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Multimodal Underwater Wireless Communications using Acoustic and Radio Technologies

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Resumo

As comunicações subaquáticas sem fios desempenham um papel fundamental na rápida expansão da Economia Azul, da qual fazem parte uma ampla variedade de atividades comerciais e industriais no mar. Para apoiar estas atividades são utilizadas plataformas robóticas de deteção marítima e subaquática, como os veículos de superfície autónomos (ASV), os veículos subaquáticos autónomos (AUV) e os veículos operados remotamente (ROV), que recolhem grandes quantidades de dados durante as suas missões. Como tal, estes veículos necessitam de ser capazes de comunicar de baixo de água eficazmente. No entanto, as características adversas dos ambientes marítimos limitam as comunicações subaquáticas sem fios a aplicações de elevada largura de banda a curtas distâncias, ou a aplicações de baixa largura de banda a longas distâncias.

Atualmente, existem três tecnologias para as comunicações subaquáticas: comunicações acústicas, rádio frequência (RF) e óticas. As soluções acústicas são capazes de cobrir longas distâncias, mas com largura de banda bastante limitada. As comunicações RF proporcionam um elevado débito, mas estão condicionadas a curtas distâncias, tipicamente alguns centímetros debaixo de água. As soluções óticas oferecem igualmente elevada capacidade de transmissão, mas são sensíveis à turbidez da água e necessitam de linha de vista, o que reduz o seu alcance.

Esta dissertação tem como objetivo desenvolver, implementar e validar um gestor multimodal de comunicações subaquáticas sem fios - Aquacom, que integre as tecnologias num único sistema, de modo a aproveitar as vantagens de cada uma, e mitigar as suas desvantagens, abstraindo o utilizador da alternância entre tecnologias e agregando-as. Ao combinar as características de cada tecnologia, o Aquacom permite a transferência contínua de dados sem fios. Além disso, em comparação com a investigação anterior em soluções multimodais, que normalmente integram comunicações óticas e acústicas e cenários e aplicações específicas, esta dissertação alarga o âmbito ao não ter como objetivo um cenário específico e ao incorporar também comunicações RF, um aspeto que tem sido menos explorado nas abordagens multimodais existentes.

Neste trabalho, foi desenvolvido um novo mecanismo de transição entre interfaces capaz de alternar entre tecnologias RF e Acústicas, enquanto mantém a transferência de dados continua, usando a relação sinal-ruído observada para a tecnologia RF. Relativamente às comunicações RF, adotámos o conceito de redes tolerantes ao atraso (DTN), um tipo de rede especificamente desenvolvido para lidar com interrupções e atrasos nas ligações. Além disso, foi desenvolvidou um mecanismo de ordenação capaz de gerir a receção de dados fora de ordem, e um mecanismo de agregação que combina a capacidade das tecnologias RF para aumentar a velocidade de transmissão. O Aquacom foi validado em ambiente laboratorial num tanque de água doce nas instalações do INESC TEC/FEUP, utilizando modems rádio e acústicos. Os resultados obtidos demonstram o potencial da solução proposta para aumentar a eficácia e eficiência das comunicações em ambiente subaquático.

Palavras-Chave: Redes Multimodais, Comunicações subaquáticas, Comunicações Acústicas, Comunicações RF, DTN.

Abstract

Underwater wireless communications play a fundamental role in the rapidly expanding Blue Economy, which includes commercial and industrial activities at sea. Maritime and underwater sensing platforms, such as Autonomous Surface Vehicles (ASVs), Autonomous Underwater Vehicles (AUVs), and Remotely Operated Vehicles (ROVs), are used to support these activities. Effective communication capabilities are essential to transmit the large amounts of data these platforms can collect. However, the harsh propagation characteristics of the ocean pose significant challenges, limiting underwater wireless communications to either high bandwidth applications at short ranges or low bandwidth applications at long ranges.

Traditional underwater wireless communication technologies, namely Acoustic, Radio Frequency (RF), and wireless Optical, offer unique advantages and limitations. Acoustic solutions offer a longer operational range but suffer from limited bandwidth. RF communications provide high throughput but are constrained to short ranges, typically a few centimetres underwater. On the other hand, optical solutions also provide high throughput capacity but are sensitive to water turbidity and require precise beam adjustments, which reduces their range to a few meters.

To address the limitations and benefit from the advantages of current technologies, this dissertation aims to develop, implement and validate a multimodal underwater wireless communications manager - Aquacom, integrating acoustic, radio, and optical communications in a single system with seamless handover and aggregation between technologies. By combining the characteristics of each technology, Aquacom enables continuous wireless data transfer and supports the development of applications for underwater scenarios. In comparison to previous research on multimodal systems, which typically only integrate optical and acoustic communications and target particular scenarios and applications, this dissertation broadens the scope by not targeting a specific scenario, using multiple interfaces simultaneously and incorporating RF communications as well, an aspect that has been relatively less explored in existing multimodal approaches.

To achieve this, we developed a new interface switching mechanism capable of performing the seamless handover of data between technologies by evaluating the Signal-to-Noise ratio (SNR). We adopted the concept of Delay-Tolerant Networks(DTN), a type of network specially designed to handle intermittent connectivity. Additionally, we developed sorting and aggregation mechanisms to manage out-of-order data and combine the capacity of multiple communication links, enhancing the throughput. Aquacom represents a promising solution to address the challenges of underwater communications and support activities in the dynamic and growing Blue Economy. Aquacom was validated through lab tests in a freshwater tank at INESC TEC/FEUP facilities, utilizing both radio and acoustic modems. The results obtained demonstrate Aquacom's potential to enhance the effectiveness and efficiency of underwater communications.

Keywords: Multimodal Networks, Underwater Communications, Acoustic Communications, RF Communications, DTN.

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Guilherme Moreira

“Our greatest glory is not in never falling,
but in rising every time we fall.”

Confucius

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Abbreviations and Symbols

API	Application Programming Interface
ASVs	Autonomous Surface Vehicles
AUVs	Autonomous Underwater Vehicles
BP	Bundle Protocol
CTM	Centre of Telecommunications and Multimedia
DTNs	Delay Tolerant Networks
EIDs	Endpoint Identifiers
Gbit	Gigabit
IBR-DTN	Institut für Betriebssysteme und Rechnerverbund Delay Tolerant Network
IEEE	Institute of Electrical and Electronics Engineers
INESC TEC	Institute for Systems and Computer Engineering, Technology and Science
ION	Interplanetary Overlay Network
IP	Internet Protocol
km	Kilometer
Kbit	Kilobit
KB	Kilobyte
LoS	Line-of-sight
Mbit	Megabit
MB	Megabyte
MCS	Modulation Coding Scheme
RF	Radio Frequency
ROVs	Remotely Operated Vehicles
RTT	Round-Trip Time
SNR	Signal-to-Noise ratio
TCP	Transmission Control Protocol
TL	Transmission Loss
URIs	Uniform Resource Identifiers

Chapter 1

Introduction

This introductory chapter contextualizes the dissertation by presenting a brief overview of underwater wireless communications, the main motivations of the multimodal approach, the objectives of this dissertation and its contributions. In addition, it provides a brief description of the structure of the document.

1.1 Context

In recent years, there has been an increasing interest in commercial and industrial activities at sea, also known as the Blue Economy. These activities include not only traditional activities such as fishing, aquaculture, transportation, and tourism, but also emerging activities such as offshore wind farms, environmental ocean monitoring, and deep-sea mining. Portugal is among the countries investing the most in the Blue Economy and these investments are expected to play a key role in post-pandemic recovery [1,2].

Given the complexity and high costs of manned missions, these activities are increasingly supported by Autonomous Surface Vehicles (ASVs), Autonomous Underwater Vehicles (AUVs), Remotely Operated Vehicles (ROVs) and other sensing platforms, such as underwater landers and observatories [3]. These platforms need effective communication capabilities to transmit the collected data. However, the harsh propagation characteristics of the water limit underwater communications to either short-range, high bandwidth applications or long-range, low bandwidth applications, which makes real-time data transfer difficult.

Traditional underwater wireless communications are based on Acoustic, Optical and Radio Frequency (RF) technologies. Acoustic communications are the most used technology as they can reach longer distances, but due to the low propagation speed of sound underwater, they suffer from very high latency. Additionally, the lower frequency of operation limits the achievable data rate, in the order of kb/s. Optical communications can achieve higher data rates. Nonetheless, the turbidity of water reduces its effective range to a few meters, making them unsuitable for long-range applications. Similarly, RF communications are able to achieve higher data rates and, in comparison to Optical communications, are not affected by water turbidity. However, they suffer from electromagnetic attenuation underwater, which drastically reduces their range of operation [4]. Therefore, a system relying purely on a single technology is not sufficient to ensure a good throughput-to-distance ratio.

1.2 Motivation

To cope with the limitations of each technology a multimodal approach can be used. In such an approach, the three technologies can be combined in a way that, under certain conditions, the system would optimally choose the best technology or technologies and establish the communication channel. To enable the handover and link aggregation of multiple underwater interfaces, a communication manager is required. Figure 1.1 shows an illustration of a network where a manager following this approach could be deployed. As we can see, this would allow tackling different scenarios, taking the best of each technology, such as the ability of Acoustic to transmit over long distances and the high bitrate of Optical and Radio for short distance communication. Nonetheless, selecting the technology and performing switching and aggregating different interfaces is a problem yet to be solved.

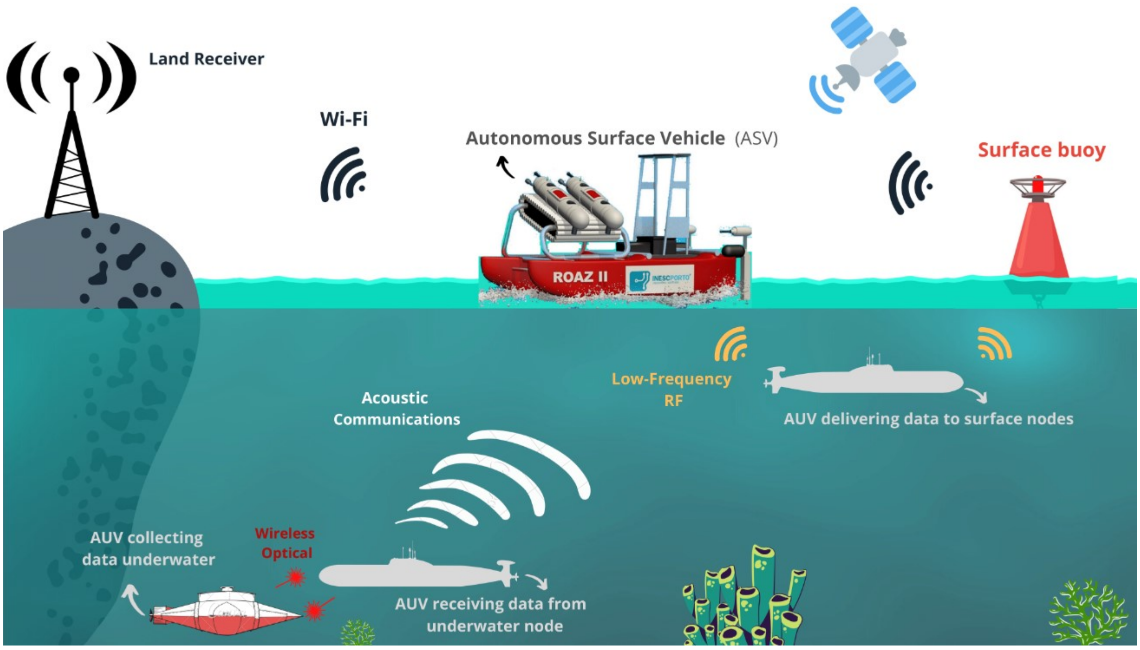

Figure 1.1: Overview of an underwater multimodal approach [3].

1.3 Objectives

Most of the research on multimodal underwater wireless communications systems only consider Optical and Acoustic communications and typically address particular scenarios and applications. This dissertation aims to develop and validate a multimodal communications solution that is able to integrate multiple underwater interfaces in a single system, thus performing a seamless handover between each technology and simplifying the development of underwater applications for any scenario, while allowing continuous wireless data transfer. Besides the handover, we also propose a solution to aggregate multiple interfaces, increasing the network performance. The following specific objectives were considered in order to achieve this:

- Development of a proactive switching mechanism based on the Signal-to-Noise ratio (SNR), in a way that unreliable, but faster interfaces send the same data as the more reliable, but slower interfaces, while transitioning between interfaces;
- Design of a Sorting mechanism capable of reordering out of order data;
- Development of an aggregation mechanism to increase the throughput of communication link;
- Creation of an underwater testbed to evaluate the proposed communications solution composed of two nodes with multiple network interfaces.

1.4 Contributions

The main contribution of this dissertation is the design and implementation of a multimodal communications solution – Aquacom – that allows the seamless selection of Acoustic, Optical and RF technologies in underwater multimodal scenarios. The proposed solution aims to advance maritime research missions by enabling faster and more reliable deployment of underwater communication systems.

Additionally, a scientific paper related to this dissertation is currently under development, with the intention of submitting it to an international conference.

1.5 Document Structure

This document is divided into six chapters. In Chapter 2, we explore the state of the art in underwater wireless communications, present the concept of Delay Tolerant Networks, and the related work on multimodal underwater wireless systems. Chapter 3 presents the proposed solution and its implementation. Chapter 4 provides a comprehensive explanation of the experimental setup developed for testing and validating our solution, along with the methodology used. In Chapter 5, we present the experimental results and engage in a detailed discussion of these findings. Lastly, Chapter 6 comprises the final conclusions, highlights possible areas for improvement, and outlines potential future work.

Chapter 2

State of the Art

In this chapter, we review the state of the art on underwater wireless communications and compare the three primary technologies: acoustic, radio frequency (RF), and optical. We also introduce the concept of Delay-Tolerant Networks and the Bundle protocol on which they are based. Additionally, we provide a comprehensive overview of existing multimodal solutions for underwater wireless communications, highlighting their benefits and limitations.

2.1 Underwater Wireless Communications

Underwater wireless communications refer to the transmission of data, video, and other forms of information through the use of wireless signals in an underwater environment. The three main technologies used to exchange data wirelessly underwater are acoustic, RF and optical communications [4]. However, due to the unique and complex propagation characteristics of water, developing reliable communications systems underwater has proven to be a challenging task.

Each technology has different characteristics and limitations. Acoustic communications are the most widely used technology for underwater communications, and they involve the transmission of data and information through the use of sound waves. This technology has the benefit of being able to transmit signals over long distances (up to 20 km), but it is very limited in terms of its bandwidth. Additionally, the performance of acoustic communications can be impacted by factors such as ambient noise, salinity, and pressure gradients in the marine environment. Despite these limitations, acoustic communications are a well-established technology that has been widely adopted in various applications.

RF communications use electromagnetic waves to transmit data and information through the water. RF has the advantage of being able to transmit data with high bandwidth and not being affected by ambient noise, turbidity, and pressure gradients, but its range is limited by electromagnetic attenuation. As a result, RF communications are typically only used for short-range communications [4].

Optical communication uses light to transmit data through the water. It has the advantage of being able to transmit data with very high bitrate, but it is limited by the fact that light does not travel far through the water, as it is easily affected by turbidity, marine fouling, and ambient lights. Additionally, it requires line-of-sight (LOS). Therefore, optical communications are typically only used for short-range (up to 100 m) communications. Furthermore, optical communications are not able to cross the water/air boundary.

In summary, the main differences between acoustic, optical, and RF underwater communications are the distance over which they can transmit signals, the data rate and bandwidth they can support, and their susceptibility to interference. Table 2.1 shows a comparison between the three technologies regarding these differences.

Table 2.1: Key differences of underwater wireless communication technologies.

