UNIVERSITY OF PADOVA

Department of Information Engineering

Master Thesis in Telecommunication Engineering

Design of a wireless remote control for underwater equipment

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Dedication

This is for:

My father Bruno Campagnaro,

my mother Sonia Salviato,

who always supported my decisions.

Abstract

Nowadays, Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) are heavily used in order to monitor the underwater environment and execute many different operations. In particular, ROVs are used in many complex and even dangerous situations, thanks to the possibility to control them remotely in real time via wired telemetry systems. For instance, they are used due to defuse bombs, or to inspect pipelines, both in normal situations and in presence of severe damage. While the presence of a wired control system is very important in order to guide a ROV, the same system often represents the main limitation in terms of mobility. In fact, the mobility of the ROV is constrained by the cable length and, as the ROV moves, there is a chance that its control cable gets entangled in rocks or man-made equipment, such as pipes. This thesis proposes a solution for this problem: a multi-technology and multi-hop wireless ROV control system. In particular, three different technologies are compared and analyzed: underwater acoustic, optical and electromagnetic (radio-frequency (RF)) communications. The purpose of this first analysis is to find the best transmission technique in terms of expected bitrate versus distance, from the ROV to the remote controller, for typical operational distances of a few meters up to about 100 meters.

List of Acronyms

AUV Autonomous Underwater Vehicle

ARQ Automatic Repeat Request

BER Bit Error Rate

bps Bit Per Second

CI Confidence Interval

CSMA Carrier Sense Multiple Access

CRC Cyclic Redundancy Check

CBR Constant Bit Rate

DESERT DEsign, Simulate, Emulate and Realize Test-beds for Underwater network protocols

DEI Department of Information Engineering

E2E End-to-End

EM Electromagnetic

EMI Electromagnetic Interference

GQR Gauss Quadrature Rule

ID Identifier

IEEE Institute of Electrical and Electronics Engineers

iid	Independent and Identically Distributed
IP	Internet Protocol
LOS	Line Of Sight
LED	Light Emitting Diode
MAC	Media Access Control
MSE	Mean Square Error
MIT	Massachusetts Institute of Technology
NS	Network Simulator
NS-MIRACLE	Multi-InteRfAce Cross-Layer Extension library for the Network Simulator
PHY	Physical layer
PN	Pseudo Noise
ppm	parts per million, turbidity metric
PER	Packet Error Rate
QoS	Quality Of Service
ROV	Remotely Operated Vehicle
ROVs	Remotely Operated Vehicles
RTO	Retransmission Timeout
RTT	Round Trip Time
RF	radio-frequency
SNR	Signal to Noise Ratio
SINR	Signal to Interference plus Noise Ratio
SIGNET	Special Interest Group on NETworking

SN Sequence Number

TDMA Time-Division Multiple Access

Tcl Tool Command Language

UDP User Datagram Protocol

WFS Wireless For Subsea

Contents

Chapter 1

Introduction

The purpose of this thesis, is make some first steps towards the development of a wireless remote control for underwater devices, such as Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). Indeed, nowadays ROVs are usually controlled by an umbilical, a wired system providing power supply and real time control. Substituting the cable with a wireless telemetry would help avoid some mobility issues, such as movement limitations due to the cable length, and the risk of cable entanglement in rocks or man-made equipment. ROVs general cost is very expensive in terms of price and power consumption for navigation, in particular compared to the power required by most of the existing modems to communicate under water. Therefore, for what concerns the transmission devices, neither budget nor power limitations are imposed during the controller design. Instead, the main constrain is to guarantee reliability and robustness: in particular, the wireless remote control has to work dependably regardless of the environmental conditions. Therefore, in a typical scenario, challenging communication conditions are considered, such as transmission through the turbid and shallow seawater of a naval harbor.

The thesis is organized in the following way: firstly, the requirements for remote ROV control are studied in chapter 2, analyzing the bitrate required to satisfy either mandatory or optional services. In particular, the essential features are position plus status control and monitoring, whereas optional services regard real-time video monitoring.
In chapter 3, as result of a bibliographic research, several existing underwater wireless communication technologies are compared, in order to determine the best way to transmit information between the remote controller and the ROV. In particular, both commercial and

prototype research modems are included in the analysis, preferring the most available and reliable modems among models with equivalent performance.
In chapter 4, in order to understand whether it is possible to extend the transmission range of the remote control system, a multi-hop wireless network is presented and analyzed. In particular, to to retrieve the network performance, some simulations of a pipelining network are performed for four different configurations, and the results are shown and compared.
In order to quantify the quality of the system designed in this thesis, the ROV behavior is observed and many results are collected in chapter 5. In particular, a system composed of ROV and controller is implemented in a network simulator, in order to observe whether the ROV correctly responds to the movement commands sent by the controller.
Finally, conclusions and future works are analyzed in chapter 6, where the results are summarized to pave the way for further system improvements.

Chapter 2

ROV remote control requirements

2.1 Introduction

In this chapter, a requirement analysis for the ROV remote control system is carried out, in order to estimate the minimum bitrate needed to guarantee the complete and reliable control of such a complex system. After this preliminary analysis, it will be possible to understand whether the current technology makes it possible to develop an underwater wireless control system or not. In particular, two subsets of control features are considered: in section 2.2, the mandatory requirements are studied, whereas in section 2.3 the optional features are analyzed. This subdivision is done in order to distinguish which requirements must be fulfilled in every condition, and which ones need to be satisfied only when the environmental conditions so allow. Furthermore, an estimation of the required bitrate per feature is done, in order to provide an approximate value for the necessary communication rate.

2.2 Mandatory features

In an ROV remote control system, some important features have to be always available, independently of the environmental conditions, in order to control and monitor the ROV movements, positions and status. In this section, the analysis of these features is done, in order to quantify (in bits) the amount of information needed to manage them. In particular, the analysis is subdivided into two sections: the transmission of the commands from the controller to the ROV, and the feedback transmission from the ROV to the controller. Thus, the modem used for the remote control system should assure, at least, the correct transmission of this information between the control station and the ROV.

2.2.1 Control Station to ROV: Control of Movements and Data Retrieval

The transmission from the base station to the ROV is needed in order to control the ROV movements and to enable and query its acquisition devices. In this thesis, it is assumed that the ROV movements are controlled by the following engines:

- at least 4 propulsion engines [1] (either hydraulic pump, electrical propellers or ducted jets), in order to drive correctly the ROV underwater;
- 4 electrical engines or hydraulic motors to control each mechanical arm movements.[2] In this thesis, we assume that the ROV is equipped with one mechanical arm.

However, it is not convenient to control each movement directly, engine per engine, because this would require a very high communication bitrate [5]. For this reason, we make the design decision to send two different types of cumulative control commands. The first type is related to the current position and includes commands such as “turn right”, “continue straight ahead for 10 meters”and so on. The second type is used to control the ROV referring to it absolute position, e.g., by sending the coordinates of a new way-point. When these commands are received, they will be converted in complex, well-defined routines by the internal ROV intelligence. This method is more efficient in terms of amount of transmitted information. In addition, from the control station, it should be possible to enable lighting, sonar and, e.g., thermometers or pressure sensors, for monitoring the system. Furthermore, there should be the possibility to enable and disable real-time video streaming and similar optional features, and to signal the decision to change transmission technology.

Thus, commands are subdivided into four classes:

0. ROV movements, relative position mode;
1. ROV movements, new way-point mode;

[1]For instance, both the Schilling models HD-ROV and UHD-ROV have 7 thrusters [1], the SMP ROV 1000 model has 4 thrusters [2] and both the AC-ROV 100 and 3000 have 6 thrusters [3].

[2]E.g. the Schilling robotic manipulators are controlled from 4 to 8 hydraulic motors [4]

2. mechanical arm movements;

3. features enabling-disabling.

The binary representation of each command is composed of two parts: while the first part represents the command class, the second part contains the command specification, with the instruction that will be performed by the ROV. As there are just three distinct command classes, 2 bits are needed to represent them. Therefore, the first 2 bits are used to indicate the command class, whereas the following ones represent the command specification.

A ROV is a complex and expensive system, that may operate in dangerous environmental conditions. Thus, each command sent by the base station has to be received with high reliability and only a very low error rate is acceptable in the received commands. As an initial choice, a (7,4) hamming code [6] is added at the end of each information word. This allows a single-error-correction and double-error-detection. The code provides a good balance between error correction and error detection with low complexity.

2.2.1.1 ROV movements, relative position mode

The possible ROV movements considered in this thesis are the following:

0. rotate horizontally from $-180°$ to $180°$;

1. flip vertically from $-180°$ to $180°$;

2. go straight from 0 to 100 meters;

3. go back from 0 to 100 meters;

4. go right from 0 to 100 meters;

5. go left from 0 to 100 meters;

6. go up from 0 to 100 meters;

7. go down from 0 to 100 meters.

Thus, 3 bits are needed to distinguish which movement the ROV has to do, and 14 more bits are needed due to the numerical value representation of either angle or length (figure 2.1(a)).

2.2.1.2 ROV movements, new way-point mode

In order to control the ROV movements by sending absolute positions, way-point coordinates have to be sent. In particular, for each position x, y and depth are sent, thus 26 bits×3=72 bits are needed to represent each way-point (figure 2.1(b)).

2.2.1.3 Mechanical arm movements

The possible mechanical arm movements considered in this thesis are the following:

0. rotate the arm from $-180°$ to $180°$;

1. raise and lower the arm from $-90°$ to $90°$;

2. turn right or left the arm from $-90°$ to $90°$;

3. open or close a tool (to fix ideas, say pliers) from $0°$ to $180°$.

Thus, 2 bits are needed to distinguish which movement the arm has to do, and 9 more bits are needed due to the numerical value representation of the angle (figure 2.1(c)).

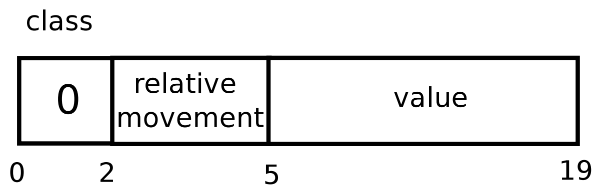
2.2.1.4 Enable-disable other features

The last class of commands is used to enable or disable optional features, in particular:

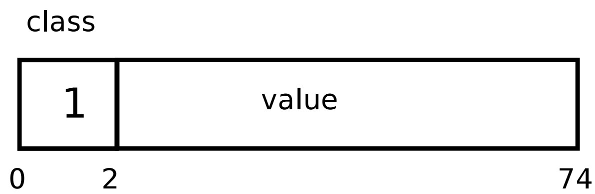
- lighting;
- sonar;
- video acquisition;
- acoustic transmission;
- electromagnetic transmission;
- optical transmission;
- thermistors;
- pressure sensors;
- salinity sensors;

- other sensors (such as density, gas, oil, ..).

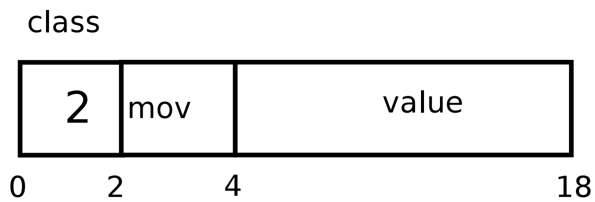
We assume there are less than fifty devices that have to be enabled or disabled. Thus, 6 bits are enough to distinguish them. 3 more bits are used to specify the precision value (in a scale between 0 and 7, where 0 means disable and 7 means enable with the highest intensity), such as quality of sensors acquisition, illumination intensity, or transmission speed. We also assume that the three different kinds of transmission (acoustic, optical and electromagnetic), are mutually exclusive: when one is enabled, all the others will be automatically disabled. The information word structure is shown in figure 2.1(d).



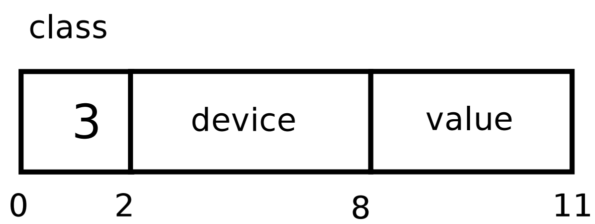
(a) class 0



(b) class 1



(c) class 2



(d) class 3

Figure 2.1. *Information word structure of each command class*

2.2.1.5 Command packets

The commands are cumulatively translated into packets in the following way: all commands are buffered, until either the full length of a packet is obtained, or a timeout occurs. At this point, they are removed from the buffer and sent to the ROV in the format of packets. Each packet is composed of a header and the payload. The packet length is 1024 bits, and the payload is composed of the commands, protected by a (7,4) hamming code. To reach the prescribed packet size, if necessary, zero-padding is employed. The header of the packet is built as follow:

- 8 bits of control information,
- 4 bits representing the source address,
- 4 bits representing the destination address,
- 4 bits representing the next hop,
- 16 bits representing the Sequence Number (SN), which is unique for each data packet,
- 10 bits representing the size of the payload,
- 16 bits of Cyclic Redundancy Check (CRC) checksum;

for a total of 62 bits of header. In this thesis, we assume that the controller does not need to send more than one command packet per second, which should also give to the ROV enough time to perform its operations. Therefore, the required bitrate to transmit commands is 1 kbps.

2.2.2 ROV to Control Station: Feedback and Monitoring

The ROV needs to transmit information to the base station, in order to ensure the monitoring of its position, status and of external conditions. In particular it should send informations about:

- position (x, y and depth): 26 bits$\times$3=72 bits;
- robotic arm status: 11 bits $\times$ 4=44 bits;
- current transmission bitrate: 8 bits;

- distance between the ROV and the control station: 8 bits;
- temperature: 8 bits;
- salinity: 8 bits;
- pressure: 8 bits;
- turbidity: 8 bits;
- 320 bits are reserved for other sensed values[3]: we assume the presence of 40 more sensors with a resolution of 8 bits each one;
- flags to indicate sensors, lights and camera status (on-off-malfunctioning-unavailable): 2 bits $\times$ 50 = 100 bits.

Thus, from this analysis, no more than 614 bits are needed for the monitoring information. In this thesis, one system status update per second is considered. This value should be enough to ensure a precise system monitoring. The information sent by the ROV is enveloped in monitoring packets. These packets are composed of an header of 72 bits plus the payload. The header is similar to the command packet's header, with the addition of 16 bits due to the acknowledgment field. In fact, every command packet should be acknowledged, and the design decision is to piggyback the acknowledgments in the monitoring packets. The packet payload, instead, is composed of the monitoring information; if some sensors are disabled, their information will not be sent, thus the size of the packet will be smaller. Therefore, the bitrate required to ensure feedback and monitoring is 686 bps.

The final estimate of the bitrate required to transmit mandatory info is 1 kbps + 0.686 kbps = 1.687 kbps $\simeq$ 1.7 kbps.

2.3 Optional feature: video live streaming

The most useful, but also the most expensive optional feature in terms of bitrate, is the real-time video streaming. The H.264/AVC MPEG-4 standard does not impose a minimum bitrate to code a video, thus, in this thesis, a research and analysis of typical requirements for real-time video transmissions is reported. The results are summarized in table 2.1:

[3]Such as velocity sensor, gas and oil revelation, illumination sensor, etc.

bitrate	quality	application
16-50 kbps	very low quality	MMS video, minimum bitrate for a consumer-acceptable "talking head" picture using various video compression schemes citesonar[a]
64 kbps	low/very low quality	video calling by a 3g mobile phone, still acceptable quality [7] [8]
128 kbps	medium/low quality	minimum bitrate for a skype video calling [9]
400 kbps	high quality	minimum bitrate for a skype high-quality video calling [9]
1.2 Mbps	HD	minimum bitrate for a skype HD video calling [9]

Table 2.1. *The most used real-time video*

[a]These values have been experimentally measured via video recording made with a Nokia 2330 device.

