UNIVERSITY COLLEGE LONDON
UCL DEPARTMENT OF SECURITY AND CRIME SCIENCE

MRes in Security Science

Data Communication for Underwater Sensor Networks

Author:
Veronika Yordanova

Supervisor:
Prof. Hugh Griffiths
Dr. Kevin Chetty

August 14, 2013

Project submitted in partial fulfilment of the requirements for the degree of **MRes in Security Science** (UCL) of the University of London in 2013.

UNIVERSITY COLLEGE LONDON
UCL DEPARTMENT OF SECURITY AND CRIME SCIENCE

MRes Project

SUPERVISOR'S DECLARATION

Name of student: Veronika Yordanova

Name of supervisor: Prof. Hugh Griffiths

I confirm that the student named above has undertaken their project under my supervision, and that they have attended meetings with me as requested, and provided me with adequate information about the progress of their research.

Supervisor's signature...

Date...

UNIVERSITY COLLEGE LONDON
UCL DEPARTMENT OF SECURITY AND CRIME SCIENCE

MRes Project

SUPERVISOR'S DECLARATION

Name of student: Veronika Yordanova

Name of supervisor: Dr Kevin Chetty

I confirm that the student named above has undertaken their project under my supervision, and that they have attended meetings with me as requested, and provided me with adequate information about the progress of their research.

Supervisor's signature

Date..

MRes in Security Science

Declaration

I, Veronika Yordanova hereby declare that this dissertation is my own original work and that all source material used has been clearly identified and acknowledged. No part of this dissertation contains material previously submitted to the examiners of this or any other university, or any material previously submitted for any other examination.

Signed..

Date...

Acknowledgements

I wish to thank Prof. Hugh Griffiths for the motivation and guidance he gave me throughout the year, and Dr. Kevin Chetty for his advice and feedback for my work. This project was funded by EPSRC Grant for Security Doctoral Training Centre no: EP/G037264/1 and Atlas Elektronik UK.

Abstract

Networked sensors have the advantage of collaboratively exploring an area of interest. This is beneficial for underwater applications such as real time surveillance and exploration, which are impractical with the current state of technology. However, there are some fundamental limits and challenges for enabling a robust and efficient deployment of such networks and they are reviewed in this paper. Acoustic, electromagnetic and optical waves are explored as potential communication carriers, as well as hybrid functionality. The theoretical fundamentals and recent advances of each physical layer technology are discussed. As a result, a recommendation for a shallow water underwater sensor network design for security application is provided. The work also provides an introduction to engineers specialising in terrestrial communications that are interested in underwater design and want to become aquatint with the fundamental differences in the two domains. The focus is on shallow water propagation and applications targeting security systems.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Underwater Sensor Networks

The conventional approach of using a single sensor for underwater monitoring missions is based on deploying instruments that record data over a period of time which are then recovered. Such technique however, is prohibitive for acquiring real-time data transmission, which is critical for surveillance and monitoring missions, since the recovery of the instruments might happen months after the beginning of the trial. Deploying single sensors also makes the mission inflexible in case of faulty equipment. This comes from the fact that it might be difficult to detect early failures with nodes that rely on recorded data. Another drawback is that the recovery of the nodes makes the mission dependant on ships, which increases the overall cost. Therefore, it is obvious that there are many cases where current techniques are not sufficient to meet the needs of particular applications.

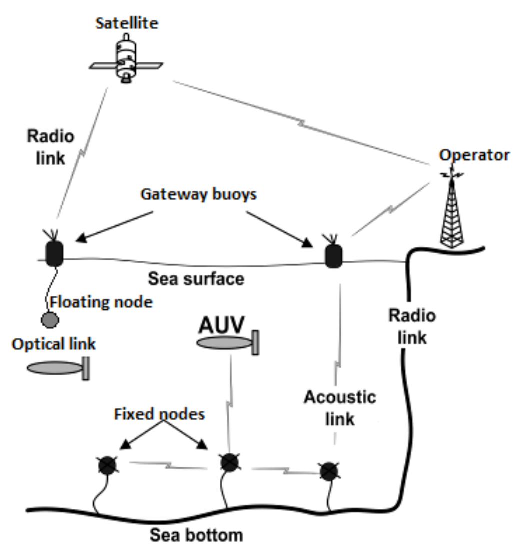

Figure 1.1: Underwater network

Underwater operations requiring large area coverage and long term functionality are only possible with a network of sensors performing collaborative tasks, rather than using a single sensor for data collection. Benefit for industry and commercial organisations from underwater sensor networks (UWSN) has been recognised recently and has led to increased efforts in testing new technologies. Another application is in scientific research of deep ocean sites. However, security applications, such as monitoring sites and structures, have been identified for long time and led the initial research advances in this field. A diagram presenting an ad hoc network design, including acoustic, optic and radio frequency (RF) links between static, floating and moving nodes is displayed in figure 1.1.

Potential gains from using network over single sensor technology include flexibility and covering large area of interest. For example, data can be collected from various locations but also, if one node is faulty, the network can be readjusted or at least continue functioning with reduced quality, rather than terminating the operation. Another advantage is the ability to add autonomous vehicles with coordinated tasks as opposed to controlling them from a platform. Finally, underwater network research is advancing and this might lead to reduced cost of ocean trials and explorations. Table 1.1 is summarising the potential benefits of UWSN.

Table 1.1: Comparison between single sensor and network technology

Single Sensor	**Network**
dependent on platform	autonomous operation
expensive	potential cost reduction
inflexible	complex environment
limited area	broad area

It is useful to study terrestrial sensor networks which have reached a mature development stage, being self-configurable with optimised energy consumption and wireless operation. Priority has been given to dense deployed networks that utilise short-range and multi-hop communication with low cost nodes. UWSN, by comparison, are still in an early stage of development. Each node is likely to be around 100 times more expensive and therefore the deployment is sparse, usually requiring kilometres long transmissions. Such a network typically has a central node rather than modems communicating with each other. Attempts are being made in applying successful technologies and design principles from terrestrial networks to UWSN research. However, this is not a trivial matter as there are some fundamental differences between the two mediums. Firstly, RF does not propagate as freely in water as in air and the preferred physical layer technology for long range wireless underwater communication is acoustics. Such transmissions are restricted from the medium characteristics to very low frequency signals, in the kHz range, leading to severe limitations in operational bandwidth and available data throughput. The second major problem is the speed of sound, which is five orders of magnitude lower compared to RF signal through air. The propagation delay in underwater communications thus becomes a significant issue, especially for node geolocation and synchronisation, which is a vital information for any network. Finally, the resource management is very different for UWSN compared to on-ground ones. This comes from the fact that the nodes life is limited by their batteries and replacement is a costly process.

Although implementing an UWSN is a challenging task, there are some applications that can greatly benefit from it, and others that are simply impossible without creating a link between the monitoring nodes. One example is mine countermeasure operations. First, an area needs to be scanned for existing mines and once an object is detected, it have to be neutralised. Such task can be greatly facilitated if a swarm of robots operates in a controlled and collaborative manner as shown on the diagram in figure 1.2.

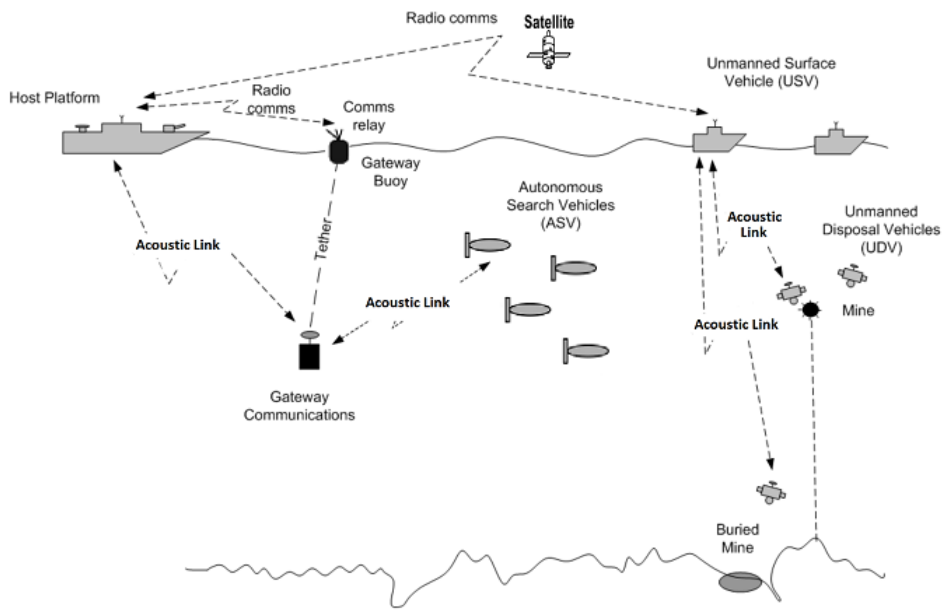

Figure 1.2: Underwater network for mine countermeasure operations

There is increased interest of ad hoc networks and adding moving nodes, such as autonomous underwater vehicles (AUV) to operate in collaboration with static nodes. Currently, the limitation of AUVs is their inability to communicate with each other. One solution is to connect them with a tether but this imposes a restriction on manoeuvrability. Therefore, UWSNs are expected to provide capabilities for low-rate data transfer between moving platform for control and telemetry. Such improvements can also be applied to a monitoring system in coastal regions for detecting unauthorised vehicles.

One of the main issues associated with underwater networks research is the fact that currently there is no internationally accepted standard framework established in the research community. This has resulted in many techniques proposed and developed independently which have not been integrated to a single functional scheme. Attempts to solve this problem have been done, for example (Chitre et al. 2007) where several research communities have combined efforts. However, this is not a trivial task as various applications dictate different limitations and requirements. Therefore, more research communities need to contribute an input and work towards accepting a common framework. On the other hand, conclusions about research challenges and future directions concerning different parts of the underwater network architecture are consistent and have been summarised over the years by many authors. Some of the most frequently cited papers are (Stojanovic 1996), (Akyildiz et al. 2002), (Akyildiz et al. 2005) and (Chitre et al. 2008). The focus is divided between the layers of the network structure. Examples for the physical layer include adopting robust and efficient communication techniques; the data link layer research needs alternative error correction schemes and improved multiple access; the network layer protocols has the issue of tackling the delay in time critical applications and retransmissions optimisation for delay-tolerant ones; the transport layer protocol needs to achieve reliable packet transport, as well as congestion and flow control. The practical issues when designing an UWSN are mainly in overcoming the fundamental limitations imposed by the communication channel, difficulties in applying medium access control protocols, the cost of trials and energy efficiency of the deployed nodes.

