FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Data Muling for Broadband and Long Range Wireless Underwater Communications

Nuno Francisco Monteiro de Barros Moreira

MASTER IN ELECTRICAL AND COMPUTERS ENGINEERING

Supervisor: Rui Lopes Campos

Co-Supervisor: Filipe Borges Teixeira

24 June 2019

Resumo

Ao longo dos anos tem sido verificado um aumento do interesse na exploração das comunicações sem fios subaquáticas. Este interesse tem sido motivado, principalmente, pela necessidade de estabelecer um meio de transferência eficaz de grandes quantidades de dados provenientes de pontos remotos no oceano. Estes dados podem surgir de estações de exploração ambiental, da actividade da indústria petrolífera ou da recolha de dados oceanográficos provenientes de veículos submarinos autónomos. Estas actividades requerem soluções inovadoras capazes de garantir transmissões de débitos elevados com custos reduzidos.

Dadas as limitações presentes nas soluções existentes - ópticas, acústicas e radiofrequência - urge criar soluções que tirem proveito das capacidades de cada uma das soluções actuais, por forma a minorar as limitações. As comunicações ópticas permitem obter débitos elevados contudo, esta solução está limitada pela necessidade da existência de linha de vista e por uma elevada dependência do grau de turvidez da água. Por sua vez, as soluções acústicas conseguem cobrir grandes distâncias debaixo de água conseguindo-o, no entanto à custa da utilização de larguras de banda reduzidas. Esta limitação deve-se às frequências de operação, o que se traduz num baixo débito binário. Para além disso, dada a baixa velocidade de propagação das ondas acústicas na água envolve também atrasos que não são desprezáveis a longas distâncias. Por fim, as soluções baseadas em radiofrequência (RF) existentes permitem obter débitos elevados apenas a curto alcance, devido à elevada atenuação sofrida pelas ondas electromagnéticas em meio subaquático. Não existe, portanto, uma solução que permita comunicações de banda larga a grandes distâncias em ambiente subaquático.

Esta dissertação tem como objectivo o desenvolvimento de uma solução que permita débitos elevados, na ordem do Mbit/s, e grande alcance, na ordem dos km, em ambientes subaquáticos, tanto em água doce como em água salgada. Para tal é considerado um conjunto de mulas subaquáticas autónomas, baseadas na solução GROW, que tiram proveito dos débitos elevados de curto alcance das comunicações RF ou ópticas e do elevado alcance das soluções acústicas. As mulas subaquáticas são veículos que transportam a informação entre dois nós e criam um canal de comunicação entre eles onde a transmissão de dados é baseada em protocolos de comunicação desenhados para redes com limitações de conectividade, conhecidas por Redes Tolerantes a Atrasos e Falhas (DTN).

Nesta tese é especificado e implementado um protocolo que permita executar um algoritmo de escalonamento das mulas da solução GROW, tirando partido de um canal de controlo acústico permanente e uma rede DTN para transferência de dados. O protocolo desenvolvido foi testado em ambiente subaquático no laboratório da FEUP / INESC TEC. Os testes realizados consistiram na recolha de dados presentes num nó submergido num tanque de água doce (Survey Unit), e um nó colocado à superfície da água (Central Station), usando o protocolo implementado para a gestão das mulas. Os resultados obtidos mostram que é possível atingir um débito equivalente na ordem do Mbit/s com um alcance de até 5 km. Estes resultados demonstram que a solução proposta permite comunicações sem fios de banda larga e longo alcance em meios subaquaticos.

Abstract

There has been an increasing interest in the exploration of underwater wireless communications. This interest has been related mainly to the need of establishing a reliable way of transferring large amounts of data gathered at remote locations in the ocean. This data may come from environmental exploration, oil and gas industries, or marine information gathered by Autonomous Underwater Vehicles (AUVs). These activities require innovative solutions that can provide high throughput at low costs. With this in mind, and given the current solutions - Optical, Acoustic and Radio Frequency -, there is a growing need to create a solution that takes advantage of each technology and overcomes their limitations. In the case of optical communications, they can provide high bitrates, but require line of sight and depend significantly on water turbidity. Although acoustic solutions can provide a long range of operation, they have a low bandwidth due to the frequency of operation, therefore they are not suitable for transferring high amounts of data. Finally, current radio frequency (RF) solutions allow high bitrates but are limited by the operating range, due to the substantial attenuation of electromagnetic waves underwater. Thus, there is no solution for broadband long-range underwater communications.

The aim of this dissertation is to develop a solution that simultaneously increases the throughput and range of underwater wireless communications. To achieve this, a set of underwater data mules are used within the GROW framework. A data mule is an underwater vehicle that carries data between two nodes and creates a virtual communication link between them. Mules will take advantage of the high bitrates of RF or optical wireless communications and the long-range associated with acoustic solutions.

In this dissertation, communication protocols designed for delay and disruption tolerant networks (DTNs) are explored, and a protocol that enables the scheduling of mules of the GROW solution is designed and implemented, taking advantage of an out-of-band acoustic channel for controlling the mules, and the DTN for data transfer. The proposed solution was evaluated in a freshwater tank available at FEUP / INESC TEC facilities. The tests consisted in using the implemented protocol to collect data from an underwater node - the Survey Unit-, and retrieving it to the surface node - the Central Station. The obtained results show an equivalent throughput in the order of 1 Mbit/s and an operation range of about 5 km. These results show that the proposed solution can provide broadband and long range wireless underwater communications.

Agradecimentos

Aos meus orientadores, Doutor Rui Campos e Eng. Filipe Borges Teixeira gostaria de agradecer por me aceitarem no INESC TEC CTM e orientarem a minha tese. Agradeço todo o aconselhamento, a orientação, sugestões e motivação. À restante equipa do INESC TEC CTM, agradeço a ajuda e feedback ao longo das fases desta dissertação.

Agradeço aos amigos e amigas de todos os momentos, das batalhas de pequeno e das grandes batalhas, na sala de estudo ou a percorrer quilómetros numa estrada.

Este trabalho, embora assinado por mim, é fruto de todas as discussões e conversas na pala com quem me tem apoiado e acompanhado durante estes 5 anos, do Duplo Mortal Encarpado Sai de Maca e da Isabel: Um muito obrigado a todos por toda a paciência, amizade e companheirismo.

Gostaria de agradecer à tia Tala por todo o carinho, preocupação e, também, pelo arroz do forno.

Aos meus irmãos, que me conhecem melhor que ninguém, e sentem de perto o meu feitio.

Finalmente, aproveito esta oportunidade para expressar o meu mais profundo e sentido agradecimento aos meus pais, por todo o carinho, compreensão e incansável apoio que me dão. Pela educação e por todas as oportunidades. Pelos meus irmãos. Muito Obrigado!

Nuno Francisco Moreira

"Em todos os manicómios há doidos malucos com tantas certezas!
Eu, que não tenho nenhuma certeza, sou mais certo ou menos certo?"

Álvaro de Campos

Contents

List of Figures

List of Tables

Abbreviations

ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
BP	Bundle Protocol
CTM	Centre of Telecommunications and Multimedia
DTN	Delay Tolerant Network
EID	Endpoint Identifier
EMI	Electromagnetic Interference
IEEE	Institute of Electrical and Electronics Engineers
FEC	Forward Error Correction
LED	Light Emitting Diode
LOS	Line of Sight
LT	Luby Transform
RF	Radio Frequency
SNR	Signal to Noise Ratio
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
URI	Uniform Resource Identifier
UWB	Ultra Wide Band

Chapter 1

Introduction

1.1 Context and Motivation

Over the past years, one of Portugal's and the European Union's main goals has been the exploration and exploitation of the ocean. This goal has been achieved not only through traditional activities like fishing, transportation, and tourism, but also through emerging activities such as deep-sea mining and environmental monitoring. To support these activities, long-range communications are required in order to serve both mobile and fixed platforms at remote ocean areas, and out of range of land infrastructure. Creating a new infrastructure to cover a vast ocean area is challenging to implement and manage, thus very expensive.

The harshness of the ocean requires expensive resources and complex logistics for supporting manned missions, especially underwater. Consequently, the use of autonomous underwater vehicles (AUVs) is increasingly seen as a cost-effective means to carry out underwater missions [1]. These vehicles may collect vast amounts of data (in the order of gigabytes) that may include high-quality video and bathymetric data. The typical solution is to upload this data either at the end of the mission or by surfacing. This causes a delay in data processing and visualisation, delays possible adjustments in the AUV's mission, whose direction may depend on the collected data. There is also an energy downside of this approach: the energy consumption increases and introduces significant dead-times between consecutive AUV missions.

A possible solution for data upload from the AUV is to have broadband underwater communication between the AUV and a Central Station, so that the collected data can be uploaded during the mission. Research in this domain has been focused on three areas: acoustic communications, radio frequency communications, and optical communications [2–4]. Acoustic communications are able to provide underwater communications with long range. However, the bitrate that can be achieved with this technology is in the order of some kbit/s, making them unsuitable for transmitting large amounts of data. In the case of the radio frequency, in order to have a large bandwidth, the range has to be reduced considerably, which means that the AUV needs to travel to the Central Station in order to upload the information. The only solution that may allow underwater short to medium range communications and high bitrate is the use of optical communications, but this solution requires fine beam adjustments and depends significantly on the turbidity of the water.

The underwater exploring missions have been growing in the last years, not only in number, but also in complexity, which leads to the collection of large amounts of data that needs to be uploaded from underwater survey nodes such as AUVs. However, such communications' demand can not be fulfilled by the current acoustic, radio frequency (RF) and optical technologies. As a result, there is the need for a different approach for effective broadband underwater communications.

In order to overcome the limitations of current solutions, the FCT GROW project [5] has proposed to use a data mule based on the Delay Tolerant Network (DTN) for a long-range broadband underwater wireless communication. A data mule is a small and agile AUV that is equipped with short-range high-speed and long-range low-speed wireless communication hardware. The mule will travel back and forth between the AUV and the Central Station, creating a virtual link between these two nodes. This avoids the AUV surfacing, allowing for collection of data without interrupting the mission. An illustration of the envisioned solution is presented in Figure 1.1, showing two data mules between an AUV and an Autonomous Surface Vehicle (ASV). These data mules will have the role of courier between the AUV and the ASV.

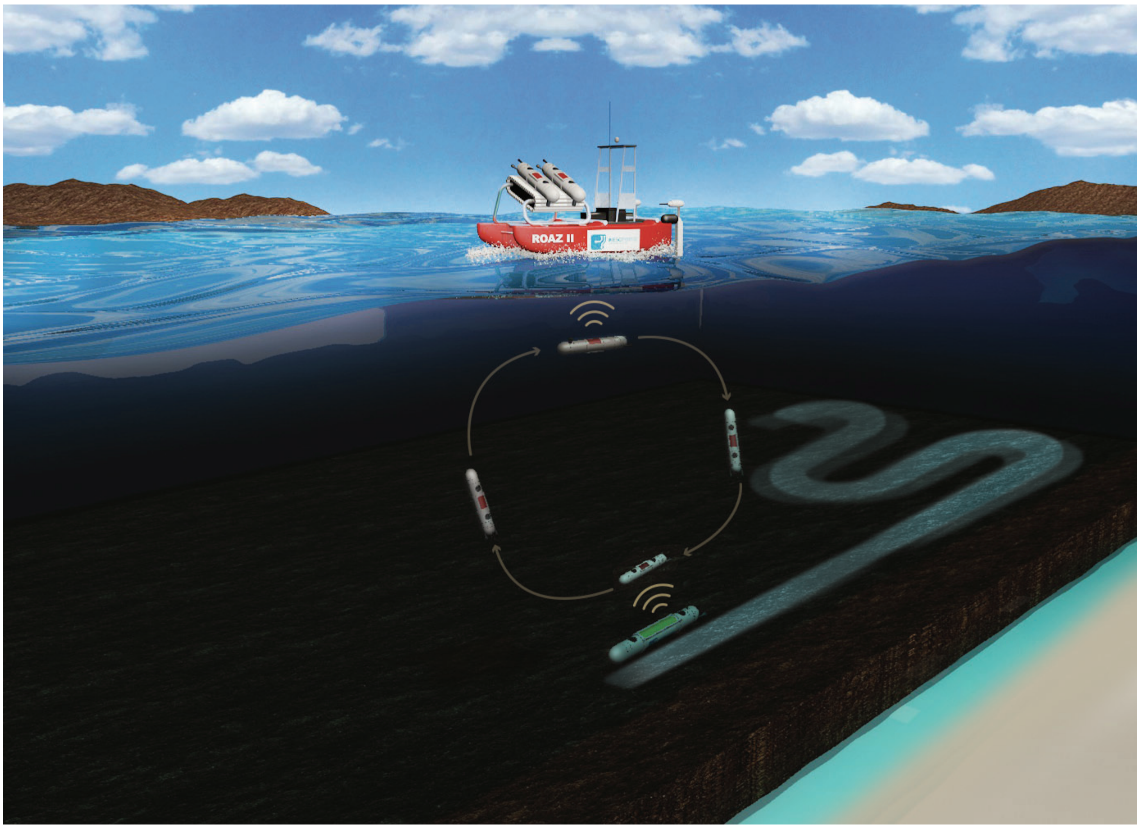

Figure 1.1: Illustration of the GROW solution for broadband underwater wireless communications [5].

With the use of a DTN and the Bundle Protocol [6] (BP) it is expected to obtain a significantly higher equivalent throughput and thus a much faster transmission of data. This will make it possible to receive data at the Central Station and provide the ability to send commands to an AUV during the mission.

1.2 Objectives

This dissertation arises from previous work in underwater scenarios at INESC TEC [7] and in the FCT GROW project [5]. Its main goal is to design, implement, and test a communications protocol to enable the control and execution of a scheduling mechanism of underwater data mules in an DTN. The protocol must be implemented taking advantage of a state of the art DTN, and explore it coupled with a permanent acoustic control link between the Central Station, the AUV, and the data mule to transmit the schedule of the Data Mules.

1.3 Contributions

This dissertation's main contribution is the design, and implementation of the Underwater Data Muling Protocol (UDMP), used to execute the scheduling of the Data Mules which was tested in an experimental setup. The proposed solution is expected to allow the advance of deep ocean missions by enabling underwater broadband and long range communications.

1.4 Document Structure

The document is organised as follows, Chapter 2 explores the existing underwater communications solutions concerning their characteristics, capabilities and limitations, the concepts of Delay Tolerant Networks and its implementations. The Underwater Data Muling Protocol (UDMP), proposed in this dissertation, is explained and described in Chapter 3. In Chapter 4, the experimental planning is shown, as well as test scenarios, and evaluation metrics used in our tests. Chapter 5 presents the theoretical and experimental evaluation of the proposed solution. Finally, in Chapter 6 the final conclusions, proposed improvements, and future work are presented.

Chapter 2

State of the Art

In this chapter, we review the state of the art on underwater wireless communications and compare the most used technologies – acoustic, optical, and radio frequency. The Delay Tolerant Network concept is also explained, together with the Bundle Protocol and its implementations, such as the IBR-DTN.

2.1 Underwater Wireless Communications

Underwater data exchange can be performed using three different technologies: RF, Acoustic and Optical. Table 2.1 presents a summary of the main benefits and limitations of each technology [8].

Table 2.1: Comparison of underwater wireless communication technologies

	Benefits	Limitations
RF	• Crosses air/water/seabed boundaries easily • Prefers shallow water • Unaffected by turbidity, salinity, and pressure gradients • Works in non-line-of-sight; unaffected by sediments and aeration • Immune to acoustic noise • High bandwidths (up to 100 Mb/s) at a very close range	• Susceptible to Electromagnetic Interference (EMI) • Limited range through water
Acoustic	• Proven technology • Range: up to 20 km	• Strong reflections and attenuation when transmitting through water/air boundary • Poor performance in shallow water • Adversely affected by turbidity, ambient noise, salinity, and pressure gradients • Limited bandwidth (0 b/s to 20 kb/s) • Impact on marine life
Optical	• Ultra-high bandwidth: gigabits per second • Relative low cost	• Does not cross water/air boundary easily • Susceptible to turbidity, particles, and marine fouling • Needs line-of-sight • Requires tight alignment of nodes • Very short range

Despite the high bandwidth achievable with RF communications, their limitations are centred on their range. In order to obtain a high bandwidth, the operating range has to be reduced, in the order of dozens of centimetres. Acoustic communications are seen as a proven technology due to the extensive research and commercial improvements, and can provide communications up to 20 km, they posses a very limited bandwidth due to operating conditions such as ambient noise, pressure, and turbidity, that negatively impact its operation. The optical solution may be able to provide the largest bandwidth of the three solutions, but requires line-of-sight and tight alignments of the beam to work properly. Also, the operating range is very short, limiting the scenarios where this technology can be applied.

2.1.1 Acoustic Wireless Communications

Underwater acoustic communications are characterised by a lower bitrate and higher delays when compared to RF and optical technologies. Kularia *et al.* [9] have characterised the underwater acoustic channel based on the Propagation Delay T_p, which is the time taken by the signal to reach the destination from the sender. This depends on the distance, d, in meters, between the destination and sender, and the speed of sound, c, in meters/second, underwater.

$$Tp = \frac{d}{c} \tag{2.1}$$

The above formula depends on the speed of sound formula proposed by Medwin in [10]. The formula, presented in Eq. 2.2, depends on the Temperature T in degrees Celsius, Salinity S in parts per thousand and Depth D in meters.

$$\begin{aligned} c = {} & 1449 + 4.6T + 0.055T^2 - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 + 1.340(S-35) \\ & + 1.630 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 - 1.025 \times 10^{-2}T(S-35) - 7.139 \times 10^{-13}TD^3 \end{aligned} \tag{2.2}$$

The authors in [11] also characterised the acoustic channel with the Attenuation and Transmission loss. According to the Thorp formula [12], the transmission loss TL of the signal can be defined as shown in Eq. 2.3:

$$TL = SS + \alpha \times 10^{-3} \tag{2.3}$$

with the attenuation factor, α, shown in Eq. 2.4, and Spherical Spreading factor, SS, given by Eq. 2.5:

$$\alpha = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2}\,\{db/km\} \tag{2.4}$$

$$SS = 20\log(r) \tag{2.5}$$

where r is the range in meters and f the frequency in kHz.

With the equations presented before, the authors computed tables for 100m of depth for the Attenuation factor, Spreading factor, as well as the Transmission Loss, as seen in Table 2.2.

Table 2.2: Attenuation and Transmission Loss at 100m

Frequency in kHz	**Attenuation Factor in dB/km**	**Transmission Loss in dB**
10	1.1565	40.0011
15	2.3985	40.0023
20	4.0208	40.0040
25	5.9299	40.0059
30	8.0298	40.0080
35	10.2319	40.0102
40	12.4606	40.0124

In their work, Kularia, *et al.* [9] also analysed the Spreading Loss, Absorption Loss and Signal to Noise Ratio (SNR). Spreading Loss is a type of transmission loss and is expressed in dB as:

$$PL_{spreading}(r) = k \times \log(r) \tag{2.6}$$

it depends on the transmission range r, in meters, and it has two types: k=1 for cylindrical spreading, k=2 for spherical spreading. Results for a range between 10 and 100 meters are presented in Table 2.3.

Table 2.3: Cylindrical and Spherical Spreading

Range (m)	**Cylindrical Spreading (dB)**	**Spherical Spreading (dB)**
10	10	20
20	13.01	26.02
30	14.77	29.54
40	16.02	32.04
50	16.99	33.98
60	17.78	35.56
70	18.45	36.9
80	19.03	38.06
90	19.54	39.08
100	20	40

When considering the Absorption Loss, it is defined in [9] as:

$$PL_{absorption} = \alpha \times r \times 10^{-3} \tag{2.7}$$

The results for Frequencies ranging from 100 kHz to 1000 kHz are shown in Table 2.4.

