UNIVERSITY OF TARTU
FACULTY OF SCIENCE AND TECHNOLOGY
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Benchmarking an Underwater Optical Communication System

Bachelor Thesis (9 EAP)

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Abstract

Benchmarking an Underwater Optical Communication System

Abstract: Due to the vastly different properties of water compared to air, different approaches should be taken for wireless communications. Compared to air, the performance of some communication techniques are improved underwater, while some others are deteriorated. In this thesis, an overview of the current state of wireless underwater communication is given. Additionally, a simple wireless optical communications system is tested for it's susceptibility to different underwater factors like turbidity and turbulence.

CERCS: T180 Telecommunications engineering

Keywords: underwater communications, wireless optical communications

Veealuse optilise side süsteemi testimine

Kokkuvõte: Kuna vee ja õhu omadused on väga erinevad, on mõistlik nende puhul traadita side pidamiseks kasutada erinevaid lähenemisviise. Mõni sidepidamisviis toimib paremini vee all kui vee peal, kuid samas on ka vastupidiseid juhtumeid. Käesolevas töös antakse ülevaade traadita veealuse side hetkeseisust. Lisaks testitakse ühe juhtmevaba optilise sidesüsteemi vastupidavust erinevate veealustele teguritele nagu hägusus ja turbulents.

CERCS: T180 Telekommunikatsioonitehnoloogia

Märksõnad: Veealune side, traadita optiline side

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Glossary

Attenuation The weakening of the signal travelling through a medium.

Frequency The amount of waves passing by a certain point in a second. Measured in hertz (Hz). 1 Hz = 1 wave passing by every 1 second.

Latency The amount of time taken by the signal to get from the transmitter to the receiver.

Salinity Saltiness of the water.

Turbidity The optical haziness of the water.

Turbulence The chaotic flow of a liquid or gas.

Wavelength The distance between identical points on a wave between two consecutive waves.

1

Introduction

Above ground, wireless communication has become an essential part of the everyday life of an average person. Most of these wireless technologies like 4G, Bluetooth, WiFi and GPS work by using high-frequency radio waves, which are able to transmit high amounts of data at high speeds. Unfortunately, these waves get almost instantly attenuated upon coming in contact with water. Because of that, other approaches must be taken for data transmission. Although fiber optic cables running on the seabed provide the vast majority of high-speed internet connection between continents[1], using cables for communication with non-stationary entities like submarines is not preferred, as the cable could get damaged or stuck by the environment or the marine life.

Underwater wireless communication is usually established using optical, acoustic or low-frequency radio waves. This thesis delves into the current state of wireless underwater communication along with it's capabilities, use cases and difficulties. Additionally, various experiments are conducted on a simple optical underwater communications system in order to find the impact of the different environmental factors on the optical signal.

1.1 Outline

This thesis is structured as follows:

- Chapter 2 gives an overview of the currently used wireless underwater communication techniques along with their pros and cons, uses and the available products.

[1] https://www2.telegeography.com/submarine-cable-faqs-frequently-asked-questions

- Chapter 3 gives additional information about the different aspects of turbulence and turbidity that are needed to understand some of the tests conducted in the following chapter.
- Chapter 4 describes the tests and their results that was conducted in order to find the impact of the environment on optical underwater communication.
- Chapter 5 presents the summary of the work.

2

Overview of the different underwater wireless communication techniques

This chapter provides an overview of the various techniques used for wireless underwater communications today. It will discuss the advantages and disadvantages of each technique, their effect on the environment, as well as their use cases and available products. The chapter primarily focuses on the three most commonly used techniques. These being: communication via acoustic, optical and radio waves. Lastly, other approaches to wireless underwater communication are briefly discussed.

2.1 Underwater acoustic communication

Acoustic communication utilizes sound waves to transmit data. In water, sound travels faster than in air, moving at approximately 1500 m/s compared to around 340 m/s in air [2, 3]. This is still a relatively slow speed, meaning that there might be a noticeable delay if communicating between long distances. The data transfer rate of acoustic communication depends on the frequency of the waves used. Higher frequencies allow for greater transmission rates, but for shorter distances as they attenuate more in water. For instance, a sound wave with a frequency of 100 kHz can travel about 100 meters, whereas frequencies under 1 kHz it can travel for thousands of kilometers [4]. Meanwhile the data rate for these frequencies ranges from a few bits per second to hundreds of kilobits per second [4].

Another factor considered when choosing the frequency of sound used for communication is the presence of outside noise. This falls into two categories: ambient noise, which is consistently present in the water and site-specific noise, which occurs only in certain locations, such as the cracking of ice in polar regions or the shrimp snapping in warmer waters [5]. Using a frequency with less noise associated with it is preferred. The main sources of ambient noise in the most commonly used frequency range for underwater acoustic communication of 100 Hz - 100 kHz is mostly affected by the sound made by the motion of the water surface, whilst the lower range of 10 - 100 Hz is mostly affected by distant shipping activities [6].