The main goal of my PhD research is designing and evaluating an adaptive and intelligent UWSN. The ability of autonomous self-organising nodes when there is a need to adapt to topological or environmental dynamics, will bring increased robustness of the system. The other focus of the study is on removing the need of central node from the network and bringing the intelligence to the individual nodes. The ability of independent operation gives opportunity to add new capabilities or customisation of any particular node. Such optimisations are common in other problem domains related to network research as well. However, the main distinction is that data transmission for UWSN is performed in underwater environment, which imposes some unique challenges. Moreover, it is likely that issues arising from the communication between nodes affect higher layers of the network and drive decisions about topologies and protocols. Therefore, the first year of my studies is focused on the fundamental limitations of underwater data communications since the physical layer is the basis of every network architecture.

1.2 Underwater communications

This project presents an extensive study on the available physical layer technology choices and provides a summary of current advances. However, the focus is kept on security related design, such as mine countermeasures, harbour protection and surveillance, and some scenarios are not explored due to impractical implementation for such applications. The set aims include:

Primary goal: Quantitative assessment of techniques enabling underwater communication and performance comparison

The ability to evaluate the capabilities of current underwater communication technology is important practical limitation for further network design. Recently, many new approaches have been adopted successfully from terrestrial applications. However, the increased capabilities have also brought inherited trade-offs and some of them have been assessed in this work.

The result of this study is aimed at being able to compare different types of physical layer technology by their performance. The use of one technique over another may be obvious in some cases but they can also be considered to assist each other where appropriate. This will be the basis of further research in UWSN design.

Secondary Goal: Difference between UWSN and terrestrial networks

As part of this study, the difference between on-ground and underwater sensor network research has been examined. This need comes from the fact that many researchers with experience in terrestrial networks have been attracted by the challenges imposed by the underwater medium. Also, a lot of work has already been done related to network design and it is useful to be able to transfer knowledge from the terrestrial domain to the underwater one. Therefore, as a secondary goal of this study, I would like to point out some of the main distinctions concerning the channel characteristics.

1.3 Research design

The research question of this study is aimed at investigating the current state of underwater communication and examining techniques to make it more efficient and robust. In order to asses performance, evaluation parameters, such as data rate and bit error rate (BER), are presented to give an idea of system requirements for typical underwater applications. There are four types of signals that can be used to characterise most existing systems: control messages, telemetry information, speech and video signals (Stojanovic 2001). However, only control and video transmissions are considered here as most likely to be used for security applied network.

Control

Control signals are a set of pulses in charge of on/off commands of nodes and devices. They also carry navigation and status information. Therefore, such signals require low data rates of about 1 kbps, but at the same time high reliability since they carry highly important data.

Video

Video signals have bit rate requirements between 10-500 kbps and BER around 10^{-3}-10^{-4}. What is specific for underwater images is that they have low amount of details and contrast. Such characteristic gives the ability to use high compression ratios and reduce the size, and therefore the requirements for video transmission. Nevertheless, such signals have the greatest demand for bandwidth.

Table 1.2 is summarising the system requirements for typical underwater applications.

Table 1.2: System requirements

Type of Signal	**Bandwidth**	**Bit Error Rate**
Control	1 kbps	very low
Telemetry	$\sim$ 10 kbps	$10^{-3} - 10^{-4}$
Speech	$\sim$ 3 kbps	10^{-2}
Video	10 - 500 kbps	$10^{-3} - 10^{-4}$

Both acoustic and alternative physical layer technologies are investigated in this research, such as RF and optics. As shown further in Chapter 2, they have very distinctive physical characteristics and behaviour in the water medium. However, due to time constraints, only selected technologies applied to the acoustic channel have been simulated as this is the typical choice of technology for underwater communications. Recent advances on RF and optics are provided by a literature review where results from laboratory and trial experiments are presented to evaluate and compare their performance for particular applications. Figure 1.3 is showing a block diagram of the proposed research design.

1.4 Contribution

The contribution of this work can be summarised by:

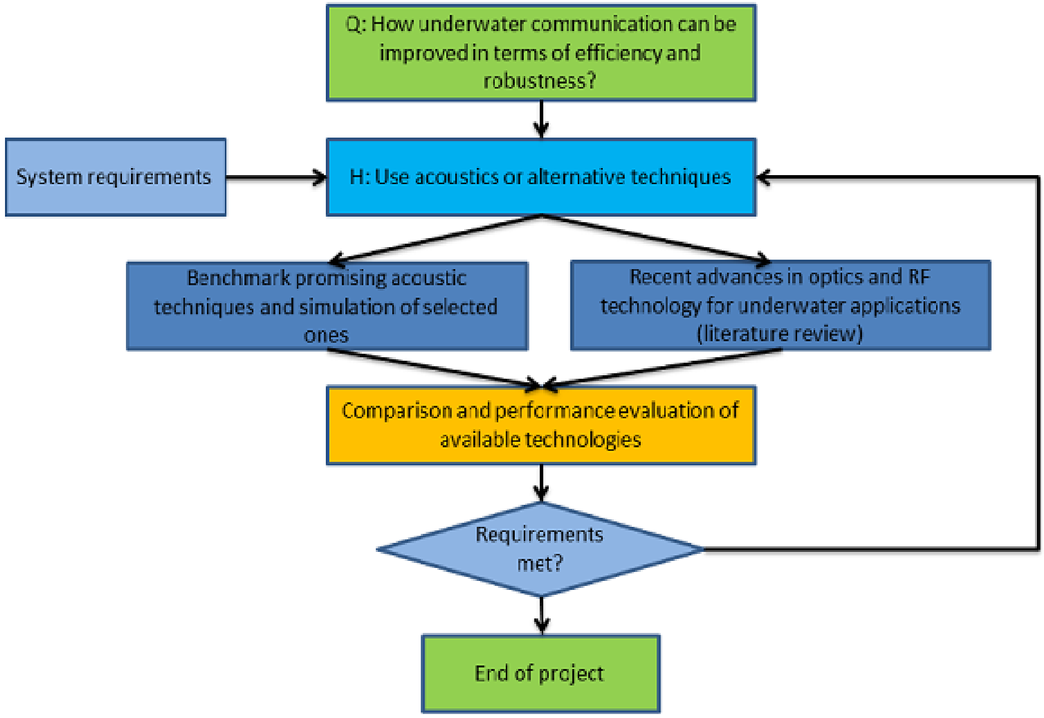

Figure 1.3: Research design diagram

- Comparing quantitatively the performance of available underwater communication technology;
- Introducing the differences between terrestrial and underwater communication and networks;
- Exploring the fundamentals of different types of waves considered for underwater communication carriers;
- Investigating less popular, but promising, techniques that are still in research phase, but might have an impact in future;
- Recommending shallow water design for security application

The rest of the work is divided between theoretical background of the acoustic, electromagnetic and optical signals in water medium in Chapter 2, and discussion on the advances achieved in recent years for underwater communications in Chapter 3. The last chapter summarises the addressed technologies and draws conclusions and recommendations for further sensor network design.

Chapter 2

Theoretical background

Acoustic, optic and RF signals have very different physical properties. This chapter summarises the main contributions that fundamentally limit each technology performance and gives perspective of certain advantages that could be exploited.

2.1 Acoustics

An acoustic signal is a sound wave produced by a vibrating object which motion is transferred to the surrounding medium. Such mechanical wave propagates with approximate speed of 1500 m/s in water. However, this 'standard' speed changes and causes different behaviour for transmissions in deep or shallow water environment. Other phenomena affecting the acoustic signal, such as path loss, noise, multipath and Doppler spread are also taken into consideration when designing an acoustic modem and therefore are explored in more detail in this chapter. This is later used to explain the benefits and issues associated with wireless acoustic networks.

2.1.1 Sound Propagation

Sound speed in water changes with temperature ($\sim +3.4$ m/s for 1 °C), salinity ($\sim +1.2$ m/s per ppt) and pressure due to depth ($\sim +17$ m/s for every 1000 m)(Waite 2002). These parameters vary with season, location, weather and time of the day. While the salinity can be considered constant in some cases for simplicity, the variation of temperature with depth is causing the separation of a typical deep sea into a layered structure to characterise its different behaviour. Usually, the first defining element of an underwater system is whether it is designed for deep or shallow water application. The surface layer, or duct, has a constant temperature due to the wind, waves and rain mixing the water. Typically, there are numerous reflections and refractions from the surface or caused by ray bending when the temperature starts to decrease. Due to such variations, the propagation in real oceans has specifics, such as formation of shadow zones where the sound intensity is greatly reduced, when sound waves bend downwards and penetrate the duct toward lower speed profiles. There could also be reflections from the bottom of the sea if the area of interest is littoral. Surface and bottom transmission losses reduce the the signal strength and add to the difficulty of designing an efficient communication system for shallow water application. On the other hand, deep water horizontal transmission is characterised by focusing of the rays by refraction between two different temperature layers making the propagation possible for long ranges. Deep water systems often exploit vertical sound paths that are less rapidly varying temporally and spatially.

However, this study is focused on shallow water applications, as most security is needed in the littoral areas, and the deep water channel will not be explored in detail.

2.1.2 Path Loss

Path loss, or attenuation measures the decrease of signal intensity between transmitter and receiver. The main contributors are spreading loss, dependent on distance, and absorption loss, which is a function of both distance and frequency.