	Technology		
Differences	Acoustic	Optical	RF
Range	Very high (up to 20km)	Low (up to 100m) Requires LOS	Very Low (up to 10m)
Throughput	Very low (order of Kbit/s)	High/Very high (order of Gbit/s)	High (order of Mbit/s)
Interference	Ambient noise Salinity Pressure gradients	Turbidity Particles Marine Fouling	Electromagnetic Attenuation

In the following 3 subsections, we analyze the propagation models of each of the aforementioned types of underwater wireless communications in more detail.

2.1.1 Acoustic Wireless Communications

Underwater acoustic communications use sound to transfer information and, due to the lack of alternatives, they are currently the dominant technology for wireless underwater communications [5]. Mackenzie in [6] presented a formula to obtain the speed of sound (c in *m/s*) (Eq. 2.1), with a standard error of 0.070 *m/s* for depths of up to 8000 km. It considers the dependence of acoustic waves on temperature T in degrees Celsius, salinity S in parts per thousand and depth D in meters.

$$\begin{aligned} c =& 1449.96 + 4.591T - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 + 1.340(S-35) \\ &+ 1.630 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 - 1.025 \times 10^{-2}T(S-35) - 7.139 \times 10^{-13}TD^3 \end{aligned} \tag{2.1}$$

Kularia *et al.* [7] defined the propagation delay T_p, i.e., the time taken by a sound wave to travel between two nodes, as Eq. 2.2:

$$T_p = \frac{d}{c} \tag{2.2}$$

where d is the distance in meters between two nodes and c the speed of sound.

By applying Eq. 2.2, along with the values for the speed of sound obtained from Eq. 2.1 and provided in [8], we can generate the plot in Fig. 2.1 which shows the propagation delay of sound underwater at various depths and for two fixed distances between two nodes (100 m and 250 m). This plot demonstrates that the propagation delay of sound increases with both depth and distance between the nodes. The propagation delay of sound underwater does not prove to be problematic even for longer distances, however, the transmission time at a low data rate (a few bits/s) will lead to a significant delay.

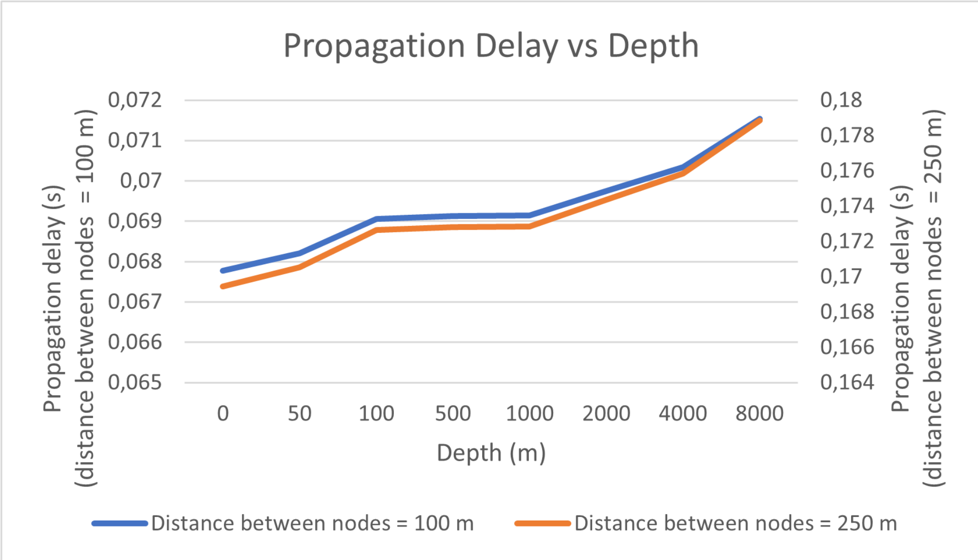

Figure 2.1: Propagation Delay of Sound vs Depth.

In the context of underwater acoustic communications, understanding the required power (P) to achieve a given range is essential. One key factor influencing this power requirement is the transmission loss (TL in dB) of the acoustic wave, which represents the decrease in sound intensity from the sender to the receiver as it travels through the water.

The TL, Eq. 2.3, can be defined as the sum of the absorption loss (PL_a in dB), Eq. 2.4, and the spreading loss (PL_s in dB), Eq. 2.5. The former is used to describe the energy loss that occurs in the form of heat as a sound wave propagates underwater. The latter is used to describe the decrease in sound level that occurs as a sound wave propagates away from its source [7].

$$TL = PL_s + PL_a \tag{2.3}$$

$$PL_s(d) = \alpha \times d \times 10^{-3} \tag{2.4}$$

$$PL_a(d) = k \times 10log(d) \tag{2.5}$$

where d is the transmission range in meters, α is the attenuation factor in *dB/km* given by Eq. 2.6, where f is the frequency in kHz, and k is the spreading factor. K is used to describe the geometry of sound wave propagation, which can take on three different values: 1 (spherical spreading), 1.5 (practical spreading), and 2 (cylindrical spreading). Practical spreading refers to situations where the distance between the source and the receiver is larger than half of the water depth, but not large enough to qualify as cylindrical spreading [9, 10]. In [7] it is concluded that the Transmission Loss (TL), Spreading Loss due to Spherical spreading PL_s, and Spreading Loss due to Attenuation

PL_a all increase with frequency.

$$\alpha(f) = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75\times10^{-4}f^2 + 0.003 \tag{2.6}$$

In [9], assuming that the required power for quality of reception is P_o, the required power (P) in watts to achieve a given range is determined using eq. 2.7:

$$P(d,f) = P_o \times 10^{\frac{TL(d,f)}{10}} \tag{2.7}$$

Table 2.2 shows a list of some acoustic modems available on the market, along with their characteristics [11, 12].

Table 2.2: Characteristics of available acoustic modems.

Model	Distance (m)	Rate (Kbit/s)	Operating Frequency (kHz)	Power (Watts)	Depth (m)
LinkQuest UWM1000	350	9.6 to 19.2	26.77 to 44.62	2	Up to 200
LinkQuest UWM2000	1500	9.6 to 19.2	26.77 to 44.62	8	Up to 4000
LinkQuest UWM3000	5000	2.5 to 5	7.5 to 12.5	12	Up to 7000
LinkQuest UWM40000	4000	4.8 to 9.6	12.75 to 21.25	7	Up to 7000
LinkQuest UWM10000	10000	2.5 to 5	7.5 to 12.5	40	Up to 7000
FAU Hermes modem [13]	120	up to 87.7	60 to 380	32	12
EvoLogics S2CM HS	300	up to 62.5	120 to 180	8.5	Up to 2000
EvoLogics S2CR 48/78	1000	up to 31.2	48 to 78	60	Up to 2000
EvoLogics S2CR 42/65	1000	up to 31.2	42 to 65	60	Up to 2000
EvoLogics S2CR 18/34	3500	up to 13.9	18 to 34	80	Up to 2000
EvoLogics S2CR 7/17	8000	up to 6.9	7 to 17	80	Up to 6000

From Table 2.2, it can be seen that the maximum distance for these modems is 10 km, with a maximum bitrate of 5 kbit/s. Overall, the majority of acoustic modems are able to achieve low data rates over long distances, making them suitable mainly for control purposes.

2.1.2 Radio Frequency Wireless Communications

Radio frequency (RF) communications are commonly used for wireless connections in terrestrial scenarios. However, this type of communication shows very limited results underwater [4]. In [14] the propagation of RF waves, Eq. 2.8, is presented by a complex constant, γ:

$$\gamma = \sqrt{jw\mu(\sigma + jw\varepsilon)} = \alpha + j\beta \tag{2.8}$$

where σ is the conductivity of the medium, S/m, $\mu = \mu_r.\mu_0$ is the permeability of the medium in N/A, $\varepsilon = \varepsilon_r.\varepsilon_0$ is the permittivity of the medium in F/m, α is an attenuation factor, Eq. 2.9 and β

is a phase factor, Eq. 2.10 [15].

$$\alpha = w\sqrt{\mu\varepsilon}\left[\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{w\varepsilon}\right)^2}-1\right)\right]^{\frac{1}{2}} (Np/m) \tag{2.9}$$

$$\beta = w\sqrt{\mu\varepsilon}\left[\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{w\varepsilon}\right)^2}+1\right)\right]^{\frac{1}{2}} (rad/m) \tag{2.10}$$

The real part of the permittivity ε_r can be defined with the Debye model, eq. 2.11 ,and depends on the complex frequency:

$$\varepsilon_r = \varepsilon_\infty + \left[\frac{\varepsilon_s - \varepsilon_\infty}{1+\left(j\frac{f}{f_{ref}}\right)}\right] \tag{2.11}$$

where ε_s is the real relative permittivity at low frequencies and ε_∞ is the real relative permittivity at high frequencies both in F/m, f_{ref} is the relaxation frequency in Hz, and ε_0 is the dielectric permittivity of the free space in F/m.

The power at the receiving end can be expressed as follows [16]:

$$P_r(dBm) = P_t + G_t + G_r - L_{FSPL} - L_{water} \tag{2.12}$$

where P_t represents the transmission power, G_r and G_t represent the gains at the receiver and the transmitter antenna, respectively, L_{FSPL} represents the free space path loss and L_{water} represents the attenuation of the RF waves underwater.

In [15] the attenuation of the RF waves underwater was calculated. Considering a conductivity with a value of σ = 4 S/m (i.e. sea water), the value of L_{water} at 2.4 GHz is around 1000 dB/m. Considering a conductivity with a value of σ = 0.01 S/m (i.e. fresh water), the value of L_{water} at 2.4 GHz is 269 dB/m and at 700 MHz is 28 dB/m, which are considerably lower values. Therefore, it is possible to understand that underwater channels experience strong signal attenuation as the water conductivity increases. Additionally, at lower frequencies the attenuation is considerably lower which makes it possible to reach further distances, albeit with lower data rates. The authors also conducted multiple experiments using an IEEE 802.11 Wi-Fi network operating at three different frequencies (700 MHz, 2.4 GHz and 5 GHz). For the 700 MHz frequency band, the authors used a dipole antenna designed at INESC TEC. [17]. The results of these experiments, including TCP throughput measurements, are presented in Table 2.3.

Table 2.3: RF underwater throughput [18].

Frequency	Distance (cm)	Throughput (Mbit/s)
768 MHz	90	22
2.462 GHz	20	100
5.240 GHz	7.5	61

In summary, RF communications suffer from high attenuation due to the high conductivity and the high permittivity of water, limiting its range to less than 1 m. Nevertheless, they do not need LoS and are not affected by turbidity. The results shown in Table 2.3 also demonstrate that RF communications can be a suitable solution in short-range scenarios.

2.1.3 Optical Wireless Communications

Optical communications use light to transfer information and, similarly to RF solutions, also can achieve high data rates. On the other hand, in optical communications water behaves as a dielectric instead of a conductor, leading to less attenuation of the transmitted signal. However, attenuation persists and increases significantly with distance. In addition to this, light propagates 4 to 5 orders of magnitude faster than acoustic waves underwater, thus enabling much lower latency.

The main issues related to optical communications are the requirement of Line-of-Sight (LoS) and the water turbidity, which rapidly increases the attenuation. The first issue can be dealt with beam alignment processing algorithms. The second issue can not be overcome, due to the fact that water turbidity can not be controlled. This means that the achievable distance when using optical communications, although superior than using RF, is still highly constrained [19].

One key concept in understanding the behavior of light in water is the Beer-Lambert model, which describes the relationship between the intensity of light and the absorption and scattering of light by a medium. It is a widely used approach for describing the attenuation of the underwater optical channel due to its simplicity. The loss factor is given by $e^{-c(\lambda)d}$, thus the power at the receiver can be defined by [19, 20]:

$$P_r(\lambda, d) = P_t e^{-c(\lambda)d} \tag{2.13}$$

where P_t is the power at the transmitter, $c(\lambda)$ in m^{-1} is the beam extinction coefficient, which describes the losses due to absorption and scattering, eq. 2.14 , and d is the distance between the receiver and the transmitter.

$$c(\lambda) = \alpha(\lambda) + b(\lambda) \tag{2.14}$$

here a(λ) and b(λ) are the absorption coefficient and the scattering coefficient, respectively, in m^{-1}. These are strongly dependent on the type of water and the depth. As such, the attenuation of the optical signal is also strongly dependent on the type of water (Fig. 2.2). In [21] the authors describe in more detail the coefficients a(λ) and b(λ). Normally, wavelengths within the range of 450 to 500 nm (blue and green lights) are used, as they are known to have lower attenuation underwater [20].

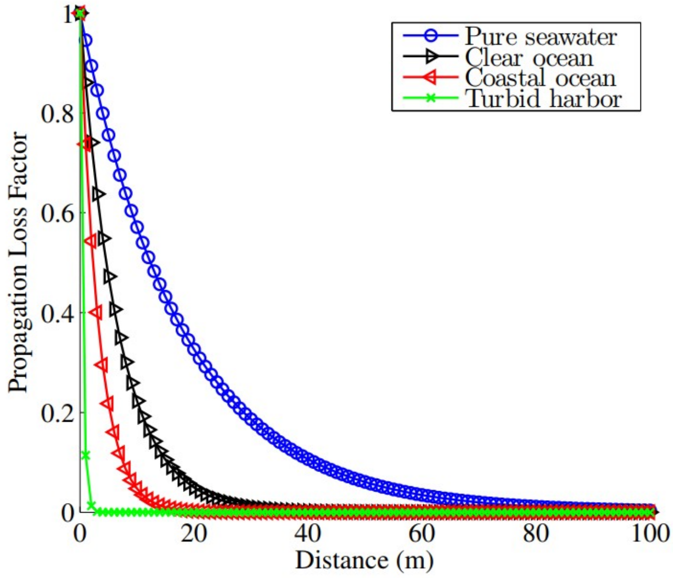

Figure 2.2: Attenuation of the optical signal (propagation loss factor) [19]

Overall, optical communications achieve higher data rates (in the order of Mbit/s) than RF and acoustic communications. Table 2.4 presents a survey of some of the optical modems available on the market.

Table 2.4: Characteristics of commercially available optical modems.

Model	Range (m)	Data Rate	Maximum Depth (m)
Hydromea LUMA 100 [22]	up to 2	100 kbit/s	6000
Hydromea LUMA X UV [22]	up to 30	10 Mbit/s	6000
BlueComm 200 [23]	up to 150	2.5 to 10 Mbit/s	4000

2.2 Delay Tolerant Networks

Delay Tolerant Networks (DTNs) are a type of networking technology designed to operate in challenging environments where we may find excessive delays and unreliable connections. These networks were initially developed to enable communication in the space environment, where delays can be long, and even the speed of light can appear slow due to the vast distance between planets. However, this type of approach has the potential to be applied in a wide range of scenarios on Earth where disruptions in communication may be common, such as in remote areas, disaster response situations, and military or scientific applications [24].

The Internet is designed to operate with continuous and typically bidirectional end-to-end paths, short round trip times, symmetric data rates, and low error rates. However, these assumptions are not necessarily met in the aforementioned scenarios. This means that protocols such as TCP/IP, which are commonly used for Internet communications, are not well suited for these scenarios. DTNs can be used to overcome these challenges [25]. Since the challenges of communications in underwater environments are similar to those present in the previous scenarios, DTNs can be applied in underwater networks.

DTNs use the store and forward message switching method to overcome the problems related to intermittent connectivity, long or variable delay, asymmetric data rates, and high error rates. This method consists in moving entire messages or fragments from one node to another until the message eventually reaches its final destination. DTN routers must have a way of storing permanently the message because [24]:

- A link to the next hop may not be available for a long time;
- One node may send or receive data much faster or more reliably than other nodes;
- A message may need to be retransmitted if an error occurs or if a receiving node declines acceptance of a forwarded message.

To deal with the disruptions in connectivity, in DTN networks, contacts can be either opportunistic or scheduled [24]. In this dissertation, the focus is on opportunistic contacts, which occur when nodes try to communicate during unscheduled times and happen to be in range of each other.