Table 2.4: Variation of Absorption Loss with Frequency

Frequency (kHz)	Absorption Loss (dB)
100	2.329
200	2.742
300	3.429
400	4.392
500	5.629
600	7.142
700	8.929
800	10.99
900	13.33
1000	15.94

Regarding the SNR characteristics, the authors in [9] considered all the losses described above. This allows us to estimate the SNR of the acoustic channel:

$$SNR = SL - TL - NL + DL \tag{2.8}$$

where

$$SL = 10\log\left(\frac{I_l}{0.067 \times 10^{-18}}\right) \tag{2.9}$$

and, for deep water,

$$I_l = \frac{P_l}{4\pi \times 1m \times d} \tag{2.10}$$

In [13], information about the current commercial acoustic solutions were gathered. The survey can be found in Table 2.5, where it is possible to see that the maximum rate is limited to 31.2 kbit/s at a range of 1000 m. In order to increase the range, we must decrease the rate, where the available solution only allows a rate of 9.6 kbit/s for a 10 km distance. This is not suitable for transmission of large amounts of data such as pictures, videos, and bathymetric information.

Despite the low bitrate provided, acoustic communications are suitable for sending control messages, as considered in this dissertation, for controlling the data mule over long distances.

Table 2.5: Characteristics of currently available acoustic modems

Model	Distance (m)	Rate (kbit/s)	Frequency (kHz)	Power (W)	Depth (m)	Weight (kg)
LinkQuest UWM 1000 [14]	350	17.8	26.77 to 44.62	2	Up to 200	4.2
LinkQuest UWM 2000 [14]	1500	17.8	26.77 to 44.62	8	Up to 4000	4.8
LinkQuest UWM 2200 [14]	1000	35.7	53.55 to 89.25	6	Up to 2000	3
LinkQuest UWM 3000 [14]	5000	5	7.5 to 12.5	12	Up to 7000	4.1
LinkQuest UWM 3000H [14]	6000	5	7.5 to 12.5	12	Up to 7000	4.1
LinkQuest UWM 4000 [14]	4000	8.5	12.75 to 21.25	7	Up to 7000	7.6
LinkQuest UWM 10000 [14]	10000	5	7.5 to 12.5	40	Up to 10000	21
EvoLogics S2CR 48/78 [15]	1000	31.2	48 to 78	60	Up to 2000	2.25 to 8
EvoLogics S2CR 40/80 [15]	2000	27.7	38 to 64	60	Up to 2000	1.39 to 8
EvoLogics S2CR 42/65 [15]	1000	31.2	42 to 65	40	Up to 2000	2.3 to 8
EvoLogics S2CR 18/34 [15]	3500	13.9	18 to 34	65	Up to 2000	2.4 to 9.4
EvoLogics S2CR 12/24 [15]	6000	9.2	13 to 24	57	Up to 6000	2.99 to 7.78
EvoLogics S2CR 7/17 [15]	8000	6.9	7 to 17	80	Up to 6000	4.7 to 7.78

In [16] the authors revise and compare the current acoustic modem solutions, both commercial and experimental, In Table 2.6 it is possible to see the characteristics of the current experimental solutions.

Table 2.6: Experimental Acoustic Solutions

Model	**Distance (m)**	**Rate (kbit/s)**	**Frequency (kHz)**	**Power (mW)**	**Depth (m)**	**Wheight (kg)**
A low cost and high efficient acoustic modem [17]	100	17.8	0.32 to 10	12 to 24	n/a	4.2
An integrated, underwater optical/acoustic communications system. [18]	100	17.8	n/a	n/a	n/a	4.8
Design of a low-cost underwater acoustic modem. [19]	350	35.7	35	750	n/a	3
An ultra-low power and flexible acoustic modem design to develop energy-efficient underwater sensor networks. [20]}	240	5	85	108	n/a	4.1
Reconfigurable acoustic modem for underwater sensor networks. [21]	2000	5	9 to 14	n/a	n/a	4.1
Underwater Acoustic Communications: Design Considerations on the Physical Layer. [22]	50	8.5	80	n/a	n/a	7.6
AquaNodes: an underwater sensor network. [23]	400	5	30	n/a	n/a	21
Designing an Adaptive Acoustic Modem for Underwater Sensor Networks. [24]	200	31.2	9	n/a	n/a	2.25 to 8
Development of a 1 Mbps low power acoustic modem for underwater communications. [25]	12	1000	1000	2400	0,5	n/a

The analysis of Table 2.5 and Table 2.6 reveals that in the commercially available solutions, the operating range and rate are better when compared to the experimental solutions. Except for the solution presented in [25], where the authors presented an acoustic solution that is capable of providing a large throughput, but the range of operation is very limited when compared to the others solutions. Although, by analysing the power consumption and weight of the commercial solutions it is clear that most of these solutions can be challenging to carry on a small and fast data mule.

2.1.2 Optical Wireless Communications

In optical wireless communications, light is used to transmit information. It consists of oscillations of the electromagnetic field, so it also presents similar characteristics to the RF waves, operating at higher frequencies.

The authors in [26] have demonstrated the use of high-speed underwater visible light communications using Light Emitting Diodes (LEDs). As shown in Figure 2.1, visible light frequencies are the least attenuated. Wavelengths in the 470 nm range are the least attenuated in general. This depends on the characteristics of the water, since absorption and scattering are influenced by the chemical and biological characteristics of the water [27].

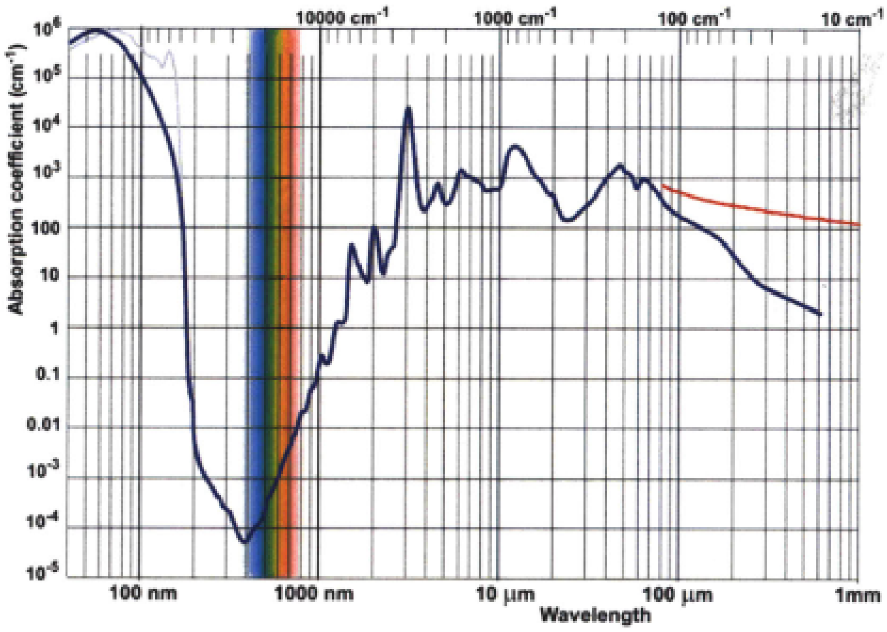

Figure 2.1: Absorption coefficient of electromagnetic radiation at various wavelength [27]

In Figure 2.2, it is possible to observe the minimum underwater absorption is in the blue light wavelength (490–450 nm), and so, used by many commercial systems and experiments [26].

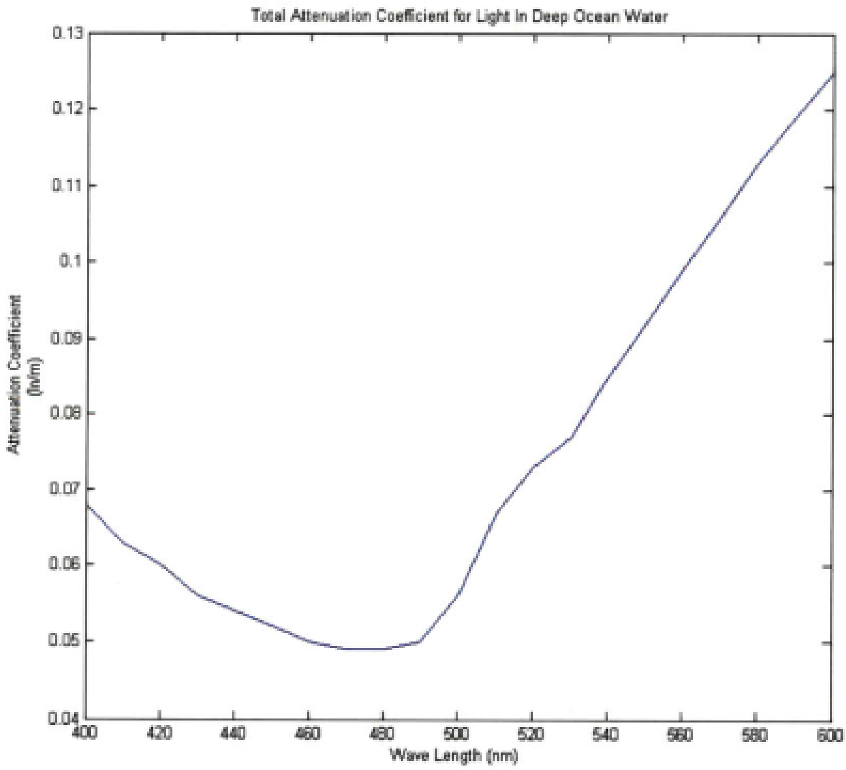

Figure 2.2: Underwater absorption coefficients visible light wavelengths [27].

Although high bitrates can be obtained using optical systems, in the order of hundreds of Mbit/s [26], the big throwback is the requirement of line-of-sight (LOS), which is not always assured in aqueous environments [28]. To overcome this problem, the advance of recent LED technologies has been explored and enabled the development of a high level of light intensity, fast switching speeds, high efficiency, and optimal wavelengths for underwater light transmissions solutions. The use of lasers may be a better solution for higher data rate due to a much better collimated light beam than LED, but this solution is more sensitive to misalignment [28] and turbidity of the water.

Despite its limitations, optical communications can provide data rates in the order of Mbit/s, more than the acoustic and RF solutions. In Table 2.7 it is possible to see a survey commercial on optical modems.

Table 2.7: Current Available Optical Modems

Model	Distance (m)	Operating Frequency	Rate	Maximum Depth
AQUAmodem 500 [29]	250	27 - 31 kHz	25 - 100 bits/s	200 m
AQUAmodem Op2 [30]	1	610 – 575 THz (cyan visible light)	10.2 Kbytes	3500 m
SA Photonic Neptune [31]	10 - 200	616 - 563 THz	10 - 250 Mbit/s	N/A

2.1.3 Radio frequency Wireless Communications

Radio Frequency waves are electromagnetic waves with frequencies below 300 GHz. Due to the highly conducting nature of water, few underwater RF systems have been developed even though they had received considerable attention during the 1970s [32]. Unlike optical solutions, the RF systems do not require LOS and are not affected by turbidity, allowing large bandwidth at a close range. This can be seen as a complementary technology for the other solutions' limitations.

In [33] the bandwidth, radiation pattern, and maximum expected operating range of two similar dipole antennas, when operating in underwater environments, were analysed. In this experiment, the results show that with the use of frequencies bellow GHz, the attenuation is progressively reduced and the range grows from 5 cm to 5 m, whose throughput reaches 550 kbit/s in freshwater.

Underwater propagation of RF waves is slower when compared to its propagation in the air. This is mainly due to dissolved salts in the water that lead to a high permittivity and electrical conductivity. Despite the slower propagation speed, as the operating distances are small, this effect can be neglected.

The propagation of RF waves is characterised by a propagation constant, γ, [34]:

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} = \alpha + j\beta \tag{2.11}$$

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

The propagation constant is a complex value that can be expressed by an attenuation factor α and a phase factor β [35]:

$$\alpha = \omega\sqrt{\mu\varepsilon}\left[\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\right)\right]^{1/2} (Np/m) \tag{2.12}$$

$$\beta = \omega\sqrt{\mu\varepsilon}\left[\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} + 1\right)\right]^{1/2} (rad/m) \tag{2.13}$$

The real part of the permitivitty ε is dependent on the complex frequency, and is commonly described with the Debye model [35]:

$$\varepsilon = \varepsilon_\infty + \left[\frac{\varepsilon_s - \varepsilon_\infty}{1 + j(\frac{f}{f_{ref}})}\right] \tag{2.14}$$

where ε_S and ε_∞ are the real relative permittivity at low and high frequencies, respectively, 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 wavelength λ is and velocity are given by [35]:

$$\lambda = \frac{2\pi}{\beta}(m) \tag{2.15}$$

$$v = \frac{\omega}{\beta}(m/s) \tag{2.16}$$

In order to estimate a link budget it is necessary to calculate the received power using:

$$P_{rx}(dBm) = P_{tx} + G_{tx} + G_{rx} - L_{FSLP} - L_{water} \tag{2.17}$$

Where P_{rx} is the received power in dBm, P_{tx} is the transmission power in dBm, G_{tx} and G_{rx} are the transmitter and receiver antennas gains in dBi. L_{FSPL} and L_{water} are the free space path loss and water attenuation, that depends on the conductivity and operation frequency of the water.

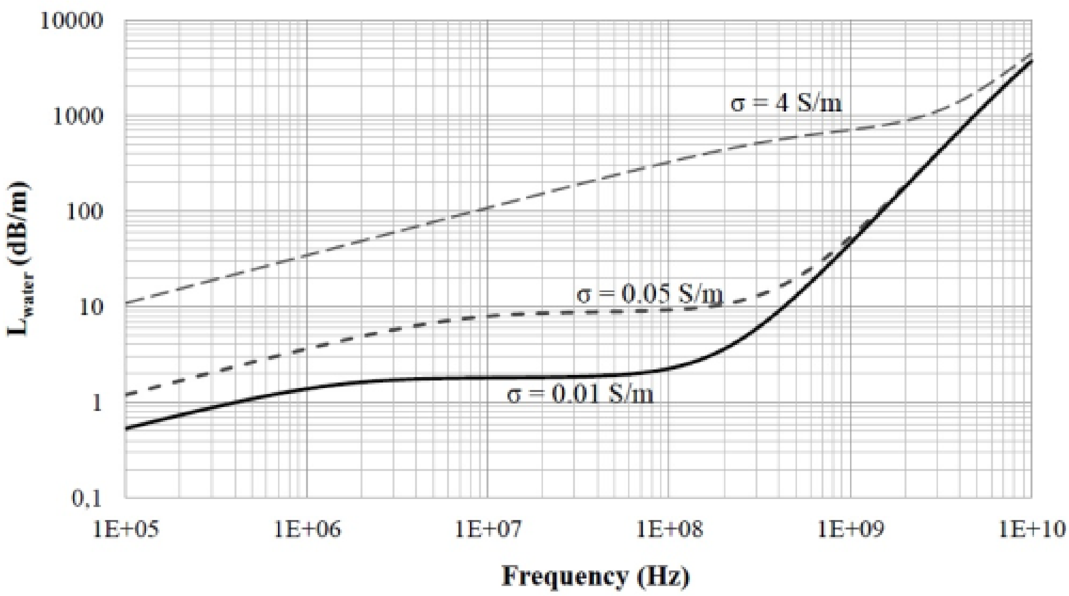

Figure 2.3: RF attenuation.

When considering RF communications, it is possible to understand from Figure 2.3 the reason why research has been done mainly in the Very Low Frequency band. The attenuation of RF waves decreases with the decrease of both the conductivity and frequency. Due to this fact it is, in general, the easiest way to reduce attenuation and, therefore, achieving a higher range, as shown in [36] and in [37]. In [38], simulations at 3 kHz with distances between nodes of 40 meters were done to obtain a larger range of communication, and in [39] the freshwater underwater maximum ranges for different low frequencies has been determined, as shown in Table 2.8.

Table 2.8: Maximum Range for different frequencies in freshwater

Frequency (kHz)	Range (m)
1	22
10	16
100	6

In [4], underwater wireless communication experiments were done with IEEE 802.11 Wi-Fi network operating at various frequencies (from 700 MHz to around 5 GHz). Regarding this experiment, the TCP throughput results are presented in Table 2.9.

Table 2.9: RF underwater throughput [4]

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

These results are in line with the goal of this dissertation. At a close range (20 cm), the commonly available solutions allow enough throughput to deliver large amounts of data to a data mule and, the acoustic link is widely tested and is proven to be reliable enough in order to deliver control messages to the data mule. It is important to mention that, for sea water, the frequencies used must be lower than the presented, in order to overcome the attenuation.

2.2 Delay Tolerant Networks

The use of AUVs has been rising in recent years due to the increase in the investment in underwater activities and thus resulting in a need for communication in these environments. These environments can be associated with the concept of Intermittently Connected Network (Challenged Network).

> "An Intermittently Connected Network, also known as a Challenged Network, is an infrastructure-less wireless networks that support the proper functioning of one or several wireless applications operating in stressful environments, where excessive delays and unguaranteed continuous existence of end-to-end path(s) between any arbitrary source-destination pair, result from highly repetitive link disruptions." [40]

These environments have constraints that ressemble the constraints present in space exploration such as:

- Intermittent connectivity: There is not an end-to-end path, so the TCP/IP protocol do not work in these cases;
- Long or variable delay: Long propagation delays between nodes and variable queuing delays at nodes raise the end-to-end delay to the point that the internet protocols can not work, because they rely on quick acknowledgements;
- Asymmetric Data Rates: The internet protocols are prepared for asymmetry, but if they are large they defeat the conversational protocols;
- High Error Rates: Errors in links require correction or re-transmission which results in more bits, more processing and more network traffic.

These constraints lead to the need for a solution that can accommodate these challenges. One possible solution is the DTN, consisting of network of smaller networks. It is an overlay on top of special-purpose networks, including the Internet. Initially developed for interplanetary use, it has since evolved and can have diverse applications on Earth, accommodating multiple wireless technologies, such as radio frequency (RF), ultra-wideband (UWB), free-space optical, and acoustic (sonar or ultrasonic) technologies [41]. In this dissertation, both RF and acoustic technologies will be explored.

DTNs overcome the problems associated with intermittent connectivity, long or variable delay, asymmetric data rates, and high error rates by using store-and-forward message switching. Store-and-forward message switching is the basis of operation of any DTN and DTN protocol, and has been used for a long time in diverse areas, such as the postal systems, for example [41]. DTNs can be easily explained as a whole message or fragments being moved from one storage place on one node to another storage place on another node, in order to eventually reach the destination. This technique requires DTN routers to have permanent storage in order to store the message in their queues for the following reasons [41]:

- The link to the next hop may not be available for a long time;
- One node may communicate much faster or reliably than the other one;
- A message may need to be re-transmitted due to errors or rejection of the transmitted message;
- Avoid buffer overflow by having enough storage space;

However, using this technique in a Challenged Network such as this, requires an adequate balance between good delivery rates and delay, in order to manage the limited power of the data mule properly. In [40] the authors propose two design positions:

- Position I: High reliability is achieved by making judicious decisions;
- Position II: Low delivery delays are achieved by undertaking some risks;

In the first position, the network resources are conserved in order to be used in the right time by, using techniques such as deleting the distributed copies once the transmitting node receives a successful delivery to its ultimate destination, freeing up buffer space. This position makes multiple copies of the message to be injected in the network wasting scarce bandwidth and power. In the second approach, a risk is taken by sending messages to nodes with random delivery probability. The author argues that the probability of successful delivery increases by disseminating the message to the a large enough number of nodes. However, this solution may cause nodes' buffers to overflow.