The spreading loss can be modelled following a spherical spreading law where the power is considered to radiate isotropically. This implies that the signal is not bounded by any obstructions and therefore perfect conditions are considered. A cylindrical spreading law, where the power is limited by parallel planes (this could be surface and sea bed) is modelled by cylinders of increasing radii surrounding the static source. When calculating the overall attenuation due to path loss, the spreading loss is included in the calculation via the spreading factor k, which is 10 for cylindrical spreading and 20 for parallel spreading. In practice, the commonly used value for calculating shallow water loss is k=15 as a compromise. Equation 2.1 gives the spreading loss in dB where r is the distance travelled by the sound ray:

$$Loss_{spr} = klog(r) \tag{2.1}$$

Absorption loss can be developed through two principal mechanisms. The viscosity loss is proportional to $\sim f^2$ and affects both salt and fresh water. The other contribution is the molecular relaxation loss - it is only present in salt water. The mechanism is to absorb energy by turning molecules to ions due to the change in sound pressure. Signals with frequency under 500 kHz are affected, which includes working frequencies of most existing systems. The absorption loss is expressed by the absorption coefficient α, dB/km, and several empirical formulae are available for calculating it. Its strongest variation is due to frequency, although it depends on depth, temperature and salinity as well. Approximations for α are available for 'standard' sea water (temperature 10 ° C and 35 ppt salinity). One of them is the Thorp formula (Thorp 1967), (Fisher & Simmons 1977):

$$\alpha = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75 \cdot 10^{-4} f^2 + 0.003 \tag{2.2}$$

$$\alpha = 0.002 + 0.11\frac{f^2}{1+f^2} + 0.011 f^2 \tag{2.3}$$

Equation 2.2, is used for frequencies above few hundred Hz, while 2.3 is valid for lower frequencies ($f \leq 400$ Hz). In both equations, f is in kHz and α is in dB/km. Figure 2.1 is showing the variation of the absorption coefficient with frequency. Its rapid increase sets an upper limit on the usable frequency for acoustic communication for particular distance.

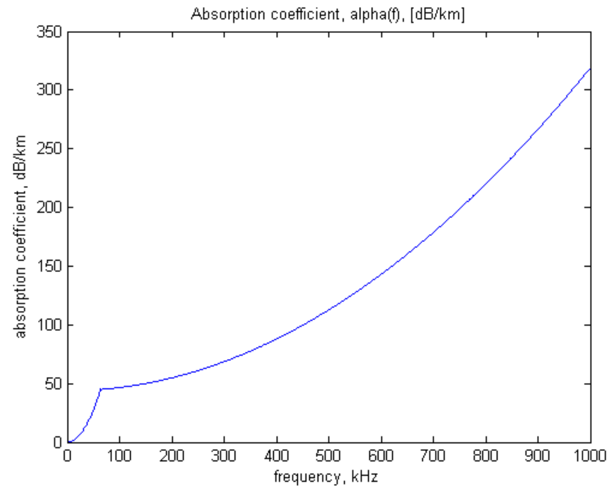

Figure 2.1: Throp absorption coefficient as function of frequency f, in dB/km

The absorption loss in dB can be calculated by multiplying $\alpha(f)$ by the transmission distance as shown in equation 2.4:

$$Loss_{abs} = \alpha r 10^{-3} \tag{2.4}$$

The combined effect of spreading and absorption loss is displayed in figure 2.2 using equation 2.5 where the attenuation $A(r, f)$ is in dB/km:

$$A(r, f) = Loss_{abs} + Loss_{spr} \tag{2.5}$$

2.1.3 Noise

Ambient noise represents the background sound pressure level used for reference when measuring signal strength. While it is very well-defined for deep water, shallow water noise sources are variable in time and place. For example, depending on the location of the site, marine life might influence greatly the level of ambient noise. Such is the case with the warm coastal waters of Singapore, where snapping shrimps create a non-Gaussian impulses, dominating the noise level beyond 2 kHz (Chitre 2007). However, the general case of ambient noise can be described as coloured Gaussian distribution with continuous spectrum. Here is the mathematical representation of the main sources contributing to noise in the frequencies of interest for wireless acoustic communication (WAC). (Urick 1984), (Stojanovic 2007).

$$N_{turbulence} = 17 - 30 \log f \tag{2.6}$$

$$N_{shipping} = 40 + 20(s - 0.5) + 26 \log f - 60 \log(f + 0.03) \tag{2.7}$$

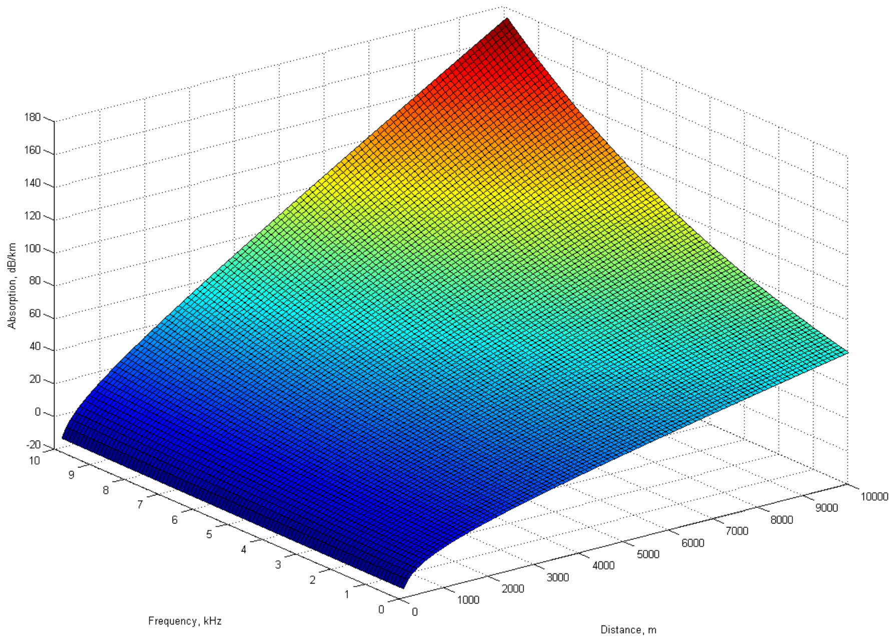

Figure 2.2: Attenuation loss as a function of frequency and distance , in *dB/km*

$$N_{waves} = 50 + 7.5w^{\frac{1}{2}} + 20\log f - 40\log(f + 0.4) \tag{2.8}$$

$$N_{thermal} = -15 + 20\log f \tag{2.9}$$

$$N_{total} = N_{turbulence} + N_{shipping} + N_{waves} + N_{thermal} \tag{2.10}$$

The above equations represent the empirical formulae of the power spectral density (p.s.d.) of the main ambient noise contributors in dB re μ Pa per Hz and the variable f is in *kHz*.

Turbulence noise due to tidal currents is given in equation 2.6. It affects only very low frequencies, where $f < 10$ Hz. However, most applications does not consider this part of the spectrum.

Shipping activity is considered a dominant ambient noise factor for $f \sim 10$ - 100 Hz. The low frequency contributions created by propellers can travel hundreds of kilometres. Hence, this is not a local phenomena and is added to the total background noise equation. In equation 2.7, the variable s characterises the shipping activity factor and its value varies between [0,1], with 0 corresponding to low ship activity and 1 to high.

Depending on the wind speed w, in m/s, the sea surface motion varies. The waves are dominant contributor to noise in the frequency region $f \sim 100$ Hz - 100 kHz as shown in equation 2.8. This is the operating region for most systems using acoustic communication.

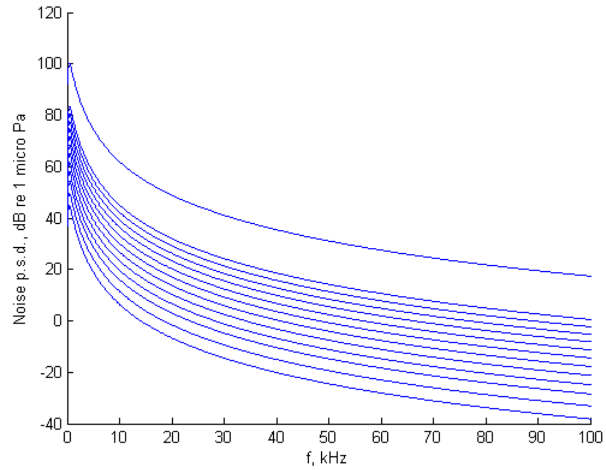

Figure 2.3: Variation of noise through all states in the Beaufort scale

Figure 2.3 shows a comparison between various sea states and the noise p.s.d. associated with them. The wind speed parameter varies according to the Beaufort wind force scale (Jebson 2007), where the scale starts from Beaufort number 0 for calm sea, and ends at 12 for hurricane force. The noise raises with increase of wind speed. For this figure, state 12 is calculated using the record wind speed in the United Kingdom, 63.3 m/s from 13 February 1989, near Fraserburgh, Aberdeenshire (MetOffice 2013). Therefore, depending on the weather conditions, the noise can have very large variations - in the order of 40 dB between calm water and hurricane winds.

The contribution from equation, 2.9 gives the dependency of noise with frequency in the high end of the spectrum, $f > 100$ kHz. As shown in Figure 2.1, the absorption in this region increases rapidly with distance and communicating nodes have to be located very near to each other. This is why this region is rarely exploited for acoustic applications.

Table 2.1 gives a summery of ambient noise and the affected frequencies.

Table 2.1: Ambient noise summary

Type of ambient noise	Affected frequency
Turbulence	$f < 10\ Hz$
Shipping activity	$f\sim 10Hz - 100\ Hz$
Waves	$f\sim 100\ Hz - 100\ kHz$
Thermal	$f > 100\ kHz$

The four main noise factors are added together in equation 2.10 which shows the combined effect of their contributions. Figure 2.4 is showing the variance of ambient noise as a function of frequency and shipping activity in calm water with wind speed of 0 m/s. It is clear how the noise is decreasing with frequency up until a minimum, after which the thermal noise becomes dominant and the noise level starts increasing. The lowest frequency displayed in this figure is 1 kHz. Since the shipping activity has its greatest contribution in lower frequency, as shown in table 2.1, its effect is adding little to the variance of the other parameters.