For what concerns the bitrate used for a standard video call, the value reported in Table 2.1 is an over-estimate of the needed one, because it includes both video and audio, and the latter is not necessarily required in an underwater video monitoring. In fact, the main sound that could be heard in sub-sea environment, is typically the ROV motors' noise. The minimum bitrate required for the transmission of an acceptable operational video is 64 kbps. To prove this, several experiments have been performed, using different low-quality video-camera devices, and for video with lower bitrate than the proposed one, the resulting quality does not provide a sufficient resolution to monitor the environment. Therefore, if the transmission bitrate is less than 64 kbps, a slide-show system may be preferred to a very low quality video monitoring. To this end, some pictures are taken periodically and sent by the ROV to the controller, in order to monitor the environment. The specifications of the low quality images considered are reported in Table 2.2: to allow slide-shows with a very low bitrate, we need to either decrease the image size or increase the transmission period [4]. Thus, a trade-of between images size and delivery delay has to be found. For instance, the rouge decision taken in this thesis is: image size $\geq\ 240\ \times\ 230$ pixels that correspond to an

[4]In this thesis the transmission period is the fixed time interval between the transmission of two successive images by the ROV to the controller.

image dimension of 162 kbit, delay ≤ 6 s, so the minimum bitrate needed for a slide-show transmission is $162/6 = 27$ kbps.

size	dimension	period	bitrate
120×160 pixels	80 kbit	8 s	10 kbps
120×160 pixels	80 kbit	4 s	20 kbps
120×160 pixels	80 kbit	2 s	40 kbps
240×230 pixels	162 kbit	8 s	20.25 kbps
240×230 pixels	162 kbit	6 s	27 kbps
240×230 pixels	162 kbit	4 s	40.5 kbps

Table 2.2. *Low quality JPEG images slide-show.*

2.4 Summary of quality of service requirements and conclusions

In this chapter, we carried out an analysis of the controller bitrate requirements for the remote ROV control system , finding a lower bound for the system bitrate. This bound depends on the desired Quality Of Service (QoS), thus, the control system can work also in very challenging environments if a low QoS is accepted. As explained in the following chapters, in this thesis the design decision is to provide always the best QoS according to the environmental conditions, switching communication technology and varying the bitrate when is needed. Six system modes are proposed (table 2.3), from MODE 0 to MODE 5, in order to understand which services are available according to the transmission bitrate.

mode	minimum bitrate	mandatory features	optional features
MODE 0	2 kbps	yes	none
MODE 1	30 kbps	yes	slide show
MODE 2	70 kbps	yes	low/very low quality video
MODE 3	130 kbps	yes	medium/low quality video
MODE 4	402 kbps	yes	high quality video
MODE 5	1.4 Mbps	yes	video HD

Table 2.3. *System QoS modes*

This initial classification is based totally on the required bitrate to provide a service with acceptable quality, regardless of the existing underwater communication devices. After the analysis of the underwater transmission technology in Chapter 3, the control modes in Table 2.3 will be reviewed in retrospective, and reconsidered or redefined in light of the capability of each technology to support them (section 3.5).

Chapter 3

Underwater telecommunication techniques comparison

3.1 Introduction

In this chapter, we survey the state of the art of underwater communication technologies, paying special attention to those that operate at short and intermediate ranges (1 to 100 meters). In order to establish a communication link between two devices located underwater, three different classes of modems are available: the first one uses acoustic waves, the second one optical waves and the last one electromagnetic waves. As explained in the following sections, no best technology can be clearly identified, because the transmission performance is highly dependent on the distance between the transmitter and the receiver, on the environment and on other external conditions. In fact, for short and very short communication ranges, optical and RF modems can be used, but acoustic waves are required in order to establish medium and long-range communication. In this chapter, a comparison of the three existing underwater communication techniques is done, by varying the transmission range, and by considering the environmental conditions listed in table 3.1. The latter conditions are typical of a port, where the waters are typically shallow, salty and turbid. This scenario is one of the most challenging for underwater transmissions, for this reason, in this thesis, it is considered as a worst-case benchmark, to ensure the reliability of the control system designed.

characters	**details**
water salinity	salty seawater, average salinity around 35 ppt [10]
conductivity	$\sigma = 4:5$ $[\frac{S}{m}]$ [11]
type of transmission	horizontal transmission in shallow water
turbidity	high turbidity: 1.0 [ppm] [12]
temperature	$-2:40°C$ [10]
spreading coefficient	cylindrical k=1, spherical k=2, practical k=1.5 [13] [14]
speed of sound	on average 1500 m/s [13] [14]
operating range	short range: 0÷100 meters
required Bit Error Rate (BER)	BER$\leq 10^-6$.

Table 3.1. *Typical environmental conditions considered.*

3.2 Underwater acoustic communications

Nowadays, the most studied and used underwater telecommunication technology is based on acoustic signals. In fact, this technology provides some important advantages, e.g. it allows long transmission ranges, good reliability and robustness. On the other hand, the available bandwidth is very limited and its performance are often poor, especially in the case of horizontal transmission in shallow and salty water. [15] A list of advantages and disadvantages is presented in table 3.2.

In order to find reliable information about the possible transmission bitrate and range, during the literature search it has been necessary to pay attention to conditions that are sometimes left hidden in data sheet or even papers, such as the transmission type and the environment considered during the communication tests. Indeed, in the underwater acoustics literature (like [17] and [18]), many research experiments and simulations are presented where some successful transmissions with high bitrate are claimed. These values were retrieved by testing the communication in ideal conditions, like deep water and vertical transmissions, or communication in fresh or distillated water. These conditions are unrealistic and very advantageous compared to the typical undersea environment where ROVs typically operates. Thus, from all the retrieved data, only the information that respects the

benefits	**limitations**
Proven technology	Strong reflections and attenuation when transmitting through water/air boundary
Range: up to 20 km	Poor performance in shallow water
No Line Of Sight (LOS) problems	Adversely affected by turbidity, ambient noise, salinity and pressure gradients
Reliability and robustness	Limited bandwidth
Many commercial acoustic modems	Impact on marine life

Table 3.2. *Acoustic communication: advantages and disadvantages [15] [16].*

conditions listed in table 3.1 is selected, in order to retrieve the acoustic transmission performance in terms of bitrate versus range.

We will also distinguish between commercial modems that can be bought off the shelf (table 3.3), and prototypes developed by Universities (table 3.4). Some experimental modems provide good performance and an high level of reliability, but cannot be straightforwardly purchased. Many of them are presented in literature; for simplicity in this section we present only the experimental modems that yield better performance than commercial ones. Therefore, also in the concluding comparison (section 3.5) two different scenarios will be considered: the commercial one, where only the modems available in the market are considered, and the global one, where also the experimental modems are assumed to be available. Having said that, the results of the comparison are summarized in Tables 3.3 and 3.4.

Range [m]	**Bitrate [kbps]**	**Company**	**Transmission context**	**Useful** [a]
350	17.8	LinkQuest Underwater Acoustic Modems UWM1000 [19]	horizontal, very shallow water	YES [b]
1000	31.2	Evologics S2C R 48/78 Underwater Acoustic Modem [21]	horizontal shallow water	YES [c]
1000	35.7	LinkQuest Underwater Acoustic Modems UWM2200 [19]	near vertical	NO
1200	1.2	LinkQuest Underwater Acoustic Modems UWM2000H [19]	horizontal, very shallow water	YES
1500	17.8	LinkQuest Underwater Acoustic Modems UWM2000 [19]	near vertical	NO
2000	31.2	Evologics S2C R 42/65 Underwater Acoustic Modem [21]	vertical	NO
3500	13.9	Evologics S2C R 18/34 Underwater Acoustic Modem [21]	horizontal shallow water	YES
6000	5	LinkQuest Underwater Acoustic Modems UWM3000 [19]	horizontal, very shallow water	NO
6000	0.320	LinkQuest Underwater Acoustic Modems UWM3000H [19]	horizontal, very shallow water	YES

Table 3.3. *Underwater acoustic communication: comparison among the bitrates of commercial modems.*

[a] YES means that the modem can be used in the considered scenario for the controller development.

[b] Worse results where obtained in Singapore's warm shallow waters, which is one of the most challenging underwater environment [20].

[c] Better results were performed in Baltic Sea shallow waters, whereas worse results where obtained in Singapore's warm shallow waters [20].

Range [m]	Bitrate [kbps]	Company - University	Transmission context	Useful [a]
40	380	UNSW Canberra, under test	horizontal OFDM, high BER	NO
60	500	Oki Electric Industry [17] [18] [22]	vertical deep, PSK	NO
100	87.768	Hermes modem by Florida Atlantic University [23]	horizontal, shallow water, QSK	YES
200	90	MIT [24]	deep-sea, OFDM	NO
300	40	University prototype [22] [b]	horizontal, very shallow water 16-QAM	YES

Table 3.4. *Underwater acoustic communication: comparison among the bitrates of prototype modems.*

[a]YES means that the modem can be used in the considered scenario for the controller development.
[b]Company or University's name is not available in the cited reference [22].

3.2.1 Results and Conclusion

For the wireless remote control system designed in this thesis, acoustic modems are useful because, although they provide limited bandwidth, they assure some degree of reliability and robustness also for long range communication. However, they fulfill the needed bitrate to assure the mandatory features (section 2.2). Furthermore, considering the prototype modem "Hermes", it is possible to transmit a low-quality video (section 2.3) in a range of 100 meters. Thus, with acoustic technologies, the controller can operate between middle and long range, but only in mode 0 to 2 (section 2.4).

3.3 Optical transmission

Though acoustic transmission (section 3.2) have been the default wireless communication method for underwater applications due to their long coverage range, the need for high speed communications has prompted the exploration of non-acoustic methods that have previously been overlooked due to their distance limitations. For scenarios where high speed, but only moderate distances are required, nowadays the most used technology is optical communications. Indeed, many companies manufacture low distance high

speed optical modems for the underwater environment (like [25] and [26]). Furthermore, some Universities are studying this technology to improve it's performance and to propose solutions to overcome LOS problems [27] [28]. Actually, to establish an optical communication, the transmitter needs to be aligned with the receiver. Moreover, the Signal to Noise Ratio (SNR) depends also on the angle between the optical axis of the receiver and the line of sight between the two devices involved in the communication. The most challenging environmental conditions for this technology, are turbid and shallow seawaters. In fact, high turbidity attenuates the signal propagation and ambient light noise causes performance reductions. Therefore, the closer to the surface the transmission is, the higher the sun light noise is and the worse the communication becomes . This is why, during the literature research, only the transmission tested in these conditions are considered to be useful for the controller design. For instance, Sonardyne [25] produces BlueComm OATS, a high bitrate modem that can transmit at a rate of 20 Mbps up to 200 m, however, this device can work only in deep dark water.
Details on two different models for underwater optical communications are available in [29] and [12].
Blue and green lights, which have a wavelength of 470 and 550 nm respectively, are the most used for underwater optical communication [30].
A list of advantages and disadvantages of this transmission technique are shown in table 3.5.

benefits	**limitations**
Ultra-high bandwidth: gigabits per second	Susceptible to turbidity, particles, and marine fouling
Low cost	Does not cross water/air boundary easily
	Needs line-of-sight
	Requires tight alignment of nodes
	Very short range

Table 3.5. *Optical communication: advantages and disadvantages [15] [16].*

To analyze the available modems, also in this section two sub-cases are analyzed: in the first one (table 3.6) we show the optical modems available off the shelf, whereas, in the second one, we report prototypes designed by Universities (figure 3.7). In this case, the number of commercial modem is much less than the prototypes: thanks to the low cost and the high availability of Light Emitting Diode (LED) and light sensors, many Universities built their own optical modem.

Range [m]	**Bitrate [Mbps]**	**Company and product**	**Transmission context**	**Useful** [a]
1	19200 baud	AQUATEC AQUAmodem Op1 [31]	not available	NO
20	5	Sonardyne BlueComm HAL [25]	shallow water	YES
40	10	Ambalux 1013C1 High-Bandwidth Underwater Transceiver [26]	depends on conditions	NO[b]
200	20	Sonardyne BlueComm OATS [25]	deep water	NO

Table 3.6. *Underwater optical communication: comparison among the bitrates of commercial modems.*

[a] YES means that the modem can be used in the considered scenario for the controller development.
[b] Experiments in [27] obtained 9.69 Mbps at 11 meters in the turbid Ontario lake.

Range [m]	**Bitrate [Mbps]**	**Company and product**	**Transmission context**	**Useful** [a]
2	10^3	Space and Naval Warfare Systems Center [30]	both	YES
3	2	Keio University [12]	high turbidity	YES
3	10	Keio University [12]	no turbidity	NO
6.5	10	MIT [32] [b]	turbidity, low power led	YES
8	1	MIT [32]	turbidity, low power led	YES
9	0.10	MIT [32]	turbidity, low power led	YES
11	20	Penguin Automated Systems Inc. [27]	omni-directional, ideal in lab.	NO
11	10	Penguin Automated Systems Inc. [27]	omni-directional, turbid water	YES
15	1.5	Penguin Automated Systems Inc. [27]	omni-directional, turbid water	YES
100	1-10	Woods Hole Oceanographic Institution [28]	omni-directional, deep water	NO

Table 3.7. *Underwater optical communication: comparison among the bitrates of prototype modems.*

[a] YES means that the modem can be used in the considered scenario for the controller development.
[b] The values reported in [32] should be taken as a lower-bound.

3.3.1 Results and Conclusion

Despite the short communication range, optical modems are able to transmit at very high bitrate. Thus, for what concerns the remote control system designed in this thesis, the commercial modem Sonardyne BlueComm HAL can be used in order to allow HD video monitoring for short range (MODE 5). Although the Ambralux 1013C1 High-Bandwidth Underwater Transceiver declares higher performance, its transmission rate depends on environmental conditions. Indeed, with this device, a successful transmission of 9.69 Mbps at 11 meters was performed during a test in the Ontario Lake turbid water. However, this information is not sufficient to infer the transmission performance for the scenario considered in this thesis. The last consideration concerns multi-hop transmissions. Though some prototyping modems achieve omni-directional communications, all the commercial ones allow just directional transmissions. Therefore, only some particular prototypes built ad hoc can be used to transmit in a multi-hop network (such as the network analyzed in Chapter 4): this is a technological limitation.

3.4 Electromagnetic fields

While acoustic (section 3.2) modems are useful in underwater communications to transmit low bitrate at long range, to transmit at a high bitrate at short and very-short ranges either optical (section 3.3) or RF Electromagnetic (EM) modems could be used. In this section, an overview of the current underwater RF communication technology is presented, in order to understand whether this technology can be useful or not for the controller design. The first consideration is that, transmitting underwater via EM modems yields both advantages and disadvantages. On one hand, its performance does not depends on any environmental conditions, and high bitrate transmissions are supported; on the other hand, it suffers from limited transmission range and Electromagnetic Interference (EMI). In addition, the attenuation of electromagnetic signals is much lower in fresh water than sea water, due to the different conductivity. [1] Therefore, the environmental conditions considered in this thesis are very challenging for this technology. Other benefits and limitations of using EM in underwater are listed in table 3.8, whereas the propagation characteristics of RF transmission in water medium using EM waves are described in [11].

The most important institution that studies and builds underwater EM modems retrieved in this thesis, is Wireless For Subsea (WFS) Technology. In particular, using Seatooth technology, WFS's products support wireless data communications and networking with divers, ROVs and AUVs and subsea and buried sensors and actuators [33]. Furthermore, each commercial modem (table 3.9) is provided by an additional acoustic low-bitrate link for long range transmission. Moreover, in collaboration with Nautilus Oceanica, its researchers in [16] carry out an analysis of the underwater EM technology, making a prediction of data rates for different ranges. These and other theoretical results are shown in table 3.10.