2.2.1 Intermittent Connectivity

As stated before, one of the main constraints of the underwater medium is the effective range of the current wireless communications solutions, which leads to intermittent connectivity. In order to deal with this, DTNs isolate delay and disruptions with the store-and-forward technique. In a DTN the connectivity can be opportunistic or scheduled:

- During opportunistic contacts, nodes try to send and receive data during unscheduled times when two or more nodes happen to be in reach of each other;
- During the scheduled contacts, nodes can predict their future positions and arrange their future communication session. These contacts may involve sending messages between nodes that are not in direct contact or storing the information until it can be forwarded. Thus, the use of scheduled contacts requires time-synchronisation throughout the DTN [41].

In Figures 2.4 and 2.5 ([2]), both types of intermittent connectivity are shown.

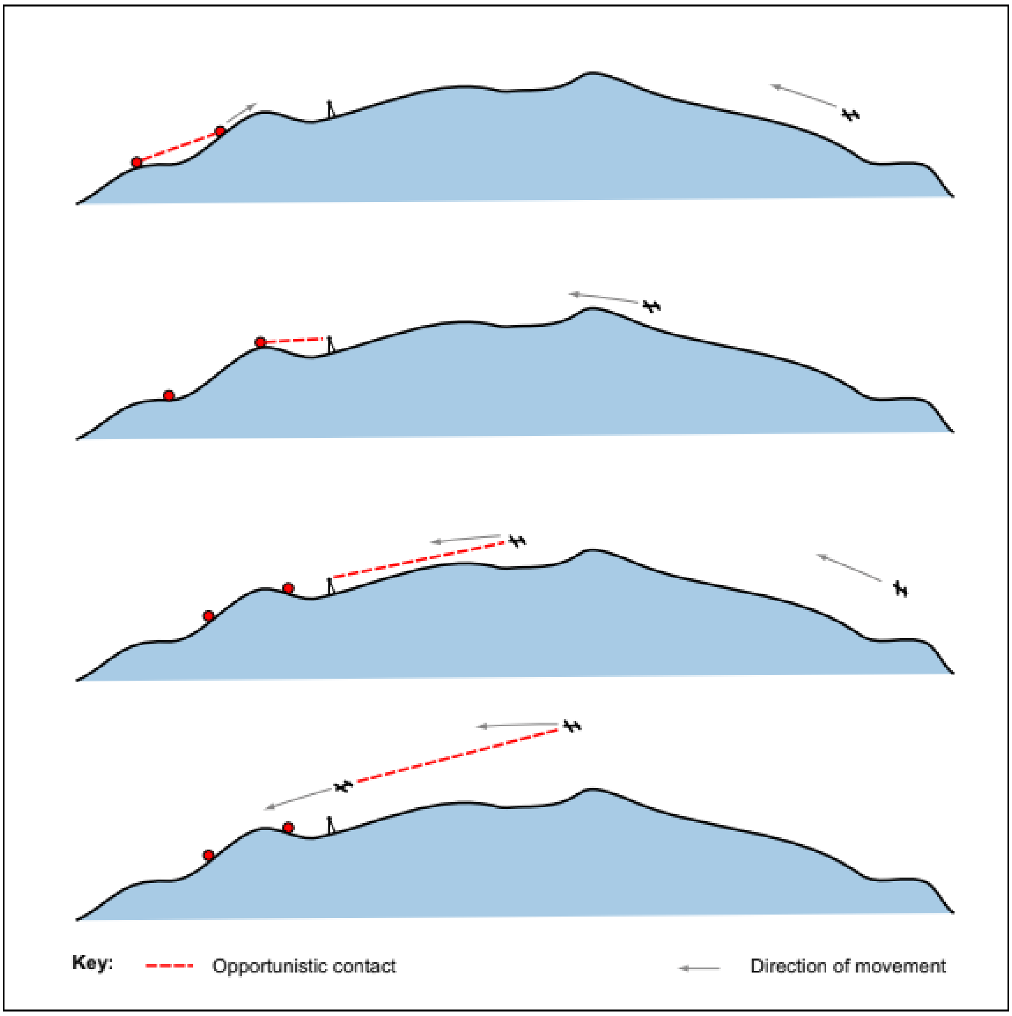

Figure 2.4: Opportunistic Contact [2].

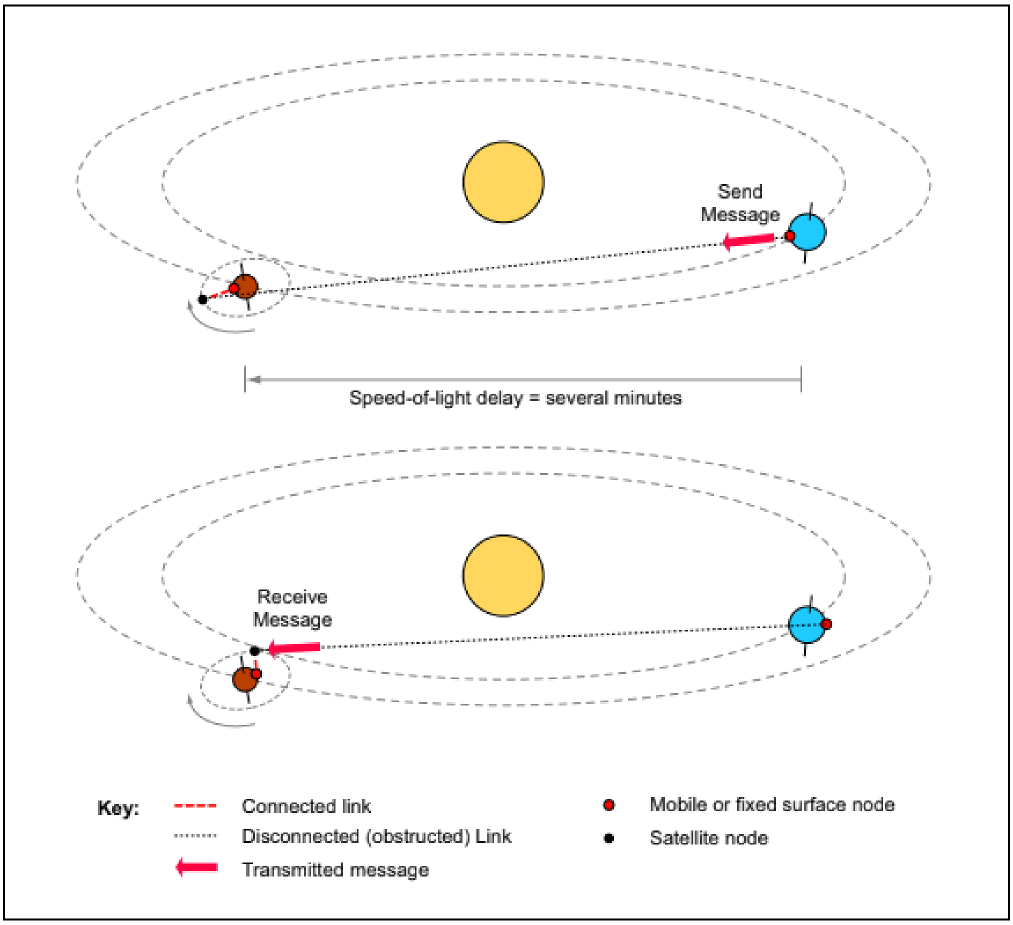

Figure 2.5: Scheduled Contact [2].

In Figure 2.4, the message is sent from the source node to another passing node, from that to cell tower and finally to a passing aeroplane. Figure 2.5 shows how the sending node takes advantage of the propagation delay by knowing the position of the receiving node and estimating when to send the message.

2.2.2 Bundle Protocol

The Bundle Protocol (BP), defined in the RFC 5050 [6], is a protocol designed to work on DTNs. It is an implementation of a store-and-forward message switching technique. It aggregates data in bundles and sends them through bundle payloads. In [41] the author explains bundles as:

> "Bundles consist of three things: (1) a bundle header consisting of one or more DTN blocks inserted by the bundle-protocol agent, (2) a source-application's user data, including control information provided by the source application for the destination application that describes how to process, store, dispose of, and otherwise handle the user data, and (3) an optional bundle trailer, consisting of zero or more DTN blocks, inserted by the bundle-protocol agent. Like application-program user data, bundles can be arbitrarily long."

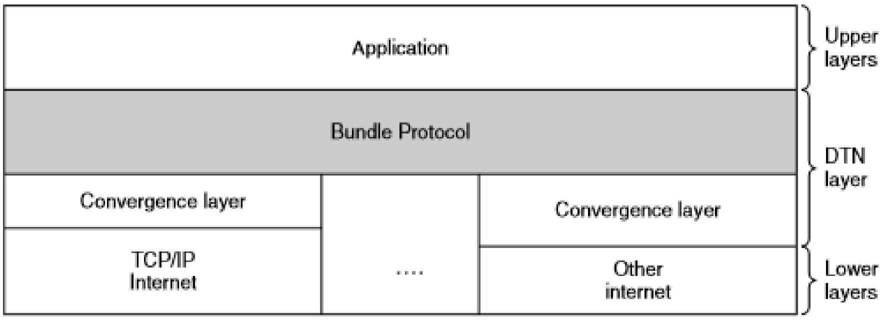

Figure 2.6: DTN Protocol Stack [42].

As it is possible to observe in Figure 2.6 ([42]), the primary protocol is the BP. It sits on top of a convergence layer so that it can communicate with multiple protocols such as TCP, UDP or other kinds of networks. The convergence layer is just a glue layer that matches the interfaces of the protocols that it joins. By definition, there is a different convergence layer for each different lower layer transport. Convergence layers are commonly found in standards to join new and existing protocols [42].

In a DTN, a node can have multiple roles at any time, namely source, destination or forwarder of bundles [41]. In Figure 2.7 we show the three roles. The source and destination nodes only send or receive bundles and thus require persistent storage to deal with long delay links. These nodes can also participate in custody transfer of the bundles. In the Forwarding mode, the node forwards bundles between other nodes. In this mode, there can be two situations, shown in Figure 2.7, either Routing equivalent forwarding or Gateway equivalent forwarding. In the first mode, in the middle of Figure 2.7, the nodes work in the same lower-layer protocols (A). In the second, on the right of Figure 2.7, the nodes work in different lower-layer protocols (A and B), and the forwarding node needs to support all these protocols.

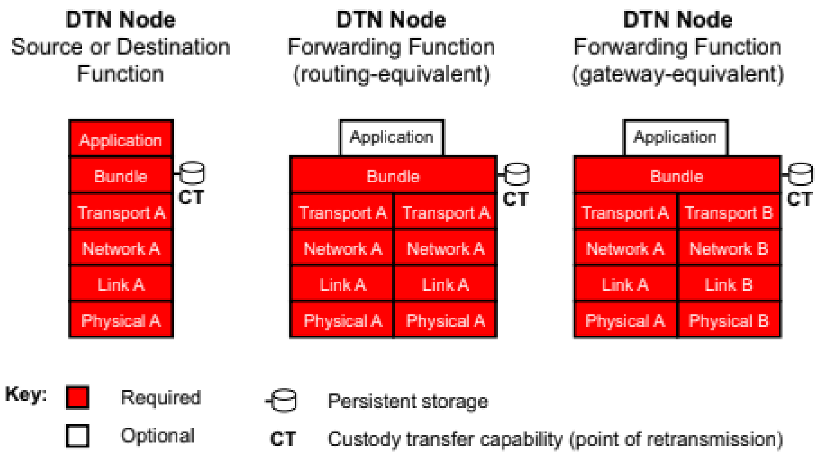

Figure 2.7: DTN Nodes Roles [41].

Node identification in a DTN, it is done using Endpoint Identifiers (EIDs) with a maximum size of 1024 bytes and can be treated as a Uniform Resource Identifier (URI). This notation can be used either to identify a single node or to identify a group of nodes and uses the syntax <scheme_name>:<scheme-sprecific_part>. In order to ensure the acknowledgement of delivery in a DTN, a solution of custody transferring was implemented. In fact, the node that currently holds a bundle is set as custodian, when the bundle is transferred to another node, either the destination or another node, the custody is also transferred.

The mechanism of custody transferring is detailed in Figure 2.8 ([40]), and it shows a node (S) receiving data and storing it in its permanent storage (a and b). Then, the bundle is sent to another node (I1) that also stores the data in its storage (c and d). After a request time-out, S tries to transfer custody with a Custody Transfer Request. If I1 accepts it, S can now delete the data from the persistent storage (e and f) [40].

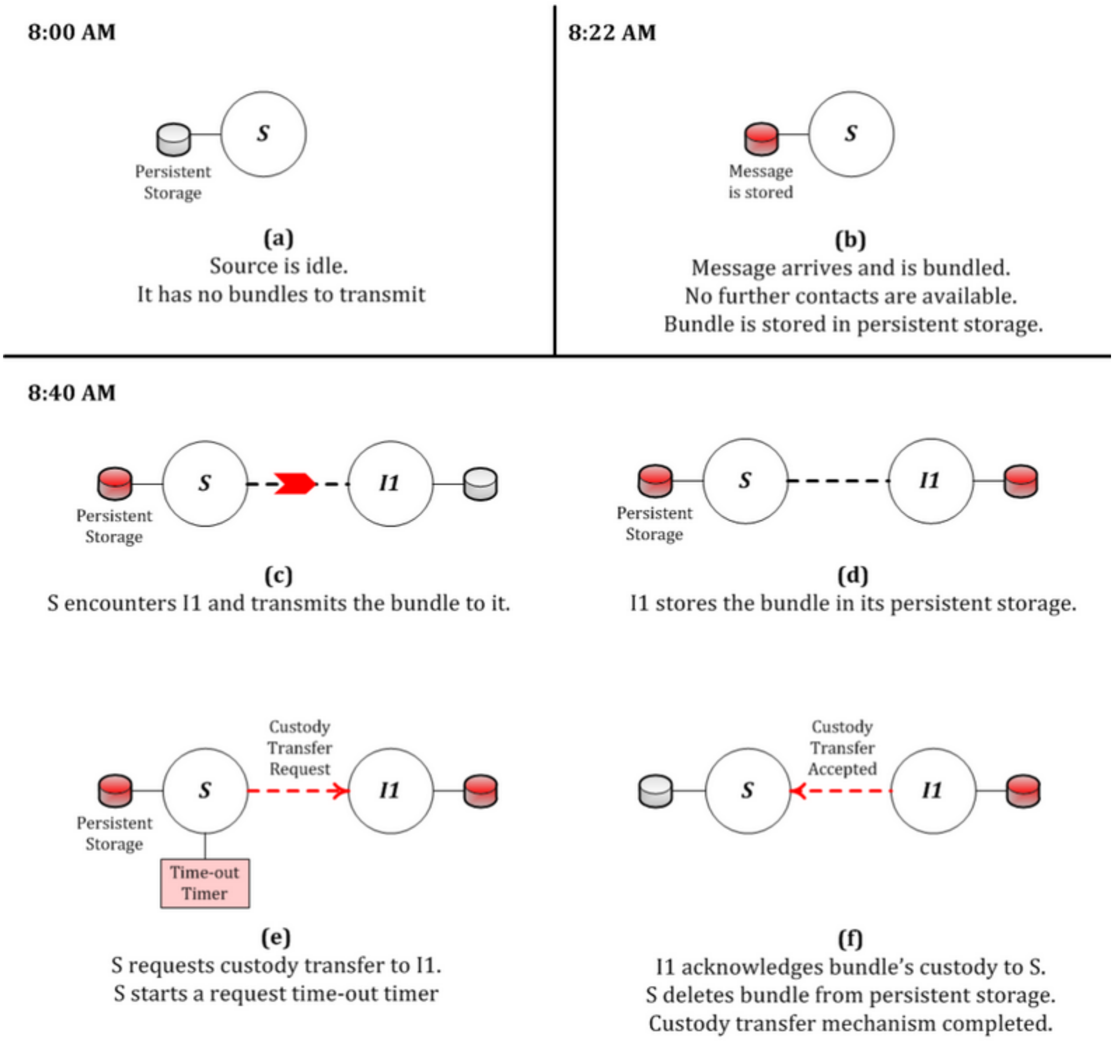

Figure 2.8: Custody Transfer [40].

The bundle protocol can be explained with a message exchange sequence diagram. In Figure 2.9 ([7]), three nodes (node1.dtn, node2.dtn, node3.dtn) establish a communication. The communication starts with a "Hello message" from node 2 to node 1 that is answered with a forwarding request that can be either accepted or rejected. If the request is accepted, then a copy of the bundle is sent, and an ACK message is returned. After receiving the ACK message, the sending node (node 1) never sends the same bundles and requests custody to node 2 in the same way as the bundle exchange happened.

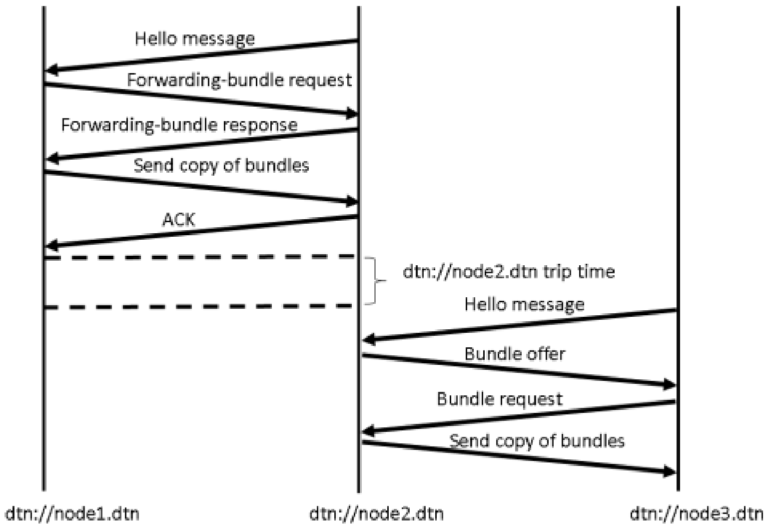

Figure 2.9: Message Sequence Diagram [7].

2.2.3 Bundle Protocol Implementations

Regarding the Bundle Protocol Implementations, there are some interesting solutions already available. Currently, the most developed DTN implementations supported by DTN-RG (Research Group) are the DTN version 2 [43] and ION (Interplanetary Overlay Network) [44]. In [45] the author enumerates several DTN implementations:

- DTN2 [43] is the Delay Tolerant Networking reference implementation and complies to the RFC5050;
- ION (Interplanetary Overlay Network) [44] is an implementation of the RFC 4838. ION currently runs on various platforms;
- Postellation [46] is another RFC 5050 implementation with some considerations. It is a Lean Bundle protocol implementation, has a smart HTTP proxy and allows easy deployment of DTN networks;
- IBR-DTN [47] is designed for embedded systems, running OpenWRT [48], and can be used as a framework for DTN applications. IBR-DTN supports the TCP and UDP convergence layers, the Bundle Security Protocol, and IPND neighbour discovery specifications;

- JDTN [49] is a Java-based implementation of RFC 5050 and 5326. It can run on any platform that supports Java, as well as a set of UIs for Android;
- LTPlibe [50] is an implementation of the RFC 5326 from Trinity College.

In [7] the author has studied and evaluated the use of data mules for transporting data in a DTN and has shown in their results the capabilities of this solution to transfer data with better equivalent throughput and range than the currently available solutions. In this dissertation work, this implementation will be revisited, and the control mechanism for a multitude of data mules will be developed.

2.2.4 Underwater DTN

The author in [51] proposes a framework for mobile underwater acoustic networks using an acoustic link that can adapt itself to the environment. This framework offers the TCP/IP protocol suite and uses four data classification planes: perception, intuition, management and adaptation. In the perception plane, the data of each TCP/IP layer is gathered and it is possible to create an accurate view of the current network state. The intuition plane uses the perceived data to infer information from the data. The management plane work as a shared database that keeps track of information to allow the functioning of perception and adaptation. Finally, the adaptation plane uses data from the management plane and adapts for each layer.