Figure 2.5 is also calculated with equation 2.10. It gives the noise level dependence with frequency and

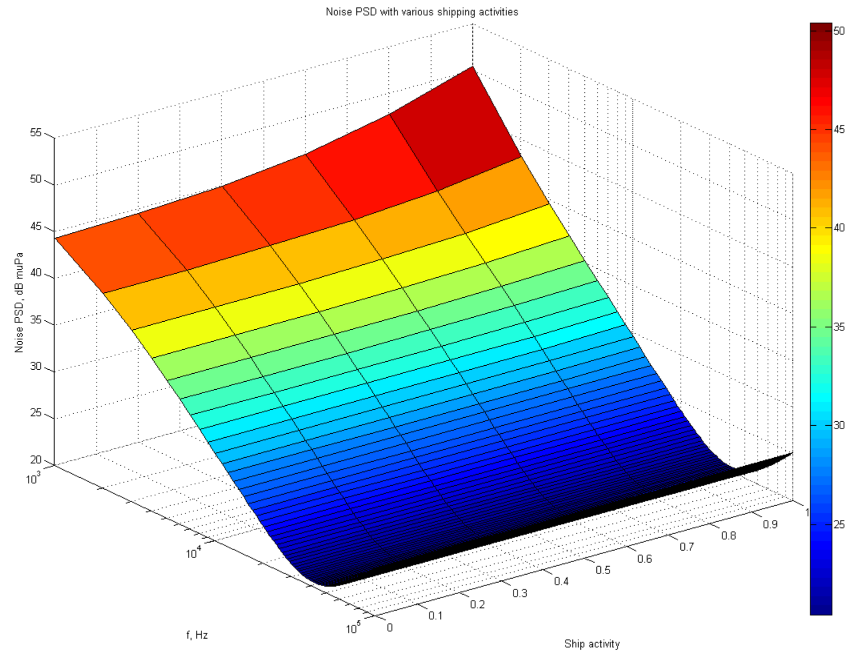

Figure 2.4: Ambient noise p.s.d. N(f) as a relation of shipping activity

wind speed, while the shipping activity is considered to have minimum effect (s=0). The frequency has the same effect as the previous figure - decreasing the noise level up to a boundary in which the thermal noise becomes dominant. However, with reference to figure 2.3, it shows how the increase of wind speed rises the ambient noise level and changes the frequency at which wind speed stops being dominant and thermal noise is the leading contribution.

What is interesting in these graphs is that noise $N(f)$ decreases with frequency up to a certain level. This relation is imposing a lower limit on the working frequency, while the path loss $A(r, f)$, as shown in figure 2.2 is setting the upper frequency boundary. Those two contributions, also referred as the AN product (Stojanovic 2007) represent the frequency dependent component of the signal-to-noise ratio (SNR). Figure 2.6 is an example of the relation between available frequency and various distances. It shows the trade-off between optimal frequency band and node distance. This is the limitation imposed on a simple case of transmission without any modulation or multiplexing techniques applied.

In conclusion, table 2.2 shows a rule of thumb classification accepted in the underwater community giving the relation between operational range and available acoustic bandwidth for data transmission.

Table 2.2: Available acoustic bandwidth according to operational range

Classification	**Operation Range, km**	**Available Bandwidth, kHz**
Very Short	< 0.1	> 100
Short	0.1 - 1	20 - 50
Medium	1 - 10	~ 10
Long	10 - 100	2 - 5
Very Long	1000	< 1

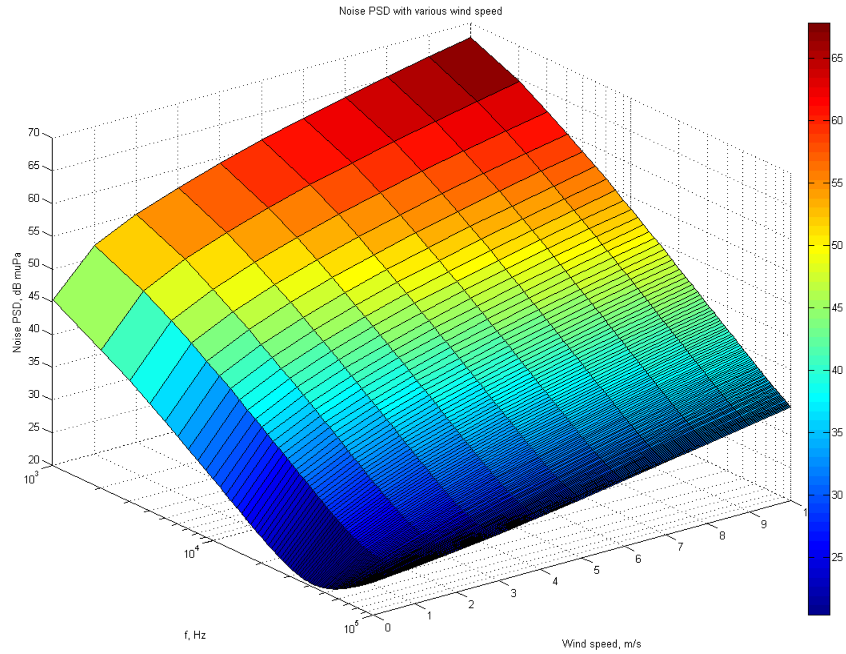

Figure 2.5: Ambient noise p.s.d. N(f) as a relation of wind speed

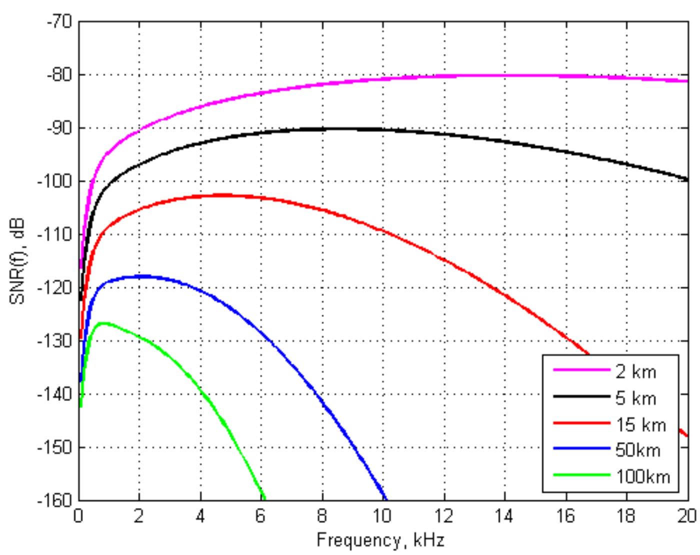

Figure 2.6: 1/AN representing the frequency dependant part of SNR

2.1.4 Multipath propagation

Multipath propagation is the phenomenon when a transmitted signal reaches the receiver in different paths. One of the possible paths is the line-of-sight connection, where a signal travels in straight line until reception. However, it is likely that some fraction of the signal will also be reflected at or diffracted by an interacting object from the surrounding environment. In the case of underwater acoustic communication, such can be the surface and bottom of the ocean. The negative effect of multipath propagation is that every component has different amplitude, delay and phase shift.

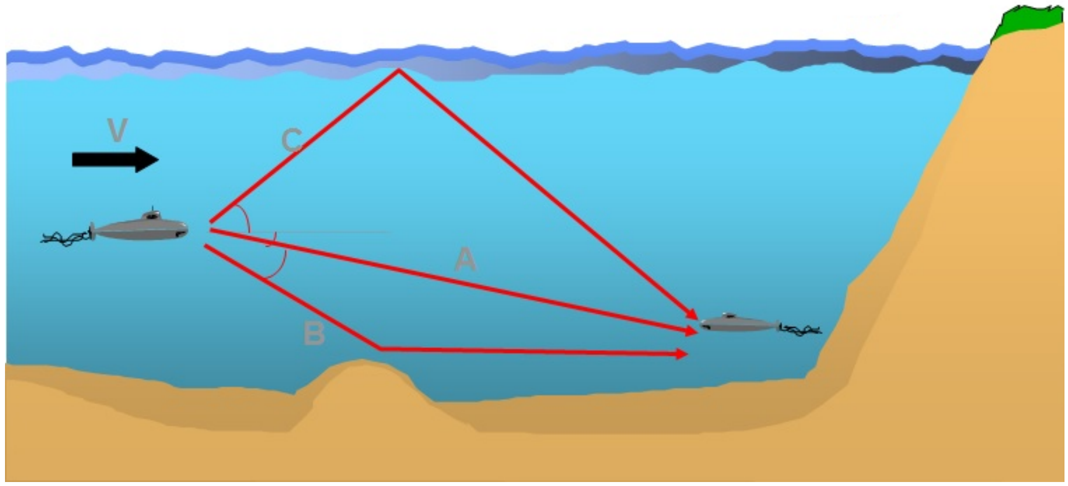

Figure 2.7: Multipath in underwater acoustic communication (Hardie 2012)

If either the transmitter, receiver or interacting object is changing its position with time, the travelling distance of a multipath component (MPC) changes. The main implication comes from the fact that when various paths are interfering, they might add destructively and affect the communication channel by causing errors or reducing critically the amplitude of the total signal. This effect of rapidly changing the amplitude with time due to phase shifted MPCs is known as small-scale or fast fading. The large-scale or slow fading is observed when there is a big obstruction in the direct path between the transmitter and receiver and the signal is greatly reduced or shadowed. The amplitude change in this case is varying gradually and over greater distance.

Due to the fading caused by multipath propagation, the bit error rate (BER) decreases linearly with increasing the SNR as opposed to non-fading channels, where this function is exponential. The reason for the slower BER reduction is that the SNR is not constant, but the probability of its value reaching a minimum is taken into account. Therefore, improvement of BER is not possible by only introducing more powerful transmitter to the system (Molisch 2012). Another consequence of multipath propagation is signal frequency dispersion. Due to the different MPCs, the channel impulse response is not a single delta pulse, but consecutive pulses instead. Each of them has various time of arrival, amplitude and phase. This effect creates intersymbol interference (ISI) causing difficult detection in the receiver. It can be described by the interference of subsequent symbols that cannot be properly distinguished since they arrive at the same time. ISI errors cannot be affected by increasing the SNR either. They are dependent on the ratio between symbol duration and the impulse response duration. Therefore, to eliminate the ISI problem, the ratio of those two variables have to be altered.

Multipath propagation is a common problem in various domains. Years ago, it could be observed in analogue TV where it created duplicated images and blurred the picture. Nowadays, it disturbs radar operation by detection of ghost targets that imitate the existing ones. In digital communications it affects the quality of the link.

Similar to terrestrial radio systems, underwater acoustic transmission suffers from multipath alike. There is a large variation in the effect with changing the water depth due to the fact that multipath formation is different in shallow and deep water. The boundary between both is considered to be 100 m but this definition is not a strict one. For deep water propagation, multipath can be formed due to ray bending. It occurs when there are different sound speed profiles and the sound is channelled bending the rays in the direction of the lowest sound speed. For littoral areas, in addition to the direct path, multiple possible contributions are added from sea bed and surface reflections. However, the multipath is not the fundamental performance limitation itself, but rather the fluctuations in time associated with each path that can vary from a few milliseconds to several seconds (Catipovic 1990). On the other hand, temporal instability of multipath contributions may cause the direct path to account for less energy than some of the delayed signals, which might cause errors in the receivers.