[1] The conductivity of sea water is typically around 4 S/m while nominally fresh water conductivity is quite variable but typically in the mS/m range (e.g. 0.01 S/m). [16]

benefits	**limitations**
Crosses air/water/seabed boundaries easily	Susceptible to EMI
Prefers shallow water	Limited range through water
Unaffected by turbidity, and pressure gradients	Depends on water conductivity
Works in non-line-of-sight; unaffected by sediments and aeration	
High bandwidths (up to 100 Mb/s) at very close range	

Table 3.8. *Electromagnetic communication: advantages and disadvantages. [15] [16]*

Range [m]	**Bitrate [Mbps]**	**Company and product**	**Transmission context**	**Useful** [a]
up to 0.1	10-100	WFS Seatooth S500 [33]	not known	YES [b]
4-7	75-156 kbps	WFS Viewtooth [33]	not known	YES
4-10	25-156 kbps	WFS Seatooth S300 [33]	not known	YES
up to 50	10 bps-8 kbps	WFS Seatooth S200 [33]	not known	YES

Table 3.9. *Underwater electromagnetic communication: comparison among the bitrates of commercial modems.*

[a] YES means that the modem can be used in the considered scenario for the controller development.

[b] Conservative interpretation of this table: 0.1 m 10 Mbps, 4 m 156 kbps, 7 m 75 kbps, 10 m 25 kbps and 50 m 10 bps

Range [m]	**Bitrate [Mbps]**	**Company and product**	**Transmission context**	**Useful** [a]
0.2	10-100	WFS Technologies [16] [34]	seawater	YES
1-2	1-10	WFS Technologies [16]	seawater	YES
10	20-50 kbps	WFS Technologies [16]	seawater	YES
10	156 kbps	NWCL [34]	not specify	NO
50	1-10 kbps	WFS Technologies [16]	seawater	YES

Table 3.10. *Underwater electromagnetic communication: comparison among the bitrate of prototype modems.*

[a] YES means that the modem can be used in the considered scenario for the controller development.

3.4.1 Results and Conclusion

Despite the short communication range, electromagnetic modems can transmit at very high capacity. In addition, they provide omni-directional transmission, in contrast to optical communications. However, optical modems outperform EM devices. Therefore, in this thesis we chose to use the RF transmission technology for the wireless remote control design.

3.5 Comparison of results and final considerations

In the previous sections, thanks to a bibliographic research, three different underwater telecommunication techniques are analyzed. By comparing advantages, disadvantages and typical usage scenarios, many commercial and prototype modems are presented. The global results are now analyzed, firstly observing only the commercial modems (section 3.5.1) and then finding the best solution available, including also prototype modems (section 3.5.2). Finally, given the available bitrates, a redefinition of the system modes in light of the transmission ranges is performed in section 3.5.3.

3.5.1 The best solution with commercial modem

The commercial modems available in the market, provide either very high capacity over short and very-short ranges, or very low capacity over long ranges. Whereas, according to the bibliographic research, no devices are available for intermediate range transmission.

In particular, very short range transmissions are covered by an EM modem, short ranges by optical transceiver and long ranges by acoustic modems. More details are shown in table 3.11.

Distance [m]	**Bitrate**	**Company and product**	**Technology**
0.1	10 Mbps	Seatooth S500 [33]	electromagnetic
11	9.69 Mbps	Ambalux 1013C1 High-Bandwidth Underwater Transceiver [27] [26]	optical
20	5 Mbps	Sonardyne BlueComm HAL [25]	optical
1000	31.2 kbps	Evologics S2C R 48/78 Underwater Acoustic Modem [21]	acoustic
3500	13.9 kbps	Evologics S2C R 18/34 Underwater Acoustic Modem [21]	acoustic
6000	320 bps	LinkQuest Underwater Acoustic Modems UWM3000H [19]	acoustic

Table 3.11. *underwater communication: commercial modems bitrate comparison*

3.5.2 The best solution with no technological limits

In this section, all the retrieved modems are compared, in order to find the best possible solution. In this case, all EM modems are outperformed by the optical ones, also for very-short communication range. In addition, some acoustic prototypes, provide middle range transmissions at medium to low bitrate. Therefore, short and very short ranges are covered by optical transceiver, whereas acoustic modems are used for middle and long ranges. More details are shown in table 3.12 and figure 3.1.

Distance [m]	Bitrate	Company and product	Technology
2	1 Gbps	Space and Naval Warfare Systems Center [30]	optical, prototype
11	10 Mbps	Penguin Automated Systems Inc. [27]	optical, prototype
20	5 Mbps	Sonardyne BlueComm HAL [25]	optical, commercial
100	87.768	Hermes modem from Florida Atlantic University [23]	acoustic, prototype
300	40	University prototype [22], [a]	acoustic, prototype
1000	31.2 kbps	Evologics S2C R 48/78 Underwater Acoustic Modem [21]	acoustic, commercial
3500	13.9 kbps	Evologics S2C R 18/34 Underwater Acoustic Modem [21]	acoustic, commercial
6000	320 bps	LinkQuest Underwater Acoustic Modems UWM3000H [19]	acoustic, commercial

Table 3.12. *underwater communication: existing modems bitrate comparison*

[a] Company or University's name is not available.

3.5.3 Conclusions and Considerations

With the current technology, a redefinition of the controller modes has to be done. In fact, at 20 meters there is the change of transmission device: from the broadband 5 Mbps optical modem BlueComm HAL [25], to the 87.768 kbps Hermes acoustic modem [23]. With this change, the work mode switches drastically from MODE 5 to MODE 2, skipping out both MODE 3 and 4. The hope, in the future, is that the UNSW Canberra prototype acoustic modem will achieve better performance in terms of BER, thus the MODE 3 could be achieved from 20 to 40 meters range. Therefore, with the current proven technology analyzed in this thesis, MODE 3, 4 and 5 are reached at the same range, and they should be grouped in a unique mode called MODE VideoHD. A summarize of these considerations is shown in table 3.13 and figure 3.2.

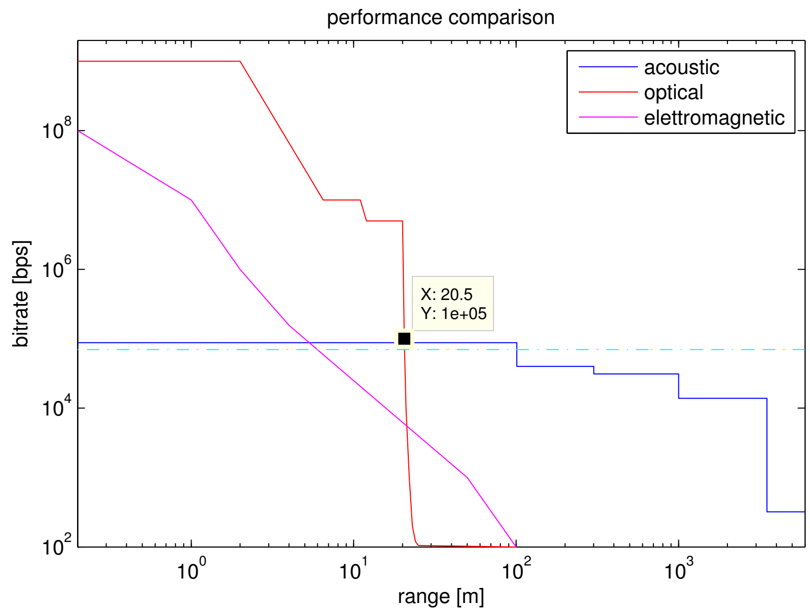


Figure 3.1. *Existing modems bitrate comparison*

Distance [m]	Bitrate	Mode	Company and product	Technology
20	5 Mbps	MODE VideoHD	Sonardyne BlueComm HAL [25]	optical, commercial
100	87.768	MODE 2	Hermes modem from Florida Atlantic University [23]	acoustic, prototype
1000	31.2 kbps	MODE 1	Evologics S2C R 48/78 Underwater Acoustic Modem [21]	acoustic, commercial
3500	13.9 kbps	MODE 0	Evologics S2C R 18/34 Underwater Acoustic Modem [21]	acoustic, commercial

Table 3.13. *underwater communication: existing modems bitrate comparison*

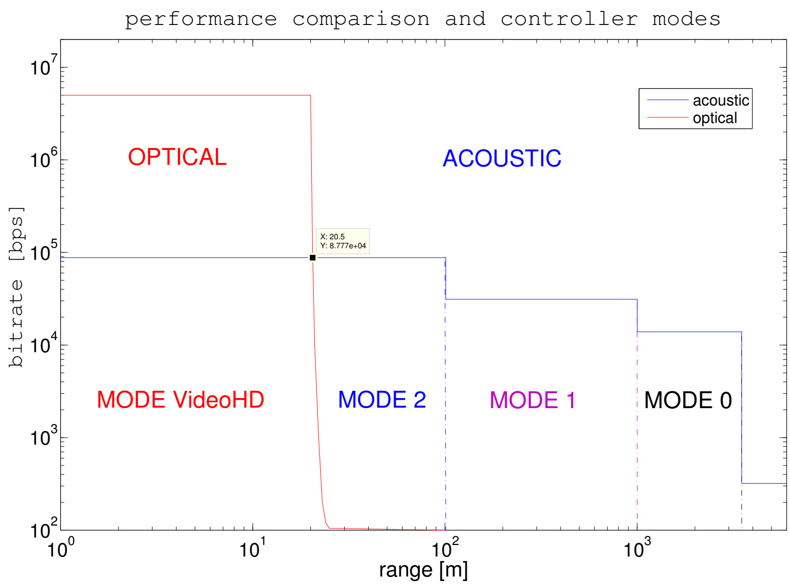


Figure 3.2. *Controller design: transmission rate and QoS vs range.*

Chapter 4

Multi-hop network

4.1 Introduction

The goal of this chapter is to analyze a multi-hop acoustic network, in order to understand whether is possible to extend the communication range of a single hop system. After a preliminary analysis, some simulations were performed to retrieve performance of the network transmission. The structure of the chapter is the following: firstly, in section 4.2, the descriptions of the used protocols is provided. Then, in section 4.3, the underwater acoustic channel is analyzed, in order to estimate the possible transmission range and the minimum power required for a low packet error rate. With the retrieved value, some matlab network simulations were performed to obtain the required performance (the results are collected in section 4.4). Finally, in section 4.5, the results are commented and a base line for future works is suggested. We remark that that, although in section 3.5 both optical and acoustic modem are considered, to implement a multi-hop network an omni-directional transmission technology is needed. Therefore, in this chapter only acoustic modems are used.

4.1.1 Considered Scenario

The considered scenario is a network of $n + 2$ nodes equally spaced and placed in salty, shallow and turbid ocean water, such as a port, or a oil pipeline area. Each node transmits via Hermes Acoustic Modems [23]. These acoustic devices can cover middle range transmission (up to 100 m), at 87.768 kbps, using frequencies between 260 and 375 khz. In this system, not all the bandwidth is used to send data. In fact, on one hand the frequencies between

347 and 375 kHz, are used to trigger data packets and send the preamble of the transmission. On the other hand, either a bandwidth of 50 kHz or 75 kHz (depending on the mode), with a carrier frequency of 300 kHz, is used to send Pseudo Noise (PN) sequences and data packets. Thus, the following values are used to set up the simulation: data bandwidth $B = 75khz$ [35], carrier frequency $f = 300khz$ and a bitrate of $C = 87.768\ kbps$. For what concerns the transmission, both data and acknowledgement packets are long $L_{pck} = 1024$ bits, due to the need to simulate both control and monitoring packets, as described in chapter 2. [1] The signal propagation is described by means of two effects (eq.(4.1)): the channel attenuation, due to the distance l and the frequency f, plus the Rayleigh fading R, where $R^2 = h \sim exp(1)$.

$$P_R = R^2 P_T / A(l, f) = h P_T G_u. \tag{4.1}$$

The attenuation is described as following:

$$\begin{aligned} A(l, f) &= A_0 l^k a(f)^l, \\ G_u &= 1/A(l, f). \end{aligned} \tag{4.2}$$

Due to the very challenging environmental conditions, the geometry coefficient to model the acoustic channel, k, was chosen as 2 [2], while A_0 is a unit normalizing constant and $a(f)$ the absorption coefficient (for f in khz):

$$10 \log_{10} a(f) = \left(0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f^2} + 2.75 \cdot 10^{-4} f^2 + 0.003 \right) \frac{1}{914.4} [db/m]. \tag{4.3}$$

The ambient noise is assumed to be Gaussian, and has four noise sources: turbulence, shipping, waves and thermal noise. The noise formulas used are described in paper [14], a shipping factor $s = 0.5$ and no wind ($w = 0$) are considered. These metrics are used in order to define the outage probability as the event occurred when the SINR (eq.(4.5)) falls below a predetermined threshold. When SINR is greater than this threshold, a correct packet transmission occurs. Otherwise a transmission error takes place [36]. Therefore, the success probability of a packet transmission is defined as

$$P_s = P[SINR > \theta] \tag{4.4}$$

[1] The ACK are supposed to be piggybacked in monitoring packets sent by the ROV to the controller.

[2] k=2 means spherical spreading, the worst case possible, while k=1 means cylindric spreading and k=1.5 is used for real spreading. [14]

where

$$SINR = \frac{P_R}{N + P_I}, \tag{4.5}$$

$P_I = \sum_{k=1}^{r} P_{I_k}$ is the interferences power, and N the noise power. Thus, the outage is useful to set out operating range and minimal transmission power (section 4.3). In this project the target $\theta = 15dB$.

4.2 Details on the network protocols

Routing process with pipelining is a routing protocol that uses a pipelining paradigm [37] to retrieve data packets, from the sender node to the receiver, via a multi-hop linear network provided with n intermediate nodes. In this network, nodes are equally spaced and the correction of error transmission is done via selective repeat Automatic Repeat Request (ARQ), saving out of order packets in a buffer at the receiver (for simplicity the buffer dimension is assumed to be infinite).

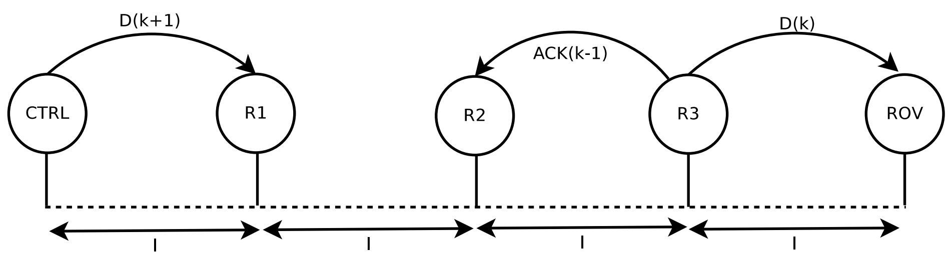


Figure 4.1. *Network topology with $n = 3$. In the current time slot, nodes CTRL and R3 has to transmit.*

Figure 4.1 shows the topology of the network: a controller has to send some commands to a ROV, in a multi-hop system with n relays (three in the figure). The network protocol uses static routing with pipelining, over a Time-Division Multiple Access (TDMA) Media Access Control (MAC) layer [3]. In particular, two nodes can transmit simultaneously, only if the distance between them is exactly three hops, in order to avoid interference as much as possible. For instance, during the first time slot, the first and the fourth nodes are active, then, at the second time slot, the second and the fifth nodes are active, and so on. When an intermediate node is active, it can transmit both data and acknowledgement packets to the

[3]The TDMA is chosen for simplicity. Other type of MAC layers could be used, the important thing is that assures the synchronization of the transmission.

adjacent nodes.[4] Instead, when the first node (the controller) is active, it has either to send to the next node a new data packet, or to retransmit a non acknowledged packet. An example of the system operations is shown if figure 4.2.