This framework also allows a balancing mechanism based on reliability and latency requirements at the time of sending. When a message is sent the application informs the reliability and latency requirements, then each individual layer decides if they can adapt to meet the requirements. This framework's drawback, according to the author in [52], is that it is only a framework and no protocol definition is specified, and only an overview is given, so it is not possible to know how it will perform.

Delay-tolerant Data Dolphin [53] is a solution that aims to increase the power efficiency of underwater DTNs by using the mobility of collector nodes, called dolphins, that collect data from static nodes. The nodes are equipped with an acoustic modem that serves two purposes: 1) transmits data, and 2) informs the other nodes of its presence. In [53], the dolphin nodes can move randomly or have a scheduled mission. When a dolphin receives data from a sensor node, it comes to the base station on the surface and delivers it. The performance of this solution depends deeply on the number of collector nodes and, as the nodes move randomly, some fixed nodes may not be visited which may result in data loss.

In [54] the authors propose a data retrieval protocol to collect data from a specific network region optimally. The retrieval device is sent out in the area of interest to collect data from the sensor nodes and, as the channel conditions and requirements vary, the protocol adapts to achieve efficiency. In this solution the Luby Transform (LT) as well as Forward Error Correction (FEC) codes are used. The sensor node has the following operational steps: data gathering while passively listening for the receiver beacon; as the beacon is received, time synchronisation occurs, and the amount of data is informed; after a broadcasts message is received, containing the receiver ID and

LT encoding parameters, the node starts to send data until a *finish* signal is received. The retrieval node follows the following operational steps: announces its presence by broadcasting beacon signals and sets up time synchronisation; receives status packets from the sensor nodes, calculates the transmission time for each sending node and selects the one with similar transmission times; broadcast messages with the LT codes to the selected nodes. After that it receives and decodes the received packets. From the remaining nodes it selects another set of nodes and acts in the same way. When all the senders have successfully transferred the data, a broadcast *finish* message is sent to all senders indicating the end of the communication. According to the author in [52], the main limitation of this protocol is the restriction on the supported applications. Besides that, the data transmission is initiated by the receiver and within a single hop, which means that the receiver node has to come in the range of all senders and that will, possibly, have a negative impact in the retrieval latency.

As seen by the examples above, the use of DTNs has been explored, and it has a great potential to evolve in order to improve broadband data transmission in underwater missions.

Chapter 3

Proposed Underwater Data Muling Protocol

This chapter presents the proposed Underwater Data Muling Protocol (UDMP). In this chapter, the system architecture is explained, as well as the protocol stack, message body, and state machines. The message sequence diagrams are also presented in order to better explain the reasoning of the proposed solution.

3.1 Overview

Deep sea exploration and exploitation missions are growing in number, as well as the amount of data gathered in these missions. Due to the harshness and complex logistics of offshore missions the use of increasingly more capable AUVs is also a reality. These AUVs have a good endurance and, therefore, are capable of performing long missions and collect large amounts of data, in the order of gigabytes. This data can vary from bathymetric data, topological data, and high definition video. Retrieving the data collected during these missions is fundamental, as the currently available methods do not provide reliable and fast enough underwater communications.

GROW [5] is a novel solution for Long-Range Broadband Underwater Wireless Communications between a Survey Unit (stationary or mobile) and a central Station Unit. In the GROW solution, shown in Figure 3.1, a DTN is implemented using fast and agile AUVs as Data Mules equipped with high bitrate short range wireless communications, and long-range acoustic out-of-band control links.

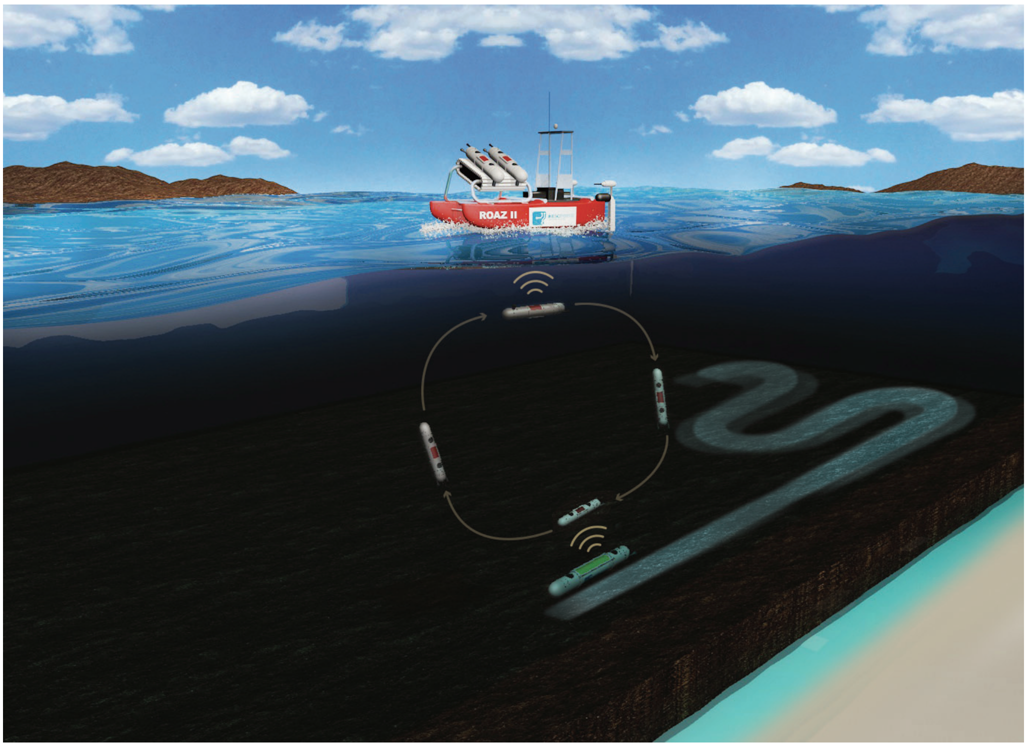

Figure 3.1: The GROW proposed Solution [5].

The proposed solution is composed by three main components:

- Station Unit – a station at sea surface (e.g. buoy or autonomous surface vehicle) that is responsible for scheduling the different Mule Units available through the long-range acoustic link, receive the data transported by the Mule Unit, and transmit it to shore.
- Survey Unit – an autonomous vehicle, such as a lander or an AUV, that executes the acquisition and the logging of data.
- Mule Units – small and agile AUVs that enable the establishment of a virtual bi-directional delay-tolerant communications' link between the Station Unit and the Survey Unit, travelling back and forth between the Station Unit and the Survey Unit and taking advantage of a high-speed, short-range wireless communications' link.

In the proposed solution, the close range advantages of the RF and optical communications are used to transfer data between the nodes. In addition to that, an out-of-band acoustic link is used to aid the Data Mule Units scheduling and positioning. In order to allow the scheduling of the Data Mule Units, the Underwater Data Muling Protocol (UDMP) is proposed. This protocol takes advantage of the permanent acoustic link and establishes a set of messages that are exchanged between the nodes, in order to coordinate the mules and allow the transfer of files using the tools available in the IBR-DTN implementation. The UDMP protocol is described in Section 3.2.

3.2 UDMP Protocol Overview

The proposed Underwater Data Muling Protocol (UDMP) is a communications protocol that enables the control and execution of the scheduling of the Data Mule Units. The protocol runs on the Station Unit, on the Survey Unit, and on each of the Mule Units.

In Figure 3.2, the protocol stack for all the participants is shown. The UDMP protocol runs on top of two wireless interfaces: 1) short range, high speed DTN, consisting of IBR-DTN [47], a state-of-the-art DTN implementation; 2) a permanent long-range out-of-band acoustic link between the Station Unit, the Survey Unit, and the Mule Units for sending and receiving control commands to and from the Mule Units. IBR-DTN provides a set of applications, such as *dtnsend* and *dtnrcv*, that allow the correct transfer of files between the nodes.

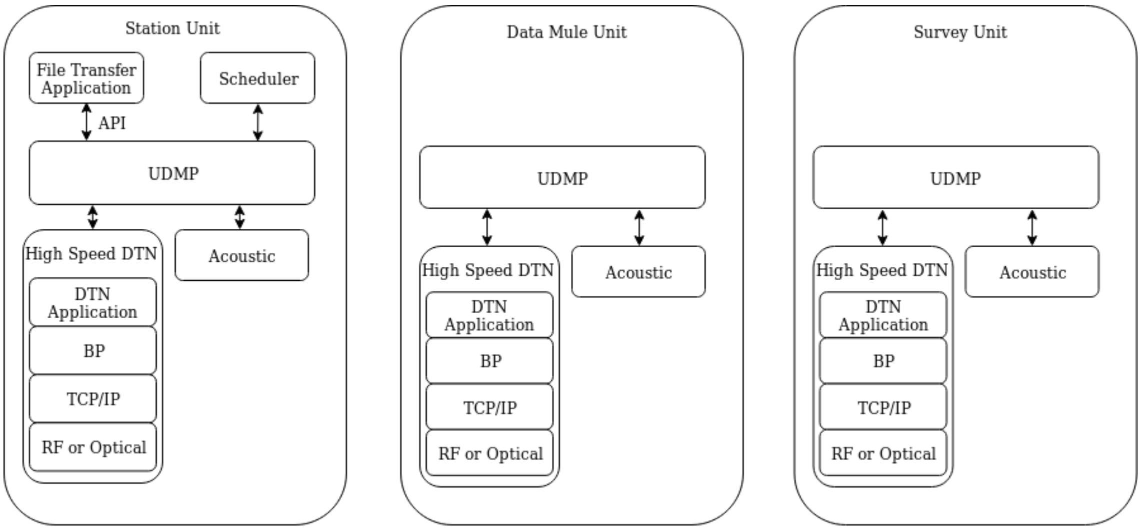

Figure 3.2: The proposed UDMP protocol stack.

As shown in Figure 3.2, the Station Unit is the UDMP manager as it is where the user can interact with the system. The Station Unit is equipped with a permanent connection to an onshore station, reachable through the Internet, and is where the user can specify the desired action: send or receive a certain file. The Station Unit instance is where the File Transfer Application runs, using the UDMP API and the scheduler instance. The implementations of the Data Mule Unit and Survey Unit UDMP instances are similar as they both only need to run an instance of UDMP. In order to explore the UDMP, an API that communicates with the protocol implementation was developed. This API allows the application to gather the data present in the AUV. In the API a set of functions have been implemented in order to interact with the protocol implementation.

The API has the following functions:

- **get_mule_configuration**(): Allows the retrieval of any mule characteristics.
- **set_mule_configuration**(): Allows the definition of any mule characteristics.
- **get_files**(): Allows the collection of the specified files.

- **get_stats()**: Allows the user to get a status update of each data mule state.

Each of these functions represents an implementation of a set of messages proposed in the protocol and that are explained in the next section. They allow the application to request and control the operation through the acoustic link, dispatch mules, and call the IBR-DTN tools to receive the requested file chunks.

Briefly, the UDMP protocol works as follows: – Upon receiving an application request from the user at the Station Unit, such as a file transfer request, the central Station Unit queries the Survey Unit about the size of the data to be transferred and informs the scheduling algorithm. The scheduling algorithm calculates the number of Mule Units to deploy, and informs the Survey Unit of its decision.

The UDMP instance running on the Station Unit acts as manager, sending mission commands for each Mule Unit and splitting the original file at the Survey Unit in different chunks. These chunks are generated using the *split* command, available on Unix-based operating systems, and named sequentially by appending the part number to the original filename. The chunk is then transmitted to the respective Mule Unit using the IBR-DTN tools. Upon receiving all chunks of the file, the UDMP reassembles the file at the Station Unit - for this the *cat* command is used. When a Data Mule Unit approaches the Survey Unit or the Station Unit it requests to dock and informs the file chunk to exchange.

3.3 UDMP Messages

In order to allow the proper functioning of the protocol, a set of messages are proposed. The message structure was designed bearing in mind the constraints of the acoustic link, and as such the message size was kept as small as possible. Another consideration was that all of the messages are broadcasted in the acoustic link.

The message structure follows a header plus payload structure. The complete message structure is shown in figure 3.3:

- The Header is composed by the first two fields and represents the Source and Destination of the message. Both fields have a fixed size of 6 octets.

- The Payload follows a Type-Length-Value approach with eleven different types of UDMP messages.

The third field of the message is the type of message and has a fixed size of 4 octets. This field is used to differentiate the message data. The Length field specifies the size of the body field. Finally, the Body field contains the data of the message, and its size is specified on the Length field.

Field	Source ID	Destination ID	Type	Length	Body
Octets	6	6	4	0 - 8	0 - 255

Figure 3.3: Message Body

Eleven types of UDMP messages were defined. These are the core messages that allow for the operation of the protocol. The set of messages is:

- **Type 00**: get_data_size() - Used to query the size of the file requested by user.
- **Type 01**: data_size() - Used to inform the size of the file.
- **Type 02**: number_of_mules() - Used to inform the AUV of how many mules will be dispatched.
- **Type 04**: ack() - Used to acknowledge the reception of the *number_of_mules()* message.
- **Type 05**: send_mule_req() - Used to inform the Data Mule Unit of the file chunk id.
- **Type 06**: send_mule_resp() - Used to acknowledge or deny the send mule request.
- **Type 07**: dock_req() - Used to inform the mule arrival, the file chunk id and request to dock.
- **Type 08**: dock_resp() - Used to acknowledge the dock request and allow it or not.
- **Type 09**: data__chunk_sent() - Used to inform the Station Unit that the file chunk has been transferred to the mule.
- **Type 10**: data_received() - Used to inform all the nodes that the file chunk has been received at the Station Unit.

In case a response fails to be received after a given timeout, there is a retransmission mechanism that will retransmit the message one more time.

3.4 UDMP Message Sequence

In order to show the exchanged messages between the nodes, Figures 3.4, 3.5 and 3.6 show three different states in which the system may exchange messages. Figure 3.4 refers to the case when there is a single Data Mule Unit available. Figure 3.5 addresses the case when there are two Data Mule Units available. Figure 3.6 depicts the error handling mechanism for when there is a timeout in the Data Mule Unit data retrieving process.

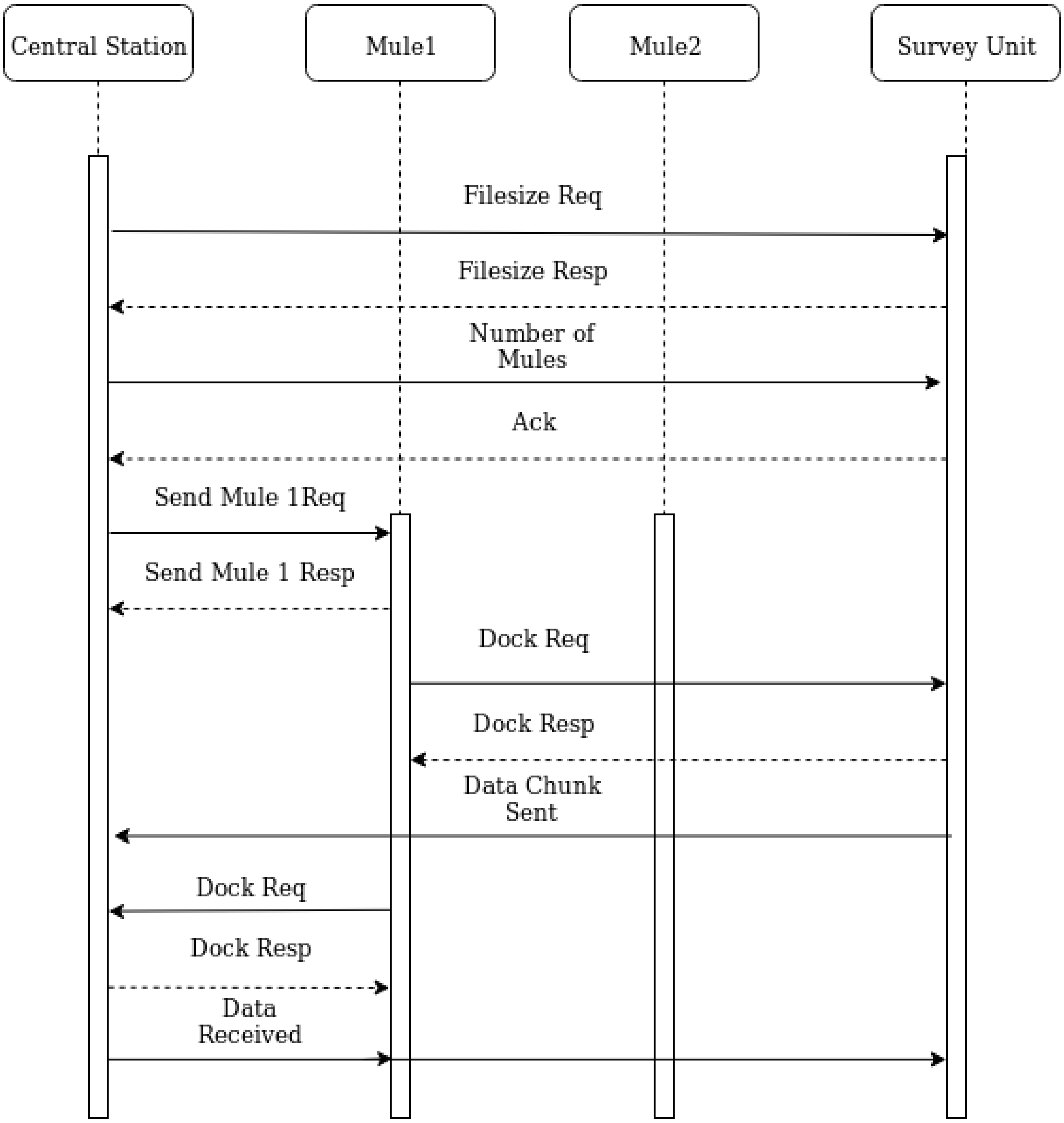

Figure 3.4: Message sequence diagram for 1 Data Mule.

Figure 3.4 shows the message sequence diagram of the system working in a single Data Mule Unit configuration. It is visible that during the normal functioning of UDMP, all the nodes can communicate between themselves and no Data Mule Unit is lost. This is the simplest scenario because there is no timeout, and the scheduling mechanism only needs to dispatch the Data Mule once.

In Figure 3.5 the normal functioning of the system with multiple mules is demonstrated. After informing the Survey Unit of how many Data Mules are being dispatched, the Central Station dispatches each Data Mule Unit by querying the Data Mule Unit with a *send_mule_request()* message. Following that process, each Data Mule Unit travels to the Survey Unit and collects the file chunk it had been assigned to, and travels back to transfer it to the Central Station. When the two file chunks are received at the Central Station Unit, the nodes are informed with a *data_received()* message. In this scenario there is no timeout, and the scheduling mechanism only needs to dispatch the mules one time.

On the other hand, Figure 3.6 presents the scenario where there is a timeout due to a Data Mule unresponsiveness. The most probable causes for this behaviour are a Data Mule getting lost, being out of reach of the acoustic link, battery depletion or hardware failure.

In this scenario, the scheduling mechanism needs to dispatch another available mule. The process of dispatching another mule follows the same approach of the initial dispatchment. The Control Station queries the Data Mule, informing it of the assigned file chunk: if the request is accepted the process continues, otherwise the control station queries another Data Mule.