2.1.5 Doppler Spread

When the transmitter, receiver or some of the obstacles which reflect the acoustic signal changes its velocity due to random movement, this causes a frequency shift in the transmitted signal, or a Doppler shift. In the presence of multipath propagation, each path can have different rate of phase change. The difference in Doppler shift for the multipath components is associated with Doppler spread, that accounts for time variation of the channel response. This phenomenon is highly problematic for horizontal shallow water transmissions where the presence of multipath propagation is dominant. It causes ISI at the receiver, especially when high frequency signals are used.

Although channel variability is a recognised difficulty for stationary nodes, it is even more severe limitation for underwater communication with mobile sensors. The problem of time synchronisation becomes obvious when the speed of sound underwater and the speed of radio waves in air is compared. A valid approximation of the sound speed in water is 1500 m/s. On the other hand, the speed of radio signals in terrestrial communications is 300 000 000 m/s. This five order of magnitude difference dictates the fundamental difficulty of implementing time synchronisation and high throughput for underwater acoustic communication in comparison with terrestrial communication. A typical AUV speed is around 50 km/h and the ratio of the vehicle speed to the sound speed becomes 10^{-2}. In comparison, a mobile node using radio channel and having a speed of 100 km/h, has a ratio of 10^{-8}. This leads to the conclusion that even moderate movement in the underwater platform brings substantial Doppler spread, while such problem is trivial in the terrestrial communication environment.

2.2 Radio frequency

2.2.1 Underwater Wireless

Using RF for the physical layer is the main technology enabling terrestrial communications and therefore a lot of knowledge and experience has been obtained during the years. When it comes to using RF for UWSN, the advantage over acoustics is mainly the higher operation frequency and velocity speed, which results in increased bandwidth and reduced latency. For example, the dielectric constant for water reduces the underwater electromagnetic (EM) waves speed with a factor 9 compared to free space propagation, to 33 333 333 m/s (Lanbo et al. 2008). This is still a large improvement over the acoustic speed propagation which is 1500 m/s. However, there limiting factors prohibiting the use of EM waves in sea water.

The propagation in fresh and sea water is very different due to the electric conductivity for both mediums. The absorption loss for fresh water does not depend of frequency and therefore RF signals can propagate easily through it. Seawater absorption, on the contrary, is frequency dependent and the medium loss is growing with increasing the operational frequency. On Figure 2.8 can be seen a comparison between acoustic and RF attenuation for different working frequencies. The formulae used to calculate the attenuation coefficient $\alpha(f)$ are (Waite 2002):

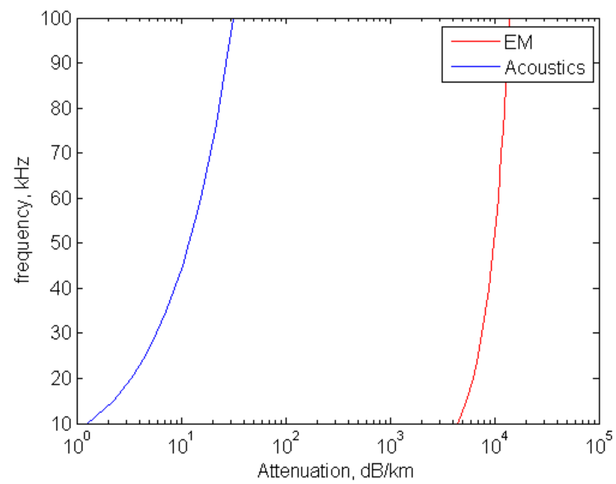

Figure 2.8: Acoustic and RF attenuation comparison

$$\alpha_{EM} = 1400 f^{\frac{1}{2}} \frac{dB}{km} \tag{2.11}$$

$$\alpha_{acoustics} = 0.05 f^{1.4} \frac{dB}{km} \tag{2.12}$$

In equations 2.11 (EM attenuation in sea water) and 2.12 (acoustic attenuation in sea water) , the frequency f is in *kHz*. The figure clearly shows that even using the low end of the RF spectrum, the EM losses are so great for the highly conductive sea water, that it effectively behaves as a short circuit. Therefor, whenever EM waves are considered for underwater communications, usually only the low frequency spectrum is regarded suitable. However, the use of long wavelengths would requite large physical antenna aperture and high transmission power. Therefore, using RF wirelessly is impractical for underwater communications with classical approaches.

Although EM signals are highly attenuated in sea water, part of the energy crosses the water boundary into air or propagates through the low conductive seabed. Such multipath signals can be considered beneficial, and exploited as low-loss and covert mean of communication. They would also travel much higher distance compared to the component travelling through water. Such wireless EM 'lateral' or 'surface' propagation can be combined with a buoy system of floating surface nodes or signals reaching to the coast station.

2.3 Optics

Compared to the RF spectrum, optical waves do not suffer from such high attenuation in seawater. However significant amount of the energy is scattered and the ambient light in the shallow regions has an adverse effect on propagation. Nevertheless, the due to the high signal frequency, very high data rates can be achieved.

For deep water application, where the level of ambient light is low, and using a monochromatic light, the major issue is the scattering. Attenuation due to scattering depends on the level of turbidity, which measures the clouding effect from suspended particles. Turbidity is the equivalent of attenuation coefficient as introduced for acoustic propagation. However, the two processes have different physics: attenuation is caused by signal energy transforming into heat, while scattering is the loss due to diffraction in all directions. When using Mie scattering model to evaluate the characteristics of the optical channel and estimate the limits of propagation, the turbidity is the defining factor for achieving accurate results (Lanbo et al. 2008).

Nevertheless, the ability to use lasers has been recognised back in the 80s as a mean for submarine communication (Wiener & Karp 1980). More specifically, the blue/green spectrum has the highest propagation capabilities. Lower frequencies, corresponding to red and orange colour, are restricted by absorption and scattering due to planktonic components . The boundary for the highest end of the spectrum is set by absorption of water, due to its frequency dependency. Therefore the violet light is excluded as well. Coloured dissolved organic matters, known as 'yellow substances' dissolved in the water and the refractive index add an extra attenuation. (Shofrin 1998), (Jaruwatanadilok 2008).

Sensors using optical waves for communication have the advantage of achieving large data rates, compared to acoustic wireless communications. The reason is that the operational frequency differs with 6 orders of magnitude (optical waves are in THz, while working acoustic frequencies are in kHz) and therefore using blue/green lases for underwater communication can provide throughput in the order of few *Mbps*. Another advantage is that light waves are not affected by multipath. Disadvantages include the need of very high precision of the narrow laser beam and relatively small range of operation. Lasers are considered suitable for deep water applications, where the water is clear. For shallow water application, which this research is focused on, this technology might not be feasible.

Chapter 3

Discussion on recent advances

In order to tackle the fundamental channel limitations, different techniques have be developed to enhance the communication between nodes. Evaluating them is not a trivial problem as results and data gathered from experiments and simulations sometimes cannot be compared due to the use of various coding techniques, modulations, receiver algorithm or assumptions for the channel. Here is summarised what current technologies can achieve and in what scenarios they are considered as advantageous. Since this study is focused on security applications in littoral regions, attention will be given to techniques feasible in such environment.

3.1 Acoustics

As mentioned in Chapter 2, acoustics is the typical choice to enable underwater communication applications. Although only low bandwidth transmissions can be achieved, this is still the only solution for communication over 100 m. Current research is focused on developing techniques for underwater applications that have been successfully used for terrestrial communications. However, such transition have to be done after considering all the physical differences between those two channels. The main distinction is that on-ground communication relies on narrowband RF transmissions, while the acoustic channel is inherently wideband. In figure 3.1, the optimal acoustic frequency is calculated for the minimum joint effect of attenuation and noise level in water medium, as the distance between nodes is increasing. It shows that the operational frequency is usually in kHz. On the other hand, although the acoustic bandwidth is considered low, in this case it is not negligible, because it is of the same order as the carrier frequency, which makes the channel wideband. Many wireless systems rely on the assumption that the frequency response in the channel can be considered flat, but this is only valid for narrowband signals. On the contrary, the wideband underwater acoustic channel is very frequency selective which causes some of the implications related to design solutions.

On the contrary, on-ground systems use narrowband RF signals. This comes from the fact that when comparing the carrier frequency used, usually in GHz, and corresponding bandwidths, typically ~MHz, the bandwidth is much smaller than the centre frequency. Therefore, when using promising terrestrial communication methods in developing new techniques to apply in the underwater communications domain, the need of efficient high data rate modulations is even grater, while the narrowband assumption

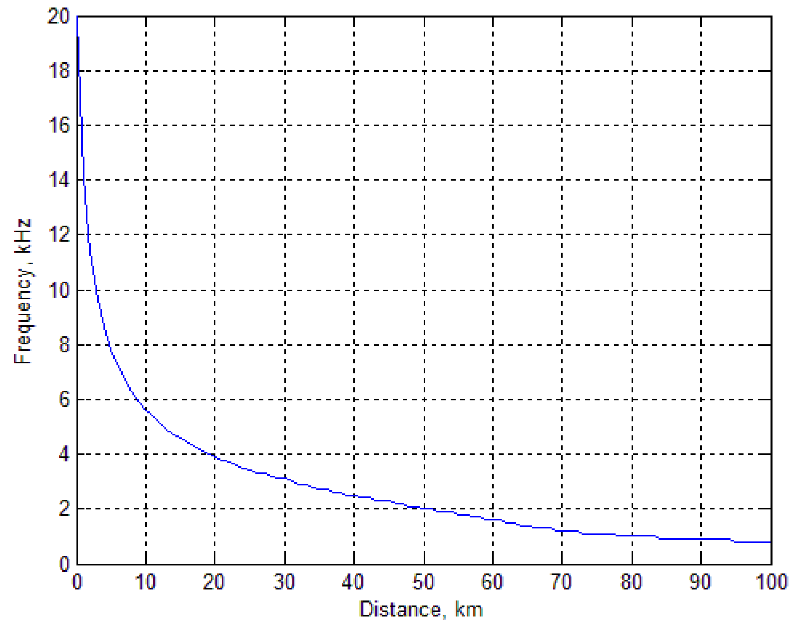

Figure 3.1: Optimal frequency as a function of distance

for signal processing is not valid.