2.2.1 Bundle Protocol

The Bundle Protocol (BP) is a key component of the DTNs. It is a set of rules that defines how the messages are exchanged between nodes in a DTN. It allows for the efficient exchange of messages between nodes, even in the presence of intermittent connectivity and it is based on the store-and-forward method. The Bundle Protocol ties the application layer with the lower layers, which are specific to each DTN node (Fig. 2.3). As such all nodes of the network use the same bundle protocol. This provides the application layer with the ability to communicate with different Internet protocols [24]. Between the bundle layer and the Internet stack protocols, there is a convergence layer that matches the interfaces of the protocols that are specific to each DTN node [26].

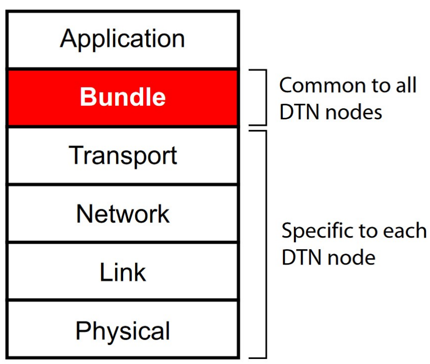

Figure 2.3: DTN Protocol Stack [24].

When a DTN-enabled application needs to send a message, the bundle layer transforms the message into one or more "bundles". Each bundle has a primary block, a payload block and an extra optional block. The primary block can be considered the header and consists of DTN blocks that contain the information needed to route bundles to their destinations. The payload block contains information about the application data and the data itself. The optional block may be inserted by the bundle protocol agent for specific services [25, 26]. The message size is not defined due to the different link capacities. Fig. 2.4 shows the message format. In the bundle protocol, bundles may be divided into fragments during transmission. These fragments are also bundles and may be divided into smaller fragments if necessary.

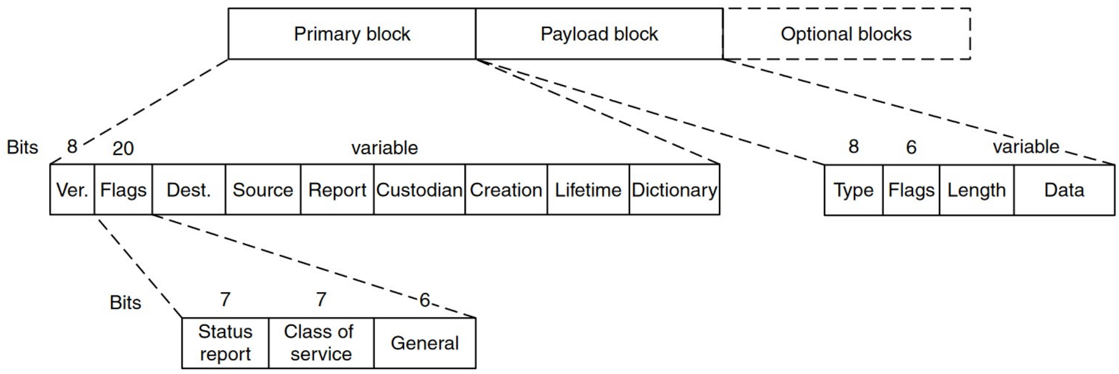

Figure 2.4: BP message format [26].

One important aspect of BP is the custody transfer mechanism, which ensures the safe and reliable delivery of messages. The custody transfer mechanism works as follows [26]:

1. When a node receives a message that it is responsible for forwarding, it takes "custody" of the bundle. This means that the node is responsible for ensuring the reliable delivery of the bundle to its next hop;

2. If the next hop is not available or if the node is unable to forward the bundle for any reason, it stores the bundle in its persistent storage until it can be forwarded;

3. If the node is unable to forward the bundle after a certain period of time, it may decide to transfer the custody of the bundle to another node that is more likely to be able to deliver it. This is called a "custody transfer request" and is also associated with a request time out;

4. If the node that receives the custody transfer request agrees to take custody of the bundle, it becomes responsible for delivering the bundle to its next hop. If the receiving node is unable to accept the custody in time, the custody transfer fails.

In DTNs, nodes are identified using Endpoint Identifiers (EIDs) and these take the form of Uniform Resource Identifiers (URIs). Additionally, nodes can play the role of source, destination or forwarding nodes [25].

2.2.2 DTN Bundle Protocol Implementations

When it comes to DTN Bundle Protocol implementations, there are several solutions currently available that comply with the standards set by the RFC 4848 and the RFC 5050, which, as previously mentioned, detail the DTN architecture and the bundle protocol, respectively. In [27] a survey regarding this topic was presented. The three main implementations are:

- DTN2 [28]: the reference implementation for a DTN implementing the Bundle Protocol. It is open-source and it was developed by Trinity College Dublin;

- ION (Interplanetary Overlay Network) [29]: a space-oriented implementation that was initially developed at the University of Ohio and now is managed by the NASA Jet Propulsion Lab (JPL). It is available under a BSD license;

- IBR-DTN [30]: specifically designed for embedded systems that run on OpenWRT [31] . It is a slim, extensible, and very portable implementation of the Bundle Protocol in C++.

In [32] the authors compared these implementations in terms of their performance. They conducted an experience to test the throughput between two nodes and another to test the opportunistic throughput. In the first test, the two nodes were always connected and the payload size was increased from 250 kB to 2 MB. IBR-DTN surpassed both DTN2 and ION. In the second test, IBR-DTN and DTN2 achieved similar results, and ION was not part of the test since it does not support opportunistic contacts.

2.2.3 Underwater DTNs

In [33] the author introduced a DTN framework that aligns well with the scope of this dissertation. This framework only uses an acoustic link. However, this link is able to adapt to the environment using four data classification planes: Perception, Intuition, Management, and Adaptation. The perception plane of the framework compiles data from each TCP/IP layer (application, transport, link and physical), such as messages detected, origin and destination of all the detected frames, latency and loss measurements, arrival time, received power and Signal-to-Noise ratio (SNR). The intuition plane uses these data to infer additional information, for instance, channel stability and quality. The management plane acts as a database that stores information about the network to enable the perception and adaptation planes to make informed decisions. The adaptation plane with this stored information verifies if each layer is capable of fulfilling the requirements of a message being transmitted. To achieve this, applications can specify their requirements for reliability and latency, and messages are only transmitted if these requirements can be met. If not, the messages are queued until either the reliability improves or the queue time exceeds the latency limit. While this approach appears promising, there is no guarantee of its performance as the authors do not provide any results.

In a survey conducted in [34], the use of DTNs in underwater communications was considered. The authors concluded that most existing solutions were routing protocols that either assumed the presence of an underwater grid of nodes or required some form of node mobility. While these solutions performed better than traditional acoustic links, they are only suitable for certain scenarios.

2.3 Multimodal Underwater Communications Systems

As mentioned in Section 2.1, each underwater wireless communication technology has its own advantages and limitations. As such, combining these technologies to take advantage of their strengths and create a more resilient system is a promising line of research. In this section, we provide an overview of the current multimodal solutions. A multimodal system, in its essence, must be able to choose the best physical technology to establish a communication link between two nodes based on the channel conditions. Several authors have already explored this concept and applied it to different scenarios. However, there are two scenarios that stand out the most: 1) the routing of messages in a network of underwater sensors [5, 35–38], and 2) the remote control of underwater vehicles [39–41].

2.3.1 Routing of Messages in a Network of Underwater Sensors

In this case, the authors are attempting to create routing protocols for an underwater network with a grid of nodes that may have different physical interfaces. Multiple links connect these nodes with varying delivery capacities, and the goal is to optimize the delivery of messages based on factors such as throughput [35, 36, 38], reliability [36], energy efficiency [37], and message priorities/fairness [38]. To achieve this, the authors have designed algorithms and protocols that are specifically focused on addressing these objectives, by taking into account the distance between nodes, and the available links between each node.

The problem with only taking into account the distance between nodes and the available links between nodes is that this way the algorithms are only making decisions based on information received from other nodes, leading to loss of transmission time and channel resources while sending information through the grid. Additionally, if the network does not react quickly, it may also lose certain connections. While these algorithms may achieve better results than traditional acoustic underwater wireless communications, they do not fully exploit the capabilities of a multimodal system. Another problem with this scenario is that the multimodality of the system is based on the assumption of a grid of nodes with different wireless communication technologies. If two nodes with different communication technologies move closer to each other, they will not be able to exchange messages and the opportunity for a faster connection is lost. To address this, all nodes in a multimodal communication system should have the same multiple physical interfaces.

2.3.2 Remote Control of Underwater Vehicles Using Multiple Technologies

In this type of approach, the authors attempt to design wireless systems that allow the remote control of underwater vehicles and assume that 1) the AUVs and the controller node have the same physical interfaces and 2) as the AUV moves it establishes or loses connection through the different technologies (acoustic, optical, and RF).

In [39], a hybrid optical and acoustic link is used for communication between an autonomous underwater vehicle (AUV) and a remote controller. The acoustic link, which has lower bandwidth, is used to track the AUV's position and to receive standard information from the AUV. The optical link is used for the remote operation of the vehicle and is only activated when the acoustic link indicates that the AUV is within range.

In [42], a different approach is applied. Instead of using the distance between nodes to switch between interfaces, the authors verify all available channels every time a link is disrupted and select the best-performing one. While this approach achieved better results than a standalone acoustical solution, it still suffered from channel disruption. In [40], the authors explored a proactive approach that uses the received signal strength of one interface to predict potential disruptions and proactively switch interfaces.

Most of these approaches use optical and acoustic communications. In [20], the authors use acoustic and RF communications to control the docking of an AUV. Here the docking stage initiates contact and if the AUV does not receive the expected signal, it calculates the required power level for correct reception and transmits it to the docking station, which adjusts its transmission power to improve communication reliability. The criterion to switch between interfaces is the distance between the nodes as well.

2.3.3 Approaches and Limitations of Multimodal Systems

The examples previously discussed earlier provide valuable insights into the existence of multimodal systems in the field of underwater wireless communications. However, it is important to note that the majority of these systems are designed for specific scenarios, limiting their generalizability and widespread applicability. While they have demonstrated promising results within their application contexts, it is essential to further explore and develop multimodal systems that can be adapted to a broader range of underwater communication scenarios.

One key aspect of multimodal systems is the decision-making process involved in switching between different communication technologies. In this regard, two primary approaches have emerged: reactive and proactive strategies.

- **Reactive approaches** involve continuously or periodically monitoring all available channels and dynamically switching to the best-performing one whenever a disruption in communication occurs. By actively assessing the channel conditions in real-time, these systems can adapt and maintain optimal communication performance. However, a potential limitation of reactive approaches is the delay incurred during the switching process. It may take some time to detect the disruption, evaluate alternative channels, and establish a new connection, leading to a temporary disruption in communication.

- **Proactive approaches** aim to anticipate potential disruptions and preemptively switch interfaces based on predictions derived from received signal information. By leveraging the received signal strength indicator and other relevant metrics, proactive systems can make informed decisions regarding the selection of the best-performing available channel before an actual disruption occurs. This proactive switching strategy can help minimize communication disruptions and enhance overall system performance. However, it requires accurate prediction algorithms and reliable models to effectively anticipate disruptions, which can be challenging to develop, particularly in dynamic underwater environments.

Despite the progress made in multimodal systems, there is still a shortage of comprehensive solutions that fully leverage all three underwater wireless communication technologies - acoustic, optical, and RF. The integration of these technologies has the potential to enhance the reliability, bandwidth, and overall performance of underwater communication systems. However, their combined utilization presents technical challenges and requires careful coordination to ensure seamless and efficient operation.

Additionally, the existing multimodal systems in underwater communication are often developed within specific application scenarios or research contexts. While these systems have contributed valuable insights, there is a need for more generalized approaches that can be applied to diverse underwater communication environments. Such approaches should address the challenges posed by varying channel conditions, environmental factors, and dynamic network topologies encountered in real-world underwater settings.

In conclusion, while multimodal systems have shown promise in improving underwater wireless communication, further research and development is necessary to overcome the limitations and challenges associated with their implementation. Future efforts should focus on developing more generalized multimodal systems that encompass all three underwater communication technologies, as well as refining the decision-making strategies for seamless switching between different modes. By doing so, we can advance the capabilities of underwater communication networks in underwater exploration, environmental monitoring, and underwater robotics.

Chapter 3

Aquacom – Multimodal Underwater Wireless Communications Manager

In this chapter, we present Aquacom, a multimodal underwater wireless communication manager. We start by outlining the objectives and requirements that our manager aims to meet. Following that, we provide an overview of our solution, giving a high-level understanding of its functioning. Next, we delve into a comprehensive description of the system architecture, providing detailed insights into each component that comprises the entire system. Additionally, we explore an underwater scenario using a message sequence diagram to illustrate the solution operation. Finally, we present two applications developed with our manager, along with their respective state diagrams.

3.1 Overview

To enable the seamless handover from one technology to another, our solution incorporates an interface switching mechanism that makes decisions based on the SNR of the involved technologies. Furthermore, to maintain connectivity between underwater nodes, our algorithm takes proactive measures based on the SNR values. This way, the algorithm can anticipate potential disruptions and swiftly switch to an alternative interface.

Adopting a proactive approach based on the SNR allows Aquacom to send data in a way that faster interfaces with low SNR values can still be used to send the same data as slower interfaces with higher SNR values. This behavior ensures that the transition between technologies occurs smoothly and efficiently and that data transfer continues uninterrupted, enhancing the overall robustness and reliability of the system.

With this proactive approach, we make more realistic assumptions about the variability of the system throughput and can dynamically adjust the size of data to be transferred at any given time. This ensures an better allocation of data transfer, taking into account the differences in capacity among the technologies.

Due to the difference in bitrate for each underwater wireless communication technology, some data is expected to be received out of order. Aquacom integrates a sorting mechanism to address this problem. This mechanism utilizes acknowledgments to identify and retransmit any lost data, either when using a single interface, transitioning between interfaces, or using multiple interfaces simultaneously.

Through the use of acknowledgments, Aquacom can ensure that any missing or out-of-order data is detected and retransmitted, thereby maintaining the integrity and reliability of the data transfer process. This sorting mechanism plays a vital role in the effective data delivery and in enhancing the overall performance of Aquacom. When combined with the switching mechanism, it enables Aquacom to aggregate multiple interfaces, thereby increasing the capacity of the communication.

In summary, Aquacom employs a proactive interface switching mechanism based on SNR to achieve seamless handover between technologies. This approach anticipates disruptions and swiftly switches to more reliable interfaces, ensuring uninterrupted data transfer and enhancing system robustness. The proactive approach optimizes data delivery by dynamically adjusting transfer size based on real-time technology characteristics, efficiently using the available capacity. To address out-of-order data, Aquacom integrates a sorting mechanism that uses acknowledgments for reliable retransmission. These combined features enable Aquacom to aggregate multiple interfaces, increasing the capacity of the communication link and facilitating smooth transitions, sustained connectivity, and efficient data transfer in our multimodal underwater wireless communication system.

Taking into consideration the lack of multimodal underwater wireless communications systems that perform a seamless handover between technologies, achieving this constitutes the primary objective of our system. Additionally, as referred in Section 2.3 there is an even bigger absence in systems that switch proactively between technologies. This also represents one of our main objectives. As such, Aquacom has the following objectives:

- It must consider two or more underwater wireless technologies and be able to aggregate them;
- It must perform the seamless handover between the technologies;
- It must use at least one of the most reliable technology in each situation;
- It must use the proactive switching approach;
- The manager should optimize the size of chunk to the capacity of each technology.

These requirements served as the foundation for designing Aquacom and guided us in creating a robust and efficient multimodal underwater wireless communications solution.

3.2 Architecture

In Aquacom, each node is equipped with multiple interfaces. Herein, we refer to the case where there is one acoustic interface, one RF interface and one optical interface. To facilitate data transmission through the RF and Optical interfaces, we employed a Delay Tolerant Network framework based on an adapted version of IBR-DTN, a Bundle Protocol implementation that, as demonstrated in Section 2.2.2, provided the best results.

