received by the hydrophone. This occurs due to the acoustic pressure in the transducer (see equation 4.1) which, by the increase of frequency, the increase of the acoustic pressure exercised by the transducer is inevitably. With a detailed analysis of the received signal by the hydrophone it is possible to verify that it resembles a BASK modulated signal, but nevertheless its demodulation process is carried out effectively, allowing to recover the binary stream correctly.

***System overview***

By making a system overview it is possible to assert that all binary digital modulations schemes presented may be used in an underwater environments using high frequencies. However, as noted during individual analysis, each model has advantages and disadvantages that must be kept in mind when implementing these type of communication systems.

It is important to note that in all practical tests presented it is possible to identify a delay between the transmitted and received signal. This delay occurs due to the demodulation process performed particularly in the filters. Since the used filters have a high order, the processing level is considerably greater, which causes some delays in the signal demodulation. However, when the signal is sent through the aquatic channel these delays are added with the delays suffered by the propagation channel. Thus, the delay in this type of transmission is obviously high.

Another important thing to consider is the fact that, during the experimental tests performed with the transducer PVDF, it was possible to verify a difference in amplitude relative to the signal received by the hydrophone and from the input signal to the ADC. This happens due to the amplification of the signal before the transmission by the aquatic environment. It should be taken in consideration that the signal suffers again an amplification in the ADC instrumentation, thus accounting a total gain of four in the system.

### ***Summary***

This chapter presents the tests scenarios and the conditions verified during the experimental tests.

In first place, all the relevant aspects about the tests scenarios, where the experimental tests were performed, were discussed in detail. Then, the important parameters, used to perform practical tests, were described. These parameters are very important and become indispensable to perform an accurate analysis of the obtained results. After this approach, all the obtained results during the experimental tests were described.

And last, but not least, it was made an analysis of the obtained results, which allowed to evaluate the effectiveness of the proposed solutions to efficiently ensure the desired goal: evaluate the binary digital modulations schemes in an underwater environment.

# 7

# Conclusions

Over the years, the underwater wireless communication systems has aroused a great interest of research due to its strong potentiality of applications in several areas that stand out research on marine life, environmental monitoring and disaster prevention. This kind of system can also provide a great support for oil and military industry. The development of these communications systems may play an important role in a near future, not only economically, but also in academic terms, and thus, increasing the research in this area of study to further enhance the development of applications in the areas mentioned above.

In this dissertation, a study of binary digital modulations using acoustic waves in underwater environments was carried out, as well as a survey on all the factors that influence the propagation of these acoustic waves in underwater environments. During this research, other underwater wireless communications systems (optical and electromagnetic) were taken into account and were briefly analysed.

Until now, the existing types of Acoustic COMmunications (ACOM) systems, uses the omnidirectional (spherical) or semi-omnidirectional (cylindrical) propagation at very low frequencies (in order of $200kHz$). So, during the study that was carried out on this dissertation a new concept of underwater acoustic communication was developed: an underwater ACOM system that performs directional communications at high frequencies ($1MHz$).

The studies and the research that were conducted in this area led to the implementation of the binary digital modulations schemes in *Matlab/Simulink* platform in conjunction with specific *Xilinx* blockset. This model will analyse and evaluate the operation of digital modulations in an underwater ACOM system in order to understand which best fits to the system.

To validate the implemented solutions, it was used a toolkit (presented in chapter 4), that made possible to perform several experimental tests in order to compare the behaviour of digital modulations in real environment relatively to the one simulated in *Matlab/Simulink*.

## 7.1 Contributions and achieved results

The aim of this investigation was to evaluate the performance of the digital modulation techniques in an underwater acoustic communication system. Accordingly, was developed a simulation system that contributed to the analysis and research of digital modulations schemes.