2.1.1 Advantages of underwater acoustic communication

Sound waves have very low attenuation underwater compared to other used communication techniques. They can also penetrate through a lot of obstacles present and are not as affected by the condition of the water as others. This has made acoustic communication a reliable long-range communication technique.

2.1.2 Disadvantages of underwater acoustic communication

Multipath propagation is a phenomenon in wireless communications, where the transmitted signal reaches the receiver via multiple different paths at different times [7]. In underwater acoustic communication this is mainly caused by the acoustic waves reflecting on surfaces and the differing speed of sound in different water conditions, [8]. Consequently, this can lead to the fading of the signal [8].

Multipath propagation is a great problem in underwater acoustic communications. Especially when operating with lower frequencies over longer distances in shallower waters, as the the time between the first and last instance of a signal will vary more there [9]. In these cases, the delay can reach up to hundreds of milliseconds [9]. A demonstration can be seen in 2.1. Besides using higher frequency where possible, the effects of multipath propagation can be reduced by applying signal processing techniques [10].

Man-made noise underwater has been shown to have negative effect on marine life by causing among others, behavioral and physiological changes to the organisms [11]. For example, the use of acoustic mid-frequency active sonars (operating between 1-10

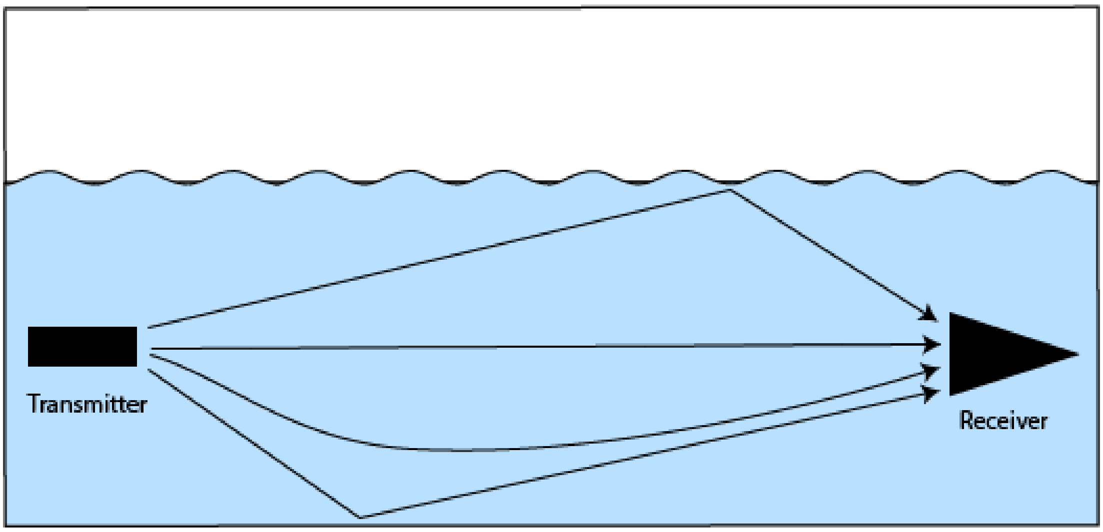


Figure 2.1: The figure shows some of the possible ways a signal can travel from the receiver to the transmitter. Problems arise, if the signal reaches the transmitter multiple times with big enough delays in between them.

kHz) during military exercises have been studied to likely be the cause of many beaked whale strandings [12]

2.1.3 Uses of underwater acoustic communication

Underwater acoustic communication currently stands as the most dominant wireless underwater communication technique used. Although having a big latency and slow transmission speeds, it is versatile, reliable and can be used over vast distances. It finds use in sonar systems as well as in communication with submarines and divers among others. Additionally, acoustic signals are also being used for ocean acoustic tomography in which information about the water condition can be extracted from the changes to the signal between the transmitter and the receiver [13].

There are many products available for underwater acoustic communications. For instance, one of the available products is the compact Subnero WNC-S40HSS4 [1], which supports a communication range up to 1 km and a data rate up to 33 kbps, with a 300 m operating depth and dimensions of 127x316 mm.

Another example is the Teledyne Marine ATM-960 [2], which has 3 switchable fre-

[1] https://subnero.com/products/wnc-s40hss4.html
[2] https://www.teledynemarine.com/en-us/products/Pages/Acoustic_Modems.aspx

quency bands, with the communication distances ranging between 2-6 km, and data rates between 80-15360 bps, along with the operating depth of 6000 meters.

2.2 Underwater optical communication

As its name implies, wireless optical communication utilizes flashes of visible light in order to send data from a transmitter to a receiver. An example of can be seen in figure 2.2. Light, being part of the electromagnetic spectrum, travels extremely fast. Although it is slowed down by water to around 225,500,000 m/s [3], it still significantly outperforms acoustic waves in this regard. This, along with the high frequency of visible light, means that optical communication can potentially transfer very large amount of data per second with practically no latency.