3.1.1 Modulations

Non-coherent modulation relies only on detecting the strength of the signal. However, information carried by the phase is lost that way, leading to reduced bandwidth efficiency and therefore such modulation is not suitable for high data rate applications. Due to challenges imposed by the underwater channel and mainly the Doppler spared, phase-tracing was not introduced until the last decade and acoustic communications relied on frequency shift keying. With the increased capabilities of digital processing, coherent modulations are currently in use, such as quadrature amplitude modulation (QAM) and phase shift keying (PSK). On the other hand, when only small control messages need to be transmitted, those modulations are not the optimal choice in terms of energy efficiency. Therefore, reconfigurable modems have been proposed to work in modes, adjusted to the channel conditions, both coherent and non-coherent (Lingjuan et al. 2013). Another problem with coherent modulations is the complexity related to compensating ISI in the time variable acoustic channel by using equalisation.

One of the topics receiving much attention lately is orthogonal frequency division multiplexing (OFDM). Multipath is one of the phenomena that has major hindering effect on underwater communication. With the problem of ISI associated with single-carrier transmission, multi-carrier modulation provides an alternative. It splits the available broadband signal into a number of narrow band channels that are transmitted simultaneously at different frequencies. The advantage of this method is the ability to put guard times between the data symbols so they do not interfere with each other in the receiver when multipath is present. This passive way of tackling the problem eliminates the need of complex equalisers and reduces the signal overhead.

There are some disadvantages associated with OFDM, such as lower capacity availability compared to single-carrier modulation, higher demand of peak-to-average power ratio and the fact that it is also very susceptible to Doppler spread. Because of this criticism, some authors avoid the use of OFDM in their systems and provide promising results for point to point and networked WAC systems (Karasalo 2011). It is impractical to state one method is better than the other since the decision strongly depends on the application and purpose of the system. However, for shallow water with long dispersive multipath channels, requiring high data rate, OFDM is considered to have an advantage.

3.1.2 Multiple-Input Multiple-Output

The concept of spacial multiplexing, or the ability to have several parallel data streams, provides a way of increasing the capacity of the system by transmitting simultaneously multiple streams. For the purposes of underwater communication multiple-input multiple-output (MIMO) has been recognised as a potential technology with promising results.

MIMO has greatest advantage over single-input single-output (SISO) in very shallow water environment (depth < 30m) where the multipath is rich and the spatial correlation between sub-channels is minimal. For example, while the increase of wind speed is adding to the noise floor of a system, it also contributes towards distinguishing between multiple signal fractions by causing the sea surface to be rough and scatter the sound energy.

Recently, MIMO techniques have been pursued actively in underwater acoustic communication research. The reason is that the available bandwidth is fundamentally limited by the medium, as seen in Chapter 2, and the alternative is to enhance the data rate by achieving better spectral efficiency. MIMO systems can realise this using multiple transmitters and parallel channels.

Various MIMO designs are suggested in the literature, often combined with OFDM as it also performs well in multipath environment (Li et al. 2009), (Bouvet & Loussert 2011). Although the multipah is suppressed well by using both technologies for modem design, there are still optimisation issues related to the OFDM guard interval leading to losses.

One of the performance metrics by which the MIMO contribution can be assessed quantitatively is the channel capacity, which gives the total amount of information that can be transmitted reliably. To evaluate the maximum theoretical capacity of a MIMO underwater system based on shallow water acoustic channel properties, the channel transfer function can be calculated by (Stojanovic 2007):

$$H(r,f) = \sum_{p=1}^{P-1} \frac{\Gamma_p}{\sqrt{A(r_p,f)}e^{-j2\pi f \tau_p}} \tag{3.1}$$

For equation 3.1 r is the distance that an acoustic ray is travelling to reach the receiver, Γ_p is the reflection loss from surface and bottom, corresponding to each multipath component p, $A(r,f)$ is the attenuation from absorption and spreading loss from formula 2.5 in Chapter 2, and τ_p is the delay. However, as this study focuses on the fundamentals of the channel, only the basic loss of a directional signal is taken into account to calculate MIMO capacity and thus the results does not depend on any predefined geometry. Therefore the attenuation is the factor defining the properties of the channel and the transfer function becomes:

$$H(f) = \frac{1}{\sqrt{A(r,f)}} \tag{3.2}$$

The capacity formula for frequency f within the transmission bandwidth, for which the shallow water channel can be considered flat, is derived in (Bouvet & Loussert 2010):

$$C(f) = log_2(I_{N_t} + \frac{S(f)}{N_t N(f)} H(f)H(f)^H) \tag{3.3}$$

The capacity $C(f)$ is measured in bits/s/Hz, I_{N_t} is identity matrix with size N_txN_t, as N_t corresponds to number of transmitters, $S(f)$ is the signal from the hydrophone, $N(f)$ is the noise power spectral density as described in Chapter 2, $H(f)$ is the MIMO transfer function with size N_txN_r, with N_r being number of receivers, and $H(f)^H$ is the complex conjugate of H. The SISO capacity for shallow water channel is obtained by the same equation, but with predefined values of N_t=1 and N_r=1. The upper capacity boundary for arbitrary SISO or MIMO channel is calculated over an additive white Gaussian noise (AWGN) channel:

$$C_{max} = min(N_t, N_r)log_2(1 + SNR) \tag{3.4}$$

Both the shallow water and AWNG channels are compared in figure 3.2 as a function of SNR. The parameters used for the calculations are set as distance at 1500 m and f=14 kHz, chosen with reference to fiigure 3.1 as an optimal frequency for the selected transmission range.

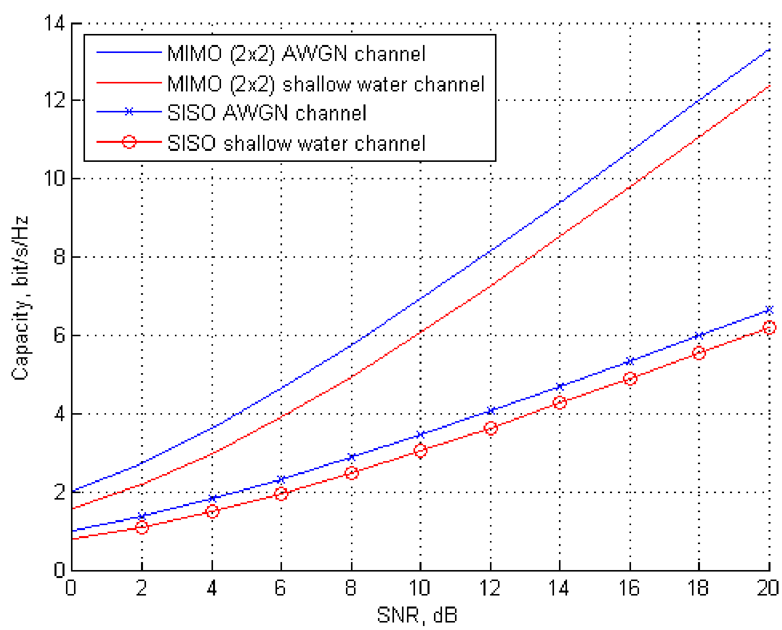

Figure 3.2: SISO and MIMO capacity as function of SNR (r=1500 m, f=14 kHz)

The graph shows that the MIMO channel capacity is increasing linearly depending on the lowest number of transmitter or receiver. Therefore, larger capacity could be obtained by adding hydrophones on both ends. The penalty of increasing the antenna elements results in reduced SNR due to co-antenna interference that adds to the noise level, although this effect is not included in the model. Another observation that could be made is that both the shallow water channel capacity curves are far below from the upper AWGN bounds. It shows that although only the attenuation is considered for the model, this is enough to demonstrate the challenge of the shallow water environment, even without adding other loss contributions. Figure 3.2 corresponds to optimal parameter selection, which means the attenuation loss is minimised. Figure 3.3 on the contrary, gives an example of using the same transmission distance, r=1500 m but with much higher frequency, f=30 kHz. The attenuation has a detrimental effect on the capacity in the shallow water, therefore it is obvious why the bandwidth of an acoustic signal cannot be broad.

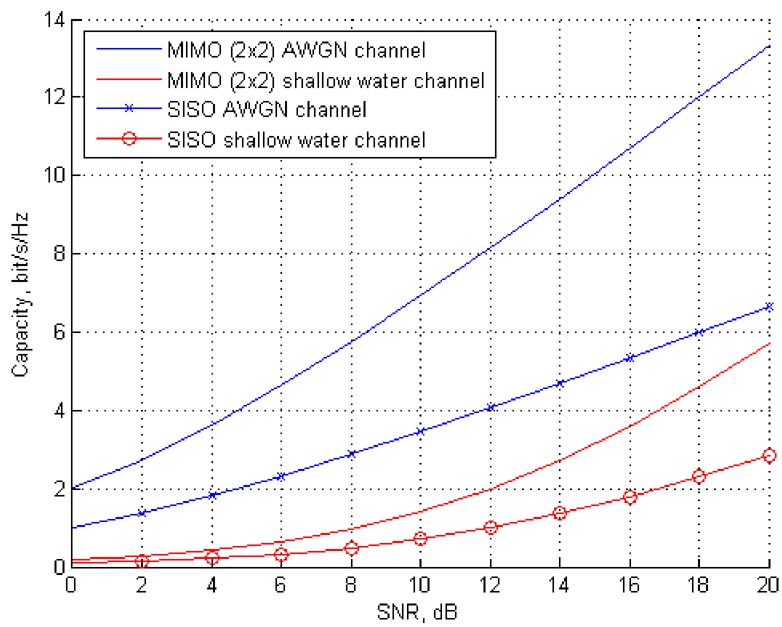

Figure 3.3: SISO and MIMO capacity as function of SNR (r=1500 m, f=30 KHz)

The theoretical capacities calculated here cannot be achieved in real oceans as there are overheads and other losses that affect the spectral efficiency, such as error correction codes, modulations, channel estimation, reflection and refraction losses, shadow zones, etc. However, MIMO is still one of the most promising technologies considered to improving the underwater communication data rate.

3.2 Optics

Underwater optical communications research is stimulated by the need of high-rate communication. One of the reasons is that nodes deployment locations are often remote and as sensors quality improves the collected data volume can be very large. Since acoustic transmission has strict limitations on operational frequency, the upper limit of available data rate is orders of magnitude lower than what can be achieved by optical communication. With reference to Chapter 2, such transmission depends extensively on the water quality and the system design is limited by the environment.