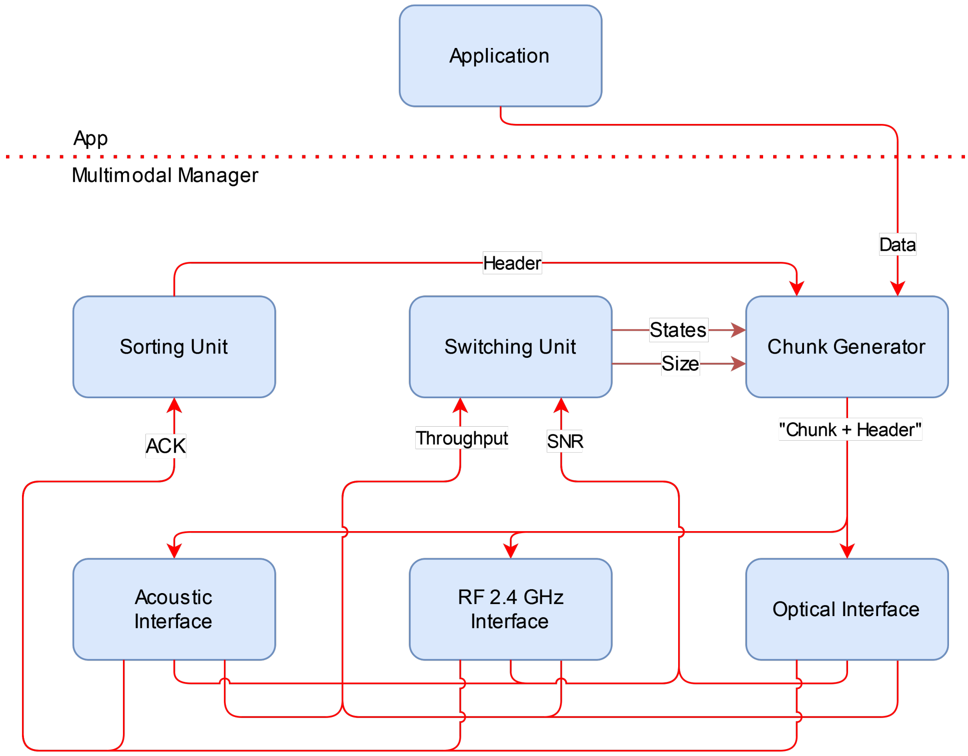

Figure 3.1: High level diagram of the Multimodal Underwater Wireless Manager.

Figure 3.1 presents a high-level diagram illustrating the architecture of our multimodal underwater wireless communications manager – Aquacom . As previously mentioned, it comprises two main units: the sorting unit and the switching unit. A third unit – the Chunk Generator – takes inputs from both the sorting and switching units to dynamically create the data chunks to be transferred. The three units are detailed in the following subsections.

3.2.1 Switching Unit

The core of the multimodal manager lies in the switching unit, which relies on an algorithm that makes decisions based on the SNR of the RF and optical interfaces. This algorithm involves categorizing the interfaces into three distinct states: 1) Off; 2) Handover; and 3) On. . These states are all detailed next. To determine the state of each interface, two SNR thresholds are utilized: a lower SNR threshold (SNR_{low}) and a higher SNR threshold (SNR_{high}).

The algorithm evaluates the SNR of each interface and compares it to the predefined thresholds. Based on this comparison, the interface is assigned one of the three states:

- **Off**: When the SNR falls below the lower threshold, the interface is deactivated or considered "Off." In this state, the interface is not actively used for data transmission due to poor signal quality.
- **Handover**: When the SNR lies between the lower and higher thresholds, the signal might still be unstable, and the interface enters a transitional state known as "Handover." During this phase, the interface functions in a redundant manner, meaning it sends the same data as the current fastest interface in the "On" state to ensure the reliable transfer of data.
- **On**: If the SNR exceeds the higher threshold, the interface is deemed "On" or fully operational. In this state, the interface is considered to offer a reliable and satisfactory connection quality, thus being able to be utilized for independent data transfer and used with other On-state interfaces for link aggregation, and increased throughput.

By adopting these SNR-based thresholds and states, the switching unit proactively adapts to the signal variations. Specifically, it dynamically adjusts the amount of data being transferred and initiates data transmission through the RF interfaces even when they are still considered unstable.

When an interface enters the "Handover" state (indicating instability) and since the short-range interfaces are DTN-enabled, the content inside the payload of the bundle transmitted through that interface is the same content as the data being transmitted through the current fastest interface, which is in the "On" state. This redundancy ensures that data continuity is maintained even during periods of interface instability. By sending the same data as the currently fastest and most reliable interface, we safeguard against potential data loss or disruption. In case the interface encounters difficulties, the data transfer is still covered by the stable and reliable interface, for instance the acoustic interface.

This proactive approach stands in contrast to a reactive one, where data transmission would only be triggered once the short-range interface becomes stable. This strategy effectively improves system reliability and responsiveness. In case, the RF or optical interface recover and stabilize, it can resume data transmission stream, thereby increasing the overall data transfer speed. By employing this proactive content redundancy approach, we mitigate the impact of the challenging underwater environment, where signal conditions can fluctuate rapidly and link instability is common, ensuring seamless and uninterrupted data flow.

In contrast, when both short-range interfaces are in the "On" state, our system takes a different approach compared to the one where we only consider reliability. Instead, the primary objective is to maximize throughput. In this scenario, the RF interfaces are aggregated to achieve a higher data rate.

Additionally, once one of the short-range interfaces is in the "On" state our system stops using the acoustic interface as it would not provide a significant improvement in data transfer speed compared to the short-range interface, due to the much lower acoustic data rates.

In Aquacom, the size of the chunk sent through the acoustic interface is defined so that when the acoustic interface is "On" and one of the RF interfaces is in the "Handover" state, if the RF interface fails to receive the acknowledgement, the acoustic interface receives the acknowledgment just before the timeout of the RF:

$$AC_{size} = T_{AC} \times RF_{timeout} \tag{3.1}$$

, where T_{AC} is the average throughput of the acoustic channel.

3.2.2 Sorting Unit

In Aquacom, the sorting unit plays a key role in mitigating the issue of out-of-order data reception caused by variations in data reception speed between the acoustic and the faster short-range interfaces. To ensure accurate and reliable data transfer, the sorting unit includes several features:

- **Sequence Number:** The sorting unit assigns a unique sequence number to each data chunk. This numbering system enables proper sequencing and organization of received data, ensuring that the correct order is maintained during data transmission and reception.

- **Acknowledgments**: The sorting unit establishes communication between the sender and receiver using acknowledgments. When the receiver successfully receives a data chunk, it sends an acknowledgment back to the sender, including the corresponding sequence number of the received chunk. This feedback mechanism enables the sender to verify the correct reception of data. Both the sender and the receiver save the sequence number of the acknowledgments that have been sent.

- **Stop Acknowledgment Propagation**: The sorting unit ensures that acknowledgments are transmitted solely through the interface where the receiver received the data chunk. This feature is particularly beneficial when multiple interfaces are sending the same chunk. For example, if the acoustic interface is "On" and one RF interface is in the "Handover" state, and the RF interface receives the chunk first, the stop acknowledgment propagation method prevents the receiver node from congesting the acoustic channel. Instead, acknowledgments are sent exclusively through the interface that successfully received the data chunk. This is why the receiver stores the number of the acknowledgments that have been sent.

- **Timeout Mechanism**: The sorting unit implements a timeout mechanism to manage data transmission delays. If the acknowledgment for a sent data chunk is not received within a specified time, a retransmission flag is activated, prompting the sender to resend the data and the receiver to resend the acknowledgment. In this case the stop acknowledgment propagation method is ignored and the receiver sends the acknowledgments in a more reliable manner, i.e, in every interface it has received the same numbered data chunk.

- **Last Chunk Flag**: The sorting unit utilizes a last chunk flag to inform the receiver about the final bundle in a data transfer. This flag allows the receiver to identify the end of the transfer, streamlining data processing and ensuring proper handling of received bundles.

To implement these features, we developed a custom header. The structure of the header was kept as small as possible keeping in mind the restrictions/constraints of the acoustic channel. The header format is depicted in Fig. 3.2.

Field	Sequence Number	Retransmission	Last Chunk	Ack Flag
Size	1 byte	1 bit	1 bit	1 bit

Field	Data
Size	Undefined

Figure 3.2: New Chunk Format.

Aquacom gives the user the ability to change the values of the timeout of each interface, the values of the lower threshold (SNR_{low}) and the values of the higher threshold (SNR_{high}). This allows for a more versatile multimodal manager. For instance, some scenarios may require a more reliable system thus a bigger difference between (SNR_{low}) and (SNR_{high}). However, other scenarios may allow for a higher risk system, thus allowing for a smaller difference between (SNR_{low}) and (SNR_{high}).

3.2.3 Chunk Generator

The chunk generator is a simple unit that breaks the file into chunks of a size defined by the switching unit, each time the acknowledgements of the chunk sent in the previous iteration is received. Its main characteristic is that it saves the size of the chunks sent previously in case it is necessary to resend one that is out of order. This would cause some issues if we were using a reactive approach, for instance, if one RF interface was sending much bigger chunks of data and suddenly stopped being available, the acoustic interface would be congested with a huge chunk of data. However, since our manager has an "Handover" state it first reduces the size of the chunk to the size of the acoustic chunk, thus avoiding the problem.

3.3 Aquacom – Sequence Diagram

Due to the interdependence of the features mentioned above, this section includes a more comprehensive and illustrative explanation using a sequence diagram (Fig. 3.3) that describes different situations that may happen when an AUV is approaching a fixed underwater station. Each situation represented in the sequence diagram is described below:

1. Initially, as the AUV is deployed, the only available interface is the acoustic interface. Therefore, our multimodal manager activates data transmission over the acoustic interface to initiate communication and sends *n* chunks of data;

2. As the AUV gets closer to the fixed station (approximately 1m), the SNR of the RF interface increases. Consequently, its state is set to "Handover", meaning that both the RF interface and the acoustic interface transmit chunk number *n+1*. The fixed underwater station receives this chunk of data through the RF interface so it sends the respective acknowledgment through this interface, stoping the transmission of the acknowledegment via the acoustic interface;

3. The AUV receives the acknowledgement and proceeds with the transmission of chunk number *n+2* on both the acoustic and RF interfaces. Again, the fixed underwater station receives chunk number *n+2* first in the RF interface, and sends the respective acknowledgment through this interface. However this time there is some turbulence and the distance between the auv and the station increases, causing the transmission of the acknowledgment to fail. Following this, the timeout of the RF interface is triggered and the AUV resends chunk number *n+2* via the acoustic interface with the retransmission flag activated so that the receiver (station) knows that it is supposed to resend acknowledgment number *n+2*;

4. After this, the AUV corrects its position causing the SNR of the RF interface to increase significantly, over SNR_{high}. As such, the multimodal manager switches the interface state to "On" and starts transmitting chunk number *n+3* over the 2.4 RF interface with the size corresponding to its full capacity;

5. As the handover procedure is the same for the Optical interface, we skip the "Handover" state and assume that the Optical interface is already "On" and that the other RF interface is still "On". This means that the manager now is going to aggregate the capacity of both RF interfaces. For this reason, chunk number *n+4* and chunk number *n+5* are sent simultaneously. The fixed station receives them and sends the corresponding acknowledgments through their corresponding interfaces;

6. After this, the AUV starts transmitting chunks number *n+6* and *n+7* through the RF interface and Optical interface, respectively. However, the station only receives chunk *n+6* and sends the corresponding acknowledgment. Since the transmission of chunk number *n+7* failed, the AUV waits till the timeout of the Optical interface, resends this chunk through the RF interface and sends the next chunk over the Optical interface (chunk number *n+8*);

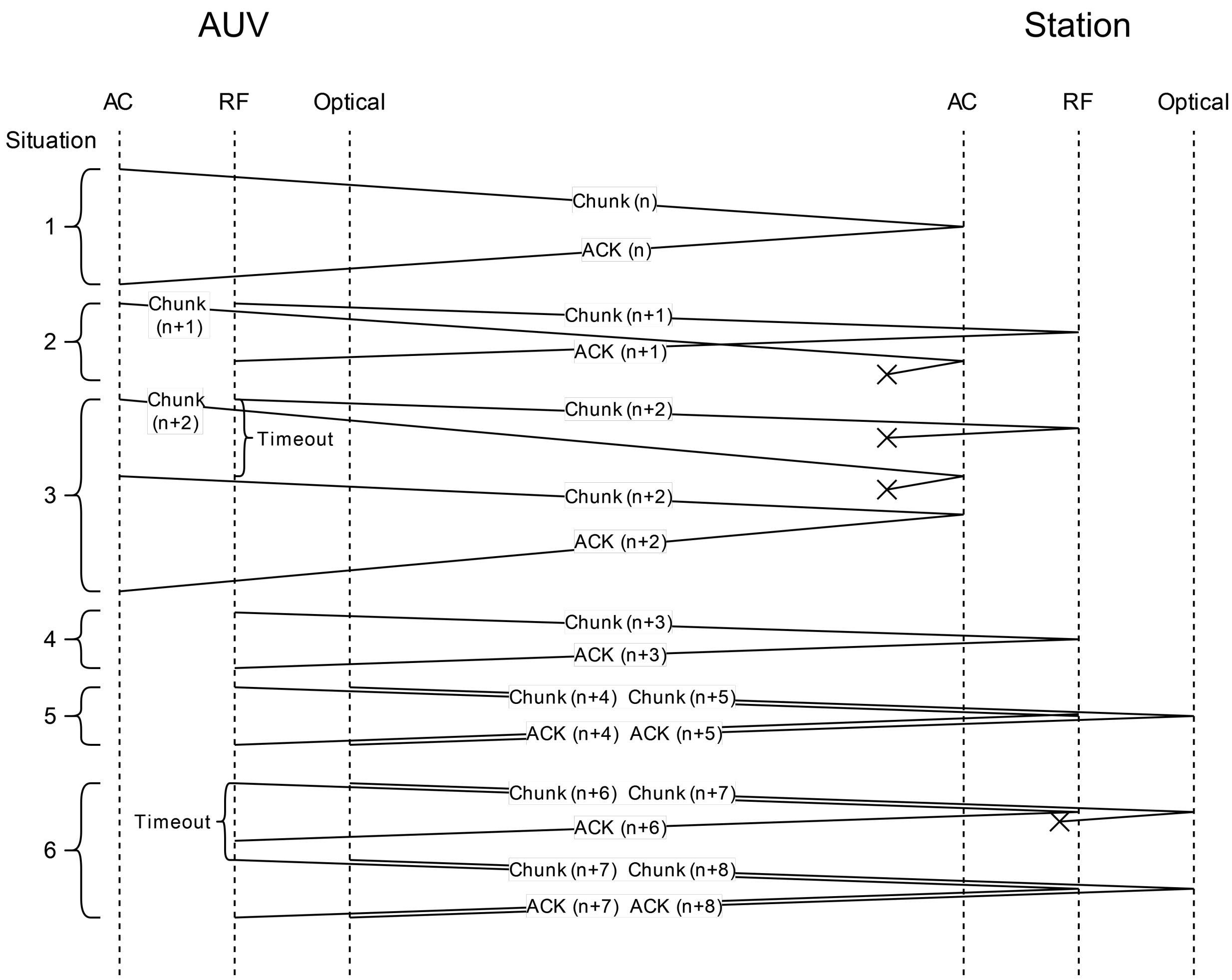

Figure 3.3: Chunk transmission sequence diagram.

3.4 Sender and Receiver State Diagrams

In order to implement Aquacom, two applications are required: the sender and the receiver. These applications enable the transmission of a file from one node (sender) to another node (receiver).