As part of this dissertation research, the following contributions have clearly been made:

- The existence of the binary digital modulations, that define wireless communications in an open environment can be applied for the transmission of acoustic signals through the aquatic environment;
- Four models of modulations schemes were developed in order to recognize which one has a better performance in an underwater environments. The existing modulation models used in ACOM system only provided the propagation of acoustic signal at very low frequencies. However, the models developed in this project were designed to perform wireless communications at high frequencies;
- The modulation schemes implemented show that they can be applied in underwater systems using higher frequencies, which are liable to be changed in order to encode more than one bit simultaneously, and therefore providing faster communication speeds;
- The simulation models offer the ability to simulate, not only the physical effects of the modulations schemes, but also to identify small phenomena that can occur during the real system implementation. The simulators also provide the ability to observe the performance of digital modulations schemes in real-time avoiding unnecessary waste of time during its implementation;

## 7.2 Future work

In conclusion, we can claim that the proposed objectives were achieved. Nevertheless, there are always countless aspects that can be improved in the upcoming future, such as:

- Improvement of the support platform modulations (FPGA), substantially increasing the level of internal processing enabling thereby, the improvement of demodulation schemes, namely the inclusion of detection systems in frequency and phase (Costas Loop and PLL);

- Implementing a modulation scheme that is able to encode more than one bit simultaneously (*M-ary* Modulations) and therefore providing higher speeds of communications;
- Implementation of multiplexing techniques. Grouping several channels to transmit them simultaneously;
- Specification of an Automatic Gain Control (AGC) in the receiver, which automatically adjusts the signal gain at the reception;
- Increase the amount of experimental tests in different environments, such as a pool or a barrage.

With the implementation of these features, it will possible to build a robust and reliable system that will be capable of operating in different underwater environments.

# References

[APM04] Ian F. Akyildiz, Dario Pompili, and Tommaso Melodia. Challenges for efficient communication in underwater acoustic sensor networks. *SIGBED Rev.*, 1(2):3–8, 2004.

[APM05] Ian F. Akyildiz, Dario Pompili, and Tommaso Melodia. Underwater acoustic sensor networks: Research challenges. *AD HOC NETWORKS (ELSEVIER*, 3:257–279, 2005.

[APM07] Ian Akyildiz, Dario Pompili, and Tommaso Melodia. "state of the art in protocol research for underwater acoustic sensor networks". *ACM Mobile Computing and Communication Review*, vol. 11, no. 4:11–22, October 2007.

[Arn10] Shlomi Arnon. "underwater optical wireless communication network". *Optical Engineering*, 49(1):015001–1 to 015001–6, January 2010.

[Bar09] Arantxa Barrio. "modelling underwater acoustic noise as a tool for coastal management". Master's thesis, University of Algarve, Faculty of Sciences and Technology, August, 2009.

[Bor10] Brian Borowski. "application of channel estimation to underwater acoustic communication". Master's thesis, Stevens Institute of Technology, 2010.

[Bru10] Heather Brundage. "designing a wireless underwater optical communication system". Master's thesis, Massachusetts Institute of Technology, Department of Mechanical Engineering, 2010.

[BS08] David Bradley and Richard Stern. *"Underwater Sound AND THE MARINE MAMMAL ACOUSTIC ENVIRONMENT A Guide to Fundamental Principles"*. U.S. Marine Mammal Commission, July 2008.

[Car86] A.Bruce Carlson. *Communication Systems, "an introduction to signals and noise in electrical communication"*. 1986.

[Con08] International Association of Geophysical Contractors. ”fundamentals of underwater sound”. Technical report, International Association of Oil & Gas Producers (OGP), May, 2008.

[Cox07] Charles Cox. ”a 1 mbps underwater communication system using a 405 nm laser diode and photomultiplier tube”. Master's thesis, Graduate Faculty of North Carolina State University, Department of Electrical Engineering, 2007.

[CSD+08] William C Cox, Jim A Simpson, Carlo P Domizioli, John F Muth, and Brian L Hughes. An underwater optical communication system implementing reed-solomon channel coding. *Proc OCEANS Conf 2008*, Quebec Cit:1–6, 2008.