	CTR	R1	R2	R3	ROV
0	D1				
1		D1			
2			D1		
3	D2			D1	
4		D2			D1
5			D2	A1	
6	D3			A1 D2	
7		D3	A1		D2
8			A1 D3	A2	
9	D4	A1		A2 D3	
10		A1 D4	A2		D3
11	A1		A2 D4	A3	

time slot

Figure 4.2. *Instance of pipeline with $n = 3$ and ideal channel (no errors). Delay = 4 and RTT = 11 time slots.*

The acknowledgements are created by the last node, the ROV. When the expected in-order packet is received, an acknowledgement is sent. Otherwise, all the received out of order packets (if any) are saved in a buffer, and a request of retransmission is sent to the previous node. This request will be forwarded, node by node (when they are allowed to do so), up to the controller. Thanks to the resequencing buffer, acknowledgements can be cumulative. Therefore, only the last in order received packet must be acknowledged. Whether a request of retransmission is required, the ROV goes to a back-off and waits a Round Trip Time (RTT), before to recheck whatever it has received. This procedure is used, in order to limit the number of retransmission requests, and in order to not to stop the pipelining process.

In addition, a second solution is proposed and simulated in order to improve the performance in terms of delay, buffer size and throughput. In particular, in this variant, a caching system is implemented in all the intermediate nodes: this allows the relays to retransmit the lost packets they have already received. Thus, this caching system allows faster retransmis-

[4]The transmission power is set such that the condition in 4.4 is satisfied only over subsequent hops. More details about this aspect are provided in Section 4.3.

sions than the original protocol. In order to understand whether this second case provides substantial improvements, both system configurations are simulated, and the corresponding performance is analyzed and compared in section 4.4.

4.3 Minimum power estimate

In this section we explain how the transmission power is chosen. Actually, the outage probability is observed, in order to find the power value which ensures the design target described below. In particular, the transmission power that ensures $P_s \geq 0.95$ is searched either for the worst link of the pipeline or for the complete End-to-End (E2E) transmission. In section 4.4, performance of both cases are analyzed and compared. To retrieve the outage, two techniques are used: Montecarlo simulation (Section 4.3.2.1), and numerical integration to solve an analytical model calculation (Section 4.3.3). Both the techniques give the same results (Section 4.3.3.1).

4.3.1 Signal to Interference plus Noise Ratio (SINR)

$$SINR = \frac{P_R}{N + \sum_{k=1}^{r} P_{I_k}} = \frac{P_T R^2 / A(l,f)}{N + \sum_{k=1}^{r} \frac{P_T R^2 \cdot \nu_k}{A(l_k,f)}} = \frac{P_T h_u G_u}{N + \sum_{k=1}^{r} P_T h_{I_k} G_{I_k}} \tag{4.6}$$
$$h_u,\ h_{I_k}\ iid \sim exp(1)$$

Where $G_{I_k} = \frac{\nu_k}{A(l_k,f)}$, is the interferer k's channel power gain, that contains both the attenuation terms and the overlap factor ν_k, explained in section 4.3.2.

4.3.2 Interference overlap

The overlap factor is a normalized value used to represent the percentage of overlap between the signal and the interference. It depends on the propagation delay of the interferer, $\tau_i = l_i/c$,[5] and the time required for a packet transmission. The interference could come from the other signals transmitted simultaneously, or from signals transmitted earlier than the current transmission. An example is shown in Figure 4.3.

A time slot is composed of three parts:

$$T = \tau + T_T + T_G = l/c + L_{pck}/C \cdot 1.25 \tag{4.7}$$

[5] $c = 1500 m/s$ is the average speed of sound underwater.

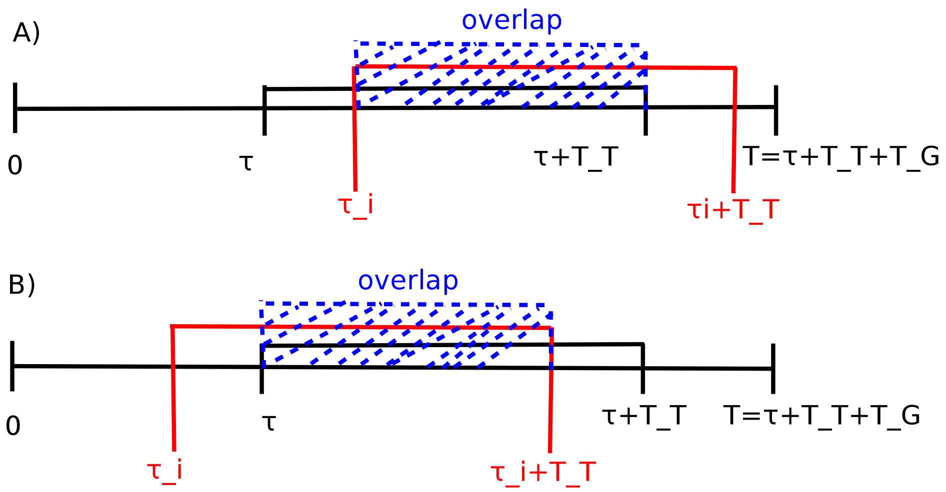


Figure 4.3. *The two possible cases of interference overlap.*

where $T_T = L_{pck}/C$ is the time required for the transmission of L_{pck} bits at bitrate C, T_G is the guard time and is chosen as $0.25T_T$ and $\tau = l/c$ is the propagation delay.
An overlap occurs, if an interferer packet arrives while the data packet is being transmitted. Therefore, the overlap factor measures this superposition, as described by 4.8:

$$\nu = \begin{cases} \dfrac{\tau + T_T - (\tau_i - t \cdot T)}{T_T} = 1 - \dfrac{(\tau_i - t \cdot T) - \tau}{T_T}, \\ \qquad\qquad \text{if } (\tau_i - t \cdot T) \in [\tau, \tau + T_T] \\ \dfrac{(\tau_i - t \cdot T) + T_T - \tau}{T_T} = 1 - \dfrac{\tau - (\tau_i - t \cdot T)}{T_T}, \\ \qquad\qquad \text{if } (\tau_i - t \cdot T) \in [0, \tau] \\ 0, \text{otherwise} \end{cases} \tag{4.8}$$

where the interferer signal was sent t time slots before the current one. For instance $t = 0$ means that the interferer and the useful signal were sent simultaneously, $t = 1$ means that the interferer was sent 1 time slot before the signal, and so on. During the simulations, all the possible interferences were considered.

4.3.2.1 Estimate via Montecarlo simulation

The first technique used to retrieve the minimum power is Montecarlo simulation [38]. This methods consist to simulate many times an experiment in order to obtain the distribution of an unknown probabilistic entity. In particular, in this case the goal is to find the minimum power estimate. To do this, from the equation of the $SINR$, the P_T is derived.

$$SINR \geq \theta \rightarrow P_T h_u G_u \geq \theta N + P_T \theta \sum_{k=1}^{r} h_{I_k} G_{I_k} \tag{4.9}$$

$$P_{T_{min}} = \frac{\theta N}{h_u G_u - \theta \sum_{k=1}^{r} h_{I_k} G_{I_k}} \tag{4.10}$$

During each experiment, N, h_u and h_I are extract independently with their own statistic. In the first system configuration, the target regards the worst link. Therefore, for each link, N_{rip} experiments were simulated, in order to find the minimum transmission power (eq (4.10)). Then, the link with the maximum power needed to achieve the target θ is chosen as the worst link, and its power is taken as the estimated value. Instead, for what concerns the second case, N_{rip} experiments of the complete E2E multi-hop are considered, and the power that respect the outage target is chosen.

During each experiment, if a power greater than zero is obtained, that value is saved, otherwise the value is not acceptable and is replaced by $+\infty$. Of these samples, if the 95 percent of them assumes finite values, the minimum power is chosen as the maximum of this subset. Otherwise, l does not allow to reach the transmission quality imposed by the target, due to excessive interference. Thus, the distance from the nodes should be increased. For instance, for a pipeline with $n = 4$, the minimum distance between the nodes to respect the target is 21 m for both the considered cases (Figures 4.4 and 4.5). Increasing the distance, the effect of the interference decreases, due to both distance attenuation and smaller overlap. Thus, the noise becomes the dominant factor that has to be observed in order to respect the target.

4.3.3 Analysis and estimate via numerical integration

The second method used to retrieve the minimum transmission power, is to use the following analysis steps. Firstly, it is necessary to explicit h_u from the SINR.

$$SINR > \theta \rightarrow h_u > \frac{\theta}{P_T G_U}(N + P_T \sum_{k=1}^{r} h_{I_k} G_{I_k}) = h_{u,min} \tag{4.11}$$

Then, it is possible to calculate the probability that h_u respects the target found in the previous step, conditioned to the noise and the interferences.

$$P(h_u|_{h_I,N} >= h_{u,min}) = \int_{h_{u,min}}^{+\infty} e^{-t} dt = e^{-\frac{\theta(N + P_T \sum_{k=1}^{r} h_{I_k} G_{I_k})}{P_T G_U}} > 0.95 \tag{4.12}$$

Now, to explicit P_T, the retrieved probability should be forced to 0.95 for the first case, and 0.95^{n+1} for the second case. The latter estimation is very rouge, because it considers every link in the same condition, while the interferences behavior are different depending on the position. However, in the working range the noise are the main factor of the SINR, thus, this approximation gives reliable values. In the following analysis equations, the first case is considered for clarity, therefore, just changing the target from 0.95 to 0.95^{n+1} the E2E case can be obtained. With this operation the minimum transmit power is found, conditioned to the amount of noise and interference.

$$P_{T_{min}|h_I,N} = \frac{-\theta N}{\log(0.95)G_U + \theta \sum_{k=1}^{r} h_{I_k} G_{I_k}} \tag{4.13}$$

Finally, in the last step, to find the minimum transmit power, it is necessary to integrate the obtained value over both the interferences and the noise's pdfs. To do this, it has to be considered that the noise is assumed to be Gaussian with a known psd σ_w^2. Thus $N = W^2$, with $W \sim N(0, \sigma_w)$.

$$P_{T_{min}} = \int_{-\infty}^{+\infty} \frac{1}{\sigma_W \sqrt{2\pi}} e^{-\frac{w^2}{2\sigma_w^2}} dw \int_0^{+\infty} e^{-h_{I_r}} dh_{I_r} \cdots \int_0^{+\infty} P_{T_{min}|h_I,N} e^{-h_{I_1}} dh_{I_1} \tag{4.14}$$

These integrals where solved numerically using the Gauss Quadrature Rule (GQR) tables, in particular the internal integrals are solved via Laguerre integration, whereas the external integral is solved via Gaussian integration [39]. The same results obtained with the Montecarlo simulation are retrieved.

One one hand, the advantages of this solution are efficiency and speed of computation, on the other hand, the integrals could become undefined [6] when the minimum distance between subsequent relays is approached (when $\theta \sum_{k=1}^{r} h_{I_k} G_{I_k} \simeq \log(0.95)G_U$). In addition, an approximation is introduced to solve the E2E case.

4.3.3.1 Minimum Power Estimation: Results and Comparison

In this section we report the minimum power estimates results for the two cases: $P_{success} = 0.95$ for the worst link (Figure 4.4) and for the E2E transmission (Figure 4.5). In addition, the results of the two different estimation techniques are compared. In particular, in both figures, the estimates obtained via numerical integration overlap to the Montecarlo simulations. As expected, by increasing the distance the needed power increases and more power

[6] E.g., by changing the precision of the calculation, the result assumes different values.

is required to reach the E2E target than in the single link case. In particular, between the two cases, we observe in average a difference of 6 dBμPa.

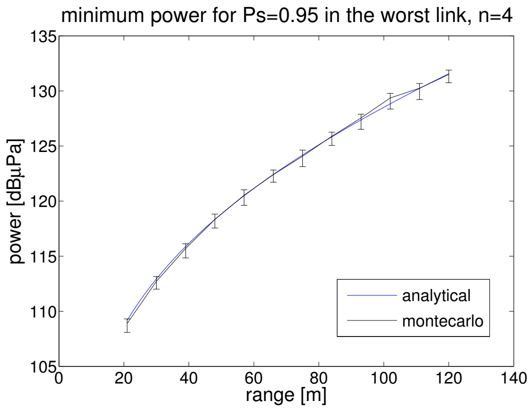


Figure 4.4. *Minimum power to allow a probability of success for a single hop of 0.95. CI = 0.95, number of repetitions* = 10^4.

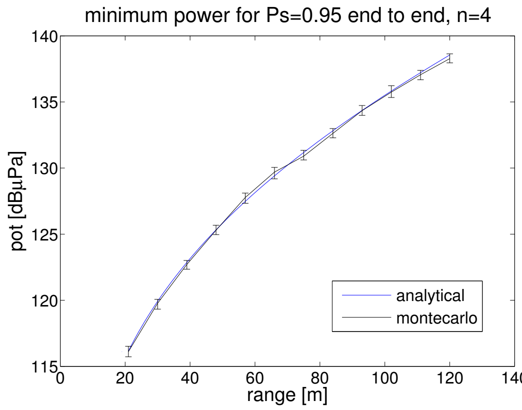


Figure 4.5. *Minimum power to allow an E2E probability of success of 0.95. CI = 0.95, number of repetitions* = 10^4.

4.4 Considered cases and Performance Results

In this section, the performance of the routing protocols are illustrated. To retrieve these values, some discrete-time simulations of the system are done in matlab.
The simulator is implemented by considering the following targets:

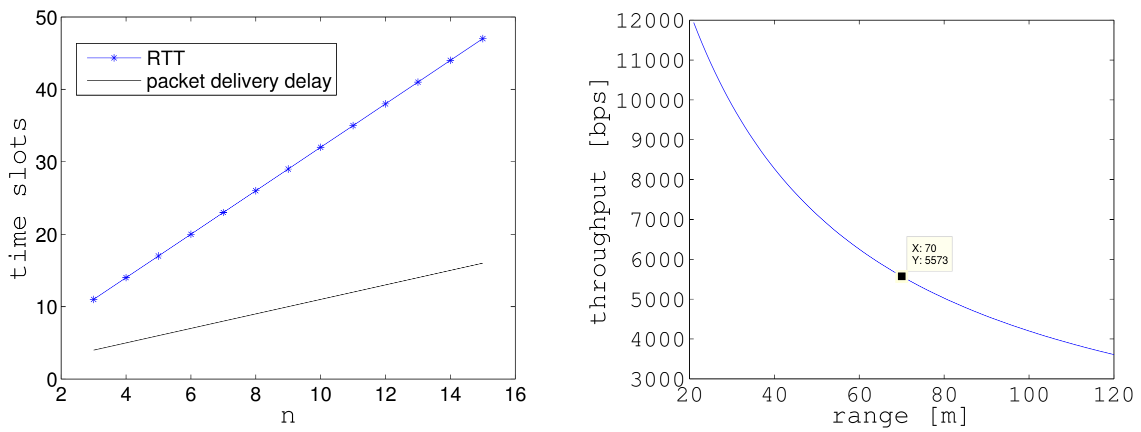
- it should be configured using the values retrieved in section 4.3 for transmission power and distance between two adjacent nodes;
- it should be scalable, in terms of number of nodes, range, channel type and variations of the protocol, such as the inclusion of a caching system and the future development of other kinds of ARQs.

To help the implementation, a scalable Linked List data structure is heavily used during the simulation. The results for different cases are shown in the following subsection.