Compared to the acoustic channel, the optical channel in seawater is much less noisy, with the biggest concern being the ambient background light coming from a constant light source like the sun. Although this can, in worst case scenarios hugely affect communications in shallow waters, the issue will subside in deeper waters [14]. There are two types of light sources commonly used for the transmitter. These being the laser diodes (LD) and the light emitting diodes (LED). The key difference between these is that the light coming from LDs is more focused and powerful, thus being more fit for use in longer distances, but the more scattered light of LEDs does not have to be directed as exactly [15]. There have also been several practical and theoretical studies made on using both of these at the same time in an hybrid solution leveraging the best parts of both systems and covering each others weaknesses [16, 17].

Usually for underwater optical communication, the shorter wavelengths that fall into the blue and green regions of visible light are preferred instead of the longer wavelengths in the red region. The reason being that these shorter wavelengths usually experience less attenuation in seawater [18]. This also explains why the water in oceans often appears to be blue. Despite that, it has been shown, that the attenuation of shorter wavelengths in water rises more sharply in more turbid and saline waters compared to longer wavelengths, meaning, that red light will perform better in these environments [18, 19]. Concluding, that there is no universal best wavelength to use in all situations.

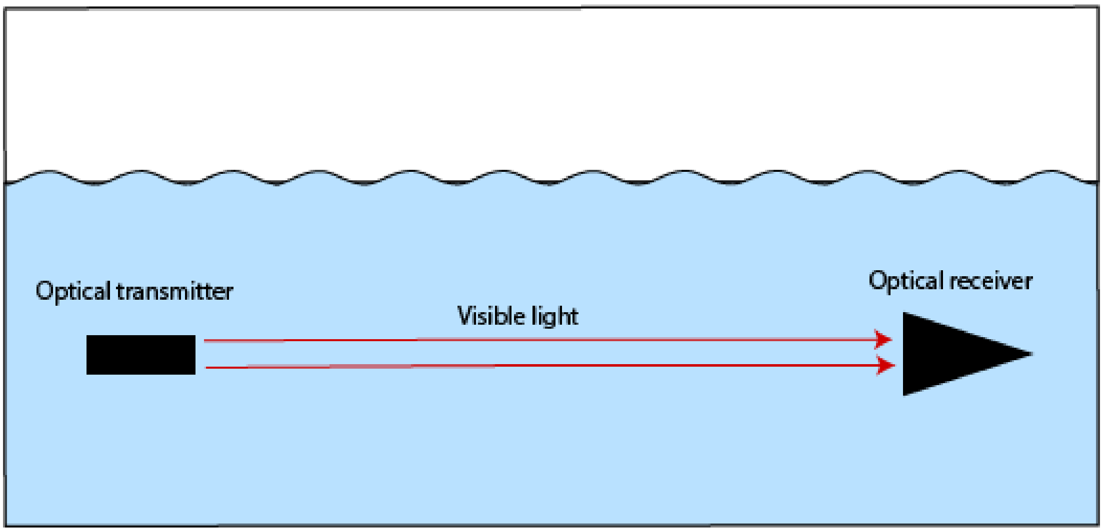


Figure 2.2: The usual setup for optical communication. Flashes of visible light are used for sending information

2.2.1 Advantages underwater of wireless optical communication

The big hurdle of acoustic communication, multipath propagation isn't as prevalent of an issue in optical systems due to the high speed of light. [3].

Long-term artificial light pollution has negative effects on the marine life, especially in the coastal areas [20]. Conversely, the effect of short-term directed light on deep-sea life has been understudied, although one of the known problems is that the fish could receive permanent damage to the eyes by the powerful directed laser, if they were to get in front of it [21]. Despite that using optics is still mostly an environmentally friendly communication technique.

2.2.2 Disadvantages of underwater optical communication

One of the main disadvantages of traditional underwater optical communication is the fact, that there needs to be a direct line of sight between the transmitter and the receiver. In order to overcome this limitation there has been a proposed non-line-of-sight (NLOS) solution in which the surface of the water is used to reflect the signal over a potential obstacle [22]. Although this approach has not yet been meaningfully implemented in any real-life scenarios, there have been studies discussing its feasibility.