One recent laboratory experiment has proven it possible to transmit error-free data at 1 Gbps, within

2 m distance in a water pipe (Hanson & Radic 2008). However, one of the assumptions made is that turbulence is negligible and is not taken into account for the water tank experiments. Such effect is considered minor in deep water environment where no shipping activity or waves are disturbing the medium. However, this is not the case with near harbour and surface sites where vessels and wind are common. Also, although some efforts have been done to reduce the interaction of light with the tank walls, this is another limitation for a controlled laboratory test and the same results are not likely to be repeated in real ocean environment. The authors of this paper report simulations that data rate of more than 1 Gbps can be supported over several tens of meters, but not in the case of harbour water where the scattering is too high. However, the proved feasibility of such transmission in water medium is motivating further research efforts for contactless high data rate modems.

Another potential communication technique using laser is based on the optoacoustic effect. When a laser is directed at an air-water boundary, the medium attenuation is creating thermal fluctuations resulting in acoustic vibrations corresponding to the laser modulation. Different types of FSK can be applied to the acoustic signal, to serve the required application data rate. The optoacoustic approach is mainly considered for spectroscopy and is not common for underwater communications. Therefore, very little research is done in this direction. However one recent publication is examining the effect of the linear regime for underwater communication applications where the energy transfer from laser power to acoustic is proportional and the medium is not changing (Blackmon et al. 2005). The paper reports data rate of 160 bps with 2 kHz bandwidth at 40 kHz centre frequency and distance travelled by the acoustic signal of 320 meters. Such data rate is an improvement over conventional acoustic modems, although the range is reduced.

3.3 Radio Frequency

RF signals are used for underwater applications by buoys or wirelessly. There are already numerous buoy networks in operation, both global and local. They are mainly focused on meteorological and climate data collection, but also some specialised networks exist, such as DART dedicated to tsunami detection and reporting. Due to the limiting absorption for EM waves in seawater, usually only frequencies between 30 and 300 Hz have been considered for underwater wireless communication, which falls in the extremely low frequency (ELF) region of the radio spectrum (Akyildiz et al. 2004). This was pioneered during the World War II by the Germans to enable communications between submarines. However, due to physical limitations, as described in Chapter 2, research interest in this area was reduced after the 1970s (Che et al. n.d.). In spite of this, some niche advantages have been considered lately.

3.3.1 Underwater Wireless

Recent theoretical and experimental studies have shown that the seawater propagation loss is much lower than expected, and RF signals can reach larger distances. The feasibility of using frequency in the MHz range and distance of about 85 m has been proven (Al-Shamma'a et al. 2004). These new capabilities are a result of a different antenna design. The conventional way is to have a direct contact between the waveguide and the seawater for launching and receiving the signal. Instead, when using an insulating material covering the metal aperture, the attenuation loss is reduced and thus the propagation distance increased. However, the trial experiments performed show attenuation in the order of 80 dB and very little of the signal energy propagates. Therefore, RF modems are appealing for short range applications, for example when using a swarm of autonomous underwater vehicles (AUVs), it might provide higher throughput than acoustic link (Frater et al. 2006). An advantage to use them in shallow water environment over acoustics is that they are not susceptible to turbidity or bubbles caused by vessels near harbours and the salinity in littoral regions does not reduce the speed of the signal.

3.3.2 Buoys

RF can be applied in underwater sensor networks by connecting floating node at certain depth with a surface buoy using a cable or optic fibre. The gathered information can then be transferred via satellite link to a surface station or onshore sink. Buoy networks are so commonly used because collected data can be processed in real time. Signals are transmitted automatically on defined intervals and the operation is relatively inexpensive. Although this provides quick and easy deployment, the communication is no longer hidden underwater. The disadvantage is that the surface floating elements can become an obstacle for navigating ships. Furthermore, in military conditions, the buoys and their transmission above water, can be detected by the enemy without much difficulty, and deactivated. For security applications, when sensors need to be kept on unknown for other parties location, such topology might not be feasible.

However, long propagation distances underwater are likely to induce prohibitive delays for real-time operations. If the applications requires large coverage area and covertness is not a priority, buoys might be invaluable in terms of providing a central node to collect the monitoring data. Furthermore, considering moving nodes, such as AUVs, a hybrid usage of buoy network fixed with optic modems to collect data in bursts might eliminate the need of acoustic transmission in this scenario, where the Doppler spread would have a major hindering effect. Despite the potential gains of such architecture, it would require a topology with very close node proximity and enhanced optical modem design.

Chapter 4

Comparison and evaluation

Table 4.1 provides a comparison of the current capabilities of acoustic, RF and optical underwater communication technology [1]. They all have very different physics and operational frequencies, which in turn dictate their limitations or advantages.

Table 4.1: Acoustic, RF and optics underwater communication comparison summery

Spectrum	**Frequency**	**Advantages**	**Disadvantages**
Acoustics	1 - 110 kHz	range up to 50 km data rate up to 100 kbps proven technology	high delay, low bandwidth severe multipath affects marine life
RF	30-300 Hz 1-20 MHz	range up to 100 m data rate up to 10 Mbps unaffected by turbidity/salinity	high absorption, large antenna high energy consumption limited water propagation range
Optics	526-668 THz	no latency data rate up to 1 Gbps no multipath	precise positioning of the beam high scattering shallow water range is few meters

Having in mind the capabilities of each signal, figure 4.1 is displaying the relation between signal to noise ratio and bit error rate expected from acoustic, RF and optic signals. The values for the SNR are set from 0 to 20 and part of the transmission loss contributions is added. BER is performance evaluation parameter that shows the amount of errors out of the total amount of transmitted bits. The loss calculated for optical signal comes from scattering and absorption. The exact values are taken for San Diego Harbour station 2040 (Petzold 1972) measurements, rather than calculated. Absorption for the acoustic and RF signal is given in previous sections, equations 2.4 and 2.11 respectively. However, each carrier is propagating with different optimal frequencies and distances due to their distinctive physical properties. Therefore, table 4.2 gives the parameters used to calculate the graph in 4.1. It shows how each carrier behaves in the shallow water acoustic channel and that none of them is reliable enough when comparing the result with the system requirements set for video and control messages in section 1.3. However, the simulation is done for the simple case of binary phase shift keying (BPSK) and no error correction techniques are used to improve the transmission.

There are some general conclusions that can be drawn for the current state of underwater communi-

[1]Some of the information is collected from (Lanbo et al. 2008)

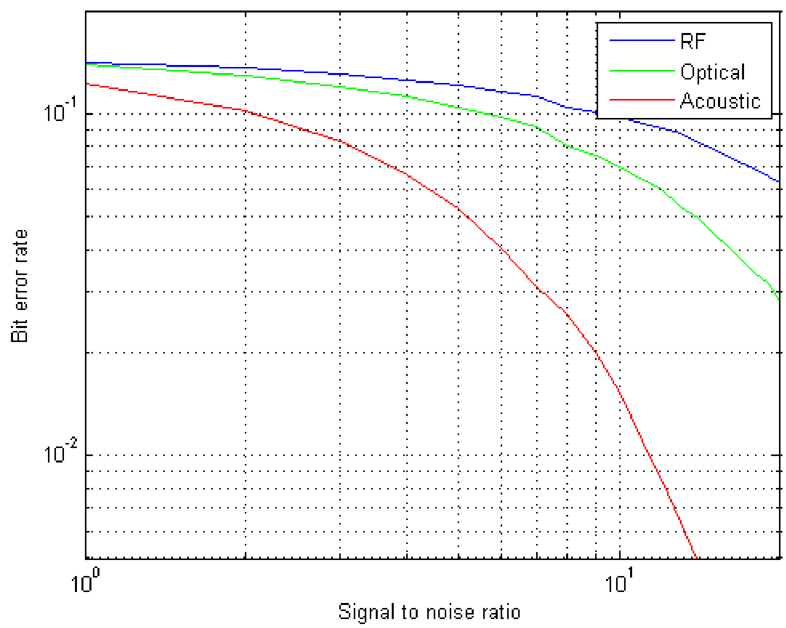

Figure 4.1: BER as a function of SNR for acoustic, RF and optical signals

Table 4.2: BER calculation parameters

Spectrum	**Frequency, kHz**	**Distance, m**
Acoustics	12	1500
RF	0.3	10
Optics	$530{\cdot}10^6$	2

cations. Using lasers as a physical layer technology in a sensor network, or even as assisting nodes working in burst mode, is not suitable for shallow waters with the current state of research. Such transmission is characterised with a potential of reaching extremely high data rates, in the order of Mbps, and no latency. This is due to the high carrier frequencies (THz) and lack of multipath for such links. However, light scattering and precise directivity of the modem beams is often limiting the signal propagation up to a few meters. Possible application of optical underwater communication is when AUVs dump collected data to a fixed bottom node, where the water is less contaminated with surface light, however currently commercial modems are not available for shallow water environment.

Acoustics is still superior to RF signals in most scenarios with underwater applications. However recent research efforts have highlighted niches where the EM spectrum might be considered, such as very shallow water (less than 30 m depth) with high amount of turbidity, which causes severe multipath when using acoustics. Since securing harbour sites is the focus of this work, this technology is an appealing alternative to conventional communication modems with expected data rates in the order of few hundreds of kbps for short distances (about 50 m). Considerable drawback, however, is that EM modems technology for wireless usage has been recently re-evaluated and only limited amount of commercial modems are available. The size and complexity of a modem antenna is also a challenge as it is proportional to the low frequencies used. Buoys are not considered suitable as communicating through them is not covert. However, if the emphasis is put on successful data transmission, buoy gateways might be inevitable for transferring data to human operators on shore.

Considering the current state of underwater technologies and the need to design a network for monitoring near-harbour sites with security application, acoustic modems are the only feasible solution. Depending on the requirements of the system and the environment specifics of the area where it will be deployed, network nodes can be selected as there is a wide range of commercially available modems for such purposes. Acoustics has a broad spectrum of usable frequencies depending on the various applications and selected topologies, but normally modems operate with carriers of several tens of kHz. This is the only available technology providing operational ranges of more than 100 m. Available data rates vary with selected modulation, error correction schemes and modem design, but several tens of kbps can be expected in short distances (less than 1 km). This is enough to cover the reduced size underwater images/videos transmission requirements. However, large latencies, due to the low sound propagation and BER, caused by multipath and Doppler spread, are causing problems in higher level protocols. Another consideration that could have ethical implications is that acoustic signals for underwater communication fall within the spectrum used by marine mammals and could disrupt their normal life.