[Dev12] Analog Devices. http://www.wvshare.com/datasheet/ADPDF/AD9244.PDF, 2005, Last access in July 2012.

[DKL+07] Matthew Dermond, Tim Kerr, Ed Lucas, Matt Millar, and Kevin Pavon. ”underwater communication technology”. *The journal of rowan engineering/mechanical*, page 6, 2007.

[dOF11] Vítor Manuel de Oliveira Fialho. *Modulações Digitais*. Instituto Superior de Engenharia de Lisboa, versão 1.0 edition, May 2011.

[dSF12] Ricardo de Sousa Fernandes. Design and implementation of an underwater communication system. Master's thesis, Universidade do Minho, November 2012.

[fD08] System Generator for DSP. *Getting Started Guide*, 10.1 edition, March 2008.

[God02] Luke Godden. ”underwater ultrasonic communication”. Master's thesis, University of Queensland, Department of information technology and electrical engineering, 2002.

[GTL06] Oscar Szeremeta Gustavo Theodoro Laskoski, Maicon Marcondes. Modulação digital, ”tópicos de comunicações”. Technical report, Universidade Tecnologica Federal do Paraná, Setember 2006.

[Gut09] Francisco Martín Gutiérrez. Implementation of a tx/rx ofdm system in a fpga. Master's thesis, Escola Politecnica Superior de Castelldefels, April 2009.

[Hau09] Ole Trygve Haug. Acoustic communication for use in underwater sensor networks, 2009.

[Hay01] Simon Haykin. *"Communication Systems, 4th Edition"*. John Wiley & Sons, Inc., 2001.

[HB02] James Hwang and Jonathan Ballagh. Building custom fir filters using system generator. In *Proceedings of the Reconfigurable Computing Is Going Mainstream, 12th International Conference on Field-Programmable Logic and Applications*, FPL '02, pages 1101–1104, London, UK, UK, 2002. Springer-Verlag.

[HSZ12] J. Heidemann, M. Stojanovic, and M. Zorzi. Underwater sensor networks: applications, advances and challenges. *Philos Transact A Math Phys Eng Sci*, 370(1958):158–75, 2012.

[IHA10] Nor-Syahidatul N Ismail, Liban Abdullahi Hussein, and Sharifah H S Ariffin. "analyzing the performance of acoustic channel in underwater wireless sensor network (uwsn)". *Mathematical/Analytical Modelling and Computer Simulation (AMS), 2010 Fourth Asia International Conference*, pages 550–555, 26-28 May 2010.

[Ins12] Texas Instruments. http://www.ti.com/lit/ds/sbas095c/sbas095c.pdf, 2002, Last access in July 2012.

[KT08] Matthew Karpeles and Dustin Torres. Underwater acoustic communication. pages 1–9, 2008.

[KW05] Steven Kah and Hien Wong. "underwater acoustic simulator for communications". *Honours Programme of the School of Computer Science and Software Engineering*, pages 1–51, 2005.

[LG06] Y. Liu and X. Ge. "underwater laser sensor network: A new approach for broadband communication in the underwater". *5th WSEAS International Conference on Telecommunications and Informatics*, pages 421–425, 27-29 May 2006.

[Lov06] Georgia Love. "the undersea world of wfs". Technical report, WFS technologies, 2006.

[LZC08] Lanbo Liu, Shengli Zhou, and Jun-Hong Cui. "prospects and problems of wireless communication for underwater sensor networks". *Wireless Communications and Mobile Computing (WCMC)*, pages 977–994, 2008.

[Mat12a] MathWorks. http://www.mathworks.com/products/matlab/description1.html, Last access in June 2012.

[Mat12b] MathWorks. http://www.mathworks.com/products/simulink/, Last access in June 2012.