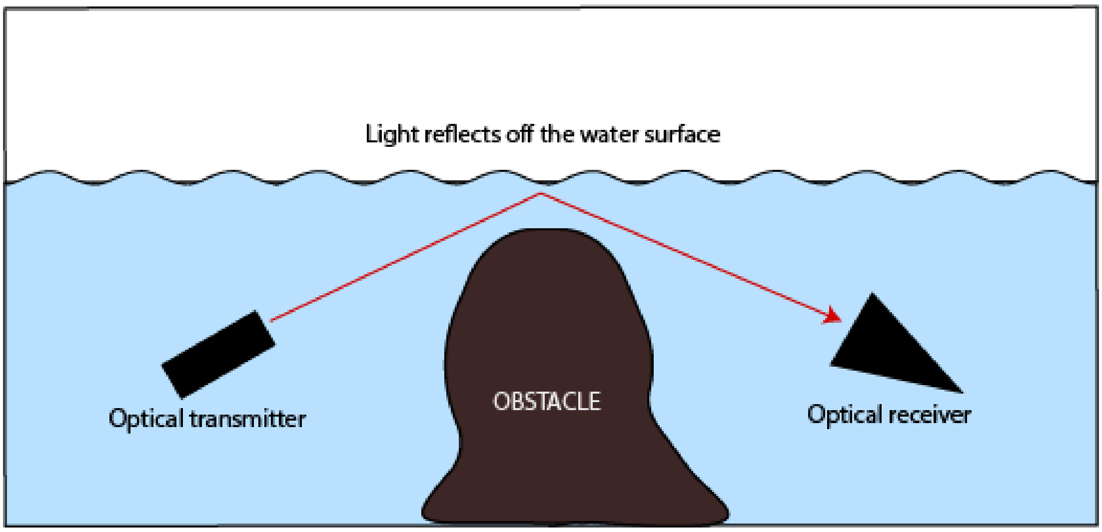


Figure 2.3: Demonstration of a NLOS system. The optical signal is reflected off the surface of the water in order to avoid obstacles that would be in the way of classical optical communication

Recent simulations by Fang et al. [23], have shown promising results for it on wavy surfaces. A figure depicting the NLOS system can be seen in 2.3.

Another one of it's problems is in maintaining connections over longer ranges. Temporary signal breaks may occur due to loose particles or fish obstructing the signal's path. This makes communication in turbid waters even more difficult.

As the light has to be directed, it is important that the transmitter and receiver are properly aligned to one another. Misalignment is inevitable in any underwater optical systems, especially in shallower waters, as the water is more turbulent there [15]. To counteract it, there are tracking systems used in order to keep the parts aligned. For example, Zhang et al. [24] have proposed a camera-based tracking system to especially work in turbulent environments.

2.2.3 Uses for underwater optical communication

Underwater optical communication shines most in situations where high-speed connections are needed. For example streaming live from an unmanned submarine under the water to remotely monitor undersea cables or structures. It could also be used to harvest data live from underwater sensors from a distance.

As an already existing optical communication technology, Li-Fi has been shown to be able to be used in underwater communication networks [25, 26].

In 2019, the Nekton research team were the first to livestream high-definition video from a submersible in the Indian ocean using Sonardyne's BlueComm wireless optical technology [27]. This product promises speeds of 2.5-10 Mbps and range up to 150 meters in low turbidity dark water [1]. Similarly, the Shimadzu MC500 [2] provides switchable data rates from 1 to 20 Mbps with the shorter maximum distance of 80 meters. The equipment used for longer range optical communication weigh mostly around 10 kg and have dimensions around 30x15 cm.

2.3 Communication using radio waves

Radio frequencies are a subset of the lowest frequencies on the electromagnetic spectrum. Their frequencies range from 0.03 Hz to 300 GHz [28]. Radio frequency currents emit radio waves. Despite being a mature technology and the lifeline of modern over-the-air communications, with finding uses in technologies like TV/radio broadcasting, wireless networking (4G, WiFi), navigation (GPS) and many others. Using radio waves for underwater communications is not as easy. This is because unlike in air, radio waves are heavily attenuated in water due to water's conductivity, absorption and other properties [29].

As with acoustic waves, the transmission speed and the maximum communication distance of radio waves are negatively correlated with each other, being dependant of the frequency used [30]. Meaning, that higher data rates are only possible over short distances, with data rate in Mbps possible only for distances about 10 meters or less [3].

For that reason, the lowest possible frequencies falling into the very low frequencies (VLF, 3-30 kHz) and extremely low frequencies (ELF, $<$3 kHz) are used. Still, VLF can only penetrate around 40m into the seawater, whilst ELF waves can penetrate up to several hundred meters [31]. Furthermore the antennas capable of sending such low frequencies must be huge ($>$100 km for ELF) and expensive, limiting their use to one-way communication only. Right now only four countries (USA, China, Russia,

[1] https://www.sonardyne.com/products/bluecomm-200-wireless-underwater-link/

[2] https://www.shimadzu.com/underwater/mc500.html

India) have constructed facilities capable of sending ELF waves for communications [31]. Additionally, the data rate when using such low frequencies is also almost non-existent. Whilst a theoretical, more compact transmitter that would fit on a submarine, has been proposed [31], it still requires advances in multiple scientific fields and is far from becoming a reality.

2.3.1 Advantages of radio wave communication

Compared to optical and acoustic communication, radio waves can transition smoothly through air/water and earth/water boundaries [30]. This property allows radio wave communication to actually expand the communications range due to multipath propagation in certain cases where the path of least resistance for the signal leads through the less attenuating mediums of air or earth [30]. This makes using radio frequency great for communicating when one of the communicating parties is not submerged.

Due to the high attenuation of radio waves underwater, the higher frequency channels experience minimal noise. While the lower ELF frequencies start to experience some more noise in deeper oceans [32].

From an environmental perspective, radio frequency communications is quite friendly. Although the electromagnetic fields created could influence the behavior of some of the marine life sensitive to it [33].