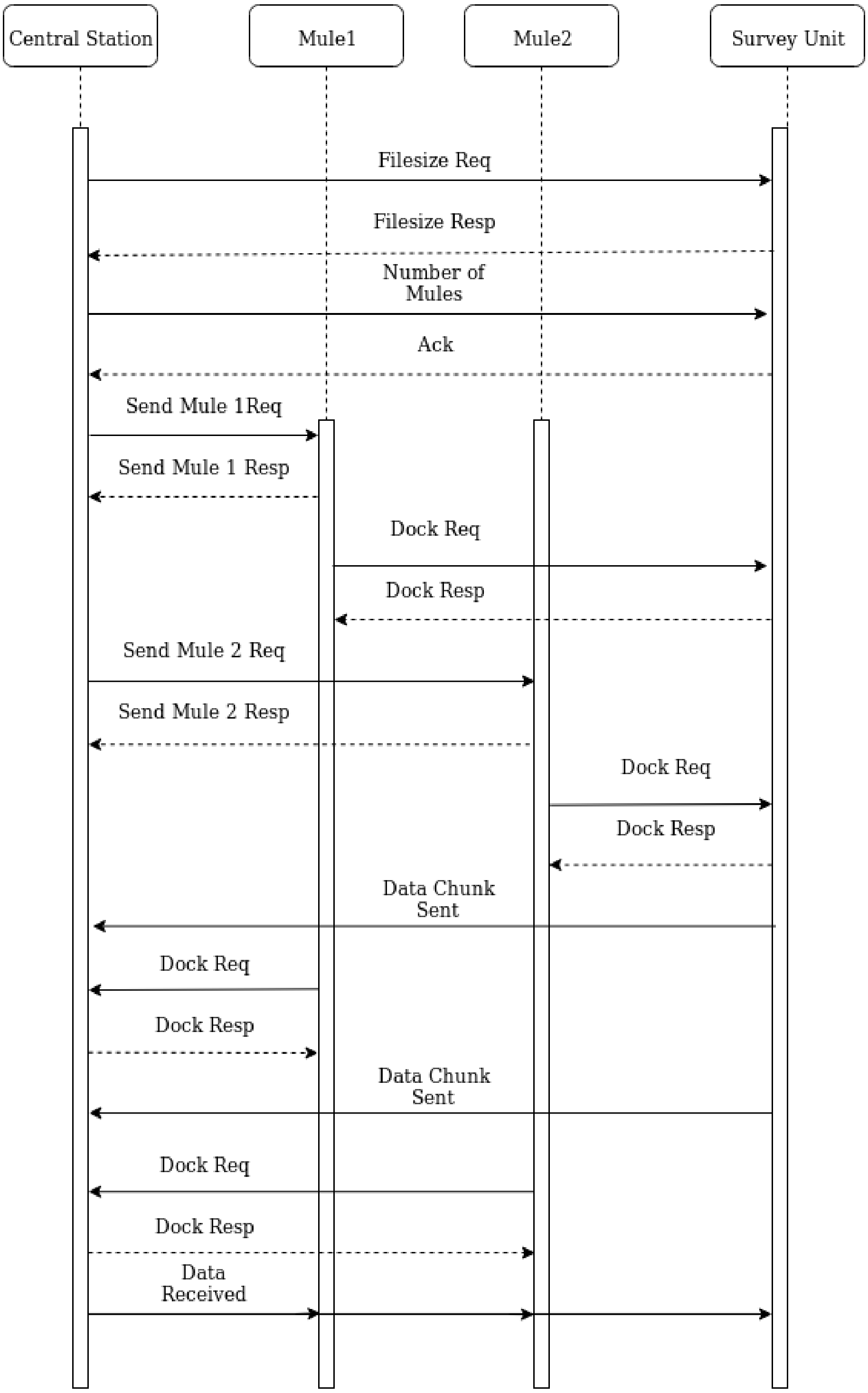

Figure 3.5: Message sequence diagram for 2 Data Mules.

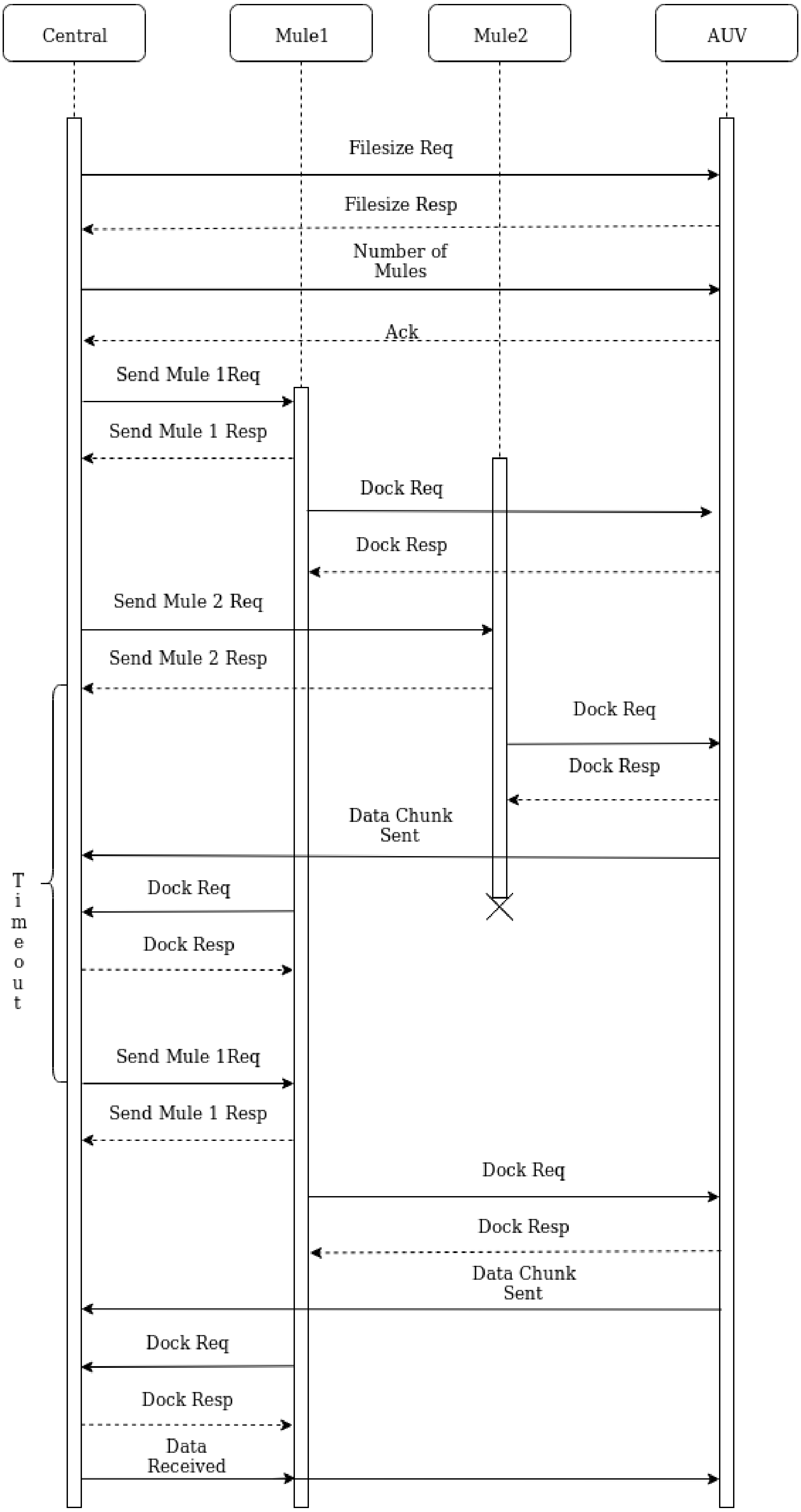

Figure 3.6: Message sequence diagram for 1 Data Mule failure.

3.5 State Machine

The UDMP has three different state machines, one for each role in the DTN. They are presented and explained next in Figures 3.7, 3.8 and 3.9.

In Figure 3.7, the state machine of the Station Unit is shown. It starts by requesting the size of the specified file in the application, using the acoustic link. When the Survey Unit answers, the data size is transmitted to the scheduling algorithm, running on the Station Unit. After the scheduling algorithm calculates the number of Data Mules to dispatch, the Station Unit informs the Survey Unit of how many Data Mule Units to expect, and the selected Data Mule Units are dispatched. If the Data Mule Unit does not answer in the specified timeout, the process of dispatching will start again.

Once the Data Mule Unit is dispatched it travels to the Survey Unit location and requests to dock using the acoustic link. In this dock request the Data Mule informs the Survey Unit of the desired file chunk. After the docking process is done, it starts the file chunk transfer to the Data Mule using the RF link and the IBR-DTN tools as a system call.

When the chunk is received at the Data Mule, the Survey Unit informs the Station Unit of the transfer, and the Data Mule travels back to the Station Unit. Once it arrives at the Station Unit, the same docking process and file chunk transfer are repeated. After all chunks are received at the Station Unit, the Survey Unit and Data Mules are informed using the acoustic link of the successful file delivery and all temporary chunks are deleted.

If a Data Mule Unit is lost during its operation, there is a timeout of two times the calculated expected time in order to deploy the scheduling algorithm again and dispatch any available mule to gather the missing data.

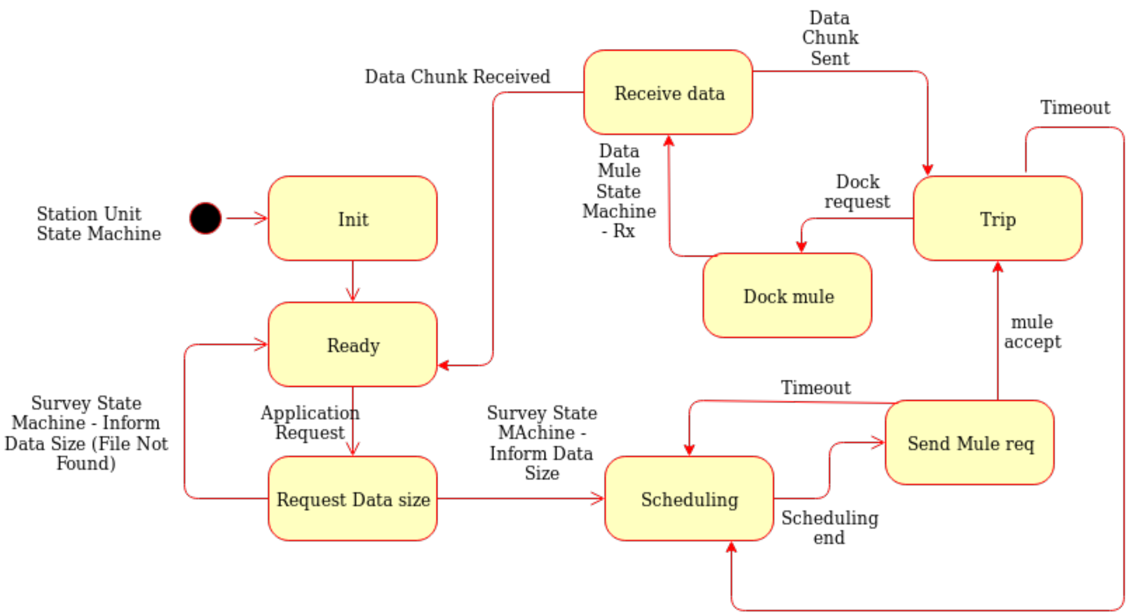

Figure 3.7: Station Unit State Machine.

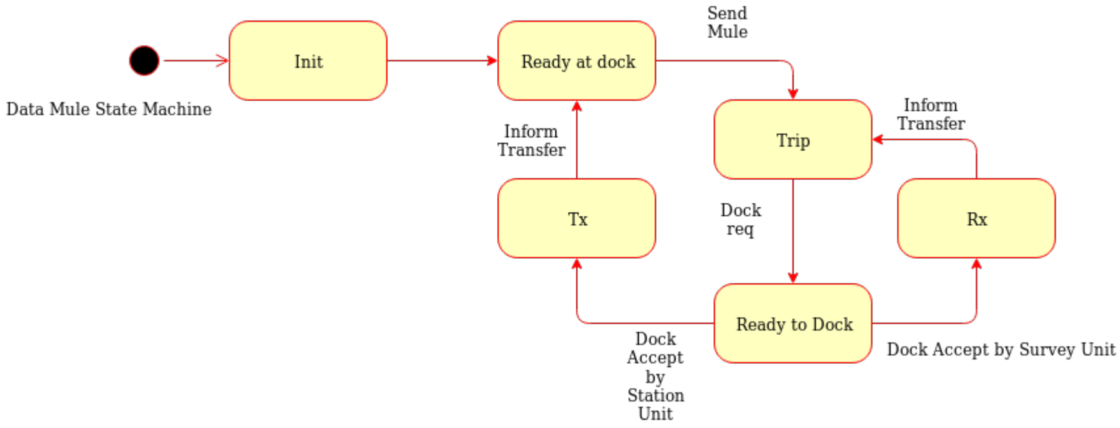

Figure 3.8: Mule Unit State Machine.

In Figure 3.8 the state machine of the Data Mule Unit is shown. The Data Mule Unit starts and stays at the docking station near the Station Unit until a send mule request is received. After that, if the request is accepted, the mule travels to the Survey Unit location and requests to dock. During the docking process, the file chunk id is sent to the Survey Unit. Following docking, the file chunk transfer begins using the RF link. When the transfer ends, the Data Mule travels back to the Station Unit, and a similar uploading process occurs.

In Figure 3.9 the Survey Unit state machine is shown. The Survey Unit's main function is to gather data and to listen to the acoustic link. When a file size is requested, if the file exists, the Survey Unit informs the Station Unit of the size of the requested file. If the requested file does not exist the Station Unit is also informed. After the Data Mule Unit is dispatched from the Station Unit, the Survey Unit waits for the mule to arrive and request to dock. Next, the file chunk id is sent and the file chunk is transferred using the IBR-DTN tools. Finally, the Survey Unit informs the Station Unit of the successful file chunk transfer and continues to gather data.

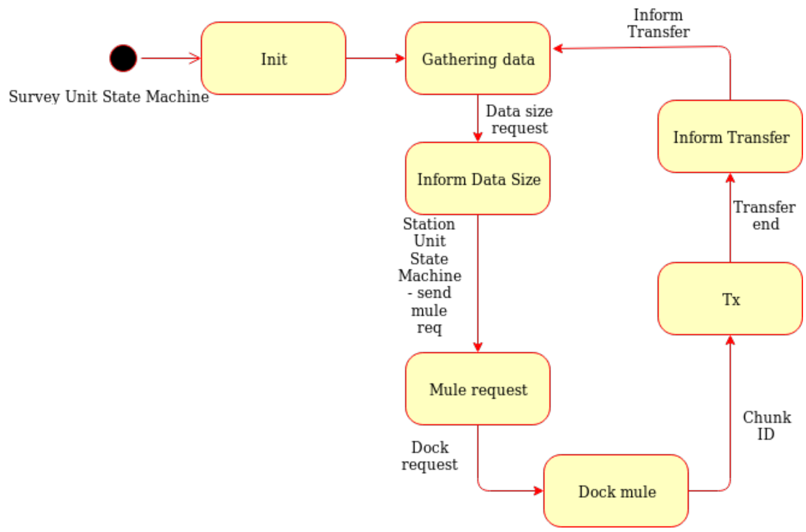

Figure 3.9: Survey Unit State Machine.

Chapter 4

Experimental Planning and Testbed Design

This chapter presents the experimental setup created, in order to test the UDMP protocol. The testbed design and specifications, as well as an analytical evaluation of the evaluation metrics are then detailed.

4.1 Test Scenario

In Figure 4.1 the proposed scenario is represented with four nodes. These nodes were used for transferring data between a Survey Unit and a Station Unit, using two Data Mule Units.

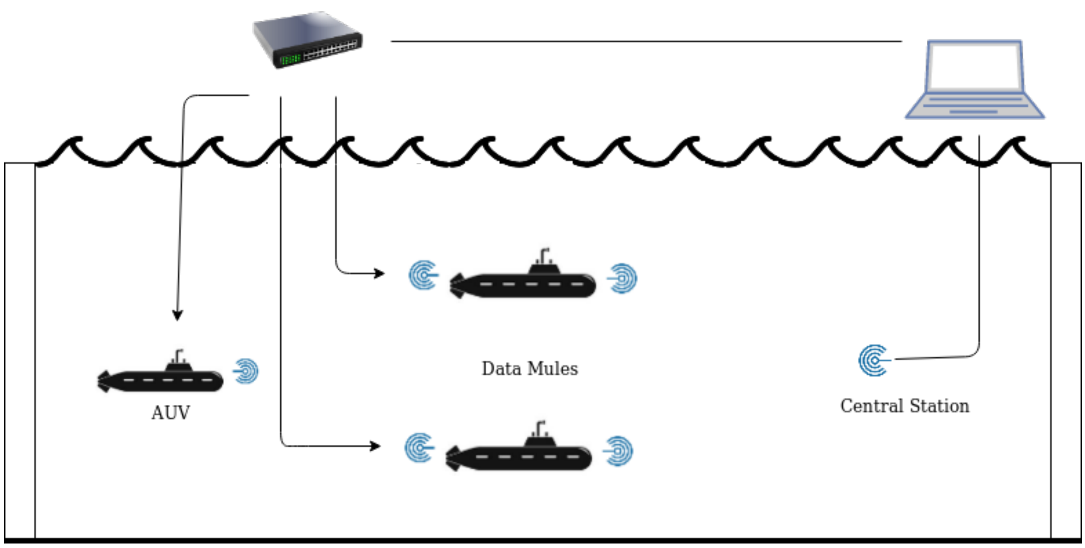

Figure 4.1: Proposed Testbed.

Two communication links were deployed: 1) acoustic control link, emulated through sockets over an Ethernet link between the nodes, used as an out-of-band control link; 2) RF data link using IEEE 802.11n communications at 2.4GHz. In the later link, the Bundle Protocol and its implementation, IBR-DTN, were used. IBR-DTN provides a set of tools that allow files to be transferred between nodes in a DTN. These tools were used alongside with the proposed protocol, to coordinate the Data Mule Units' scheduling. To support the scheduling mechanism, the developed protocol was implemented and tested with an application that allowed the retrieval of files from the Survey Unit.

During the preparation of the testbed, the acoustic link emulation was initially expected to be done using a I^2C connection between all Raspberry Pi nodes. Still, after analysing and trying to overcome the limitations of the currently I^2C available driver implementation [55], it was considered unreasonable to pursue that path. We decided to change to an Ethernet based control link.

4.2 Hardware and Software specifications

To implement the testbed and emulate a Survey Unit and Data Mule Units, three Raspberry Pi 3 B were placed inside airtight PVC cylinders and tested inside a freshwater tank at INESC TEC / FEUP facilities. The Station Unit was emulated using a personal computer and placed near the water tank. The freshwater tank has the following dimensions: length of 460 cm; width of 440 cm; and depth of 170 cm. To perform the RF communication, an external IEEE 802.11n 2.4 GHz Wi-Fi network interface card was used. The acoustic control link was emulated through sockets over an Ethernet link between the nodes. Figures 4.2 and 4.3 show the testbed implementation, where it can be seen the PVC cylinders inside and outside the water tank with the Ethernet connections.

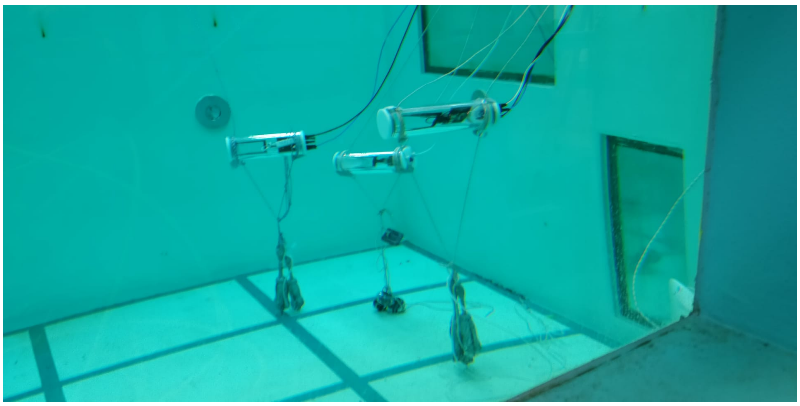

Figure 4.2: Testbed Implementation.