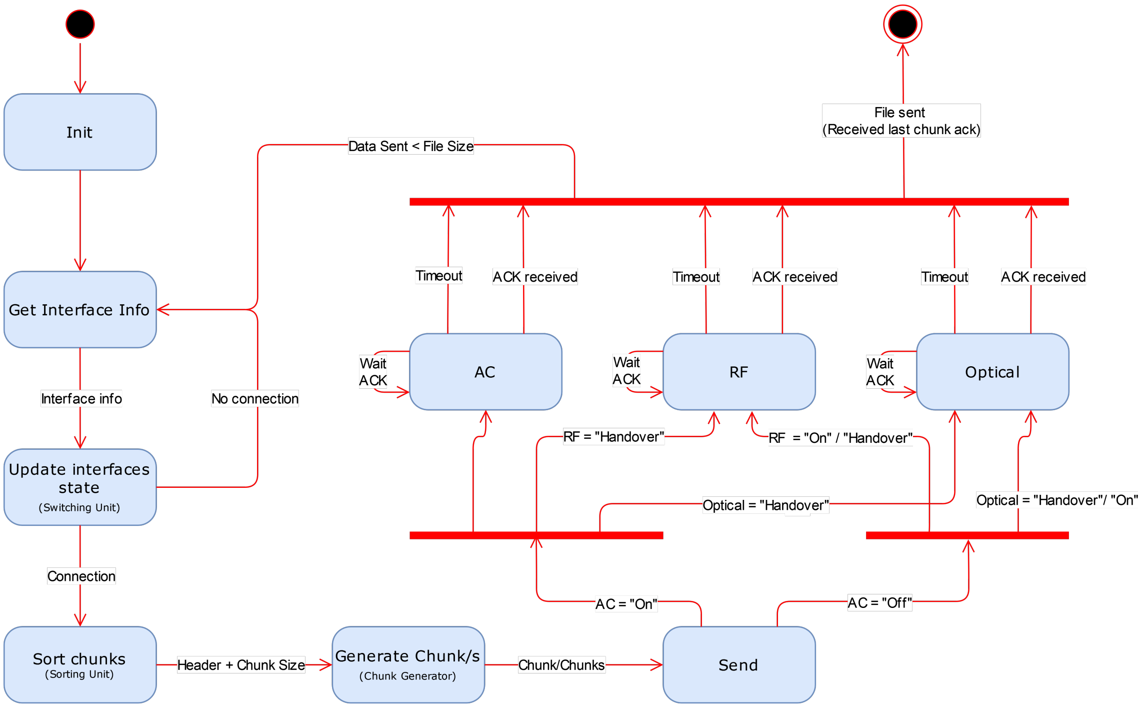

Figure 3.4: Sender state diagram

In Fig. 3.4, we present the state diagram of the sender application. Upon execution, the sender first gathers information from the RF interfaces, including received signal power, noise level, and bit rate. Using these data, it calculates the SNR. The switching unit then compares the calculated SNR with predefined thresholds $(SNR_{\text{low}}, SNR_{\text{high}})$, and updates the states of the interfaces accordingly.

If both RF interfaces are in the "Off" state, and the acoustic interface is unavailable (no connection), the sender continues this process until a connection is established. Once a connection is established, the sorting unit identifies the next chunk or chunks, generates the corresponding header(s), and determines whether the chunk is a retransmission or not. If it is a retransmission, the chunk size remains the same as the previous value. Otherwise, the chunk size is the size determined by the switching unit when it calculated the interfaces state.

Next, the application generates the chunk(s) and proceeds to send them. If only the acoustic interface is in the "On" state (with no short-range interfaces in the "On" state), the application creates multiple threads to send the same chunk over the acoustic interface and the RF/optical interfaces, but only if the RF/optical interfaces are in the "Handover" state. Otherwise, the chunk is sent solely through the acoustic interface. If the acoustic interface is in the "Off" state (indicating at least one RF/optical interface is in the "On" state), the application creates two threads to send either the same bundles over the two RF/optical interfaces (if one of them is in the "Handover" state), or different bundles distributed by the two interfaces (if both RF/optical interfaces are in the "On" state). The threads wait for the reception of the acknowledgments, and upon receiving them or in case of timeout, they return.

This process is repeated until the total amount of data sent equals the size of the file. At this point the sender receives the acknowledgment of the last chunk.

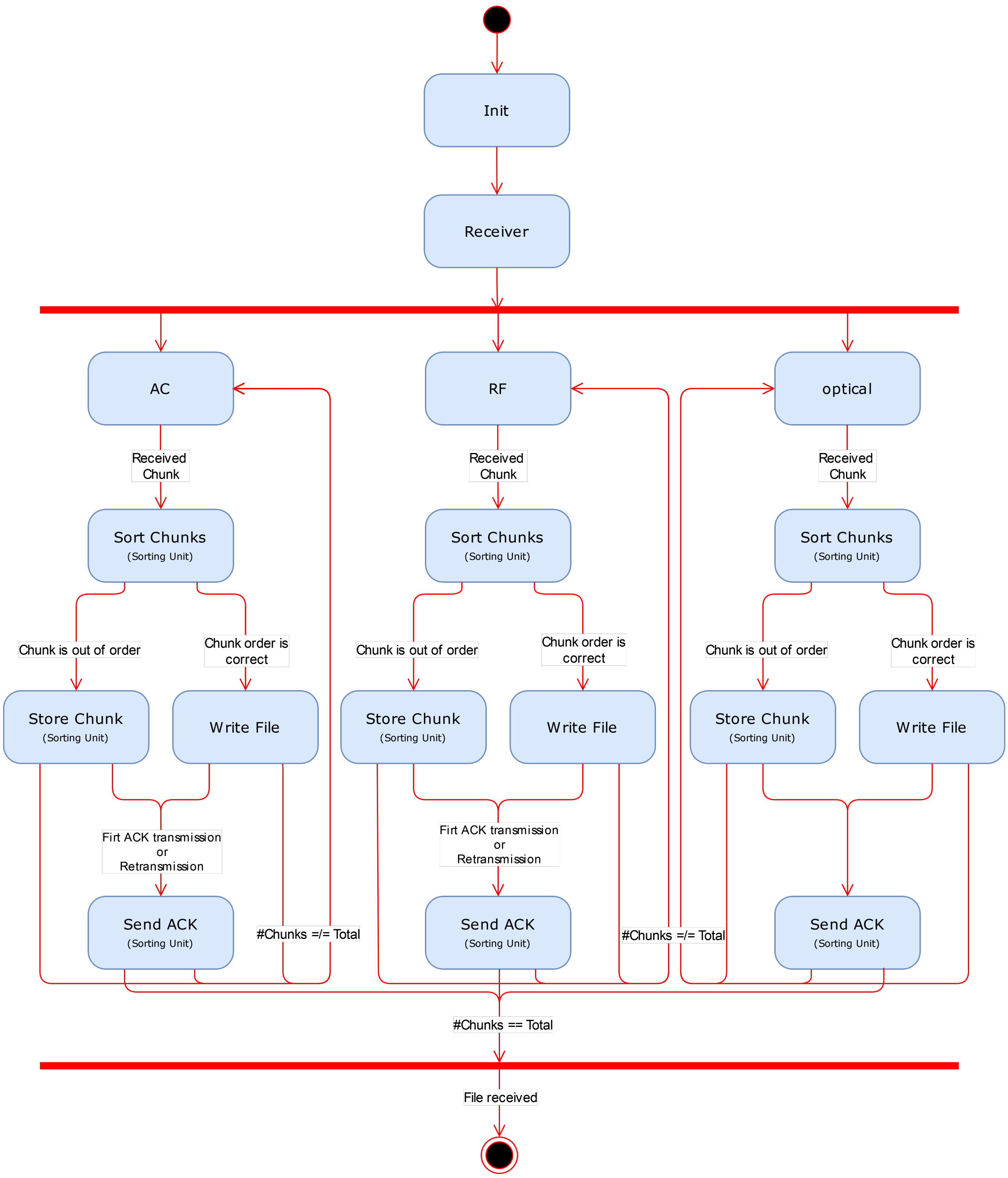

Figure 3.5: Receiver state diagram

In Fig. 3.5, we illustrate the state diagram of the receiver application. Upon execution, the receiver initiates three receiving threads: one for the acoustic interface and two for both RF/optical interfaces. When a chunk is received, the receiver sorts the chunk, i.e., analyzes its header to determine if it is in the correct order (if it is the next expected chunk) or if it is out of order. If the chunk is in the correct order, the application writes it to the file. If it is out of order, the application stores it for processing at a later stage. In either case, if it is the first time receiving the chunk or a retransmission is required, the application sends an acknowledgment to confirm receipt.

The receiver continues this process until the number of received chunks equals the total number of chunks (this value is updated when the chunk with the last chunk flag is received). This process is the same for all interfaces and ensures that all the data is received and processed correctly.

Chapter 4

Testbed Design, Implementation and Experimental Planning

In this chapter, we present the experimental setup that was carefully created to test our solution. In particular, we provide a detailed description of the design of the testbed, including the hardware and software components used in the experiments and the overall implementation.

4.1 Testbed Design

Figure 4.1 illustrates a diagram of the underwater testbed that was designed and built to conduct experiments and validate Aquacom.

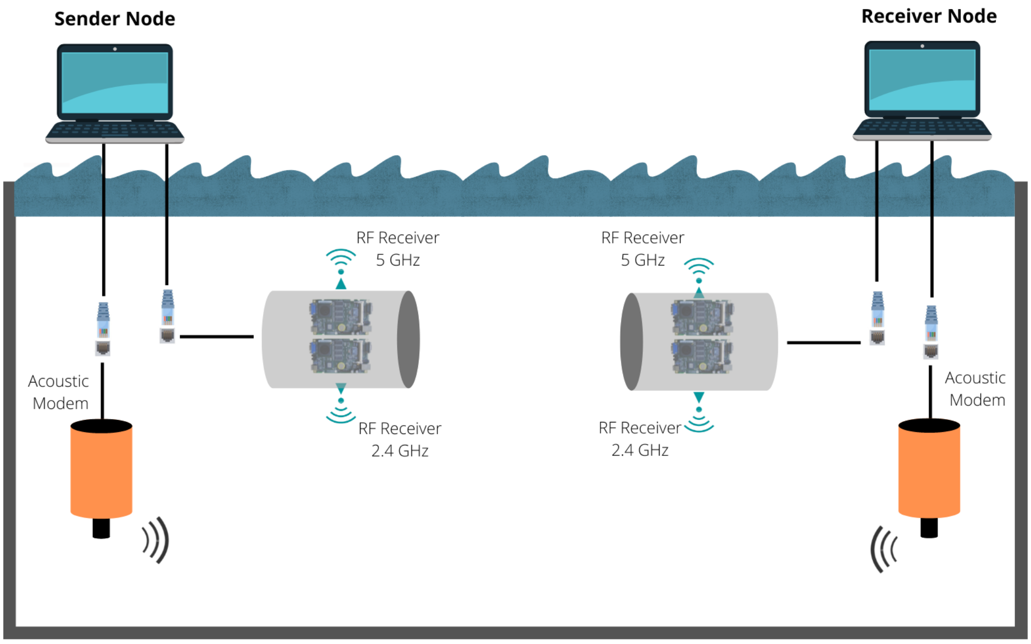

Figure 4.1: Underwater Testbed used to validate Aquacom.

The underwater testbed consists of two nodes: the sender and the receiver, both equipped with our multimodal manager. Each node is equipped with three interfaces: an acoustic interface represented by an acoustic modem, and two RF interfaces enclosed in an airtight cylinder. A secondary RF interface was used instead of the optical one for implementation reasons, but the operating logic is the same. These RF interfaces were IEEE 802.11n wireless cards operating at 2.4 GHz and 5 GHz. Consequently, each node consists not only in a single unit, but in a group of multiple units, including the user machine depicted as a laptop, an acoustic modem, and a cylindrical container for both RF interfaces. Two laptops were used to emulate the sender and receiver nodes, both running on Ubuntu, specifically, distribution 18.04.6. These laptops were positioned close to the freshwater tank, where the testbed was deployed. The freshwater tank measures 4.60m in length, 4.40m in width, and has a depth of 1.70m.

Both nodes were portable and enabled mobility testing. However, in this configuration, only the cylindrical containers moved, as they are designed for short-range RF communications. For testing purposes, the acoustical modems remained in fixed positions since they were more effective in long-range configurations. Figure 4.2, shows a picture of the testbed created at the FEUP lab.

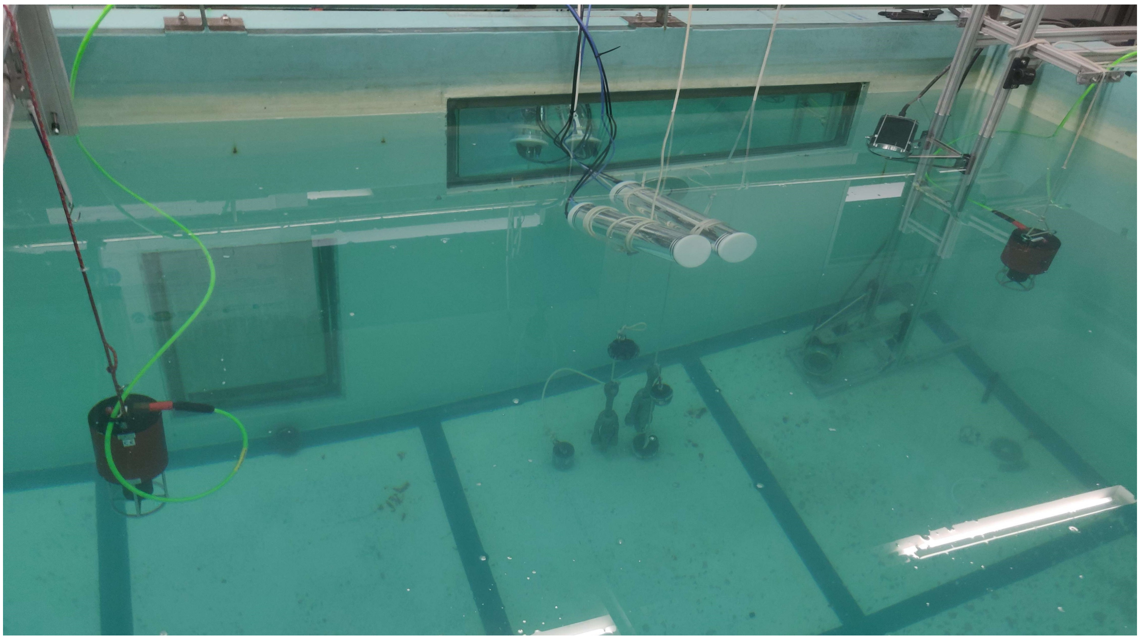

Figure 4.2: Testbed deployed in FEUP freshwater tank.

It is important to mention that since the tank at the FEUP/INESC TEC facilities is relatively small and the acoustic modems were at 2.5 meters, there were reflections of the sound waves in the walls of the tank, which may have caused additional noise. Also, other active equipment was being tested at the tank, which caused additional noise to the acoustic channel.

4.2 Hardware and Software specifications

As previously mentioned, each node is equipped with an acoustical modem and two RF interfaces inside an airtight acrylic cylinder. We used an acoustical modem from Subnero, the *M25M Silver Edition*. This modem is able to reach a depth of up to 100m, supports multi-channel communication and an announced data rate of up to 15 kbit/s [43]. Figure 4.3 shows the two acoustic modems used in our testbed and Figure 4.4 shows one of them underwater in the FEUP lab tank.