2.3.2 Disadvantages of radio wave communication

As mentioned before. Radio waves suffer deeply from attenuation in water due to the electrical conductivity in water. The conductivity of the water rises with salinity and temperature [34], leading to an even shorter communication range in these conditions.

Additionally, the design of communication modems plays a role in underwater radio frequency communication. Lower frequencies are required to communicate over longer distances, necessitating larger antennas and bulkier modems. This trade-off between frequency and antenna size could present a challenge in many scenarios.

2.3.3 Uses for radio wave communication

The aforementioned ELF and VLF waves have been used by navies around the world for basic communication with military submarines. Other than that, radio frequencies are mostly used for either very short-range underwater communication or when one of the communicating parties is above water.

The only commercially available device found for longer range underwater radio frequency communication is CSignum's EM-1 [1], which promises transfers up to 30 meters in shallow waters, with a data rate of up to 200 bps. It has an outer diameter of 110 mm, a length of 5 m and weighs 4.4 kg.

2.4 Other approaches

2.4.1 Hybrids

As the main techniques all have their advantages and disadvantages, they are often paired together to complement each other to overcome their weaknesses. This can make them more reliable and efficient.

For example, the system proposed for autonomous underwater vehicles in [35] uses three acoustic receivers in order to triangulate the direction of the incoming acoustic signal. This information is then used to align the optical modem in order to start using optical communication. In this scenario the slow but reliable acoustic signals helps to establish a much faster, energy-efficient but at the same time more fragile optical connection. Another example of hybrids is to use different communication techniques for communicating with different entities. For example using radio frequency waves when in shallow waters and trying to communicate with an aeroplane but using optical waves for communicating with other underwater entities [15].

2.4.2 TARF (Translational Acoustic-RF) communication

The TARF [1] system developed by the MIT Media Lab in 2018 is a one way communication technique from water to air. It works in the following principle: An underwater transmitter sends acoustic waves towards the water surface. When the waves reach the surface, they cause tiny vibrations on it. The receiver above water uses a sensitive radar to detect changes on the water surface. These changes are then used to decode the message. It's advantages over other techniques can be seen in figure 2.4.

[1] https://www.csignum.com/em1/

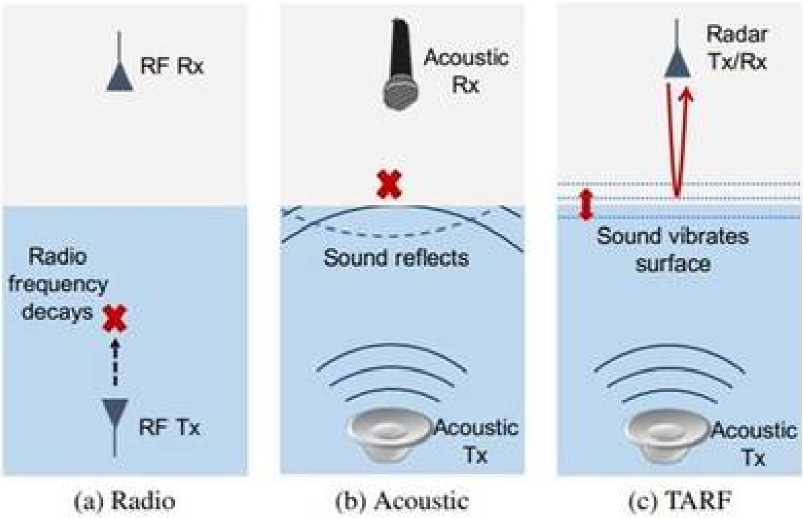


Figure 2.4: The principle of TARF communication. (a) shows that a radio transmitter cannot communicate because radio signals die exponentially fast in water. (b) shows that acoustic signals reflect off the water surface. (c) shows that a TARF receiver employs a radar to sense surface vibrations caused by acoustic pressure waves and use them for decoding. [1]

The researchers successfully demonstrated its use with short distances in a swimming pool that was concurrently used by people swimming in it, although larger waves caused by the swimmers still broke the signal [1].

Although making use of the good aspects of both acoustic and radio waves, this technology is still in its infancy and far from being used in real life scenarios. When matured it could be used for cases such as submarine to airplane communication.

2.4.3 Magneto-inductive communication

Magneto-inductive communication uses varied or modulated AC magnetic fields in order to transmit information [36]. Using magnetic fields has advantages over electromagnetic waves like having almost the same good attenuation rate in water as in air, whilst also having low delays and error rates [37]. Despite that, it is still quite a new technology and the effective communication distances are limited to the low- to mid-range [38].

2.4.4 Molecular communication

Another emerging research direction for underwater communication is molecular communication, in which information is being carried by chemical signals [39]. In molecular communication, the transmitter releases small particles such as molecules or lipid vesicles, which are then detected and decoded by the receiver [39]. It's advantages include being environmentally friendly, secure and requiring very little energy to generate and propagate [39]. In 2020 Guo et al. [40] demonstrated upwards vertical molecular communication via buoyancy. Still, in order for larger scale molecular communication to be feasible, advances in many fields must take place [39].