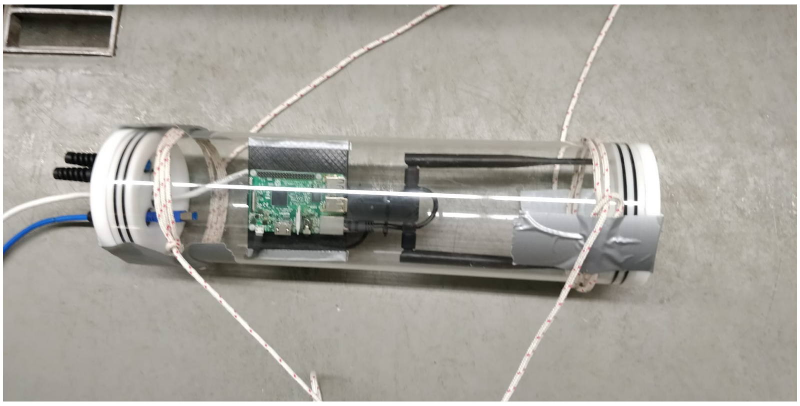

Figure 4.3: Underwater Nodes.

An application was developed to interact with the UDMP API and retrieve data from the Survey Unit. This application takes the desired file name and the desired waiting time as user input. The Survey Unit is then queried about the file size and the scheduling algorithm calculates the expected time based on the number of available Data Mule Units, the file size, the distance to the Survey Unit and the speed of the Data Mules. If the requested time cannot be met, then the application informs the user salong with the expected time. All of the messages are broadcasted to all nodes using the acoustic emulated link.

When multiple Mule Units are assigned, the UDMP splits the file into chunks. The UDMP then reassembles the original file at the central Station Unit. Each chunk is assigned to a Data Mule Unit and is transferred between the nodes using the IBR-DTN tools *dtnsend* and *dtnrecv*.

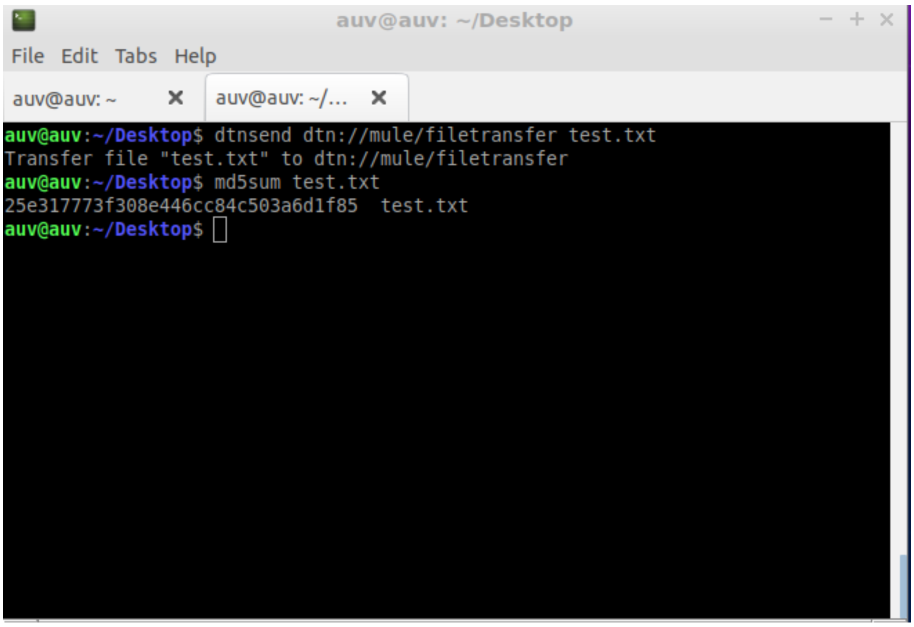

Figure 4.4: *dtnsend* usage example.

In Figures 4.4 and 4.5 it can be seen the usage of *dtnsend* and *dtnrecv* to send a file between two different machines in the same network. In *dtnsend* the user can specify the destination, the file to be sent, as well as request to transfer the bundle custody. In *dtnrecv* the user specifies where to store the received file. After that, the MD5 hash function value of both files was calculated and compared, assuring the capability of IBR-DTN to retrieve data from other nodes.

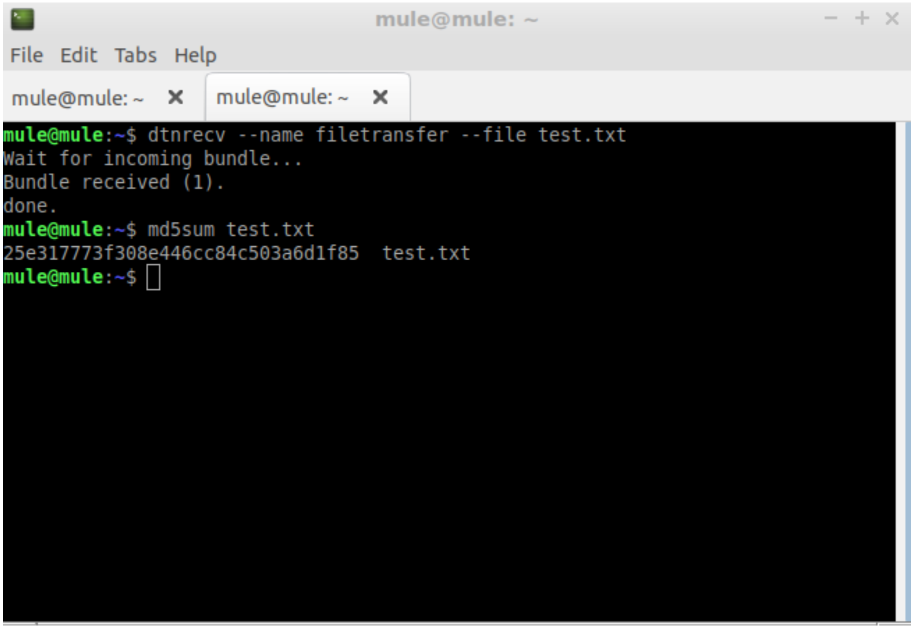

Figure 4.5: *dtnrecv* usage example.

In order to establish connection between the nodes, both in the Ethernet and RF links, two different networks were implemented. Table 4.1 shows the address schemes of the Ethernet and RF networks, as well as the identification of each node in the DTN.

Table 4.1: Implemented Networks Nodes Addresses.

Node	**Ethernet Network**	**RF Network**	**DTN**
Central Station	192.168.1.1	10.0.0.1	dtn://central
Survey Unit	192.168.1.2	10.0.0.2	dtn://auv
Mule #1	192.168.1.3	10.0.0.3	dtn://mule1
Mule #2	192.168.1.4	10.0.0.4	dtn://mule2

In this testbed two nodes were used as RF access points, the Central Station and the Survey Unit. Both networks have static IP addresses but follow a specific addressing scheme. The Ethernet Network follows an addressing scheme of 192.168.1.X with a network mask of 255.255.255.0, the RF Network uses an addressing scheme of 10.0.0.X with a network mask of 255.255.255.0. As for the DTN node identification, it follows the defined using the scheme dtn://"host name" where, "host name" is the name present in each node's Raspbian installation. Lastly, the UDMP implementation was done using Python 3 in order to have better portability.

4.3 Equivalent Throughput Calculation

This section presents the metric to be evaluated along with a sensitivity analysis of the expected results. Two scenarios, one using one Data Mule Unit and another using two Data Mule Units are studied and analysed. The main metric to take into consideration is the equivalent throughput ($R_{b,eq}$), defined by Equation 4.1. The reasoning behind the proposed formula is that the equivalent rate is given by the ratio of the transferred data over the time it took to be delivered.

$$R_{b,eq} = \frac{Datasize}{time} \tag{4.1}$$

The time, given by Equation 4.2, depends on the following variables:

$$time = T_u + T_t + N \times \left(T_d + \frac{T_{RF}}{N} + T_u \right) + T_t + T_d + \frac{T_{SR}}{N} \tag{4.2}$$

- Undocking Time: T_u - represents how long a Data Mule Unit takes to undock from the Central Station Unit;
- Travel Time: $\mathrm{T_t}$ - represents the time spent for the Data Mule Unit to travel the distance between the Central Station Unit and the Survey Unit;
- Number of Data Mule Units: N - the number of mules being used;
- Docking Time: T_d -represents how long a Data Mule Unit takes to dock from the Central Station Unit;
- Transfer Time T_{SR} - represents the time spent transferring data using the RF link;

In Figures 4.6 and 4.7 the time diagram for the system operation with one and two mules is presented. In these figures the time is represented equally spaced in a vertical line. By solving Eq. 4.2 for N = 1, as can be seen in Figure 4.6, then the total time is given by Eq. 4.3.

$$time = Undock + Travel + Dock + Transfer + Undock + Travel + Dock + Transfer \tag{4.3}$$

For the multiple Data Mule Units case, two in the example present in Figure 4.7, the time is given by the Eq. 4.4.

$$\begin{aligned} time = Undock + Travel + Dock + \frac{Transfer}{2} + Undock \\ + Dock + \frac{Transfer}{2} + Travel + Dock + \frac{Transfer}{2} \end{aligned} \tag{4.4}$$

As highlighted by the dashed line in Figure 4.7, the usage of multiple Mule Units can reduce the Time to First Byte, i.e., the time required to receive the first piece of information from the Survey Unit, since each Mule Unit needs to exchange less information.

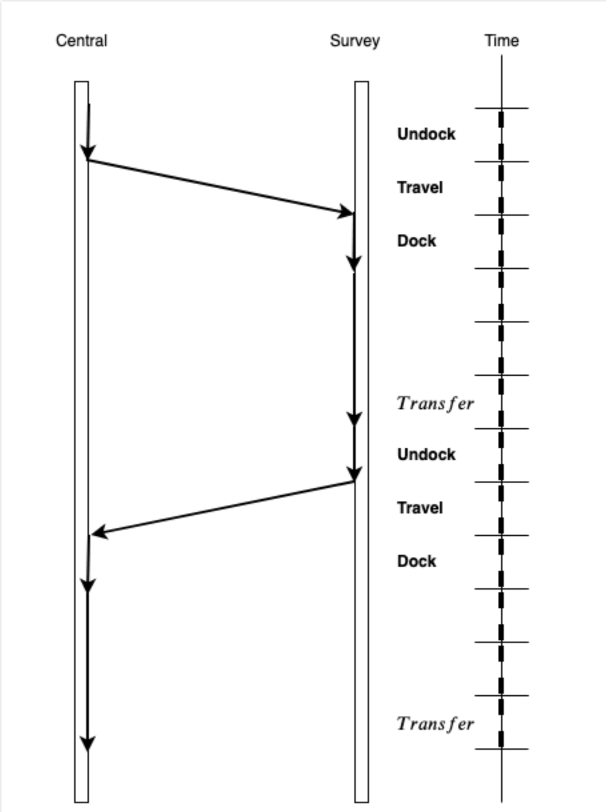

Figure 4.6: Time Diagram: One Data Unit operation.

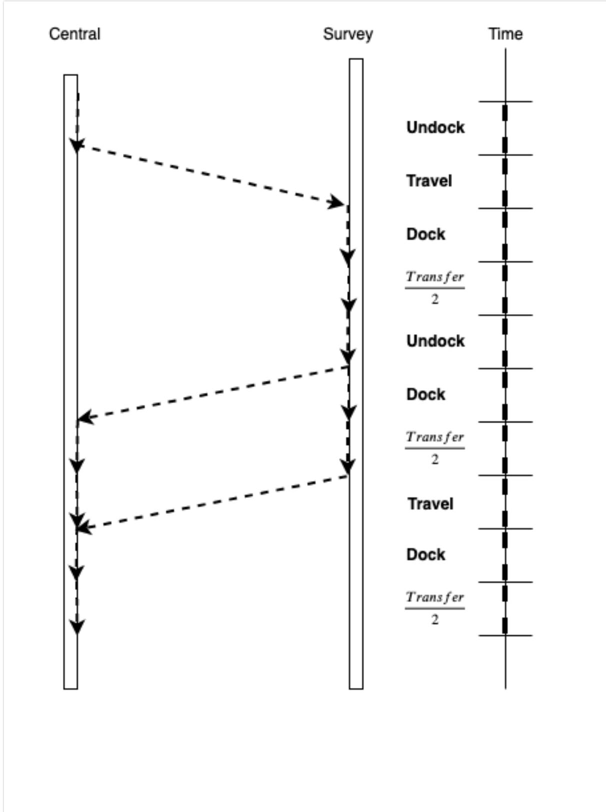

Figure 4.7: Time Diagram: Two Data Units operation.

The *Travel time*, presented in Eq. 4.5, depends on the distance between the Central Station Unit, and the Survey Unit, and the speed of the Data Mule Unit.

$$T_t = \frac{Distance}{TravelSpeed} \tag{4.5}$$

As for the *Transfer time*, presented in the Eq. 4.6, it depends on the amount of data being transferred and the short range RF link speed.

$$T_{SR} = \frac{Datasize}{TransferSpeed} \tag{4.6}$$

By reorganising equation 4.2 with *Travel time* and *Transfer time* it is possible to obtain the full expression of *time*, presented in equation 4.7. With this expression, and readjusting equation 4.1 the full expression of $R_{b,eq}$ is obtained as follows:

$$time = T_u + \frac{Distance}{TravelSpeed} + N \times \left(T_d + \frac{\frac{Datasize}{TransferSpeed}}{N} + T_u \right) + \frac{Distance}{TravelSpeed} + T_d + \frac{\frac{Datasize}{TransferSpeed}}{N} \tag{4.7}$$

$$R_{b,eq} = \frac{Datasize}{T_u + \frac{Distance}{Travelspeed} + N \times \left(T_d + \frac{\frac{Datasize}{TransferSpeed}}{N} + T_u \right) + \frac{Distance}{Travelspeed} + T_d + \frac{\frac{Datasize}{Transferspeed}}{N}} \tag{4.8}$$

During the analysis of the results collected in this testbed it was possible to obtain more information besides the directly collected (Total time and Data size).

As most of the variables required to calculate the Time, T_t, were set as fixed and predefined before the experimental testing, it is possible to extrapolate different distances per test and obtain the effective short range throughput.

First, the total time spent transferring the data using the RF link, *Transfer time* is obtained using Eq. 4.9.

$$TransferTime = TotalTime - 2 \times UndockingTime - 2 \times travelTime - 2 \times DockTime \quad (4.9)$$

With this time it is possible to obtain the Short Range throughput per test, shown in Eq. 4.10.

$$ShortRange = \frac{DataSize}{TransferTime} \quad (4.10)$$

Finally, the new Total Time is calculated in order to obtain measurements for new distances. The new Total Time is obtained by adding the *Trip Time* to the *Transfer Time*.

Chapter 5

Experimental Results

In this chapter we present the experimental results of the UDMP and compare them with the expected values. The reasoning behind the expected results, the experimental tests' explanation, as well as how the obtained results were extrapolated for various distances are also shown.

5.1 Theoretical Equivalent Throughput

During the development of the testbed, a set of parameters such as the *Docking Time*, *Undock Time* and *Travel Speed* were set fixed. These variables are defined for each Data Mule Unit and depend on each Data Mule's characteristics. Others variables, like the *Short Range Link* speed were defined using the *iperf* tool with actual measurements from the testbed. Table 5.1 shows the considered values for these parameters.

Table 5.1: Implemented Testbed Parameters

Parameter	**Value**
Docking Time	10 s
Undocking Time	10 s
Travel Speed	1 m/s
Average Short Range Link Throughput	27,099 Mbit/s

Iperf is a network bandwidth measurement tool, and was used as benchmark for the Short Range Link speed. A set of 40 tests were done, with 10 repetitions for each link, and the obtained results are presented in Table 5.2. The tests were done between the Survey Unit and the two Data Mule Units, as well as between the two Data Mule Units and the Station Unit. The average of these measurements was used to obtain the Short Range Transfer Speed. With this benchmark test and the values presented in Table 5.1, it is possible to estimate the Equivalent Throughput, $R_{b,eq}$.

Table 5.2: RF Short Link Benchmark Results

Test #	Link			
	Survey Unit - Mule 1 (Mbit/s)	**Survey Unit - Mule 2 (Mbit/s)**	**Mule 1 - Station Unit (Mbit/s)**	**Mule 2 - Station Unit (Mbit/s)**
1	25,498	26,144	28,661	28,923
2	24,152	24,886	28,539	28,827
3	24,074	25,944	28,635	28,801
4	24,685	26,747	28,705	28,862
5	26,048	26,992	28,722	28,836
6	26,057	24,637	28,609	28,748
7	25,550	25,533	28,670	28,810
8	25,489	26,712	28,999	28,722
9	25,917	24,139	28,530	28,836
10	25,279	24,652	28,582	28,818
Average	27,099			
σ	1,777			

This benchmark results show, as expected, a slightly better RF short link in the Data Mule Units to Central Station Unit links. These results come from the fact that the propagation medium of Short Range link between the Data Mule Units and the Central Station Unit is the air, which allows a more stable link and a higher SNR. With the short-range RF link characterised, which has significant impact on data transmission time to and from Data Mules, the equivalent throughput over distance, using 1 Data Mule, was estimated in Figure 5.1.

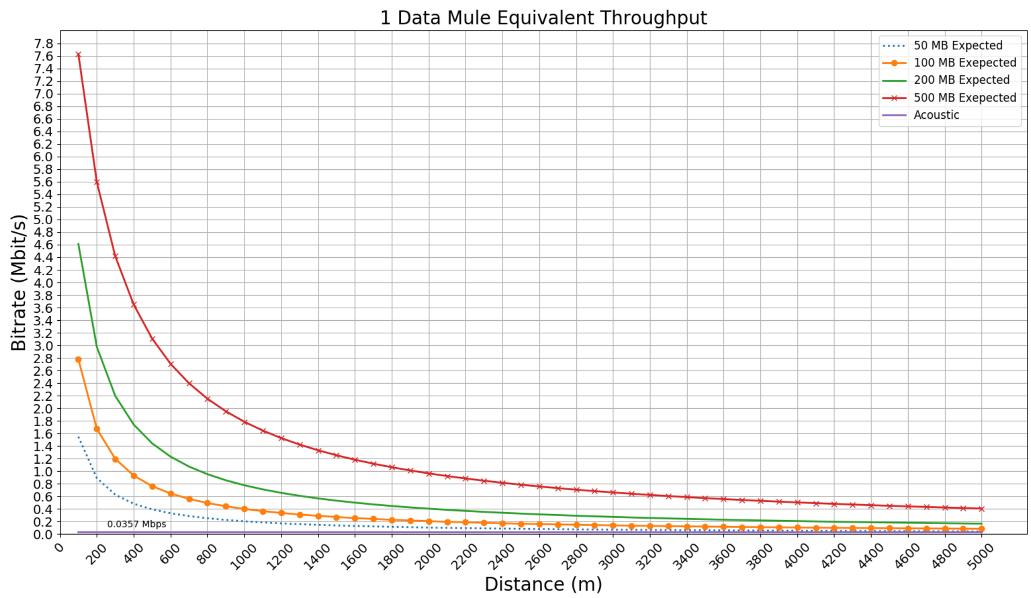

Figure 5.1: One Data Mule Expected Throughput.

This plot, based on the proposed expression for the equivalent throughput, Equation 4.8, considers different amounts of data and compares it with the fastest acoustic modem available. As it can be seen, a clear improvement in the throughput, over the acoustic link, in all the considered data sizes is expected. In a pessimistic approach, it would be preferable to transfer a file of 50 MB using a Data Mule than using the acoustic communications' solution. Another point to take into consideration by analysing the plot is the natural advantage in transferring large amounts of data over smaller amounts. This conclusion comes from the fact that, the largest slice of the operation time is spent travelling between the Central Station Unit and the Survey Unit, and that travel time is constant.