Figure 4.3: The two acoustic modems from Subnero

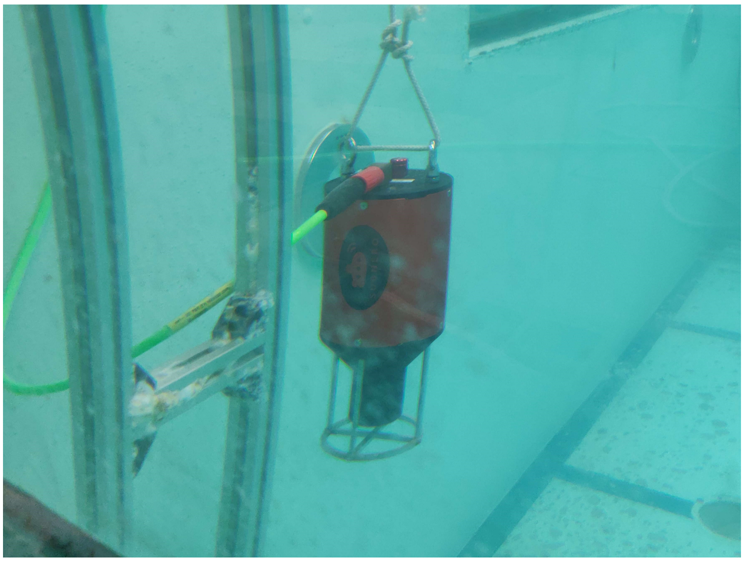

Figure 4.4: One acoustic modem from Subnero underwater.

The cylindrical containers are constructed from PVC and are designed to be airtight. Inside each one of them we placed two ALIX 3d3 system boards running Debian 8 coupled to two Wi-Fi RF cards, the MikroTik RouterBOARDs R52Hn. As such, each cylindrical container has four RF antennas, two operating at 2.4 GHz and connected to one of the ALIX boards, and two operating at 5 GHz connected to the other ALIX board; from now on when we refer to the 2.4 GHz RF interface, in reality we mean an ALIX 3d3 board coupled with an RF MikroTik RouterBOARDs R52Hn and two antennas operating at 2.4 GHz. In Figure 4.5 we can see two ALIX boards, coupled to two RF Wi-Cards and four RF antennas and in Figure 4.6 we can see them inside the airtight cylindrical container. Both RF cards Modulation Coding Scheme (MCS) were kept in autorate.

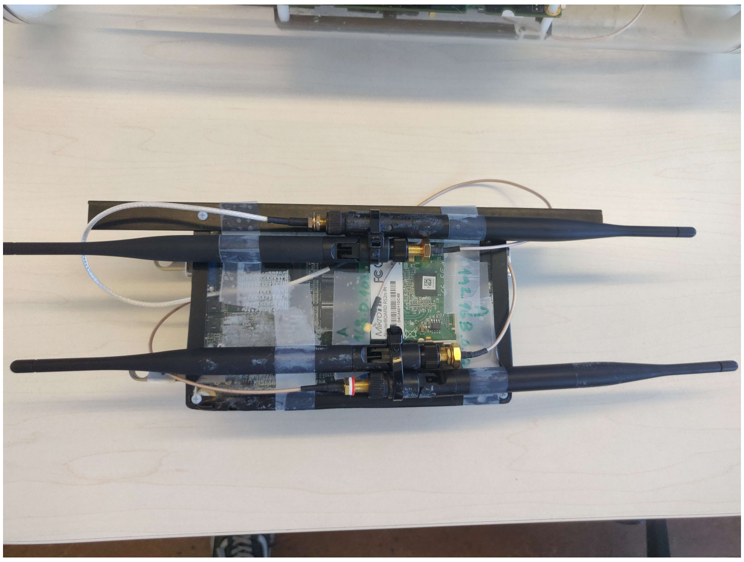

Figure 4.5: Alix 3d3 boards with RF cards and RF antennas.

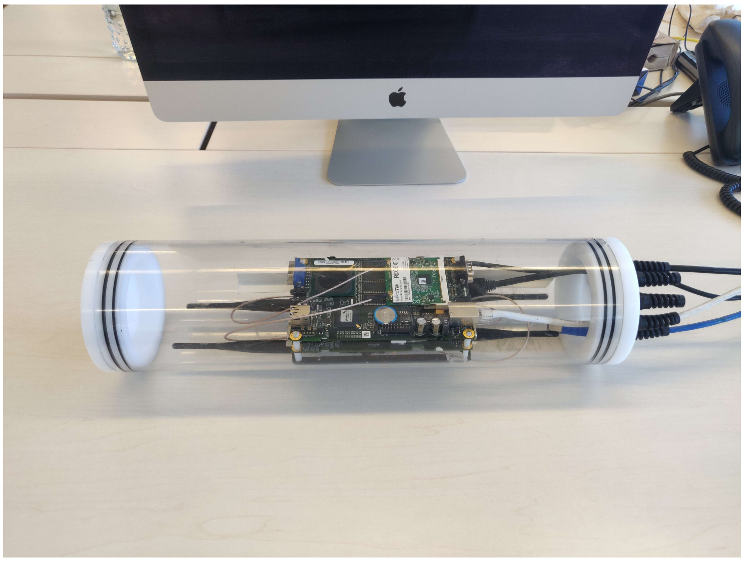

Figure 4.6: Airtight PVC cylinder housing two RF interfaces.

We have developed two applications – Sender and Receiver – to enable testing of our Multimodal Manager during experimentation. To implement the DTN network between the RF interfaces, we have used IBR-DTN release 1.0.1, which offers a set of tools. In our applications, we used two of these tools: *dtnsend* and *dtnrecv*. The *dtnsend* tool allows users to 1) send files to another IBR-DTN node by specifying the file to be sent, the destination EID (Endpoint ID) and 2) request the custody transfer. As such, we have used this tool to send the chunks and the acknowledgments over the RF interfaces as bundles. On the other hand, the *dtnrecv* tool enables users to receive a file by specifying the storage location and the source EID. We have used this tool to receive the bundles containing the data chunks and the acknowldegments.

During our implementation, we have observed a behavior in the *dtnrecv* tool that differed from our initial expectations. After receiving and saving a file, we expected the *dtnrecv* tool to automatically remove the corresponding bundle from the registration memory. However, this was not the case so we adapted the tool to perform as expected. To achieve this, we developed a Python script called *removebundle.py*. This script, takes advantage of the IBR-DTN API to clear the bundle from the registration based on its unique bundle ID, which in IBR-DTN consists of the timestamp and the sequence number of the bundle. With this modification each time the *dtnrecv* tool receives a bundle and stores it in a file, it captures the timestamp and sequence number of the bundle. Subsequently, it executes the *removebundle.py* script, which ensures that the corresponding bundle is removed from the registration memory.

Additionally, we used Subnero's Unetstack API to enable data transmission over the acoustic modems. Unetstack serves as an agent-based underwater network stack designed for Subnero modems, but can be customized to support modems from other manufacturers. It provides a range of services enabling users to control the acoustical modems and is implemented on *fjage*, which is a framework supporting agent-oriented software development [44,45]. Utilizing the *unetpy* and *fjagepy* Python APIs, we developed three Python scripts: *upload_file.py*, *download_file.py*, and *ac_sender.py*.

The *upload_file.py* script enables users to upload a file to the acoustic modem, by specifying the modem's IP address, the port to use, the file to upload, and the desired name to save the file. The *download_file.py* script serves as the counterpart, allowing users to download a file from the acoustical modem, by specifying the modem's IP address, the port to use, the file to download, and the desired name to save the file. The *ac_sender.py* script enables users to send a file from one acoustic modem to another, by specifying the source modem IP address, the port to use, the destination modem IP address, and the file to send. Our sender and receiver applications use these python scripts to implement the acoustic communications.

In IBR-DTN, the user typically runs the DTN daemon on a specific interface using the command *dtnd -i "interface name"*. Our initial goal was to enhance the IBR-DTN code to enable the DTN daemon to operate on multiple interfaces simultaneously. We succeeded in achieving this modification, allowing users to launch the DTN daemon on multiple interfaces concurrently. However, during the implementation, we encountered challenges in dynamically selecting the interface to use in real-time, which prolonged the development process beyond our initial expectations. Recognizing the impossibility of pursuing this approach, we made the decision to deploy the RF interfaces on separate machines.

4.3 Network Configuration

To establish connections between all elements of each node, we used Ethernet cable connections. This involved connecting the RF interfaces, acoustic modems, and two user laptops to a switch on the surface, effectively creating the Ethernet Network. We assigned IP addresses following the scheme 192.168.0.X, with a netmask of 255.255.255.0. For the RF wireless network, we set up an IEEE 802.11n Ad-hoc network with the IP address scheme 10.0.0.X and a netmask of 255.255.255.0. As for the acoustic network, UnetStack uses an automatic address resolution service, where a hashing function is used to map the acoustic modem names to addresses without generating network traffic. Additionally, we used the subnero software defined OFDM modulation scheme.

In the RF network, each node is a DTN node. The DTN Endpoint ID (EID) for each one follows the format *dtn://"host name"*, where "host name" corresponds to the name defined during the Debian installation process. Table 4.1 shows the IP addresses for each system in the testbed and the Endpoint IDs of the DTN network.

Table 4.1: Deployed Networks and Addresses.

Node	**Interface**	**Ethernet Network 192.168.0.0/24**	**RF Network 10.0.0.0/24**	**DTN EID**	**Acoustic Network**
Sender	Laptop 1	192.168.0.201	-	-	-
	RF 2.4 GHz	192.168.0.101	10.0.0.1	dtn://A	-
	RF 5.0 GHz	192.168.0.102	10.0.0.2	dtn://B	-
	AC	192.168.0.218	-	-	236
Receiver	Laptop 2	192.168.0.202	-	-	-
	RF 2.4 GHz	192.168.0.103	10.0.0.3	dtn://C	-
	RF 5.0 GHz	192.168.0.104	10.0.0.4	dtn://D	-
	AC	192.168.0.178	-	-	173

Chapter 5

Experimental Results

In this chapter, we describe the test methodology, provide a comprehensive analysis and discussion of the results obtained from the experiments performed on the freshwater tank. Additionally, we explore the outcomes of the experiments with the intent of giving a deeper understanding of the performance and capabilities of Aquacom.

5.1 Methodology and Testbed Scenarios

We divided the validation tests into two phases. The first phase involved assessing the performance of each individual technology. For this evaluation, we turned off the switching unit in our applications, allowing them to use only one interface at a time. During these tests, we used the sorting unit and the chunk generator to order the data chunks and generate the necessary acknowledgments. Each node remained static, as our only goal was to evaluate the performance of each underwater wireless technology. Additionally, we defined a timeout of 40 seconds for both RF interfaces and a timeout of 80 seconds for the Acoustic interface. These values were arbitrary and were kept the same during the entire testing procedure.

In the second phase, we aimed to test the effectiveness of Aquacom in handling technology transitions and aggregating RF interfaces. To achieve this, we considered two specific scenarios:

1. **Technology Transition Test:** In this scenario, we considered an AUV integrated with Aquacom, deployed at 100m from a stationary underwater station. The AUV's objective was to collect a file of 100 kB stored in the station. Although 100 kB might be relatively small by today's standards, it presents a substantial challenge for the acoustic interface, making it a suitable choice for testing. Still, it is useful for retrieving, for instance, system logs and other low size metrics. We assumed the AUV speed to be 1 m/s. Additionally, for this scenario, we considered two situations: 1) the AUV only needs to travel to the station, collect the data, and the mission ends there (**Aquacom one way**); 2) the AUV needs to travel to the station, collect the data and then go back to the initial position (**Aquacom two way**), a hypothetical scenario closer to a real mission, considered in later discussions. Both scennarios are described in Figure 5.1.

2. **RF Interface Aggregation Test:** In this scenario, we have considered two AUVs already in close proximity. This test aimed to observe the Aquacom's performance when it aggregates both RF interfaces simultaneously and uses them for data transmission. In this test, we have considered files with the following sizes: 10kB, 100 kB, 1 MB, and 100 MB.

By conducting these tests, we aimed to demonstrate the capability of our multimodal manager in handling real-world underwater communication scenarios. Additionally, our expectation was that our Aquacom would perform a seamless transition between the technologies as intended and that the overall transmission throughput would improve in comparison to the use of only one interface.

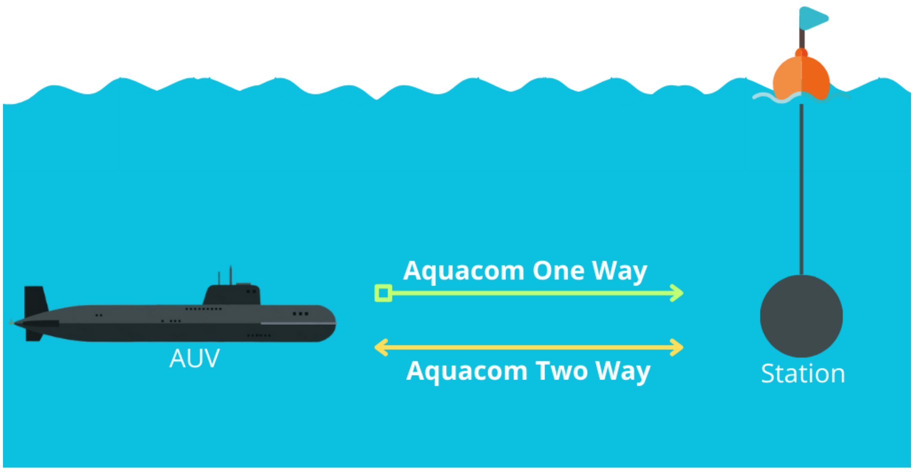

Figure 5.1: Technology transition/handover tests.

5.2 Performance Evaluation

This section presents the results of the performance evaluation for a single interface. This served as a baseline for the multimodal tests. In Table 5.1 we can observe the outcome of three tests of the acoustic channel. We obtained an average of approximately 183.41 bit/s, with a standard deviation of 52.08 bit/s.

It is important to note that we conducted a total of 6 tests using the RF interfaces, whereas only 3 were performed when including the acoustic interface. The reason behind this difference is due to the high demand and limited availability of the INESC TEC/FEUP water tank. Given the logistics required for tests involving acoustic communications, we made the decision to prioritize collecting results for all scenarios, instead of repeating the tests that included the acoustic interface.

These results are below what we expected based on the Subnero modem datasheet. To understand the reason for this behaviour, we executed some additional tests with the acoustic modems. Figure 5.2 shows the obtained delay vs transmission power and the respective packet loss ratio. These results were obtained by pinging each acoustic modem. We expected to have a higher distribution of packet lost across the entire range of power levels, however, that was not the case. What

Table 5.1: Acoustic Throughput.

Test #	Throughput (bit/s)
1	202.64
2	124.45
3	223.14
Average	**183.41**
σ	52.08

we can conclude with these tests is that the RTT was actually higher than expected, which, using Equation 2.2, at this distance and depth should be around 3ms. This might be due to the reflections and the possible cause for the low Throughput obtained. Since this was out of the scope of the dissertation, we did not investigate further. The power level with the lowest delay and less packet loss was -60 dB, as such we used this power level during testing.

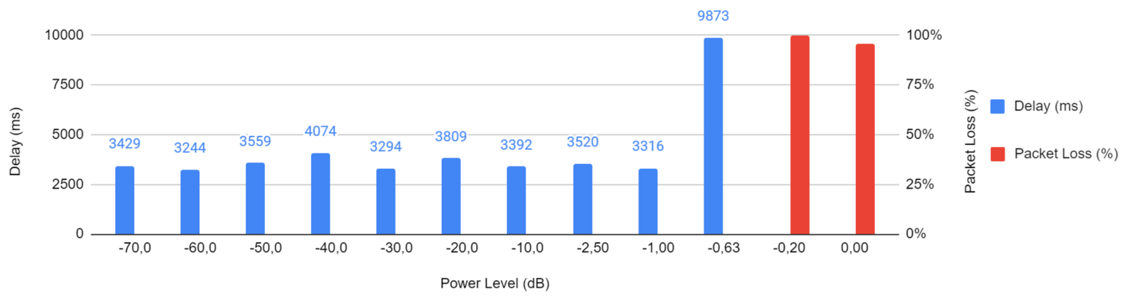

Figure 5.2: Average Delay using different Transmission Power Levels and respective Average Packet Loss.