3

Creating and Measuring Turbidity and Turbulence

This chapter provides additional information on the methods used for the creation and measuring of turbulence and turbidity in the water. This is needed for understanding some of the tests conducted in chapter 4.

3.1 Turbulence

Turbulence is the irregular flow of water. There are multiple ways of inducing it in a testing environment. In this thesis, this is done in two distinct ways. In the first method, water is stirred below the surface and for the second method, air bubbles are generated from the bottom of the testbed. Although turbulence is created in both cases, the results are expected to be different due to the optical signal needing to cross the air-water barrier in the case of bubbles.

Another way to create turbulence, would be to add together water with different gradients of temperature or salinity, like it has been previously done in [41]. Although this would emulate naturally occurring turbulence more accurately, creating such a system is also much more difficult.

In some of tests conducted in the next chapter, water turbulence is estimated, by using an accelerometer floating on the turbulent water. The absolute values of changes in the x-, y-, and z-axes recorded by the accelerometer and are summed up to obtain the total movement value for any given time. A Samsung Galaxy Active2 [1] smartwatch equipped with an accelerometer app is used for it.

3.2 Turbidity

Turbidity is the optical haziness of water caused by the suspended and dissolved solids floating in the water [42]. The dissolved particles include the salts and minerals that have dissolved in the water, while the suspended particles consist of larger particles like sand and silt [43]. The larger and heavier suspended particles tend to settle down after some time, if there is no movement in the water. Later in the thesis, while testing an optical underwater communications system, the turbidity created by these different types of particles will be looked at separately. For creating turbidity with only dissolved solids, different concentrations of food colors will be used, which completely dissolve in the water. Conversely, dirt is mixed with water to increase the amount of suspended solids in it.

Turbidity is most often given in Nephelometric Turbidity Units (NTU) by using turbidity meters, which measure the amount of light scattered at an 90 degree angle by the water [43]. In this thesis, a simpler and cheaper way of roughly estimating turbidity is used in the form of a turbidity tube, which was constructed by following the instructions found in [44].

In real world environments, the turbidity of water varies for different water bodies and seasons. For example, in the Baltic sea, the turbidity usually ranges from 1-6 NTU (with minor exceptions) for the whole year [45], while in the river Emajõgi a turbidity of 140 NTU has been recorded in September [46].

[1] https://www.samsung.com/latin_en/watches/galaxy-watch-active/galaxy-watch-active2-40mm-black-sm-r830nzkatpa/

4

Influence of Water Conditions on an Optical Underwater Communication System

In this chapter a simple optical underwater communication system is tested for durability in various water conditions. The tests will aim to give information about which factors to consider when creating a similar system for real-life use.

4.1 The testing environment

The setup of the testing environment was based of off the one used in chapter 6 of [47]. It consisted of a water tank with the dimensions of 40x20x25 cm, upon which the receiver and the transmitter were positioned on the opposite sides of the longest dimension outside the water. The receiver used was a 2.5x2.5 cm solar panel, which was connected to a small M5StickC PLUS[1] Arduino board, which handled the incoming information and forwarded it to the laptop.

The transmitter used was a 650 nm, 5 mW, 3-5 V red LD, which was connected to an Arduino ATmega2560 microcontroller. The information was transmitted as bits encoded by flashes of light. The value of the bit depended on the duration of the flash, with "0" being represented by a 10 ms long flash and "1" represented by a 30 ms long

[1] https://shop.m5stack.com/products/m5stickc-plus-esp32-pico-mini-iot-development-kit (visited 25.04.2024)

flash. Using shorter flashes than 10 ms proved to, at times overwhelm the receiving side and not be as easy to analyse. The bits were transmitted as a repeating sequence of "1000". After each individual bit, a 10 ms delay was used. When the receiver received a positive signal continuously for 25-30 ms the bit "1" was recorded. Otherwise, when the signal was positive for 5-10 ms, the bit "0" was recorded. The threshold for the receiver to detect a positive signal was set to 340 lux, which was a bit less than half of the value obtained in a baseline test.

All of the tests took place at the same location and the testbed was not moved between the tests. During testing, the temperature of the room, remained between 20-21°C degrees.

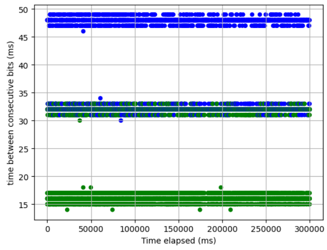
4.2 Test cases

Overall, 8 separate test cases were presented with each one measuring the impact of a different environmental variable or the combination of them on underwater optical communication. Each separate test took 5 minutes and was run two times. First time with no ambient light present and then with a LED light directly above the testbed. When the LED was on, the light recorded on the water surface was approximately 5000 lux. The receiver ambiently received around 250 of it. The tank was filled with 12 l of tap water from Tartu, with the rated turbidity of <0.33 NTU [1]. The communication took place 1 cm under the water.