Considering the usage of two Data Mule Units, the same calculations were done and the expected results are presented in Figure 5.2.

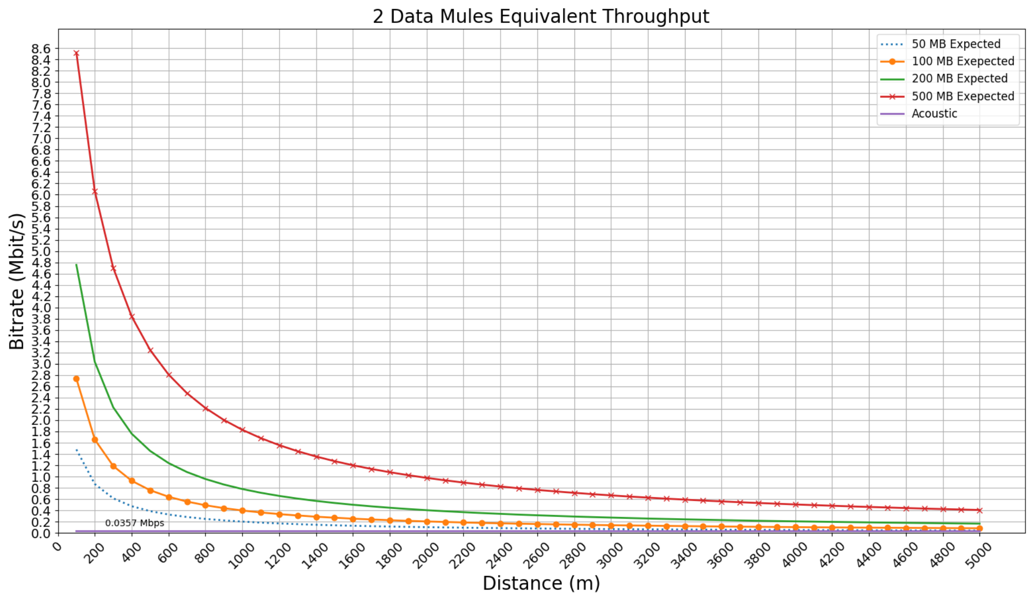

Figure 5.2: Two Data Mule Expected Throughput.

In the situation of two Data Mule Units operation, represented in the plot of Figure 5.2, the expected Equivalent Throughput is significantly higher when compared to Acoustic communications' solutions, and even with the expected results with only one Data Mule Unit.

In Figure 5.4, a detailed comparison of the expected throughput over the data size, both with one and two Data Mule Units, is presented. In this plot the distance of operation was set at 1 km. The Figure also shows that the usage of Data Mules is always preferable to using an acoustic solution. Furthermore, it also portraits the fact that the use of multiple Data Mules can improve the Equivalent Throughput, especially for large data sizes.

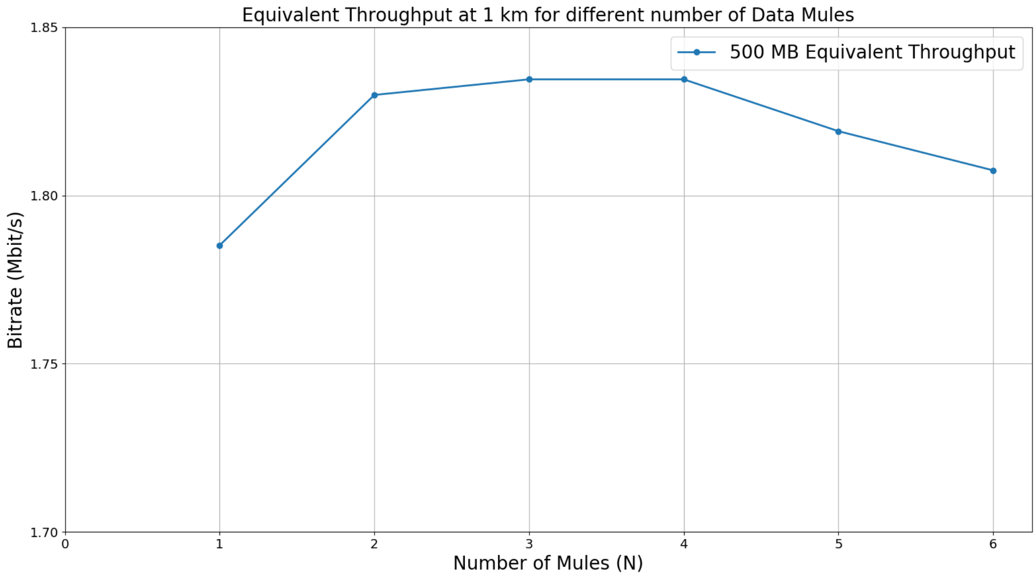

Figure 5.3: Multiple Data Mule Expected throughput at 1 km for 500 MB of data.

The plot of Figure 5.3 reinforces that the use of multiple Data Mules can improve the equivalent throughput. Although, finding the optimal number of mules to be deployed in a given scenario requires the system to have a very fine tuned scheduling algorithm to obtain the optimal Equivalent Throughput and, consequently, to reduce the time to retrieve the data. This subject is, however, out of the scope of this dissertation.

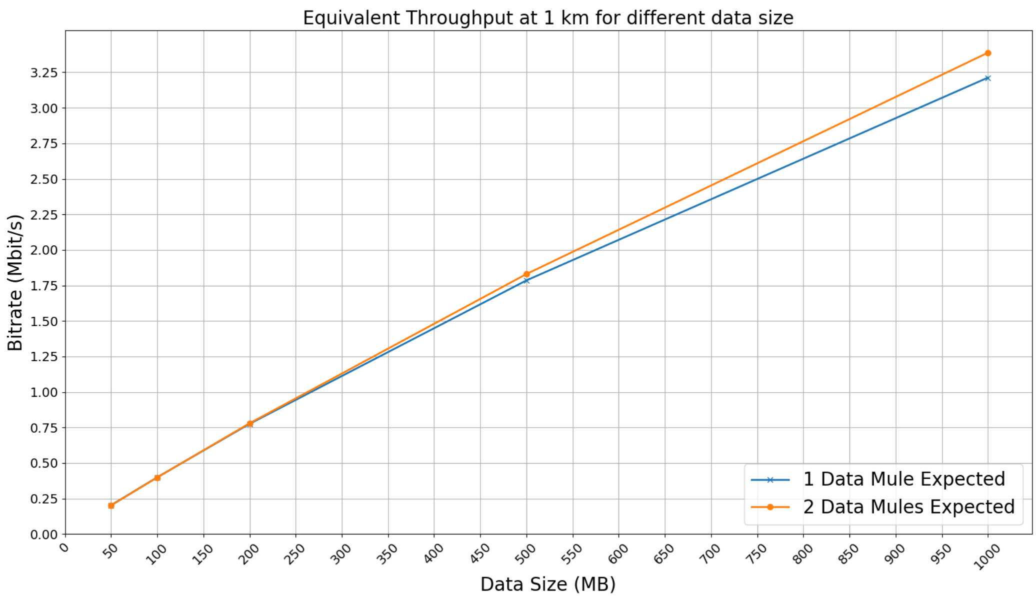

Figure 5.4: Expected Equivalent Throughput at 1 km with the increase of data size, with 1 and 2 Data Mules

5.2 One Data Mule Unit Operation

In this section, a comparison between the expected and obtained results for the operation of the system using one Data Mule is presented. The proposed solution assumes that the use of Data Mule Units can provide a higher equivalent throughput $R_{b,eq}$ than the currently available acoustic solutions.

To analyse the usage of one Data Mule it is important to consider how the Equivalent Throughput varies with the distance between the Central Station Unit and the Survey Unit. In Figure 5.5, the expected Equivalent Throughput variation with the distance is presented.

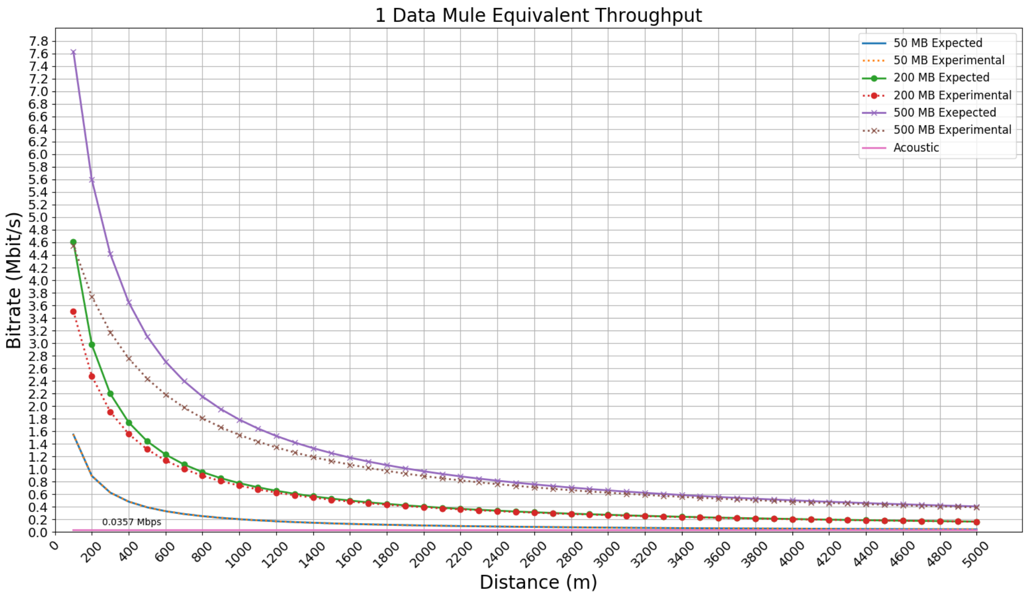

Figure 5.5: 1 Data Mule Obtained Results vs Expected

This plot considers different amounts of data and shows the best acoustic solution. The results displayed in the plot were obtained for a distance of 10 m and extrapolated for higher distances.

As predicted in the expected results, the use of Data Mules Units to retrieve data from a Survey Unit is possible and can provide a higher Equivalent Throughput. This is verified even for small data sizes of 50 MB, when compared to the acoustic communications. The advantage of the use of Data Mules increases with the data size to be downloaded from the Survey Unit.

When comparing the obtained results with the expected results, Figure 5.5 shows a clear difference between both. The main reasons for these results may be the overhead introduced by IBR-DTN, as the data is being transferred in bundles. In the Bundle protocol, defined in RFC 5050 [6], it is proposed the use of data encapsulation in bundles, on its turn IBR-DTN [47] implementation of this protocol allows the user to set the size of these bundles. In these experimental setup, the size of these bundles was kept as default, which means that the entire data is being split into 500 kb bundles. This excessive division caused the effective Short Range goodput to be considerably smaller than the expected. In Table 5.3 the average of the Short Range goodput is shown, these values were obtained as shown in Expressions 4.9 and 4.10.

Table 5.3: Short Range Goodput using IBR-DTN (Mbit/s)

File Size (MB)	1 Data Mule Unit (Mbit/s)	2 Data Mule Units (Mbit/s)
50	16,092	16,252
100	18,677	16,650
200	14,097	17,703
500	12,314	16,406

After verifying the behaviour of the Equivalent Throughput with the Distance, it is necessary to verify the predicted behaviour of the protocol with different amounts of data. In Figure 5.6, the Equivalent Throughput at 1 km is shown.

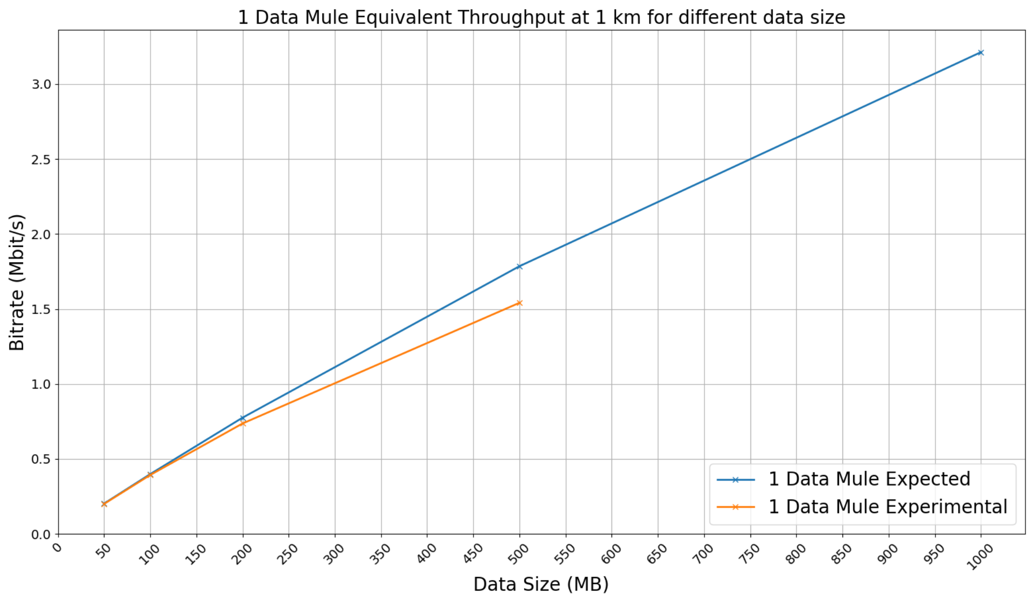

Figure 5.6: Expected and Experimental Equivalent Throughput at 1 km with 1 Data Mule

It is possible to see that for small amounts of data, the predicted results are close to those obtained and for relatively large amounts of data, such as the 500 MB sample file, the predicted results are deviate slightly. In Table 5.4 the error between expected and the obtained Equivalent Throughput is presented. It is visible that, for small amounts of data the error is very small, and it increases with the amount of data.

Table 5.4: Expected and Experimental Equivalent Throughput at 1 km with 1 Data Mule

File Size (MB)	Expected Throughput (Mbit/s)	Obtained Throughput (Mbit/s)	ε	σ
50	0,202	0,200	0,010	4,95 %
100	0,399	0,393	0,015	3,75 %
200	0,775	0,736	0,052	6,71%
500	1,785	1,541	0,158	8,85 %

One possible explanation for this is the influence of the Effective Short Range Throughput in *Transfer Time*, the time spent receiving the data in the RF Link. For a small amount of data, *Transfer Time* will be much smaller than *Travel Time*, so the effect of a lower throughput will not be much reflected in the *Total Time*. However, for large amounts of data, *Transfer Time* has a considerable importance.

The plot in Figure 5.7 shows the evolution of the expected equivalent throughput with the variation of the short range throughput for 500 MB at 1 km. One can conclude that, the slower the short-range link, the longer it is required to transfer the data. The values of the expected and obtained Short Range throughput are also marked in this plot, represented with dotted and dashed lines respectively. The plot shows that, for a Short Range Throughput higher than 100 Mbit/s the overall improvement on the Equivalent Throughput is relatively small. Moreover, the results obtained already represent approximately 70 % of the maximum.

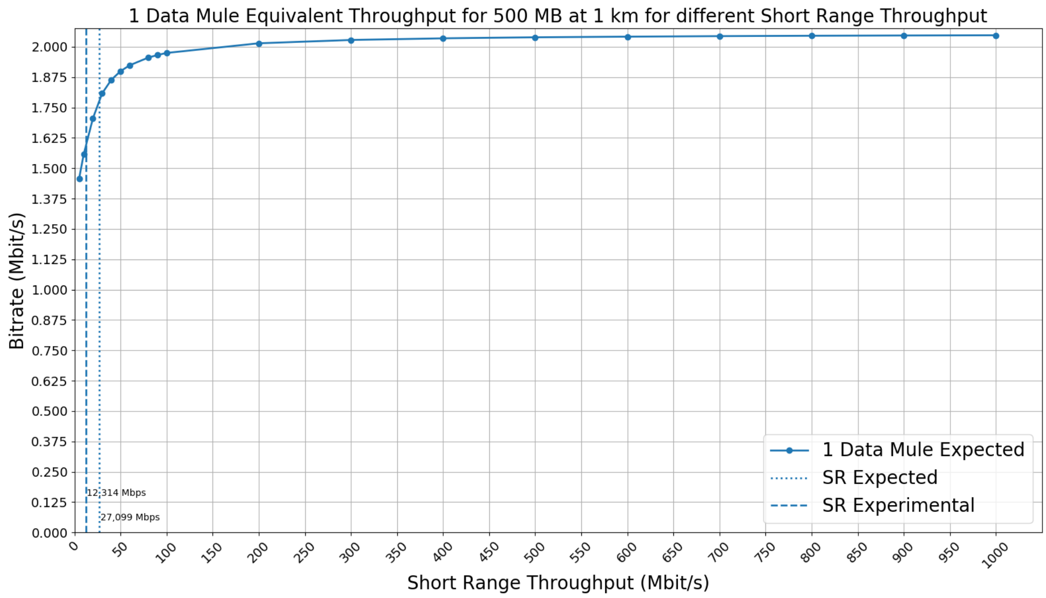

Figure 5.7: Variation of the Equivalent Throughput for 500 MB of data, at 1 km, with the variation of Short Range Throughput

5.3 Two Data Mule Unit Operation

The rationale behind the GROW solution and the UDMP protocol is that the usage of multiple Data Mule Units may improve the performance of the system, namely by reducing the Time to First Byte and increasing the overall Equivalent Throughput. In this section, the experimental results of the proposed protocol in a multiple Data Mule Unit configuration are shown.

The main result to be analysed is the Equivalent Throughput. For that analysis, the collected results were processed in the same way as in the previous section. The plot in Figure 5.8 compares the experimental with the predicted Equivalent Throughput.

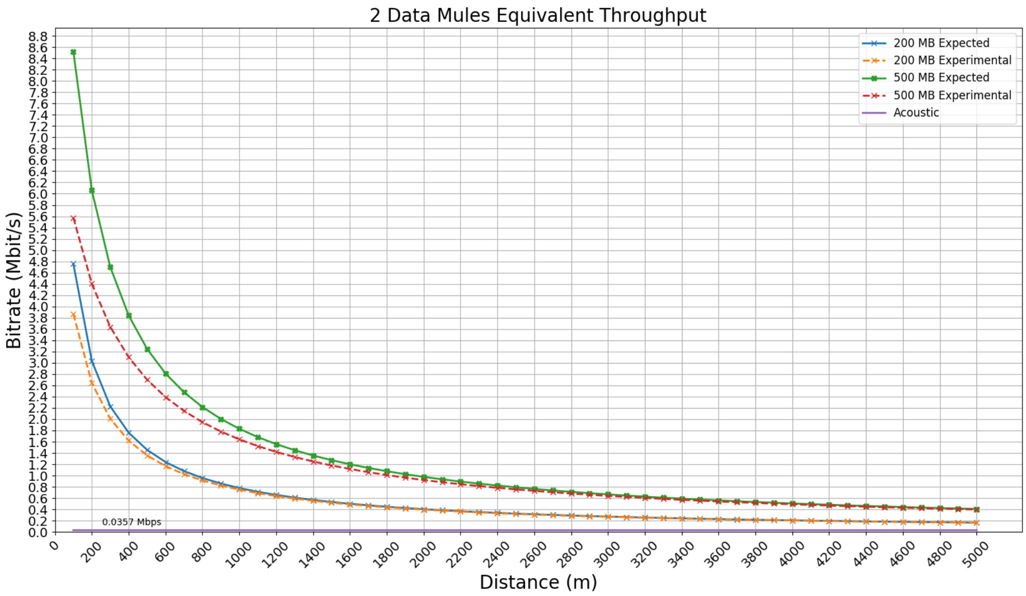

Figure 5.8: Variation of the Equivalent Throughput

The plot in Figure 5.8 shows the performance of the system in the multiple Data Mule Units configuration. To allow this analysis, different data size is considered and compares it with the fastest acoustic modem available. As predicted, the use of Data Mules to retrieve data from a Survey Unit is possible and can provide a higher Equivalent Throughput when compared to the acoustic communications. The presented plot shows the behaviour of the system with data sizes of 200 MB and 500 MB. Comparing the obtained results with the expected result there is a clear difference. As previously shown in Table 5.3, the effective Short Range Throughput is significantly smaller than the expected due to the Bundle protocol overhead. This may be the main reason for this difference, similarly to the one data mule operation mode.