Solutions applied to terrestrial networks are encouraged to be tested for the needs of underwater modems, however with some modifications to the design added. The main considerations being that acoustic signals are wideband and the problems of multipath and Doppler spread are more severe compared to on-ground RF transmissions, causing increased BER and latency, which might be detrimental for higher level protocols in a network. EM waves cannot be used in a conventional way underwater as the attenuation is too high and therefore terrestrial modems experience is not applicable.

Chapter 5

Conclusions

5.1 Conclusions and recommendations

This work gives a quantitative performance evaluation of the available technologies for underwater communication. Undoubtedly, there are much more difficulties to oversee compared to conventional terrestrial system. When an UWSN is considered, the problem of communication brings issues, such as synchronisation and geolocation, and managing the nodes. As a result, there is a great potential in considering the use of autonomous operations where the amount of control messages is minimised. On the other hand, the need to transfer large image or video messages imposes certain requirements to the system. After assessing the available technologies, it is clear that none of them is performing well at both long ranges and high throughput. Therefore, the advantage of high data rates in short distances (less than 1 km) can be exploited in multihop network topologies. For acoustic transmission, the reduced distance means lower absorption so the link can tolerate higher frequency and bandwidth, which in terms reduces the multipath effect and latencies. This is the only way to reach the data rate limits allowed by the physical boundaries for underwater communication. Following the example of terrestrial networks, with high density nodes deployment, messages can be relayed until reaching their destination, even if it is more than one hop away. However, this is not a problem that can be solved with modem advancements relying solely on physical layer technology, but rather involves system design of a network of nodes. The conclusions made in this study will allow me to address the identified problems in my further PhD project by taking into account the constraints imposed by environment and application.

5.2 Future work

Although this project is not aimed at modem design, understanding the limitations and current state of physical layer technologies is important as it might have implications for higher level protocols. The presented work will be used as a foundation of a PhD project aiming at developing network control algorithms for UWSNs.

After considering the general issues associated with underwater communications, those findings will be applied to a specific case of UNSW aimed at shallow water security application. Following the system requirements mentioned in the Chapter 1, in order to be able to transmit video signals, large bandwidth can be provided by sensor network design with short-distanced densely deployed nodes. The optimal trade-off between exploiting efficiently the modem capabilities and achieving sufficient bandwidth will be addressed in the future PhD work. The first issue with such topology comes from the ability to coordinate messaged between nodes. Such protocol design need to take into account the great hindering effect by the latency, resulting from low sounds speed propagation, as discussed in section 2.1.1. Currently, most existing systems are sparse nodes does not need to exchange coordinating messages with each other. On the other hand, there are many protocols designed for such purposes for terrestrial networks, but they cannot tolerate the latencies observed in underwater environment. There are also protocols designed for satellite communications that take into account the delay in the system, however their priority is not the energy efficiency and they cannot be applied for underwater applications without modifications. I would like to further approach this problem by testing the feasibility of time-division multiple access (TDMA) protocol based on bio-inspired networks, such as DESYNC (Degesys et al. 2007). This idea have been pursued recently for efficient terrestrial multiple access (MAC) protocols. Usually TDMA is the least desirable option for UWSN design as it reduces the efficiency of the system waiting for the scheduled node to transmit. However, a self maintaining TDMA algorithm might prove effective for dense shallow water network design and the latency problem will be investigated.

As this project is aimed at security application of UWSN, the convenience of buoys relaying messages to operation stations via satellite will be considered only as a backup necessity, in case the system requirements cannot be achieved by wireless covert transmissions. The challenge for such design comes from the efficiency demand of the multi-hop protocol as it is energy-expensive to establish new forwarding paths between nodes, especially when they are moving and located in 3D plane.

The first step of the further research includes a system overview, rather than a layer by layer separation. First the simulation environment will be selected. Currently, there are several options of open source software specifically designed for underwater networks design, however other commercial packets for general terrestrial network simulation will be considered as well. When satisfactory results are achieved by the model, given the set system requirements, validation will be performed by site trials.

Appendix A

Acronyms

- autonomous underwater vehicles (AUVs)
- additive white Gaussian noise (AWGN)
- bit error rate (BER)
- intersymbol interference (ISI)
- multiple access (MAC)
- multiple-input multiple-output (MIMO)
- multipath component (MPC)
- orthogonal frequency division multiplexing (OFDM)
- phase shift keying (PSK)
- quadrature amplitude modulation (QAM)
- radio frequency (RF)
- single-input single-output (SISO)
- signal-to-noise ratio (SNR)
- shallow water acoustic (SWA)
- time-division multiple access (TDMA)
- underwater sensor networks (UWSN)
- wireless acoustic communications (WAC)

Bibliography

Akyildiz, I. F., Pompili, D. & Melodia, T. (2004), 'Challenges for efficient communication in underwater acoustic sensor networks', *ACM Sigbed Review* **1**(2), 3–8.

Akyildiz, I. F., Pompili, D. & Melodia, T. (2005), 'Underwater acoustic sensor networks: research challenges', *Ad hoc networks* **3**(3), 257–279.

Akyildiz, I. F., Su, W., Sankarasubramaniam, Y. & Cayirci, E. (2002), 'A survey on sensor networks', *IEEE Communications magazine* **40**(8), 102–114.

Al-Shamma'a, A. I., Shaw, A. & Saman, S. (2004), 'Propagation of electromagnetic waves at MHz frequencies through seawater', *IEEE Transactions on Antennas and Propagation* **52**(11), 2843–2849.

Blackmon, F., Estes, L. & Fain, G. (2005), 'Linear optoacoustic underwater communication', *Applied Optics* **44**(18), 3833–3845.

Bouvet, P. & Loussert, A. (2010), Capacity analysis of underwater acoustic mimo communications, *in* 'OCEANS 2010 IEEE-Sydney', IEEE, pp. 1–8.

Bouvet, P. & Loussert, A. (2011), An analysis of mimo-ofdm for shallow water acoustic communications, *in* 'OCEANS 2011', IEEE, pp. 1–5.

Catipovic, J. A. (1990), 'Performance limitations in underwater acoustic telemetry', *IEEE Journal of Oceanic Engineering* **15**(3), 205–216.

Che, X., Wells, I., Dickers, G., Kear, P. & Gong, X. (n.d.), 'Re-evaluation of rf electromagnetic communication in underwater sensor networks'.

Chitre, M. (2007), 'A high-frequency warm shallow water acoustic communications channel model and measurements', *The Journal of the Acoustical Society of America* **122**, 2580.

Chitre, M., Freitag, L., Sozer, E., Shahabudeen, S., Stojanovic, M. & Potter, J. (2007), An architecture for underwater networks, *in* 'OCEANS 2006-Asia Pacific', IEEE, pp. 1–5.

Chitre, M., Shahabudeen, S., Freitag, L. & Stojanovic, M. (2008), Recent advances in underwater acoustic communications & networking, *in* 'OCEANS 2008', Vol. 2008-Supplement, pp. 1–10.

Degesys, J., Rose, I., Patel, A. & Nagpal, R. (2007), Desync: self-organizing desynchronization and tdma on wireless sensor networks, *in* 'Proceedings of the 6th international conference on Information processing in sensor networks', ACM, pp. 11–20.

Fisher, F. & Simmons, V. (1977), 'Sound absorption in sea water', *The Journal of the Acoustical Society of America* **62**, 558.

Frater, M. R., Ryan, M. J. & Dunbar, R. M. (2006), Electromagnetic communications within swarms of autonomous underwater vehicles, *in* 'Proceedings of the 1st ACM international workshop on Underwater networks', ACM, pp. 64–70.

Hanson, F. & Radic, S. (2008), 'High bandwidth underwater optical communication', *Applied Optics* **47**(2), 277–283.

Hardie, D. (2012), 'Acomms for dtn workshop', Presentation by Atlas Elektronik UK.

Jaruwatanadilok, S. (2008), 'Underwater wireless optical communication channel modeling and performance evaluation using vector radiative transfer theory', *IEEE Journal on Selected Areas in Communications* **26**(9), 1620–1627.

Jebson, S. (2007), 'Fact sheet number 6: The beaufort scale', Monograpth from National Meteorological Library and Archive.

Karasalo, I. (2011), Time-domain modelling of turbo-coded underwater communication, *in* 'OCEANS, 2011 IEEE-Spain', IEEE, pp. 1–8.

Lanbo, L., Shengli, Z. & Jun-Hong, C. (2008), 'Prospects and problems of wireless communication for underwater sensor networks', *Wireless Communications and Mobile Computing* **8**(8), 977–994.

Li, B., Huang, J., Zhou, S., Ball, K., Stojanovic, M., Freitag, L. & Willett, P. (2009), 'Mimo-ofdm for high-rate underwater acoustic communications', *Oceanic Engineering, IEEE Journal of* **34**(4), 634–644.

Lingjuan, W., Kastner, R., Bo, G. & Dunshan, Y. (2013), 'Design of a reconfigurable acoustic modem for underwater sensor networks', *IEICE TRANSACTIONS on Fundamentals of Electronics, Communications and Computer Sciences* **96**(4), 821–823.

MetOffice (2013), 'Met office: Eastern scotland regional climate'.
URL: *http://www.metoffice.gov.uk/climate/uk/es/print.html*

Molisch, A. F. (2012), *Wireless Communications*, John Wiley & Sons.

Petzold, T. J. (1972), Volume scattering functions for selected ocean waters, Technical report, DTIC Document.

Shofrin, K. S. (1998), *Physical Optics of Ocean Water*, Springer.

Stojanovic, M. (1996), 'Recent advances in high-speed underwater acoustic communications', *IEEE Journal of Oceanic Engineering* **21**(2), 125–136.

Stojanovic, M. (2001), Underwater acoustic communication, *in* 'Wiley Encyclopedia of Electrical and Electronics Engineering', John Wiley & Sons, Inc.

Stojanovic, M. (2007), 'On the relationship between capacity and distance in an underwater acoustic communication channel', *ACM SIGMOBILE Mobile Computing and Communications Review* **11**(4), 34–43.

Thorp, W. H. (1967), 'Analytic description of the low-frequency attenuation coefficient', *The Journal of the Acoustical Society of America* **42**, 270.

Urick, R. J. (1984), Ambient noise in the sea, Technical report, DTIC Document.

Waite, A. D. (2002), *Sonar for Practising Engineers*, 3rd edn, John Wiley & Sons.

Wiener, T. & Karp, S. (1980), 'The role of blue/green laser systems in strategic submarine communications', *IEEE Transactions on Communications* **28**(9), 1602–1607.