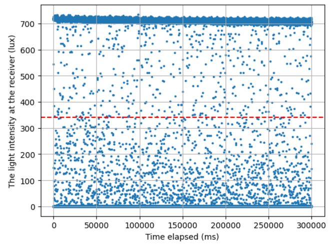
The 8 test cases conducted are:

1. Baseline
2. Turbulence
3. Air bubbles
4. Stronger air bubbles
5. Colored water
6. Air bubbles in colored water
7. Turbidity

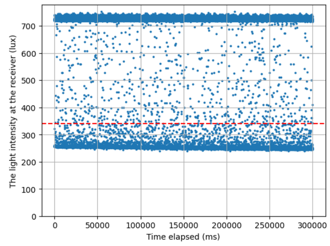
[1] https://tartuvesi.ee/vee-kvaliteet/tartu-joogivee-kvaliteedinaitajad/ , as of 07.05.2024



(a) The time difference between each received bit in milliseconds for the baseline measurement. Values over 50 on the y-axis indicate that bits were lost. Information about new bits was received every 15 ms. Each dot represents a received bit. The green dots represent the bit "0", while blue ones represent "1".



(b) The light intensity that reached the receiver at every point of time during the baseline measuring. Each blue dot represents a signal that was received by the receiver. The red line represents the threshold over which the signal was considered to be positive. The positive signal for 1-2 consecutive signals is considered to be the bit "0", 5-6 positive signals is considered as "1".



(c) The light intensity that reached the receiver at every point of time during the baseline measuring, while light was turned on. Ambient light intensity on the receiver was approximately 250 lux. Each blue dot represents a signal that was received by the receiver. The red line represents the threshold over which the signal was considered to be positive.

Figure 4.1: Figures for the baseline measurements.

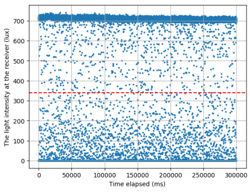
8. Turbulence in turbid water

4.2.1 Test case 1: Baseline

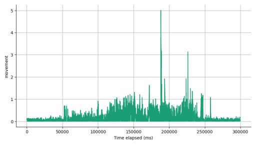
In the baseline test, the water conditions were not altered in any way. This ensured, that the testing environment works and also provides a comparison point for other tests. The water was clear and motionless for both tests.

Figure 4.1a shows the time between each received bit in milliseconds in the baseline measurement. New data was gathered around every 15 ms. In the baseline measurement, the bit "0" always arrived on either 15 or 30 ms, after the previous bit, while "1" always arrived 30 or 45 ms after. The light intensity, that the receiver picked up from the transmitter was little above 700 lux, but was boosted by around 10 lux, when ambient light was present. Figures 4.1b and 4.1c show the light intensity recorded at every point of time during the measurement by the receiver.

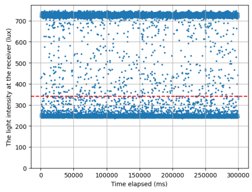
Additionally for the signal strength, the percentage of values not falling into the range of the maximum received value minus 50 and the minimum received value plus



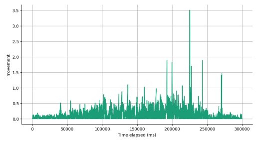
(a) The light intensity that reached the receiver at every point of time during the turbulence measuring without additional lights on.



(b) The accelerometer data for the turbulence test case with no lights.



(c) The light intensity that reached the receiver at every point of time during the turbulence measuring with the lights on.



(d) The accelerometer data for the turbulence test with lights.

Figure 4.2: Figures for the turbulence tests.

50 was calculated. From here on this value will be referenced to as the percentage of outliers. For the baseline measurements, this value proved to be 3%.

During both baseline measurements, in a 5 minute time period 11975 bits were sent from the transmitter with a 1/3 ratio of "1" to "0". All data was successfully received.

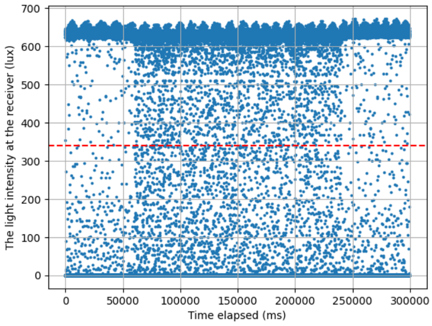
4.2.2 Test case 2: Turbulence

In order to test the effects of turbulent flow on underwater optical communication, a hand mixer[1] was used to generate flow in the water while. The turbulence was generated in a way that avoided the creation of air bubbles. Before the tests, the mixer was placed in the water adjacent to the laser beam. An accelerometer was also placed floating on the water to collect data about the movement of the water surface.

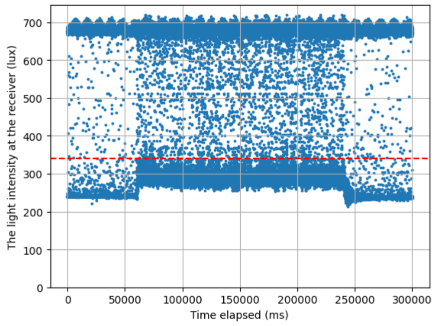
The tests were structured like so:

1. In the first minute, the mixer is in the off position.
2. In the second minute, the hand mixer is turned on at a low speed.
3. In the third minute, the speed of the mixer is raised to medium speed.
4. In the fourth minute, the speed of the mixer is raised to the maximum possible speed.