In order to verify the core assumption of the UDMP scheduling algorithm it is necessary to compare the experimental results of the use of one and two data mules, as seen in Figure 5.9.

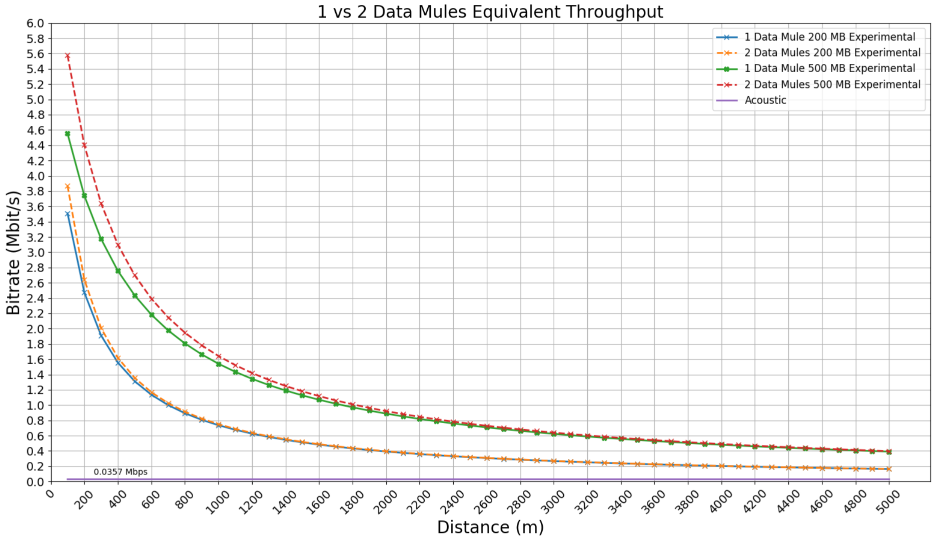

Figure 5.9: One Data Mule Unit vs Two Data Mule Units obtained results

As expected, the use of two Data Mule Units can improve the Equivalent Throughput when compared to the single Data Mule Unit operation mode. The results displayed in the plot are from the collected data and the proposed extrapolation for the equivalent throughput. This plot shows that the usage of multiple Data Mule Units can be particularly interesting in retrieving large amounts of data for long distances: even at 5 km of distance, the proposed solution may provide a better solution than the currently available acoustic communications' solutions. For instance, at 1 km of distance for 500 MB of data, the use of two Data Mule Units provides an equivalent throughput of about 46 times higher than the available on the acoustic solutions.

In Table 5.5, we present the obtained Time to First Byte and the Total Time results for 1 and 2 Mule Units operation. It is visible an overall improvement in the performance of the proposed solution when working in a multiple Data Mule configuration. As expected, the time to retrieve the data has improved with the usage of two Data Mules. The overall latency of the system has improved as well, as the Time to First Byte decreases, and follows the same trend as the equivalent throughput: it is better the larger the amount of data to collect.

Table 5.5: Time to First Byte and Total Time for 1 km

Data Size (MB)	**Time to First Byte 1 Data Mule (mm:ss)**	**Time to First Byte 2 Data Mules (mm:ss)**	**Difference (mm:ss)**	**Total Time 1 Data Mule (mm:ss)**	**Total Time 2 Data Mules (mm:ss)**	**Difference (mm:ss)**
200	35:59	35:38	0:21	37:58	36:47	1:11
500	38:40	38:17	0:23	45:21	41:54	3:27

Finally, it is worth noting that these results validate the GROW solution, as well as the UDMP protocol as a possible solution to provide broadband underwater wireless communications.

Chapter 6

Conclusions and Future Work

In recent years, there has been an increase in both the number and the amount of information collected in ocean exploration and exploitation missions. This growth is not only due to the large endurance of currently available AUVs, but also their sensors, such as high definition video and bathymetry, and has introduced the need for broadband and long range wireless underwater communications.

The solutions that are currently available for underwater communications have known limitations that make them incapable of providing the required bitrante and range. The optical solutions can provide high throughput but require fine beam adjustments and depend on the turbidity of the water. The range of operation is also very restricted. The acoustic solutions have a large range of operation, in the order of a few km, but lack in bandwidth availability. The RF underwater communications solutions are very limited in the range of operation, of a few cm, but can provide a large throughput. In order to overcome these limitations, the FCT GROW project has proposed to use a data mule based Delay Tolerant Network (DTN) for a long-range broadband underwater wireless communications. A data mule is a small and agile AUV that is equipped with short range high-speed and long-range low speed wireless communication hardware. The mule will travel back and forth between a Survey Unit (e.g., an AUV) and a Central Station at surface level, creating a virtual link between these two nodes.

The objective of this work was to design, implement, and test a communications protocol - Underwater Data Muling Protocol (UDMP) - to enable the control and scheduling of underwater Data Mule Units considered within the framework of the GROW solution. In this solution, two communication links are used: one fast short range link (RF or Optical), where IBR-DTN is deployed; and one low bitrate, long range acoustic link to allow the scheduling of the Data Mule Units. The UDMP allows the retrieval of data from a Survey Unit using a scheduling algorithm for Data Mule Units. The proposed API allows the user to interact with the protocol and create applications that take advantage of the UDMP. The protocol message structure, sequence and the state machines proposed, proved that UDMP is capable of controlling the data mule dispatchment during the execution of the experimental testing.

In order to evaluate the proposed UDMP, the protocol was implemented and tested in a underwater laboratorial environment, using airtight cylinders as real devices: one Survey Unit, two Data Mules and one Station Unit. The results obtained in this testbed proved the feasibility of the proposed concept and protocol. When comparing the results with the current available underwater wireless communications solutions, an improvement in the obtained equivalent throughput was clearly observed. This is valid when comparing the system operation in one and multiple data mule configuration. As an example, for 1 km of distance, and 500 Megabytes of data the use of two Data Mule Units reduced the data latency when compared with the use of one Data Mule, and showed a equivalent throughput of about 46 times higher than the available on the fastest acoustic solution. The results obtained for the system performance with the usage of multiple Data Mule Units are very promising and show the potential gains of using multiple data mules, with an equivalent throughput in the order of 1 Mbit/s and an operation range of about 5 km.

Several options can be explored in the future to further progress the research in underwater wireless communications and build upon the work presented here:

- **IBR-DTN optimisation** – IBR-DTN implementation is still work in progress and the behaviour of IBR-DTN daemon is still very unreliable. During the execution of the experimental work the IBR-DTN implementation proved to have an erratic behaviour.

- **Create a testbed with an actual underwater acoustic solution** – The use of a real acoustic connection instead of emulating it using Ethernet can provide a more accurate representation of the targeted scenario.

- **Explore and experiment UDMP with an optimised version of the Data Mule Unit scheduler algorithm** – At the time of writing, the GROW project is still in its initial stages. The scheduling algorithm has good optimisation potential. The performance comparison of the different algorithm versions can provide interesting results.

- **Improve the efficiency of data upload from Data Mule Units using simultaneous file chunks transmissions** – As the transmission of data from the Data Mule Unit to the Station Unit is done at the surface, it is possible to explore the RF link to run simultaneous file chunk transmissions from different Mule Units. The same principle can be used to transfer data simultaneously from the Survey AUV to multiple Mule Units, which can led to less transmission time and high equivalent throughput.

References

[1] R. Venkatesan, A. Tandon, E. D'Asaro, and M. A. Atmanand. *Observing the Oceans in Real Time*. Springer International Publishing, 2018.

[2] X. Che, I. Wells, G. Dickers, P. Kear, and X. Gong. Re-evaluation of rf electromagnetic communication in underwater sensor networks. *IEEE Communications Magazine*, 48(12):143–151, December 2010. doi:10.1109/MCOM.2010.5673085.

[3] X. Lurton. *An introduction to underwater acoustics*. Springer, 2010.

[4] F. Teixeira, P. Freitas, L. Pessoa, R. Campos, and M. Ricardo. Evaluation of ieee 802.11 underwater networks operating at 700 mhz, 2.4 ghz and 5 ghz. In *Proceedings of the International Conference on Underwater Networks & Systems*, WUWNET '14, pages 11:1–11:5, New York, NY, USA, 2014. ACM. doi:10.1145/2671490.2674571.

[5] GROW project website. https://grow.inesctec.pt/, [Accessed: 24th June 2019].

[6] K. Scott and S. Burleigh. Bundle protocol specification. RFC 5050, November 2007. URL: https://www.rfc-editor.org/info/rfc5050, doi:10.17487/RFC5050.

[7] L. Soares. *Wireless Underwater Broadband and Long Range Communications using Underwater Drones as Data Mules*. MSc Thesis. Faculdade de Engenhaira da Universidade do Porto, 2017.

[8] X. Che, I. Wells, G. Dickers, P. Kear, and X. Gong. Re-evaluation of rf electromagnetic communication in underwater sensor networks. *IEEE Communications Magazine*, 48(12):143–151, December 2010. doi:10.1109/MCOM.2010.5673085.

[9] Y. Kularia, S. Kohli, and P. P. Bhattacharya. Analyzing propagation delay, transmission loss and signal to noise ratio in acoustic channel for underwater wireless sensor networks. *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, 2016. doi:10.1109/icpeices.2016.7853300.

[10] H. Medwin. Speed of sound in water: A simple equation for realistic parameters. *The Journal of the Acoustical Society of America*, (6):1318–1319, 1975. doi:10.1121/1.380790.

[11] S. Kohli and P. P. Bhattacharya. Characterization of acoustic channel for underwater wireless sensor networks. *2015 Annual IEEE India Conference (INDICON)*, 2015. doi:10.1109/indicon.2015.7443243.

[12] R. J. Urick. *Principles of underwater sound*. McGraw-Hill, 1983.

[13] P. Freitas. Evaluation of wi-fi underwater networks in freshwater. 2014.

[14] Linkquest inc. http://link-quest.com/html/models1.htm, [Accessed: 24th June 2019].

[15] Evologics bionik lab. https://www.evologics.de/en/products/acoustics/index.html, [Accessed: 24th June 2019].

[16] S. Sendra, J. Lloret, J. M. Jimenez, and L. Parra. Underwater acoustic modems. *IEEE Sensors Journal*, 16(11):4063–4071, 2016. doi:10.1109/jsen.2015.2434890.

[17] A. Sanchez, S. Blanc, P. Yuste, and J. J. Serrano. A low cost and high efficient acoustic modem for underwater sensor networks. In *OCEANS 2011 IEEE - Spain*, pages 1–10, June 2011. doi:10.1109/Oceans-Spain.2011.6003428.

[18] N. Farr, A. Bowen, J. Ware, C. Pontbriand, and M. Tivey. An integrated, underwater optical /acoustic communications system. In *OCEANS'10 IEEE SYDNEY*, pages 1–6, May 2010. doi:10.1109/OCEANSSYD.2010.5603510.

[19] B. Benson, Y. Li, B. Faunce, K. Domond, D. Kimball, C. Schurgers, and R. Kastner. Design of a low-cost underwater acoustic modem. *IEEE Embedded Systems Letters*, 2(3):58–61, Sep. 2010. doi:10.1109/LES.2010.2050191.

[20] A. Sánchez, S. Blanc, P. Yuste, A. Perles, and J. J. Serrano. An ultra-low power and flexible acoustic modem design to develop energy-efficient underwater sensor networks. *Sensors*, 12(6):6837–6856, 2012. doi:10.3390/s120606837.

[21] E. M. Sözer and M. Stojanovic. Reconfigurable acoustic modem for underwater sensor networks. *Proceedings of the 1st ACM international workshop on Underwater networks - WUWNet 06*, 2006. doi:10.1145/1161039.1161060.

[22] M. Stojanovic. Underwater acoustic communications: Design considerations on the physical layer. In *2008 Fifth Annual Conference on Wireless on Demand Network Systems and Services*, pages 1–10, Jan 2008. doi:10.1109/WONS.2008.4459349.

[23] I. Vasilescu, C. Detweiler, and D. Rus. Aquanodes: an underwater sensor network. pages 85–88, 01 2007. doi:10.1145/1287812.1287830.

[24] L. Wu, J. Trezzo, D. Mirza, P. Roberts, J. Jaffe, Y. Wang, and R. Kastner. Designing an adaptive acoustic modem for underwater sensor networks. *IEEE Embedded Systems Letters*, 4(1):1–4, March 2012. doi:10.1109/LES.2011.2180013.

[25] M. S. Martins, N. Pinto, G. Rocha, J. Cabral, and S. L. Mendez. Development of a 1 mbps low power acoustic modem for underwater communications. In *2014 IEEE International Ultrasonics Symposium*, pages 2482–2485, Sep. 2014. doi:10.1109/ULTSYM.2014.0619.

[26] G. Cossu, R. Corsini, A. M. Khalid, S. Balestrino, A. Coppelli, A. Caiti, and E. Ciaramella. Experimental demonstration of high speed underwater visible light communications. *2013 2nd International Workshop on Optical Wireless Communications (IWOW)*, 2013. doi:10.1109/iwow.2013.6777767.

[27] H. Brundage. Designing a wireless underwater optical communication system. Master's thesis, 2010.

[28] S. Tang, Y. Dong, and X. Zhang. On link misalignment for underwater wireless optical communications. *IEEE Communications Letters*, 16(10):1688–1690, October 2012. doi:10.1109/LCOMM.2012.081612.121225.

[29] Aquamodem 500 homepage. http://www.oceanografialitoral.com/sondas/sondas-multiparam-tricas/aquamodem, [Accessed: 24th June 2019].

[30] Aquatec op2 solutions. http://www.aquatecgroup.com/aquamodem/aquamodem-op1, [Accessed: 24th June 2019].

[31] SA Photonics Homepage. http://www.saphotonics.com/high-bandwidth-optical-communications/underwater/, [Accessed: 24th June 2019].

[32] B. Benson. Design of a low-cost underwater acoustic modem for short-range sensor networks. 2010.

[33] S. I. Inacio, M. R. Pereira, H. M. Santos, L. M. Pessoa, F. B. Teixeira, M. J. Lopes, O. Aboderin, and H. M. Salgado. Dipole antenna for underwater radio communications. *2016 IEEE Third Underwater Communications and Networking Conference (UComms)*, 2016. doi:10.1109/ucomms.2016.7583457.

[34] S. I. Inacio, M. R. Pereira, H. M. Santos, L. M. Pessoa, F. B. Teixeira, M. J. Lopes, O. Aboderin, and H. M. Salgado. Antenna design for underwater radio communications. *OCEANS 2016 - Shanghai*, 2016. doi:10.1109/oceansap.2016.7485705.

[35] F. Teixeira, J. Santos, L. Pessoa, M. Pereira, R. Campos, and M. Ricardo. Evaluation of underwater ieee 802.11 networks at vhf and uhf frequency bands using software defined radios. *Proceedings of the 10th International Conference on Underwater Networks & Systems - WUWNET 15*, 2015. doi:10.1145/2831296.2831313.

[36] S. Lloret, J.and Sendra, M. Ardid, and J. Rodrigues. Underwater wireless sensor communications in the 2.4 ghz ism frequency band. *Sensors (Basel, Switzerland)*, 12:4237–64, 12 2012. doi:10.3390/s120404237.

[37] S. Sendra, J. V. Lamparero, J. Lloret, and M. Ardid. Underwater communications in wireless sensor networks using wlan at 2.4 ghz. In *2011 IEEE Eighth International Conference on Mobile Ad-Hoc and Sensor Systems*, pages 892–897, Oct 2011. doi:10.1109/MASS.2011.106.

[38] I. Wells, A. Davies, X. Che, P. Kear, G. Dickers, X. Gong, and M. Rhodes. Node pattern simulation of an undersea sensor network using rf electromagnetic communications. In *2009 International Conference on Ultra Modern Telecommunications Workshops*, pages 1–4, Oct 2009. doi:10.1109/ICUMT.2009.5345555.

[39] M. R. Frater, M. J. Ryan, and R. M. Dunbar. Electromagnetic communications within swarms of autonomous underwater vehicles. In *Proceedings of the 1st ACM International Workshop on Underwater Networks*, WUWNet '06, pages 64–70, New York, NY, USA, 2006. ACM. URL: http://doi.acm.org/10.1145/1161039.1161053, doi:10.1145/1161039.1161053.

[40] M. J. Khabbaz, C. M. Assi, and W. F. Fawaz. Disruption-tolerant networking: A comprehensive survey on recent developments and persisting challenges. *IEEE Communications Surveys Tutorials*, 14(2):607–640, Second 2012. doi:10.1109/SURV.2011.041911.00093.

[41] F. Warthman. *Delay and Disruption Tolerant Networks - Tutorial*. Sep 2015.

[42] A. S. Tanenbaum and D. J. Wetherall. *Computer Networks - 5th Ed.: International Edition*. Pearson, 2011.

[43] Dtn2 homepage. http://dtn.sourceforge.net/DTN2/doc/manual/intro.html, [Accessed: 24th June 2019].

[44] Ion-dtn homepage. https://sourceforge.net/projects/ion-dtn/, [Accessed: 24th June 2019].

[45] E. Unnikrishnan, V. Ravichandran, S. Sudhakar, and U. Subramanya. Delay tolerant network for space. *2016 3rd International Conference on Signal Processing and Integrated Networks (SPIN)*, 2016. doi:10.1109/spin.2016.7566765.

[46] Postellation project. http://postellation.viagenie.ca/, , [Accessed: 24th June 2019].

[47] ibrdtn. https://github.com/ibrdtn/ibrdtn, [Accessed: 24th June 2019].

[48] Openwrt project. https://openwrt.org/, [Accessed: 24th June 2019].

[49] Jdtn homepage. https://sourceforge.net/projects/jdtn/, [Accessed: 24th June 2019].

[50] Ltplib documentation. https://down.dsg.cs.tcd.ie/ltplib/, [Accessed: 24th June 2019].

[51] I. Katz. A delay-tolerant networking framework for mobile underwater acoustic networks. In *Fifteenth International Symposium on Unmanned Untethered Submersible Technology (UUST'07)*, 2007.

[52] R.H. Rahman and M.R. Frater. 5 - delay-tolerant networks (dtns) for underwater communications. In J.J.P.C. Rodrigues, editor, *Advances in Delay-Tolerant Networks (DTNs)*, pages 81 – 103. Woodhead Publishing, Oxford, 2015. URL: http://www.sciencedirect.com/science/article/pii/B9780857098405500058, doi:https://doi.org/10.1533/9780857098467.1.81.

[53] E. Magistretti, J. Kong, U. Lee, M. Gerla, P. Bellavista, and A. Corradi. A mobile delay-tolerant approach to long-term energy-efficient underwater sensor networking. In *2007 IEEE Wireless Communications and Networking Conference*, pages 2866–2871, March 2007. doi:10.1109/WCNC.2007.531.

[54] C. Y. M. Chan and M. Motani. An integrated energy efficient data retrieval protocol for underwater delay tolerant networks. In *OCEANS 2007 - Europe*, pages 1–6, June 2007. doi:10.1109/OCEANSE.2007.4302341.

[55] Raspberry Pi Forums. https://www.raspberrypi.org/forums/viewtopic.php?t=235740, [Accessed: 24th June 2019].