4.4.1 Ideal case: upper-bound

Firstly, the system is analyzed and simulated over an ideal channel without errors, in order to test the protocol and to retrieve the upper-bound performance. The packet delivery delay is $n+1$ time slots, that is the time required to cross $n+1$ links, instead, the time to deliver an acknowledgement packet is $1+2n$ time slots. Thus, the round trip time is $n+1+1+2n = 3n+2$ time slots (figure 4.6(a)). [7]

In this case, to calculate the throughput, the traffic generated by the controller was analyzed. The controller sends one packet, every three time slots T (eq. (4.7)). The packet size is fixed to $L = 1024$ bits [40], therefore the throughput of an ideal system is $\frac{L}{3T} \simeq 0.333 \frac{pks}{timeSlot}$. In an ideal system, without propagation delay and guard time, $T = 1024/87768 = 11.7$ ms and the throughput would be $C/3 = L/(3T) \simeq 29.256$ kbps. Actually, due to the sound speed (1500 m/s), the delay is very significant and the guard time is required to prevent asynchronous transmissions and receptions. For instance, for $l = 70$ m and $T_G = 0.25 T_T$, $\tau = 46.7$ ms, $T = 61.3$ ms and the resulting throughput is 5.573 kbps (Figure 4.6(b)). In the



(a) Packet delay and round trip time in terms of time slots versus n, in an ideal channel without errors

(b) Throughput vs range. In an ideal channel without errors, it is independent of the number of relays n.

Figure 4.6. *Ideal case performance*

next cases, the throughput will be computed by varying the number of intermediate nodes, independent of the distance, and the retrieved values will be reported in packet vs timeslots. The absolute value, in bps, can be retrieved by multiplying the normalized values per L bits and by dividing by T seconds.

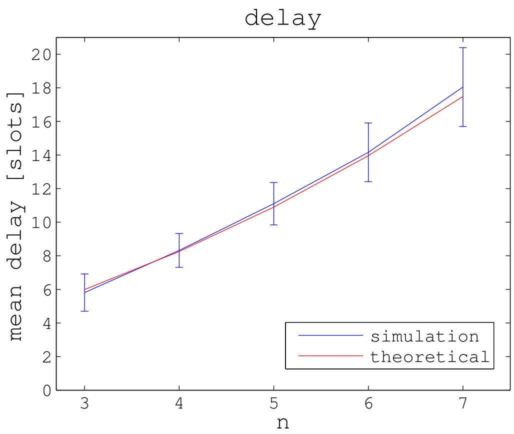
[7] It should be notice that one more time slot is needed for a retransmission, because when the NACK request is received by the controller, it has to wait one more slot to transmit. Thus, the retransmission time is $1 + RTT = 3n+3$ time slots.

4.4.2 Real case: underwater acoustic channel

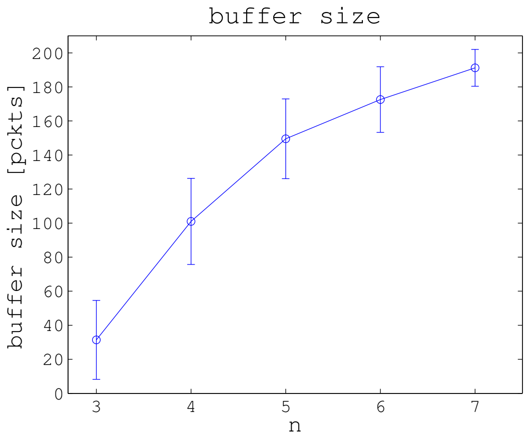
In this section, the performance of four different protocol versions are obtained via simulation and compared, in order to understand which configuration outperforms the others. In all cases, the system is simulated in underwater acoustic environment, the node distance is fixed to $l = 70$ m and the transmission power is set as explained in section 4.3. To achieve sufficient statistical significance, 100 matlab simulations of $T = 1000$ time-slots were performed for each case, in order to obtain throughput, delay and buffer size versus n, with a CI of 0.95. In the first two cases, the transmit power is set looking the worst link target. In the first one, shown in section 4.4.3, only the controller can resend lost packets, whereas, in the latter, section 4.4.4, a caching system allows also the relays to retransmit. For what concerns the last two system versions, in both cases the transmission power is set on the E2E target. The third case, shown in section 4.4.5, does not use any caches, whereas in the fourth system configuration, section 4.4.6, a caching system is implemented. The results show that, by increasing the protocol complexity, the performance improves.

4.4.3 Case 1

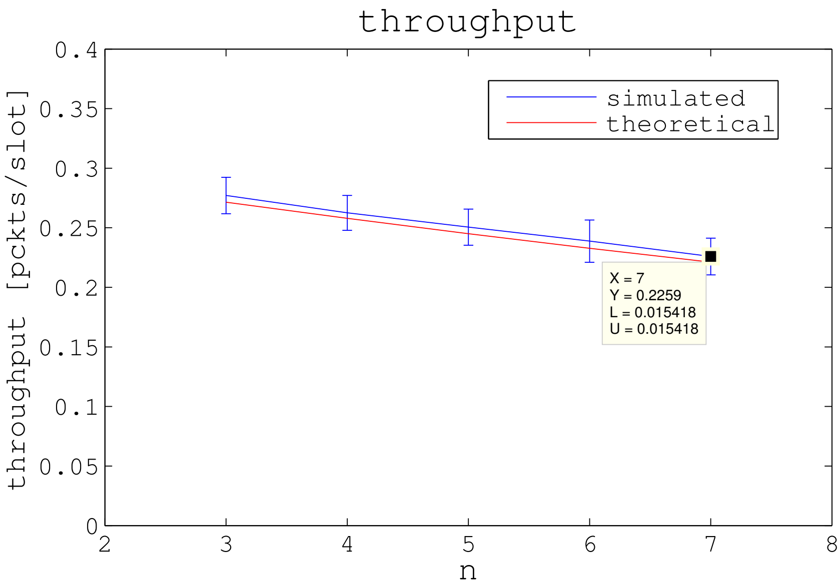
In the first case, the transmit power is chosen to ensure a success of transmission of 0.95 for the worst hop (Figure 4.4), and no caching is used in the intermediate nodes. This network has some advantages and disadvantages: on one hand, compared to the other cases, it is the easiest to set up and the cheapest in terms of complexity and power consumption. On the other hand, it is the worst in terms of performance (Figure 4.7), indeed, all the other configurations outperform this one.



(a) Delay.



(b) Buffer size.



(c) Throughput.

Figure 4.7. *Performance of case 1. Simulated time = 1000 time-slots, number of repetitions = 100.*

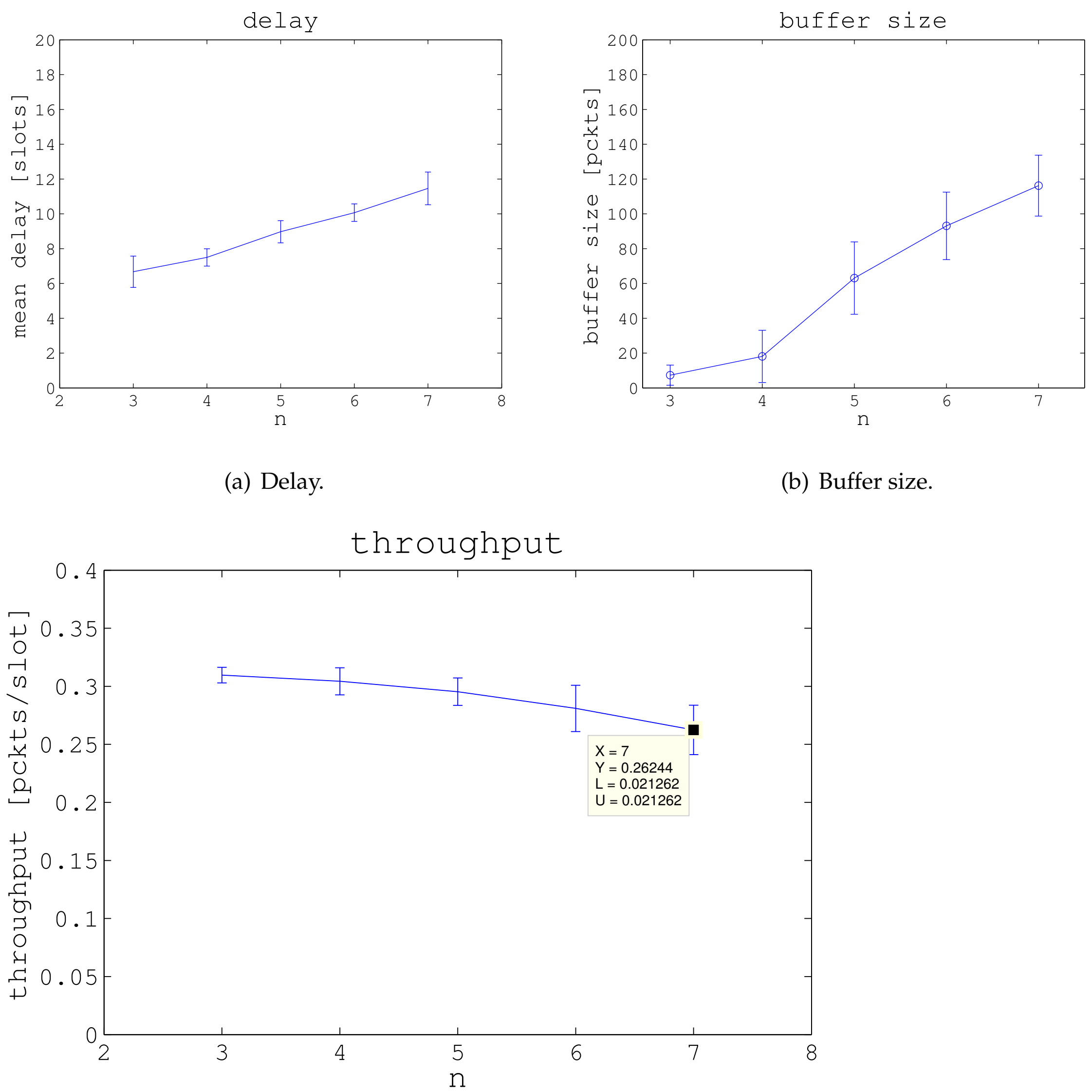
The throughput deceases by increasing the number of hops: the curve shown in Figure 4.7(c) follows the trend of $0.333 \cdot 0.95^{n+1}$. This behavior depends on the choice of the transmission power: ensuring a success of transmission of 0.95 for the worst hop, means that the more hops are present in the network, the higher the E2E error probability becomes. In particular, if each link has the same success probability, the E2E probability becomes $P_e = 1 - 0.95^{n+1}$. Each retransmission takes $1 + RTT = 3n + 3$ time slots, therefore, increasing n, both the average number of retransmissions and the time needed for a retransmission increase. Thus, the mean delivery delay d also increases for increasing n (Figure 4.7(a)), in particular:

$$d = P_e \cdot (n+1) + P_e \cdot (RTT+1) \sum_{i=1}^{\infty} i \cdot (1-P_e)^i = 0.95^{n+1} \cdot (n+1) + \frac{1-0.95^{n+1}}{0.95^{n+1}} (RTT+1) \text{ [slots]} \tag{4.15}$$

Finally, from the simulations we notice that, for $n > 4$, the number of packets received out of order becomes greater than the number of packets received in order. Therefore, by considering a real case of long time transmission, the probability of buffer overflow becomes equal to one. Thus, in these conditions, the system cannot work properly (Figure 4.7(b)). This kind of system could be used only if transmissions take short periods of time. For instance, if the controller goes in back-off and stops to send new information each time it sends 100 consecutive command packets, the system could work properly. Indeed, during the back-off, the buffer will be eventually cleared out thanks to the retransmissions.

4.4.4 Case 2

The second case is very similar to the first one, except for the presence of a caching system. Indeed, the transmit power is chosen to ensure a success of transmission of 0.95 for the worst hop (Figure 4.4), and a caching system is used in the intermediate nodes. This system configuration, provides better results than the previous one in terms of network performance (Figure 4.8). In particular, there is a significant improvement of the throughput (Figure 4.8(c)), of the packet delivery delay (Figure 4.8(a)) and of the buffer size (Figure 4.8(b)). Nevertheless, nothing changes on the global error probability, which still increases exponentially with n. For this reason, despite the general performance improvements, each curve continues to follow the trend to get worst when the number of hops increases. Thus, the global error probability is not the reason of the enhancements. The main reason, depends on the following considerations. Thanks to the presence of a caching system, retransmissions become faster than in the previous case. In particular, without any caching system only the controller could retransmit (and it takes $3n + 3$ time slots), whereas with the considered configuration each node is able to resend a lost packet he has already received.



(a) Delay.

(b) Buffer size.

(c) Throughput.

Figure 4.8. *Performance of case 2. Simulated time = 1000 time-slots, number of repetitions = 100.*

In order to quantify, in average, how faster each retransmission becomes, the following analysis is done. The considered scenario is the simplest one, where each hop has the same error probability. In this case, the average retransmission time is given, in time slots, by

$$\frac{1}{n+1}\sum_{i=0}^{n} 3i + 3 = \frac{3n}{2} + 3 \tag{4.16}$$

which is smaller than $RTT + 1 = 3n + 3$ time slots (Figure 4.9).

In spite of the performance improvements, also this system can be used only if transmis-

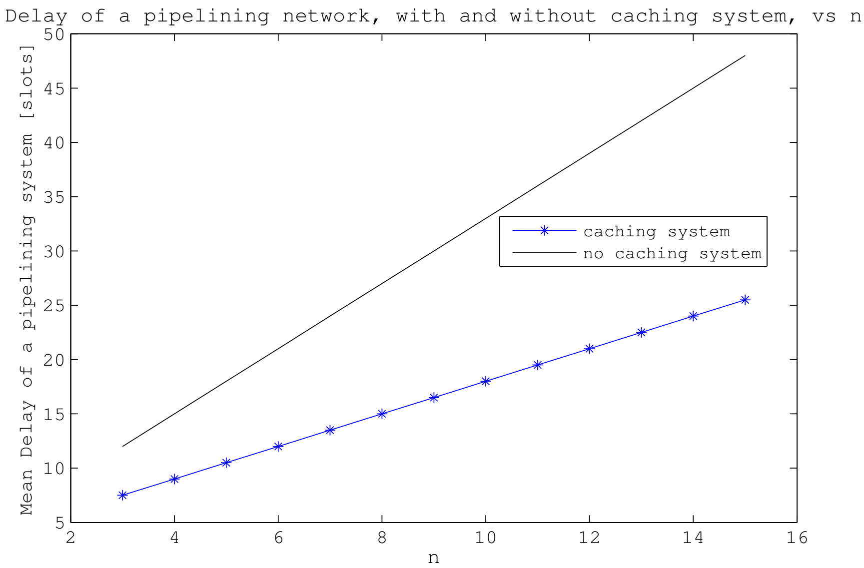


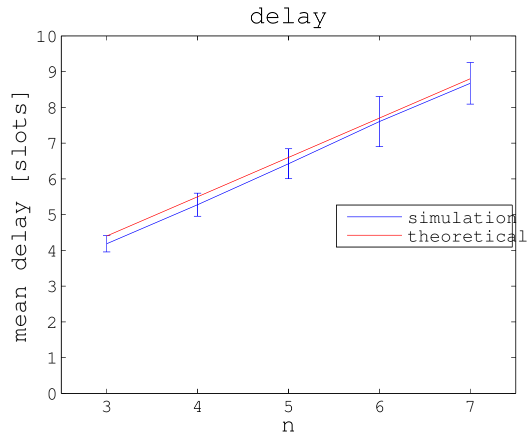
Figure 4.9. *Comparison of average retransmission delay, for a multi-hop pipelining network, either with caching system (d =* $\frac{3n}{2} + 3$ *time slots) and without (d =* $3n + 3$ *time slots).*

sions are burstly. Indeed, for $n > 5$, the number of packets in the buffer has the same order of magnitude of the number of packets received in order, thus, there is an high probability of buffer overflow.