In Table 5.2, we can observe the results of the Throughput for the 2.4 GHz RF interface. We obtained an average throughput of 4.39 Mbit/s and standard deviation of 0.31 Mbit/s.

As expected, the throughput is significantly higher than the acoustic link while also being more consistent.

Table 5.2: 2.4 GHz RF Throughput.

Test #	Throughput (Mbit/s)
1	4.39
2	4.38
3	3.79
4	4.60
5	4.60
6	4.59
Average	**4.39**
σ	0.31

Table 5.3 shows the Throughput obtained during the tests of the 5 GHz interface. We obtained an average throughput of 4.43 Mbit/s and a standard deviation of 0.74 Mbit/s. The results are as expected, the 5 GHz proves to be faster than the 2.4 GHz, however with less consistency.

Table 5.3: 5 GHz RF Throughput.

Test #	Throughput (Mbit/s)
1	3.33
2	4.37
3	3.78
4	4.99
5	5.07
6	5.06
Average	**4.43**
σ	0.74

Since our solution uses thresholds (SNR_{low} and SNR_{high}) to perform the switching between interfaces, we decided to perform some tests to characterize how the SNR of both RF interfaces changes with the distance, so that we could assign some more accurate values to the thresholds. The results of these tests are presented in Figure 5.3.

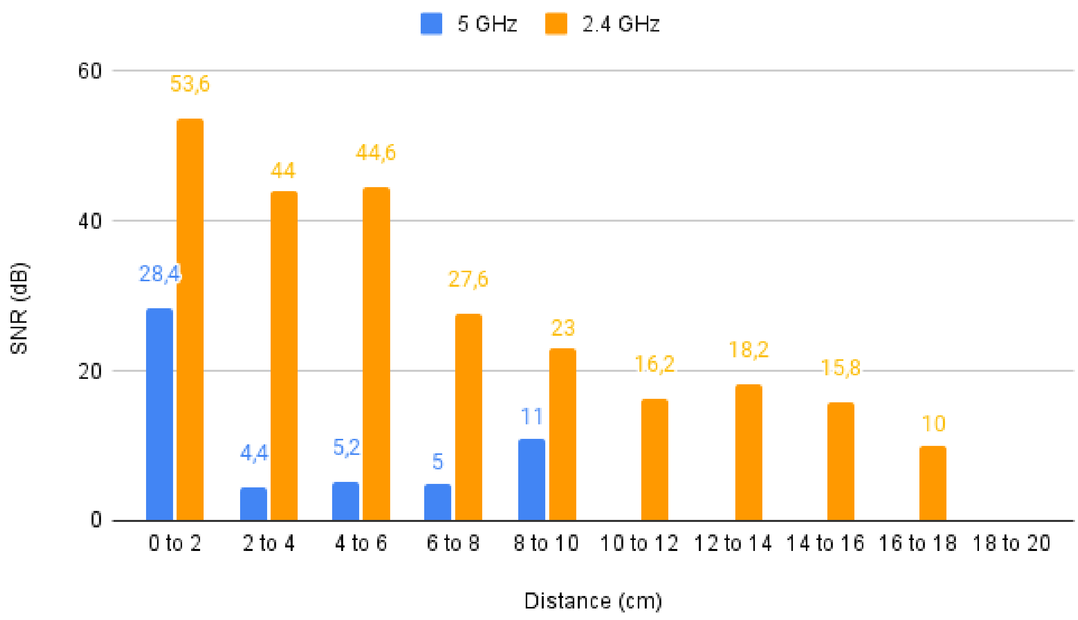

Figure 5.3: SNR variation with the distance for both 2.4 GHz and 5 GHz RF interfaces.

As expected, the 2.4 GHz RF interface shows better SNR results and is available at around 20 cm of distance. Between 10 to 16cm the SNR remains around 17 dB and between 0 and 10cm it remains consistently higher than 17 dB. With the 5 GHz RF interface the obtained results are also very similar, and the connection is lost at around 10cm. However, the SNR is consistently low between 2 and 10cm, averaging 6.4 dB in this interval. On the other hand, between 0 and 2 cm the SNR was consistently higher than 25 dB. As such, we defined the values for the thresholds shown in Table 5.4.

Table 5.4: Values defined for the switching unit thresholds.

RF interface	SNR_{low} (dB)	SNR_{high} (dB)
2.4 GHz	4	17
5 GHz	4	25

5.3 Multimodal handover results

In this section, we present the results of the technology transition test that was described in Section 5.1. Considering the speed of both RF interfaces and the size of the file we used (10 kB), it was necessary to manually turn off one of the RF interfaces so that we could observe the transition from the acoustic interface to each RF interface. Here, instead of presenting the throughput obtained, we present the time it took to transmit the file, as we think the delay is more representative of the effectiveness of our solution and a better way to compare the results.

Tables 5.5, 5.6 and 5.7 show the results obtained. When only the acoustic interface is used we obtained an average transmission time of 465.37 seconds with a standard deviation of 154.73 seconds. We used the transmission power level of - 60dB. With this power level we obtained an average RTT of 3.559 seconds. Additionally, since we defined the timeouts of the RF interfaces as 40 seconds, the size of the AC chunk was 915 bytes (Equation 3.1). Then, when sending a 10kB files we transmitted 11 chunks. Now, we can approximately calculate the time the acoustic modems were actually transmitting the file: $465.37 - 2 \times 11 \times 3.559$; which is approximately 387 seconds. With this value we can obtain the average bitrate of the acoustic modems which is 206.68 bit/s.

Using Aquacom and transitioning directly to the 2.4 GHz RF interface we obtained an average transmission time of 112.18 seconds with a deviation of 2.92 seconds, and transitioning directly to the 5 GHz RF interface we obtained an average transmission time of 137.92 seconds with a deviation of 29.17 seconds

Table 5.5: Transmission time using only the Acoustic interface.

Test #	Time (s)
1	394.80
2	642.80
3	358.52
Average	**465.37**
σ	154.73

It is important to mention that the handover between interfaces is a completely automatic process and no data loss occurs. If, for instance, one of the RF interfaces or the acoustic interface is unavailable, a timeout occurs and the bundle is retransmitted on the active interface.

The transmission time using Aquacom depends on the distance between the AUV and the stationary station. If the distance is long enough, it might take the AUV a higher amount of time to reach the station than the time required to transmit the data over the acoustic link. In this situation, there will be no remaining data to transfer over the RF interface when the AUV arrives

Table 5.6: Transmission time using Aquacom, transition from Acoustic to 2.4 GHz RF.

Test #	Time (s)
1	115.46
2	109.86
3	111.21
Average	**112.18**
σ	2.92

Table 5.7: Transmission time using Aquacom, transition from Acoustic to 5 GHz RF.

Test #	Time (s)
1	112.40
2	169.72
3	131.64
Average	**137.92**
σ	29.17

at the station. Therefore, in this case, the transmission time using Aquacom is the same as the transmission time using the acoustic interface only.

On the other hand, if the distance is not significant, and the AUV can reach the station before completing the transmission over the acoustic link, there will be remaining data. In this case, the transmission time using Aquacom is the sum of the AUV's propagation time plus the time required to transmit the remaining data over the RF interface. The remaining data refers to the size of the entire file minus the data already transferred over the acoustic interface while the RF interfaces were turned off.

The transmission time using Aquacom is given by the following equations:

$$t_{Aquacom} = \begin{cases} \frac{S_{file}}{T_{AC}}, & \text{if } S_{file} - T_{AC}.t_{AUV} \leq 0. \\ \frac{S_{file} - T_{AC}.t_{AUV}}{T_{RF}} + t_{AUV}, & \text{if } S_{file} - T_{AC}.t_{AUV} > 0. \end{cases} \tag{5.1}$$

In Eq. 5.1, S_{file} is the size of the file, T_{AC} is the average acoustic throughput, t_{AUV} is the time that the AUV takes to travel from its initial position to the station, and T_{RF} is the average RF throughput. It is important to refer that in the first equation (transmission using acoustic only), we are only using the values obtained during testing that are far from the expected.

Using the values we obtained previously and assuming that the connection with the 2.4 GHz RF interface starts at around 99.8 seconds (t_{AC} = 99.8s), the transmission time using Aquacom should be around 99.81 seconds. However, we obtained a time of 112.36 seconds, an error of approximately 12.55 seconds. The reason for this is that, as we said in Section 4.3, we used an Ad-hoc network which means that the RF interfaces need to discover each other first and in this case the average time this took was around 12.55 seconds. Nevertheless, Aquacom proved to be much faster than the acoustic solution.

We obtained similar results when forcing the direct transition from the acoustic interface to the 5 GHz interface. In this case the transmission took on average 137.92 seconds with a deviation of 29.17 seconds, which supports the idea that the 5 GHz link is more unstable than the 2.4 GHz link.

Additionally, assuming that the connection with the 5 GHz RF interface starts at around 99.9 seconds (t_{AC} = 99.9s), the transmission time should be around 99,91 seconds, which means that the Ad-hoc discovery delay we got in this case was on average 38.01 seconds. This result is worst when compared to the 2.4 GHz link due to the low SNR the 5 GHz link has between 2 cm and 10 cm.

Now, if we add the delay introduced by the RF interfaces when discovering neighour nodes (t_{delay}) to Equation 5.1, the result is approximately the same as the one we obtained.

$$t_{Aquacom} = \begin{cases} \frac{S_{file}}{T_{AC}}, & \text{if } S_{file} - T_{AC}.(t_{AUV} + t_{delay}) \leq 0. \\ \frac{S_{file} - T_{AC}.(t_{AUV} + t_{delay})}{T_{RF_{2.4}}} + t_{AUV} + t_{delay}, & \text{if } S_{file} - T_{AC}.(t_{AUV} + t_{delay}) > 0. \end{cases} \tag{5.2}$$

Nevertheless, this set of equations are restricted to the case where we are forcing one of the RF interfaces to be "Off". For the case of the aggregation of both RF interfaces, we have to consider Equation 5.3, which defines the transmission time of a file of size S_{file} using Aquacom, where t_{delay_1} is the time the nodes take to discover each others with the 2.4 GHz RF interface, t_{delay_2} is the time the nodes take to discover each others with the 5 GHz RF interface and $T_{RF_{Aggregation}}$ is the average throughput we obtained using the both RF interfaces aggregated.

$$t_{Aquacom} = \begin{cases} \frac{S_{file}}{T_{AC}}, & \text{if } S_{file} - T_{AC}.(t_{AUV} + t_{delay_1}) \leq 0. \\ \frac{S_{file} - T_{AC}.(t_{AUV} + t_{delay_1})}{T_{RF}} + t_{AUV} + t_{delay_1}, & \begin{array}{l}\text{if } S_{file} - T_{AC}.(t_{AUV} + t_{delay_1}) > 0 \wedge \\ S_{file} - T_{AC}.(t_{AUV} + t_{delay_1}) -. \\ T_{RF_{2.4}}.(t_{delay_2} - t_{delay_1}) \leq 0\end{array} \\ \begin{array}{r}\frac{S_{file} - T_{AC}.(t_{AUV} + t_{delay_1}) - (t_{delay_2} - t_{delay_1}).T_{RF_{2.4}}}{T_{RF_{Aggregation}}} \\ + t_{AUV} + t_{delay_2}\end{array}, & \begin{array}{l}\text{if } S_{file} - T_{AC}.(t_{AUV} + t_{delay_1}) > 0 \wedge \\ S_{file} - T_{AC}.(t_{AUV} + t_{delay_1}) -. \\ T_{RF_{2.4}}.(t_{delay_2} - t_{delay_1}) > 0\end{array} \end{cases} \tag{5.3}$$

It is relevant to say that since the RTT we obtained is higher than the RTT that two nodes at 4000km would have (using Equation 2.2 approximately 2.7s), for simplicity Equation 5.3 disregards the effect that distance has on transmission time while using only AC.

5.4 Multimodal aggregation throughput

Table 5.8 shows the results of the RF interface aggregation test. We obtained an average throughput of 8.56 Mbit/s and a standard deviation of 1.38 Mbit/s. This result is in line with what we would get if we added the average throughput of both interfaces ($4.43 + 4.39 = 8.82$ Mbit/s), demonstrating that our sorting unit was able to correctly sort the chunks of data between the two interfaces.

Table 5.8: Aquacom Aggregation Throughput.

Test #	Throughput (Mbit/s)
1	8.04
2	6.51
3	7.94
4	10.07
5	8.67
6	10.12
Average	**8.56**
σ	1.38

Figure 5.4 presents the graphical comparison of the average throughput and the standard deviation o each RF interface and the aggregation of both RF interfaces using Aquacom.

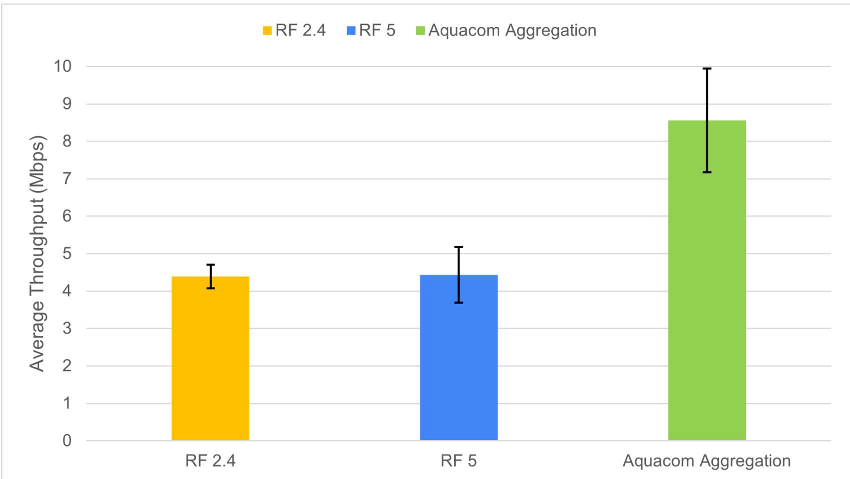

Figure 5.4: Average throughput and standard deviation comparison.

5.5 Chunck size adaptation

In this section we show how Aquacom adapts the chunk size with different SNR values. As previously explained, in the "Handover" state the RF interfaces are supposed to send the same chunk as the current fastest "On" interface. Then, when they stay "On", the acoustic interface is considered "Off" and the chunk size of each "On" RF interfaces is changed to the capacity of the respective RF link. This can be observed in the graph depicted in Fig.5.5.

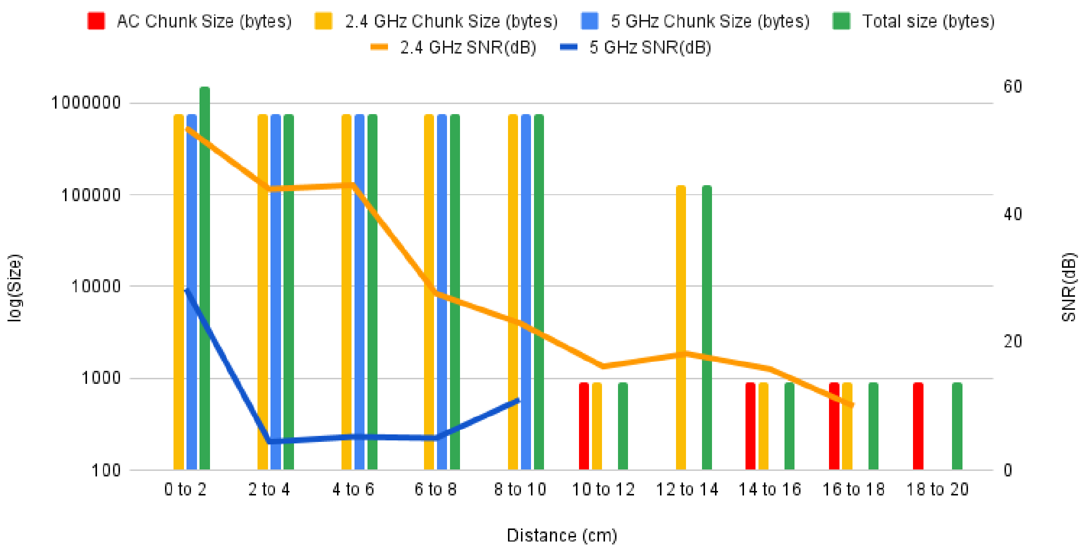

Figure 5.5: SNR and Chunk Size variation with the distance for Acoustic and the two RF interfaces.