[MCLM+10] M. Martins, V. Correia, S. Lanceros-Mendez, J. Cabral, and J. Rocha. "comparative finite element analyses of piezoelectric ceramics and polymers at high frequency for underwater wireless communications". *Elsevier, Proc. Eurosensors XXIV, Linz, Austria*, 5:99–102, September 5-8, 2010.

[Men11] Diogo Mendes. A matlab/simulink model to evaluate underwater acoustic communication systems. Master's thesis, Universidade do Minho, December 2011.

[Pal09] Guillem Palou. Underwater acoustic mimo ofdm an experimental analysis. Master's thesis, Massachusetts Institute of Technology, Setember 2009.

[PAT+09] Santiago T. Pérez, Jesús B. Alonso, Carlos M. Travieso, Miguel A. Ferrer, and José F. Cruz. Design of a synchronous ffhss modulator on a fpga with system generator. *WSEAS Trans. Cir. and Sys.*, 8(8):641–650, August 2009.

[PGB11] S.O. Popescu, A.S. Gontean, and G. Budura. Simulation and implementation of a bpsk modulator on fpga. In *Applied Computational Intelligence and Informatics (SACI), 2011 6th IEEE International Symposium on*, pages 459 –463, may 2011.

[Pre06] James Preisig. "acoustic propagation considerations for underwater acoustic communications network development". *Underwater Networks (WUWNet'06)*, pages 1–5, 25 September 2006.

[Pro12] European Community's Seventh Framework Programme. Uan - underwater acoustic network. http://www.ua-net.eu/, Last access in June 2012.

[Rho06] Mark Rhodes. "underwater electromagnetic propagation". *Hydro International*, pages 28–31, December 2006.

[Rho07] Mark Rhodes. "electromagnetic propagation in sea water and its value in military systems". *SEAS DTC Technical Conference*, page 6, July 2007.

[She05] T. Shelley. "radio waves transmit information underwater". *Eureka Magazine*, 14 November 2005.

[SP09] Milica Stojanovic and James Preisig. "underwater acoustic communication channels: Propagation models and statistical characterization". *IEEE Communications Magazine*, pages 84–89, January 2009.

[Sto99] Milica Stojanovic. "underwater acoustic communication". *Wiley Encyclopedia of Electrical and Electronics Engineering*, 22:688–698, 1999.

[Sto07] Milica Stojanovic. "on the relationship between capacity and distance in an underwater acoustic communication channel". *ACM SIGMOBILE Mobile Computing and Communications Review (MC2R)*, 11, Issue 4:34–43, October 2007.

[STS09] Anuj Sehgal, Iyad Tumar, and Jürgen Schönwälder. "variability of available capacity due to the effects of depth and temperature in the underwater acoustic communication channels". *OCEANS 2009 - EUROPE*, pages 1–6, 11-14 May 2009.

[STS10] Anuj Sehgal, Iyad Tumar, and Jürgen Schönwälder. "aquatools: An underwater acoustic networking simulation toolkit". *IEEE Oceans*, May 2010.

[Tec12a] Cetacean Research Technology. http://www.cetaceanresearch.com/documents/hydrophone specs.pdf, 2011, Last access in July 2012.

[Tec12b] Pico Technology. http://www.picotech.com/document/datasheets/PicoScope4000Series.p Last access in July 2012.

[Vir01] K. M. Virk. Design of an integrated gfsk demodulator for a bluetooth receiver. Master's thesis, Technical University of Denmark, DTU, 2001.

[Vos10] Heidi Vosbein. *"Introduction to Ocean Acoustics"*. University Corporation for Atmospheric Research (UCAR), COMET Program, 2010.

[Xil12] Xilinx. http://www.xilinx.com/s3astarter, August Last access in June 2012.

[YK11] Mohd Yusof and Shahid Kabir. "underwater communication systems: A review". *Progress In Electromagnetics Research Symposium Proceedings*, pages 803–807, March 2011.