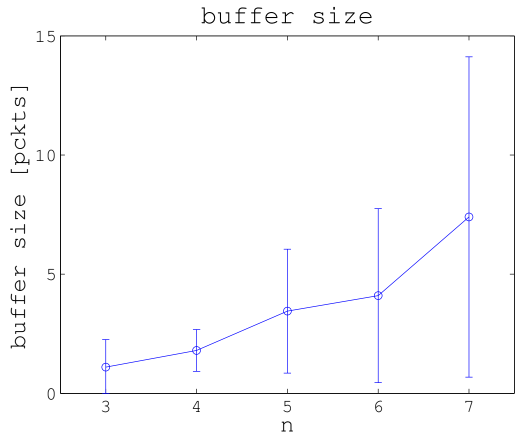
4.4.5 Case 3

In the third case, the transmit power is chosen to ensure a E2E probability of success equal to 0.95 (Figure 4.5), and no cache is used in the intermediate nodes. This system configuration provides good performance (Figure 4.10), outperforming both the previous cases. In particular, the throughput (Figure 4.10(c)) does not depend on the number of hops, whereas the delay (Figure 4.10(a)) increases linearly with n, and the buffer size (Figure 4.10(b)) grows with n. However, despite the buffer trend, its size takes smaller values than the number of packets received in order. The reason of this general performance enhancement is that, thanks to the E2E design, the global error of transmission is fixed, and does not depend on the number of nodes. Therefore, the throughput does not depend on n and is about $0.3333 \cdot 0.95 = 0.3166$ pkts/timeSlot, whereas the average delivery delay, in time slots, is:

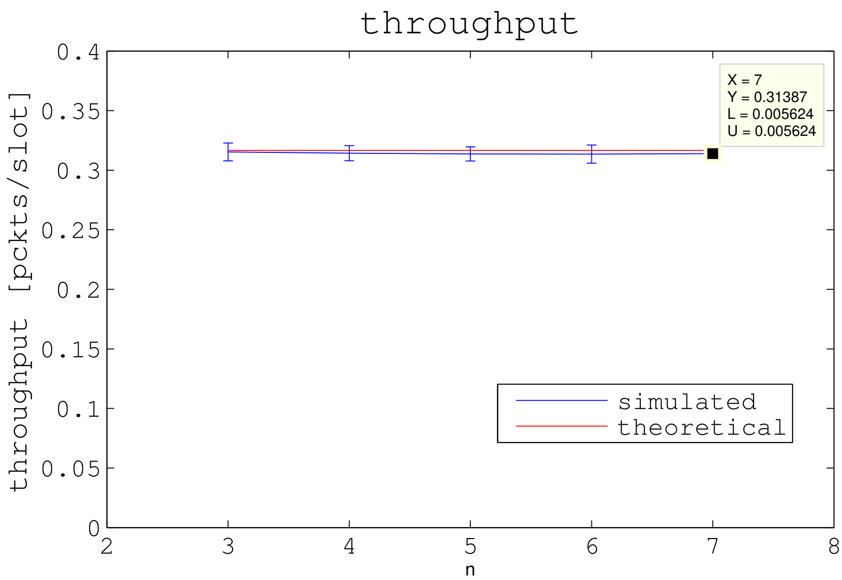
$$d = 0.95 \cdot (n+1) + 0.95 \cdot (RTT+1) \sum_{n=1}^{\infty} n \cdot 0.05^n = 0.95 \cdot (n+1) + \frac{0.05}{0.95} \cdot (3n+3) \simeq 1.1 + 1.1n \text{ [slots]} \quad (4.17)$$



(a) Delay.



(b) Buffer size.



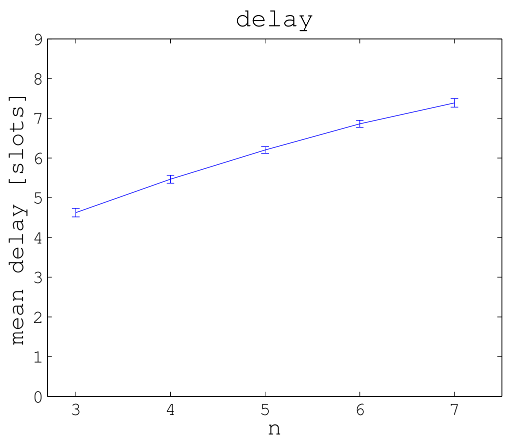
(c) Throughput.

Figure 4.10. *Performance of case 3. Simulated time = 1000 time-slots, number of repetitions = 100.*

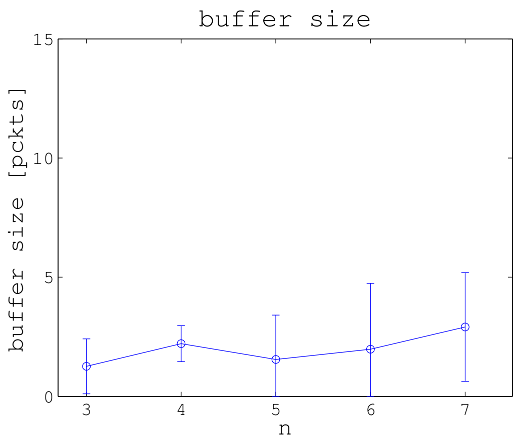
The results obtained by the simulation are very encouraging, indeed the performance are very close to the ideal case and there is a low probability of buffer overflow. Therefore, if the system is set up with this configuration, it works properly and can be used for long time transmissions with low probability of buffer overflow.

4.4.6 Case 4

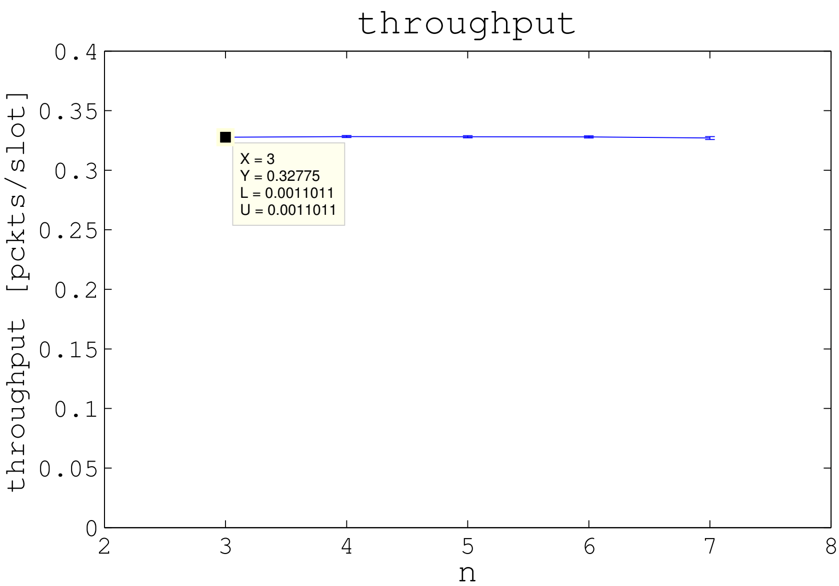
The fourth and last case bears the highest system complexity. Indeed, the transmit power is chosen to ensure a E2E transmission success of 0.95 (Figure 4.5) and a caching system is implemented in the intermediate nodes. On one hand , this system configuration is the most expensive in terms of power consumption and complexity, on the other hand it provides the best results in terms of performance (Figure 4.11), outperforming all the other cases.



(a) Delay.



(b) Buffer size.



(c) Throughput.

Figure 4.11. *Performance of case 4. Simulated time = 1000 time-slots, number of repetitions = 100.*

In fact, it combines the benefits obtained by the E2E design with the caching system. In particular, the throughput does not depend on n (Figure 4.11(c)), while buffer size (Figure 4.11(b)) and mean delivery delay (Figure 4.11(a)) follow the trend to increase slightly with n, maintaining smaller values than in the other cases.

4.5 Conclusions

The results presented in this chapter show that a pipelining network could be used to increase the transmission range of the remote control system. In particular, while for burstly transmissions the transmit power could be chosen by optimizing the worst link, an E2E design is more convenient to transmit for long periods. The caching system increases the system performance, however, it introduces an higher level of complexity at the intermediate nodes. Indeed, an additional buffer is needed and each intermediate node has to check whether a retransmission is required. Thus, the choice to use or not caches depends on the design trade-off between performance and system complexity.
Despite the multi-hop network is a feasible solution to increase the transmission range, it is not the best one. Actually, changing transmission technology may be more efficient and may outperform the multi-hop network. Indeed, to cover a range of 900 m, a pipeline with 9 Hermes nodes is needed ($n = 7$ and $l = 100\ m$), thus a throughput around 4 kbps is provided (Figure 4.6(b)). [8] Instead, using Evologics' S2C R 48/78 [21], a range of 1 km can be covered with a throughput of 31.2 kbps, although this figure likely refers to ideal conditions. Nevertheless, as soon as omni-directional optical modems start to be available, this network could be used to to extend optical range, where the propagation delay is very small (order of μs) and the achieved throughput potentially very high (order of Mbps).

[8] It is less than 1/3 the Hermes capacity, because each time slot includes the propagation time (Figure 4.6(a) and 4.6(b)).

Chapter 5

Controller simulator

5.1 Introduction

In the previous chapters, the design of a wireless remote control for ROV has been presented, by analyzing features, bitrate, working range and available technologies. In this chapter, we test the designed system, in order to prove whether the controller is reliable and provides good QoS. To test the system and retrieve its own performance, the results of some simulations are presented. In particular, in these simulations, the ROV position is driven by the controller, and the resulting path is compared with the theoretical one (section 5.3). All the simulations are implemented in the DEsign, Simulate, Emulate and Realize Test-beds for Underwater network protocols (DESERT) [41] framework, an extension of Multi-InteRfAce Cross-Layer Extension library for the Network Simulator (NS-MIRACLE).[1] The simulator structure is described in section 5.2.

5.1.1 Considered Scenario

In this section we present the scenario considered for the simulations: a network with two nodes, where the first one represents the controller and the second one the ROV. Both nodes are placed under salty, shallow and turbid ocean water [2]. While the controller position is fixed, the ROV moves at constant speed $v = 1$ m/s. The network simulator used for

[1] Both DESERT and NS-MIRACLE were developed by the Special Interest Group on NETworking (SIGNET), a researcher group of Department of Information Engineering (DEI), University of Padova.

[2] Other details are explained in table 3.1

the controller testing, is specifically designed for underwater acoustic transmission. Therefore, the system is simulated to work in MODE 0, 1 and 2 (Table 3.13), where only acoustic modems are involved in the communication. In particular, the Hermes Underwater Acoustic Modem behavior is simulated. [23] [3] The acoustic noise is assumed to be Gaussian, the shipping factor equal to 0.5, moreover, a practical spread of 2 and no wind are considered.

5.2 Simulation

In this section, is presented how the system simulator is designed and set up. In particular, to simulate the system and retrieve the performance metrics, this procedure is followed:

1. the desired theoretical path is created (Section 5.2.1);
2. the behavior of the ROV - controller system is simulated (Section 5.2.2);
3. in a post-processing phase, the performance metrics are retrieved (Section 5.2.3).

5.2.1 Path creation

The theoretical path is created before the simulation and saved in a file, formatted as in the following description:

- In each row, there is a way-point entry.
- The first column contains the sending time, i.e., when each way-point transmission is scheduled.
- The next three columns contain the way-point coordinates (x, y and z).

This file is created thanks to a matlab script, where each position is chosen by sampling a mathematical function, and the transmission time is chosen by paying attention to the following considerations. The most important things is that the controller, before to send a new way-point, waits the previous one is reached. Therefore, an analysis of the sending time has to be done. In an ideal system without any errors and retransmissions, to travel

[3] A description of used frequency, range, bandwidth and available bitrate of this particular modem, is done in section 4.1.1. These parameters are used to set up the simulator physical layer.

from the position p_{k-1} to the position p_k, the ROV takes:

$$t_{min,k+1} = \frac{distance(p_k, p_{k-1})}{v} \tag{5.1}$$

where v is the ROV speed. Thus, $t_{min,k+1}$ is the minimum time gap that the controller needs to wait before sending the next way-point p_{k+1}. However, in a real system, there are also additional delays, due to operations like queuing, processing and retransmissions. Thus, the minimum time gap can not ensure the correct reception of new way-points. Actually, the main source of additional delay is packet retransmissions. In fact, a command packet retransmission happens when, after a transmission, the corresponding ACK is not received, and a subsequent Retransmission Timeout (RTO) occurs. Thus, each retransmission causes an additional delay of RTO, therefore, the next way-point should be sent at least after $t_{min} + n_{rtx} \cdot RTO$. The number of retransmissions (n_{rtx}) is not known, thus, the decision taken in this thesis is that

$$t_{gap,k+1} = t_{min,k+1} + t_g > t_{min,k+1} \tag{5.2}$$

where t_g is the guard time. The RTO is fixed and calculated as $RTO = 2RTT_{max}$, the RTT calculated at the maximum transmission range r:

$$RTT = 2\frac{r}{c} + \frac{L_{ctr}}{C} + T_{ROV} + \frac{L_{mon}}{C} \tag{5.3}$$

where:

- $c = 1500$ m/s, is the sound speed underwater;
- $C = 87768$ bps, is the modem bitrate;
- $L_{ctr} = 1024$ bit, is the control packet size;
- T_{ROV}, is the Constant Bit Rate (CBR) period of the ROV, in seconds;
- L_{mon}, is the monitoring packet size, in bit.

5.2.2 NS2 module and protocol

In order to retrieve the system reliability, some simulations are carried out using DESERT [41]. The simulator is based on two different languages: on one hand, C/C++ classes are used for module development, on the other hand, Tool Command Language (Tcl)/OTcl scripts are used for parameter and network layers settings.

In this thesis, an ad hoc Tcl script is used, where all the stack layers are chosen from the modules in the library, except the application one. For the application layer, a new C++ add-on, called *uwrov*, is implemented. In particular, this add-on is an extension of *uwcbr*, an existing module for the application layer. Follows the description of the *uwcbr* module available in the Doxigen documentation. [4] *uwcbr* implements a CBR packet traffic between a sender and a receiver. The data traffic can be generated either by injecting packets in the network with a constant inter-arrive time period or according to a Poisson process of given rate. In addition, there is the possibility to send data packets at scheduled epochs. In this thesis, this module is specialized in two different branches: *uwrov-module* and *uwrovctr-module*. The first one is used to simulate the ROV behavior, whereas the second one is used for the controller. In addition, also the data packets are specialized, either in *control* or *monitoring packets*. Finally, an additional class is implemented in order to simulate the ROV mobility at constant speed: *smposition* (simple movements position).

The system behavior is the following: the controller has fixed position and sends control packets to the ROV, in order to control its movements. Instead, the ROV does mainly two things: firstly, it moves, with constant speed, toward the position sent by the controller. In addition, it sends monitoring packets to the controller. For what concerns the ROV mobility, the main rule is the following: the last way-point received is given priority when moving the ROV, even in case the previous one has not been reached jet.
In the list below, there is the description of the application protocol:

- The *controller* sends *control packets* to the ROV at scheduled time instants.
- Each *control packet* contains a new way-point and is identified by a SN.
- For each control packet sent, an ACK is expected to be received before a RTO, due to confirm the right transmission.
- Depending on whether or not an ACK is received, two different things could happen:
  - if the RTO occurs, the control packet is resent;
  - otherwise, if a new way-point is sent, all timeouts are reset (because the last way-point has the priority) and no retransmissions occur.

[4] Available at `http://telecom.dei.unipd.it/ns/desert1/DESERT_HTML_doxygen_doc/`.