Let us analyze the results from the Fig. 5.4, between:

- 18 and 20 cm, both RF interfaces are bellow SNR_{low}, as such, the acoustic interface is "On", which means that the chunk size and the total amount of data being sent by Aquacom is only the size assigned to the acoustic interface. In this case 915 bytes;
- 10-12cm and 14-18cm, the 2.4 GHz RF SNR was between SNR_{low} and SNR_{high} and interface was in "Handover", as such the chunk size of both the acoustic interface and the 2.4 GHz interface was 915 bytes and the total amount of data being sent by Aquacom was also 915 bytes;
- 12 and 14cm, the 2.4 GHz RF SNR was higher than SNR_{high} and the interface was "On", thus the chunk size was 125000 bytes and the amount of data being sent by Aquacom was also 125000 bytes, which in this case was the capacity of the 2.4 GHz link;
- 2 and 10cm, the 2.4 GHz RF SNR was higher than SNR_{high} and the interface was "On", and the 5 GHz RF SNR was between SNR_{low} and SNR_{high} and interface was in "Handover", as such the chunk size was 750000 bytes and the amount of data being sent by Aquacom was also 750000 bytes, which in this case was the capacity of the 2.4 GHz link;
- 0 and 2 cm, both RF interfaces SNR were higher than SNR_{high} and both interfaces were "On", thus we had simultaneous transmission and the capacity of links was 750000 bytes, thus the amount of data being sent by Aquacom was 1500000 bytes.

This demonstrates the correct operation of handover process and the correct operation of the aggregation process. If the Chunk size would be the same, when one of the RF links was Off, the

Acoustic interface would be fed up with a large chunk size, which would put the interface busy for a long period of time and would make the transition to RF (whenever it would be available) less efficient. Also, in case a bundle would have an error on the acoustic interface, the retransmission would take a longer time.

5.6 Acoustic system vs Aquacom-enabled AUV

In this chapter, we presented the results of our experiments, where Aquacom worked as intended. It was able to transition between interfaces in a seamless way, it aggregated the speed of both RF interfaces approximately doubling the throughput when the SNR was high, and and it was able to maintain the communications as reliable as possible. The results also allowed us to observe the benefits our multimodal solution offers: faster connection speed and higher reliability.

In this section we expand the results even further and explore the versatility Aquacom can offer. We assume the Aquacom-enabled AUV scenarios explained in Section 5.1. Before deploying the AUV, Aquacom calculates the fastest transmission method and only moves the AUV if it is faster to move than to only use the acoustic interface. Eq. 5.3 will be used to calculate the transmission time. Additionally, we will compare the results with a system using only an acoustic link, while assuming that in this system there is no node mobility.

The plot of Figure 5.6 shows the comparison of the transmission of a 10kB file using only the acoustic communications, Aquacom One way that never returns to its initial position and Aquacom Two way where the AUV using Aquacom returns to its initial position. As we can observe, in this case Aquacom One way is faster than the single acoustic solution until 250 meters and Aquacom Two way is faster until 500 meters.

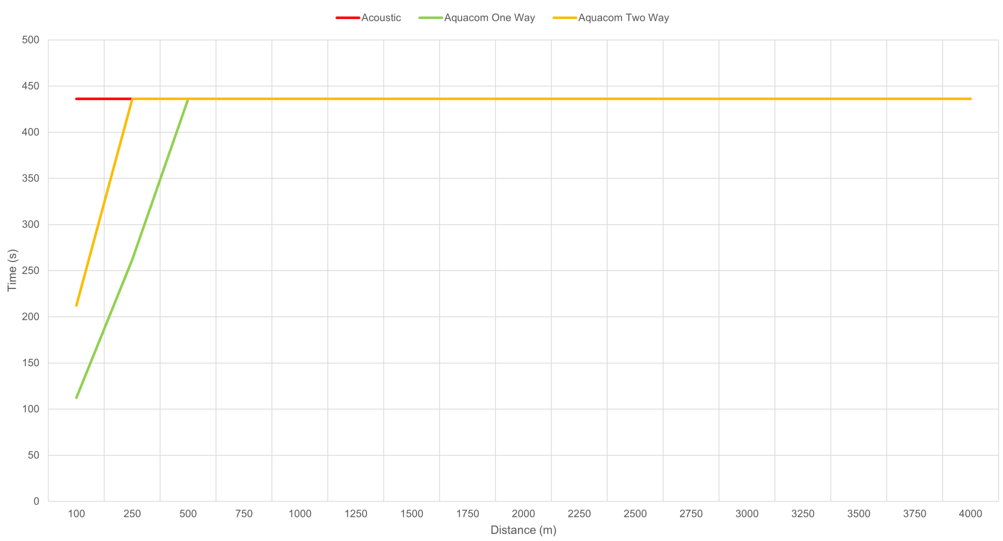

Figure 5.6: Comparison of the Transmission of a 10kB file with Acoustic, Aquacom One Way, and Aquacom Two way.

The plot of Figure 5.7, presents the same comparison for a file size of 100 kB. In this scenario, Aquacom One way outperforms the single acoustic solution at all distances between 0 and 4000 m. Additionally, Aquacom Two way achieves higher transmission speeds than the single acoustic solution until approximately 2250 m. Beyond this distance, Aquacom Two way relies solely on the acoustic interface and the AUV is not deployed.

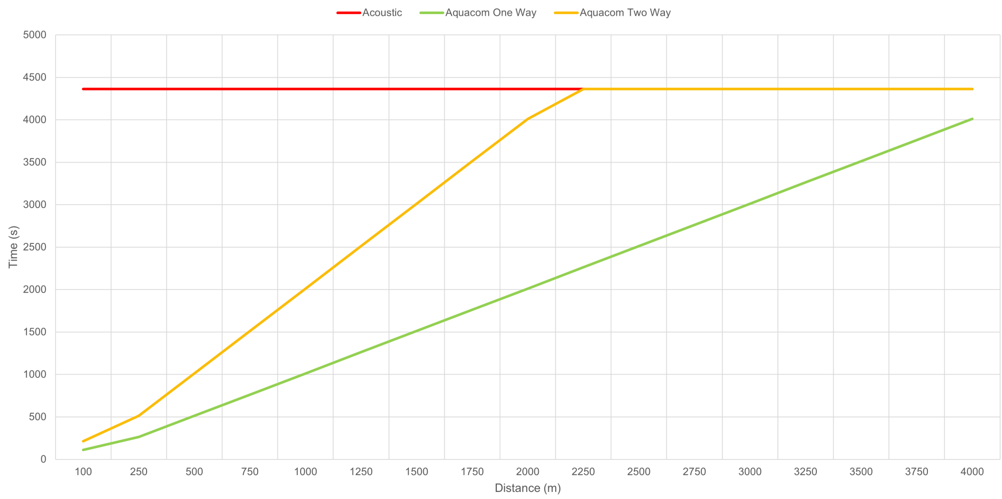

Figure 5.7: Comparison of the Transmission of a 100kB file with Acoustic, Aquacom, and the hypothetical scenario.

The plot in Figure 5.8 provides the comparison for a file size of 1 MB. Both Aquacom scenarios consistently outperform the single acoustic solution at all distances in this scenario. The difference in transmission times is substantial, to the extent that we had to use a logarithmic scale on the time axis. This illustrates the significant advantage that Aquacom offers in terms of speed compared to relying solely on the acoustic interface.

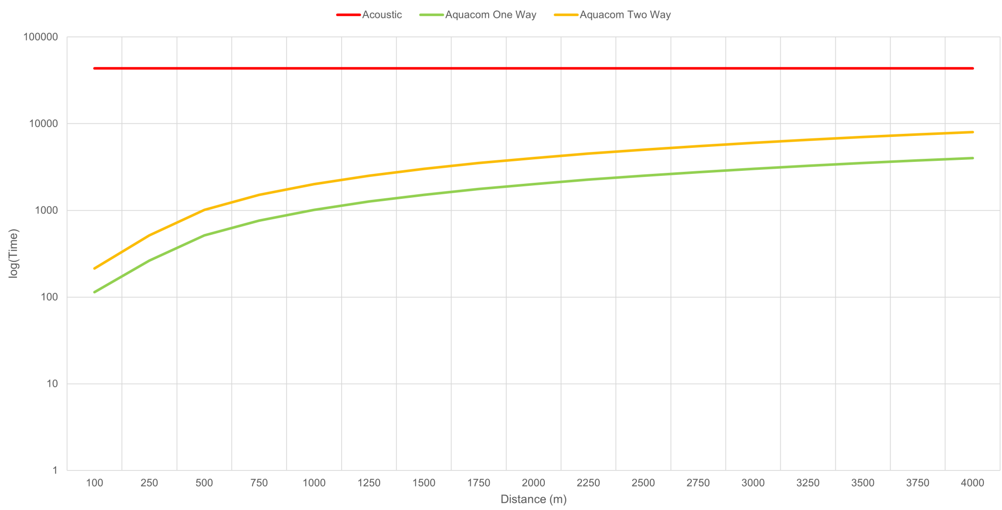

Figure 5.8: Comparison of the Transmission of a 1MB file with Acoustic, Aquacom, and the hypothetical scenario.

The advantage of Aquacom becomes even more evident as we increase the file size, as shown in the plot in Figure 5.9.

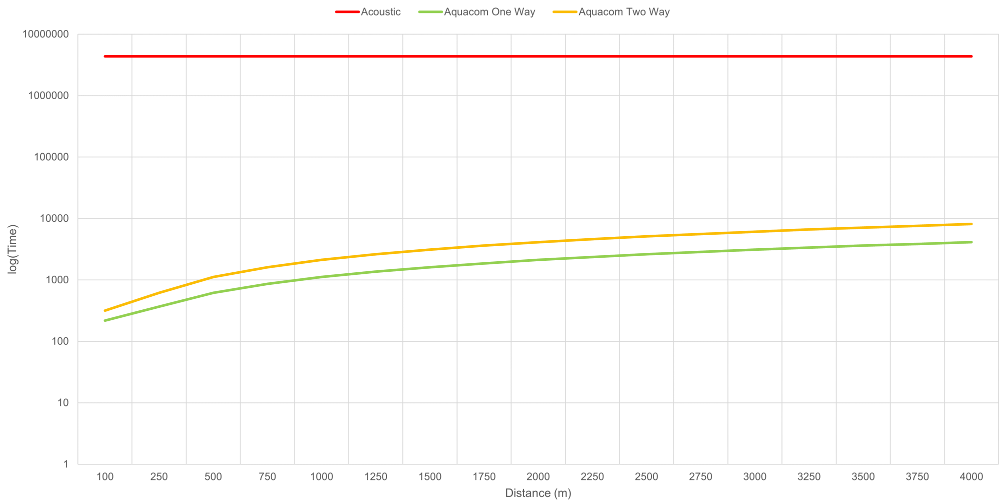

Figure 5.9: Comparison of the Transmission of a 100MB file with Acoustic, Aquacom, and the hypothetical scenario.

In conclusion, the results obtained from our experiments demonstrate the successful implementation of Aquacom, achieving its primary objective of abstracting the user from the process of switching interfaces. Additionally, we have met all the other objectives and requirements outlined in Section 3.1:

- Aquacom utilizes two or more underwater wireless technologies. Although optical communications were initially considered, due to unavailability of an optical modem, we utilized RF communications at 5 GHz as a suitable replacement.

- The manager effectively selects the RF interface with the highest Signal-to-Noise Ratio (SNR), and uses the acoustic interface if no RF interface surpasses the SNR_{low} threshold. This ensures that the manager always utilizes at least one of the most reliable technologies in each situation.

- Aquacom continuously analyzes the SNR of the RF interfaces and proactively switches between interfaces to maintain optimal performance;

- Aquacom successfully combined both RF interfaces to increase the link capacity;

- Aquacom optimizes the chunk size according to the interface actual bandwidth.

With the successful fulfillment of these objectives and the robust performance observed in our experiments, Aquacom demonstrated its potential as an efficient and versatile multimodal solution for underwater wireless communication systems.

Moreover, Aquacom can pave the way for optimizing underwater communication networks in terms of energy consumption and transmission efficiency. For instance, it may be more energy-efficient to prioritize transmission speed and not deploy an AUV in certain scenarios, while in others, it could be more energy-efficient to send an AUV even if the transmission time ends up being slower.

Chapter 6

Conclusion and Future Work

Underwater wireless communications play a crucial role in advancing underwater activities, driven by a significant surge in ocean exploration and exploitation missions in recent years. This surge has resulted in a considerable increase in the volume and variety of collected information. Despite these advancements, the harsh characteristics of water pose challenges. Currently, the three traditional underwater wireless communication technologies – acoustic, RF, and optical – individually struggle to provide reliable communication solutions. Acoustic solutions offer a broad operational range, reaching a few kilometers, making them suitable for long-distance communications. However, their bandwidth capacity is limited, which hinders the transmission of large volumes of data. On the other hand, RF underwater communications excel in providing high throughput. Yet, their range is severely restricted, typically reaching only a few centimeters underwater. Finally, optical solutions offer high throughput capacity, but they are sensitive to water turbidity, and precise beam adjustments are necessary for optimal performance. Additionally, their operational range is relatively limited, posing challenges for certain underwater communication scenarios. For these specific reasons, a multimodal system capable of combining the best of all communications technologies to mitigate their limitations is a promising research direction. Still, after surveying and analysing the current state of the art, we found that there is a lack of multimodal solutions capable of switching between interfaces in a seamless way.

In this dissertation, we developed and implemented Aquacom: a multimodal underwater wireless communications manager. Aquacom integrates multiple underwater communications interfaces, such as acoustics, RF and optical to provide a reliable and faster, thus more capable underwater link. This solution abstracts the user of the switching process by performing a seamless handover between the technologies. It does this by evaluating the SNR of the RF interfaces to perform a proactive handover of data from technology to technology. Additionally, when the SNR is high and the short-range interfaces are stable, it automatically aggregates them to achieve a faster connection. In the RF communications, we used the concept of Delay-Tolerant Networks (DTN), which were developed to specifically deal with intermittent connectivity, delays, and failures that may occur in communication between sender and receiver nodes, to overcome the delay due to the disruptions RF suffers underwater.

Aquacom was tested at INESC TEC/FEUP freshwater tank and the experimental results demonstrated it is able to successfully perform the seamless handover between technologies, which was the main goal of this dissertation. Also, it can aggregate multiple interfaces to increase the bandwidth whenever possible. In the results we can also observe the significant advantage that Aquacom offers in terms of transmission speed when compared to a system relying only on acoustics. A theoretical analysis was also presented to show the advantage of Aquacom in other scenarios.

Although the main objective of this dissertation has been addressed and the suggested multimodal manager has been validated, several aspects of our solution are left for future work:

- **Addition of an optical interface** - As previously explained, as we did not have access to an optical modem we used an 5 GHz RF interface to prove the concept. Nevertheless, since current optical interfaces can achieve ranges of up to 100m, the addition of an optical interface can demonstrate even better the true potential of a multimodal manager.

- **Explore and experiment Aquacom with an optimized version of the switching unit and the sorting unit** - Aquacom was developed from scratch for this dissertation. As such, each unit still has the potential for optimization, namely the timeouts, thresholds and chunk size estimation. This optimization may lead to better results.

- **Optimize IBR-DTN** - In its current version, the IBR-DTN daemon cannot be deployed on multiple interfaces. Implementing such a feature would enable a more optimized use of the IBR-DTN framework in this specific domain.

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