- The ROV periodically sends *monitoring* packets to the *controller*.
- Each *monitoring packet* contains the current ROV position and, if is needed, an ACK in piggyback.
- When a new waypoint is received, the ROV starts to move from the current position to the new way-point with constant speed.

Packet sizes, retransmission timeout, monitoring packet period, control packet scheduling, channel bitrate, frequency, bandwidth and ROV speed are set in the Tcl script. In particular, the scheduled path are predefined and loaded from an external file (described in 5.2.1). In addition, the ROV position is periodically checked and saved in another file, in order to allow path evaluation and comparison in post processing (section 5.2.3). It has to be noticed, that both increasing the monitoring packet size and reducing the sending period, the monitoring throughput becomes bigger. This technique could be used to simulate high monitoring, such as video transmission.
The description of the other stack layers, follows the list below:

4. Transport layer: User Datagram Protocol (UDP) provided by the *uwudp* module.
3. Network layer: static routing with Internet Protocol (IP) provided by using together the modules *uwip* and *uwstaticrouting*.
2. Data link: Carrier Sense Multiple Access (CSMA) - 1 persistent MAC protocol, provided by *uw-csma-aloha*.
1. Physical layer: underwater physical (*uwphisical*), set with Hermes parameters.

5.2.3 Performance evaluation

The performance described in this section, are observed in order to evaluate the quality of the designed system. In particular, the deviation between the original and the actual path followed by the ROV is analyzed. To do this, both the paths are sampled, and the distance (d) between the corresponding theoretical and actual positions, is observed. Every position is identified by three coordinates, (x, y, z), and the distance d between the real and the theoretical position is calculated using the Euclidean distance definition:

$$d = \sqrt{(x_r - x_t)^2 + (y_r - y_t)^2 + (z_r - z_t)^2} \tag{5.4}$$

where x_r means the abscissa of the real position, x_t is the theoretical one, and so on for the other coordinates. In addition, the average Mean Square Error (MSE) is estimated, in order to obtain a global performance index. In particular, a partial MSE is calculated for each oversampled sub-path between 2 matched way-points. Thus, the global index is the average of all the partial MSE values:

$$MSE_k = \sum_{i=1}^{N_k} \frac{(x_r - x_t)^2 + (y_r - y_t)^2 + (z_r - z_t)^2}{N_k}; \quad MSE = \frac{\sum_{k=1}^{N_{subpath}} MSE_k}{N_{subpath}} \tag{5.5}$$

Another index observed, is the guard time to the average time gap ratio, $\frac{t_g}{t_{gap}} = \frac{t_g}{t_g + t_{min}}$, [5] in order to understand the percentage of delay caused by t_g.
Finally, both theoretical and actual path are plotted in the same figure, in order to observe qualitatively whether the the two curves are overlap.
The described analysis is carried out in post-processing, after the simulation. In fact, while the theoretical path is well known and chosen before (Section 5.2.1), the actual one is saved in a file during the simulation. Thus, to evaluate these metrics, both the paths are loaded in a matlab script where the performance are retrieved.

5.3 Results

In this section, the simulation results are presented, paying attention to the network performance described in 5.2.3. In particular, three different cases are observed, in order to prove the system reliability in different situations. The cases are diversified in terms of monitoring traffic and guard time, according with 5.2.1. In particular, during the simulations, Hermes acoustic modem is involved and the system is tested either in MODE 0 (section 5.3.1), MODE 1 (section 5.3.2) or MODE 2 (section 5.3.3). In each case, the controller is placed at position (0, 0, -15), whereas the ROV initial position is (0, 100, -15); the same path is transmitted in all cases, in order to make a path deviation comparison possible. In details, the path is sampled in 101 way-points and the distance between two consecutive way-points is, on average, 20 m. Thus, since the ROV speed is 1 m/s, the time required to travel from a way-point to the subsequent one is, on average, 20 s.

[5] In the following sections, this index is called for simplicity **guard to gap ratio**.

5.3.1 Case 1: MODE 0

In the first case, the system is tested in MODE 0, where the required transmission bitrate is 2 kbps, according with section 2.2. Hermes acoustic modem is able to send data up to 87.768 kbps, thus, using this device to transmit a low bitrate, such as 2 kbps, is inefficient and can look like a waste of technology (indeed, just 2.28% of the available bitrate is used). In any event, this configuration ensures reliability, robustness and low packet error rate. For instance, from the simulations results we observe that, for the correct transmission of 101 way-points, in average 105 control packets need be sent. Therefore, for this system configuration, the control packet error rate is $4/105 = 3.81\%$. In order to examine the path deviation, the system is simulated varying the guard time (t_g), and the corresponding MSE is observed (Figure 5.1).

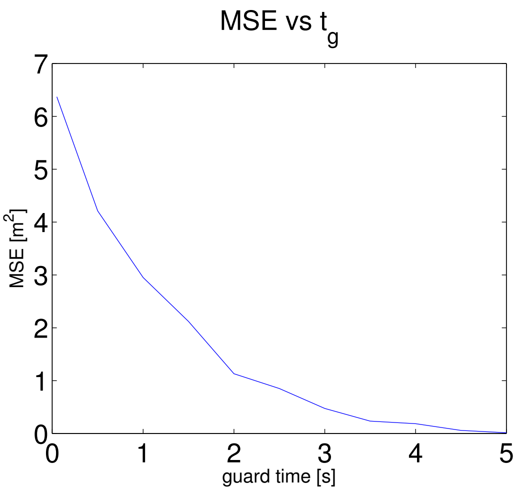


Figure 5.1. *MSE vs guard time in MODE 0.*

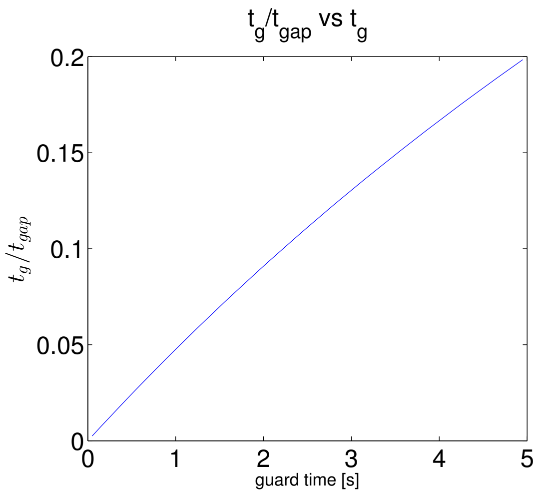


Figure 5.2. t_g/t_{gap} *vs guard time in MODE 0.*

Increasing the guard time, the system performance improves, in fact, the MSE decreases and the path deviation becomes smaller. This trend is proven by the simulations results, as explained below. Firstly, with $t_g = 0.05$ s, MSE $= 6.37\ m^2$ and the maximum path deviation is around 12 meters (figure 5.3). Instead, with $t_g = 3.5$ s, MSE $= 0.23\ m^2$ and the maximum path deviation is around 5 meters (figure 5.4), whereas with $t_g = 5$ s there is no more than 1.2 meter of deviation (Figure 5.5) and MSE $= 0.014\ m^2$. Although increasing t_g the path deviation decreases, the latency delay gets bigger (Figure 5.2). However, this system configuration provides good QoS in terms of path deviation and additional latency. Indeed, to ensure a maximum path deviation of 1 m, a guard time of 5 seconds is needed. This is an

important result, because, despite t_g induces a guard to gap ratio of the 20%, the actual path is very close to the theoretical one.
Increasing the distance between ROV and controller, the packet error transmission gets bigger, this is why, in all the analyzed cases, the maximum path deviation occurs in correspondence of the farthest way-points of the path.

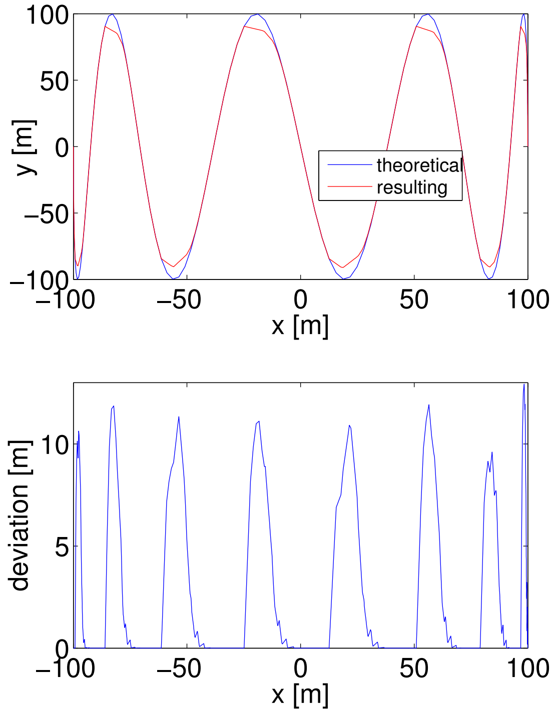


Figure 5.3. *Simulation of the system in MODE 0 with* $t_g = 0.05$ *s.*

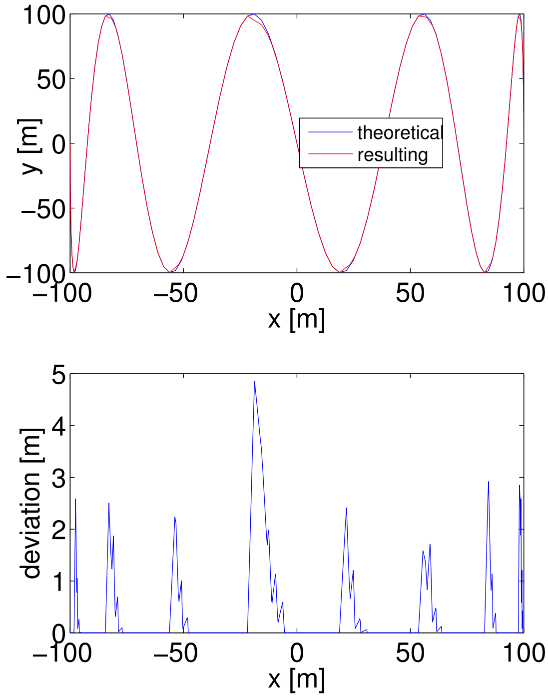


Figure 5.4. *Simulation of the system in MODE 0 with* $t_g = 3.5$ *s.*

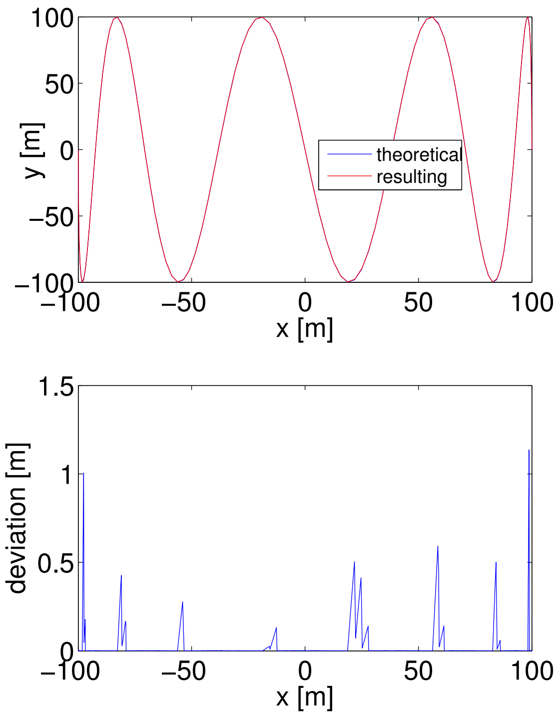


Figure 5.5. *Simulation of the system in MODE 0 with* $t_g = 5$ *s.*

5.3.2 Case 2: MODE 1

In the second case, the system is tested in MODE 1, where the bitrate is 30 kbps. This case is analyzed in the same way of the previous one, and the following results are obtained. On one hand, with this configuration, less than half bitrare provided by Hermes is used (around 35%), on the other hand, there are good reliability and a low packet error rate. Indeed, in average, for the correct transmission of 101 way-points, 112 control packets are needed, thus, the control packet error rate is $11/112 = 9.82\%$. For what concerns the path deviation versus the guard time (Figure 5.6), the system follows the same trend of the previous case.

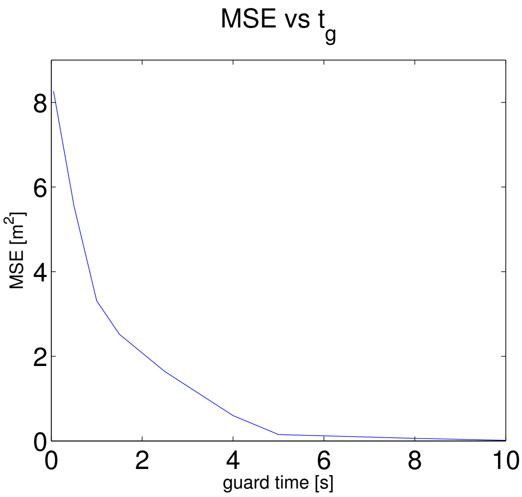


Figure 5.6. *MSE vs guard time in MODE 1.*

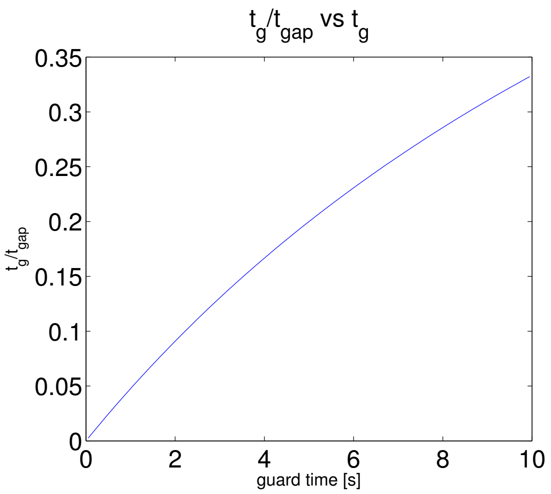


Figure 5.7. t_g/t_{gap} *vs guard time in MODE 1.*

In particular, increasing the guard time, the system performance improves, but, due to the higher packet error rate, a longer guard time t_g is needed to achieve the same MSE of 5.3.1. For instance, for $t_g = 0.05$ s, MSE $= 8.27\ m^2$ and the maximum path deviation is around 15 meters (Figure 5.3). Instead, for $t_g = 4$ s, MSE $= 0.6\ m^2$ and the maximum path deviation is around 5 meters (figure 5.4), while for $t_g = 10$ s (Figure 5.5), there are no more than 2 meters of deviation and a MSE of $0.015\ m^2$. A bigger guard time means bigger latency, as confirmed figure 5.7: to obtain less than 2 meters of maximum deviation, a guard time of 10 seconds is needed, that is half of the minimum time gap. It means that, the guard to gap ratio is 0.33.

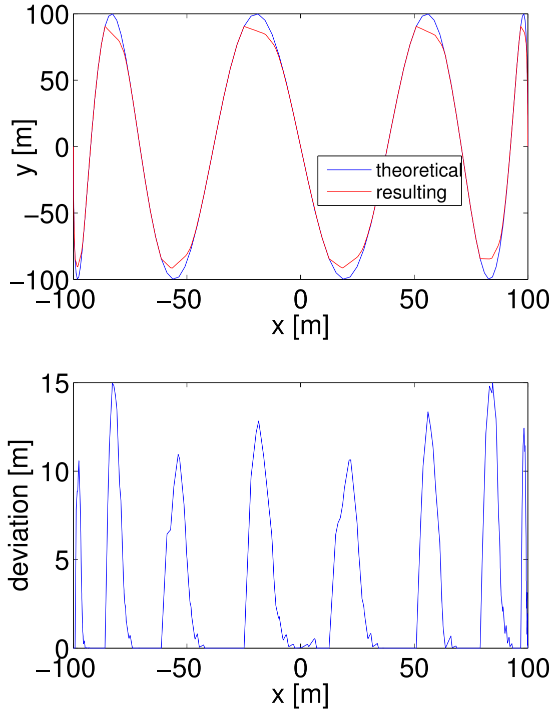


Figure 5.8. *Simulation of the system in MODE 1 with* $t_g = 0.05$ *s.*

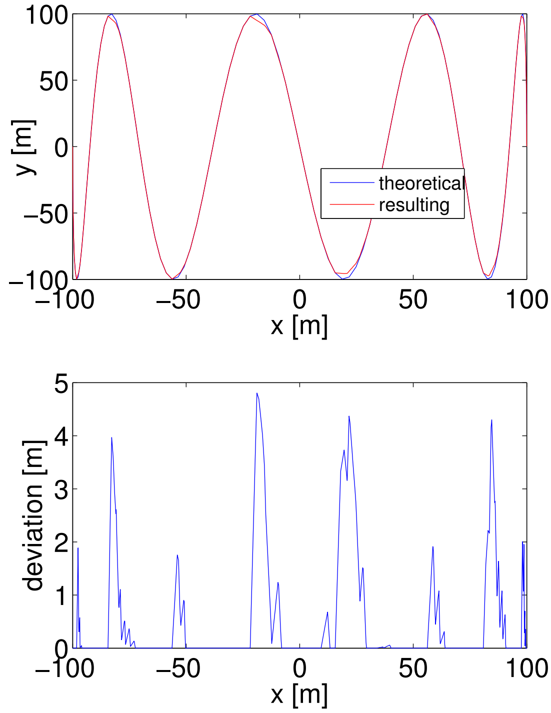


Figure 5.9. *Simulation of the system in MODE 1 with* $t_g = 4$ *s.*

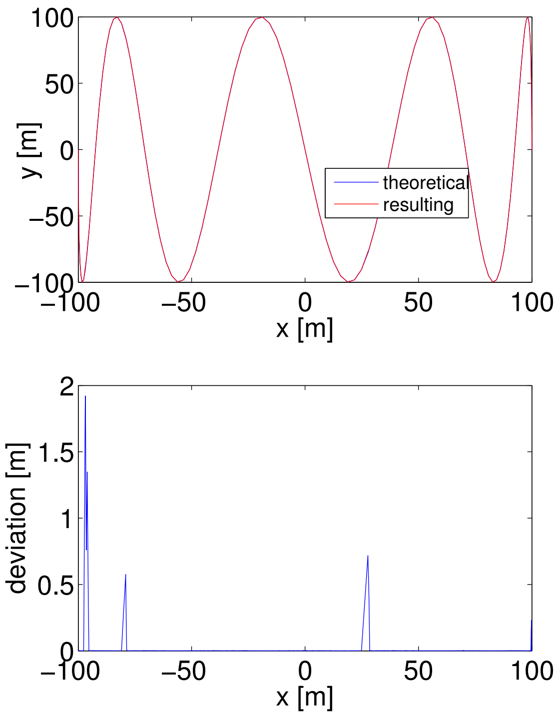


Figure 5.10. *Simulation of the system in MODE 1 with* $t_g = 10$ *s.*

5.3.3 Case 3: MODE 2

In the third case, the system is tested in MODE 2, where the used bitrate is 70 kbps. In this configuration, Hermes is used very close to the full bitrate (around 80%). However, there is a high packet error rate due to the simultaneous transmission of control and monitoring packets. In fact, due to the high traffic sent from the ROV to the controller, the channel is occupied by monitoring packets for the most of the time. This means that, on one hand, the ROV-to-controller channel is used very efficiently and a good monitoring service is provided. On the other hand, when the controller sends a packet to the ROV, there is a high probability of collision with monitoring packets. In fact, in average, for a correct transmission of 101 way-points, 262 control packets are sent, thus, the control packet error rate is $161/262 = 61.45\%$. Also in this case, to evaluate the system, path MSE and deviation behavior are observed, as the guard time changes (Figure 5.11).

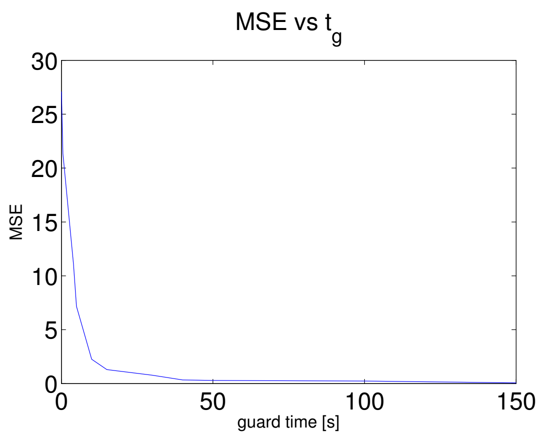


Figure 5.11. *MSE vs guard time in MODE 2.*

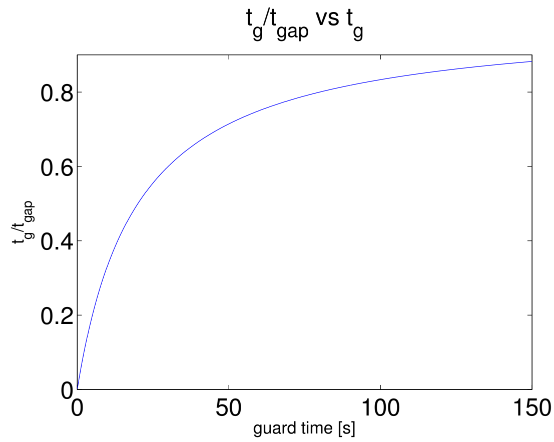


Figure 5.12. t_g/t_{gap} *vs guard time in MODE 2.*

Increasing the guard time, the path is followed better, like in the other cases. However, with this system configuration, to obtain good performance in terms of path deviation, a very long guard time is needed. Indeed, for $t_g = 0.05$ s, the MSE is 27.1 m^2 with a maximum path deviation of 35 m (figure 5.3); with $t_g = 30$ s, the MSE is 0.78 m^2 and the maximum path deviation becomes 3 m(figure 5.4), while only with a t_g of 150 s the MSE is 0.068 m^2 and the path deviation less than 2 meters (figure 5.5). In this case the guard time to obtain path reliability is bigger than $t_{gap,min}$, it means that t_g is bigger than the time needed for the ROV locomotion (in fact the guard to gap ratio is 88%, to ensure a path deviation shorter than 2 m, figure 5.12).

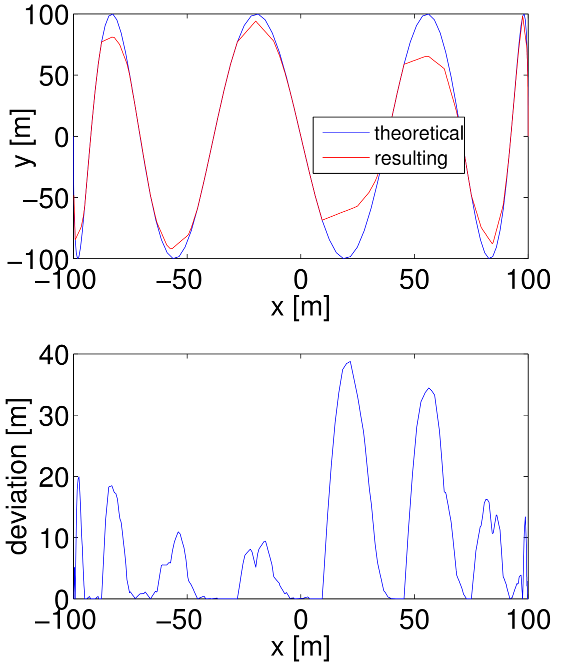


Figure 5.13. *Simulation of the system in MODE 2 with* $t_g = 0.05$ *s.*

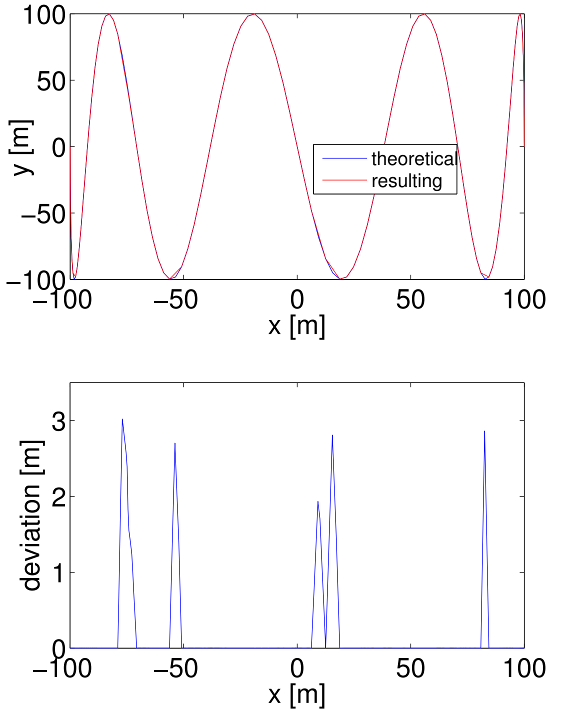


Figure 5.14. *Simulation of the system in MODE 2 with* $t_g = 30$ *s.*

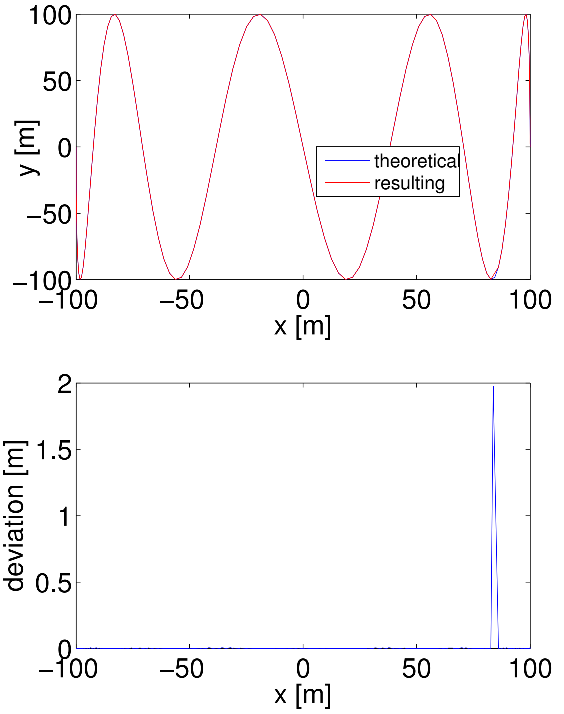


Figure 5.15. *Simulation of the system in MODE 2 with* $t_g = 150$ *s.*

5.4 Conclusions

The results show that, in the simulated system, the main source of errors is the deafen due to the simultaneous transmission of control and monitoring packets. Thus, with the high rate monitoring service provided in MODE 2, more errors occur with respect to testing the system in MODEs 0 ad 1. Furthermore, in that high monitoring configuration, the provided QoS is not acceptable, indeed, both Packet Error Rate (PER) and guard to gap ratio are too high to allow a precise and reliable control. In fact, to obtain a low path deviation, a guard time bigger than $t_{gap,min}$ is needed (Figure 5.15) and this causes high latency. Thus, the system cannot be used in MODE 2 configuration. On the other hand, the system tested in MODE 0 and MODE 1, gives encouraging results: low PER, good reliability with a low guard time. Actually, using the system in MODE 0 is very inefficient, indeed, just 2.28% of the available capacity is used, whereas, the 35% is used in MODE 1, without significant loss of performance. Thus, the system tested in the latter mode, gives the best results in terms of performance.

To improve the system performance, in particular for MODE 2, another MAC layer should be used. Indeed, the 1 persistent CSMA, gives very good results in systems where the propagation delay is smaller than the time needed due to the channel capacity. In contrast to electric and optical transmissions, where this happens thank to the high propagation speed (speed of light), in acoustic transmissions the propagation delay has the same order of magnitude of the total transmission time, due to the low speed of sound. [6] Thus, there is a high probability that a node observes the channel idle and starts to transmit, while another transmission has already begun.

In order to solve this problem, a TDMA should be used, thanks to the nature of the system. Indeed, the network is composed of 2 nodes, one that sends high monitoring traffic and one that sends some control packets, thus, the system synchronization would be easy. For instance, to ensure the synchronization, a time-stamp could be included in each monitoring packet, thus, knowing ROV position and when the packet was sent, the controller could update its internal clock. In this way, the network synchronization would be ensured. Another

[6] For instance, for what concerns a control packet transmission, it takes $\frac{1024\ b}{87768\ bps} = 0.01167\ s$ due to the channel capacity, plus $\frac{100\ m}{1500\ m/s} = 0.0667\ s$ due to the propagation delay, while both in electromagnetic and optical transmission the propagation delay is just $\frac{0.1\ km}{3 \cdot 10^5\ km/s} = 0.33\ \mu s$.

solution to avoid interference, is to use two different transmission technologies for the up and the down link: a high bitrate modem should be used to send monitoring packets, and a low bitrate modem for control packets. For instance, Hermes provides both an high bitrate modem, plus a low bitrate downlink. [7] In this way, both ROV and controller could transmit simultaneously without interference, but each control packet would take more time to be received.

[7] The Hermes downlink transmits up to 4.3 kbps using a different bandwidth than the uplink.

Chapter 6

Conclusions and future improvements

In this thesis, a multi-technology wireless remote control for underwater equipment is presented. In particular, the system is designed to control ROVs movements ad status, in order to avoid mobility limitations due to the wired umbilical cable.
The controller works in four different modes, providing different QoS, in order to respect he current transmission technology bitrate and range constrains. In particular, while position and status are controlled in the same way for each mode, there is a big difference on the provided monitoring services:

- in MODE video HD, Sonardyne BlueComm HAL ([25]) is used, and a HD real-time video monitoring is provided up to 20 m;
- in MODE 2, a low video monitoring is available up to 100 m, thanks to the Hermes acoustic prototype ([23]);
- a slide show monitoring service can be provided up to 1 km in MODE 1, thanks to the Evologics modem S2C R 48/78 [21];
- for longer range transmissions, up to 3.5 km, just position and status monitoring can be provided by Evologics modem S2C R 18/34 [21], using the controller in MODE 0.

The wireless remote control is designed to work in in very challenging environments, such as a port area, in order to ensure ROV control and monitoring in every condition. Via simulation, encouraging results were retrieved in terms of reliability, in particular:

- a multi-hop network is presented (in Chapter 4) to extend the transmission range at the expense of a throughput loss;
- the ROV is driven through a given route sending successive way-points by a command node over a single hop network, and the actual ROV path is compared to the desired path in order to quantify deviations (Chapter 5).

Despite the retrieved results prove the system quality, other solutions could be tested in order to improve the performance. For instance, as far as omni-directional optical modems (such as [27]) start to be more reliable and easily available, the multi-hop network should be tested for optical transmissions. Indeed, the retrieved multi-hop acoustic network performance are outperformed by long range devices, due to the slow propagation speed. Thus, given the current state-of-art of acoustic modems, it is better to extend the range of the remote control system by employing a different transmission technology rather than by using a multi-hop network.

For what concerns the remote control system simulation, in the proposed configuration the performance decreases by increasing the monitoring traffic, due to interference between control and monitoring packets. In order to reduce packet collisions, the system may be tested using a TDMA MAC layer, rather than the 1 persistent CSMA. Therefore, a new DESERT-module for the MAC layer is going to be designed, to test this system configuration.

Another solution to avoid interference, is to test the system using two different transmission devices from the up and the down-link. However, to simulate the system with this configuration, a new DESERT module needs to be created. In particular, a new physical layer is going to be implemented, in order to allow multi-modal communication.

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