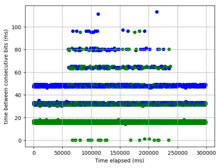
[1] Philips hr3075 https://www.shop.philips.ee/kodumasinad/koogitehnika/mikserid/daily-collection-philips-daily-collectioni-mikser-hr3705-00/



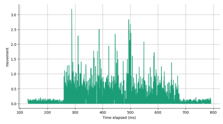
(a) The light intensity that reached the receiver at every point of time during the measurement of the air bubble test case with no lights on.



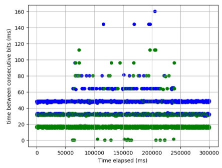
(b) The light intensity that reached the receiver at every point of time during the measurement of the air bubble test case with the lights on.



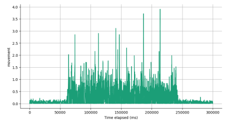
(c) The time difference between each received bit in milliseconds for the measurement. No ambient light.



(d) The accelerometer data for the bubble test case with no light.



(e) The time difference between each received bit in milliseconds for the measurement. With ambient light.



(f) The accelerometer data for the bubble test case with light.

Figure 4.3: Figures for the air bubble tests.

5. In the fifth minute, the mixer is stopped.

As figures 4.2a and4.2c indicate, the created turbulent water flow by itself had no noticeable effect on communication in clear water. The reason for that could have to do with the way turbulence was created or due to the lack of strength of the hand mixer. Additional accelerometer data for the tests can be seen in figures 4.2b and 4.2d. The percentage of outliers for the test remained roughly the same as for the baseline tests at 4%. This test was conducted again in a more turbid environment in subsection 4.2.8.

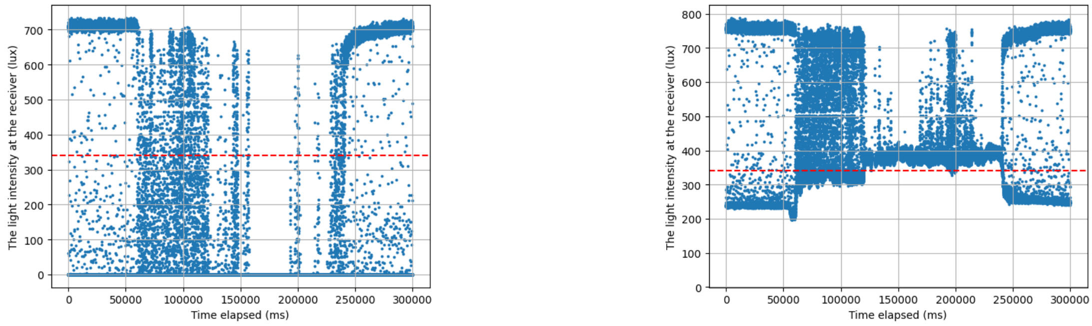
4.2.3 Test case 3: Air bubbles

The influence of air bubbles on optical underwater communication was measured, by placing an air pump capable of displacing 100 l of air directly under the laser beam. The accelerometer was again used to measure the created movement on the water surface. In the 5 minute tests, the air pump was turned on for minutes 2-4. The accelerometer data for the tests can be seen in 4.3d and 4.3f. When the air pump was turned on, a huge increase in the amount of outliers in the signal strength can be seen in figures 4.3a and 4.3b. The overall percentage of outliers for the test without lights was 14%, while it was 5% if just counting for minutes 1 and 5. For the test with the lights, the same statistics were 23% and 4%. Despite that, the maximum reached light intensity did not drop. Figure 4.3c also shows the increase in time between each recorded bit when the air pump is on. The bubbles managed to scatter some of the light so, that they no longer reached the receiver. Some other lost light signals were just attenuated to the point of no longer triggering the set threshold. In the dark, a total 11215 bits were received with the "1" to "0" ratio of 0.3. Notably more "1" bits were lost than "0"-s. This can be explained by the longer signal needing more time to be sent, making the window of disruption bigger. Also some of the broken "1" bits are read as "0" by the receiver. If the threshold would have been set to trigger for every received signal that was above 0, a slight improvement could be seen, with an additional 206 bits being received.

In figure 4.3e can be seen the results when test was run with the lights turned on. Interestingly as seen in figure 4.3b, the the minimum amount of light received actually increased when the air pump was turned on in the light. Overall 11473 bits were received with the "1" to "0" rate of 0.31 marking a noticeable improvement over the test run in dark. This is due to the way that the threshold is effectively being lowered by the ambient light.

4.2.4 Test Case 4: Stronger Air Bubbles

A more potent way of using a hand mixer for generating air bubbles was also used. The mixer was run using the same principles as in subsection 2, but this time, turbulence was created closer to the water surface, which lead to a high amount of created bubbles. The resulting figures are presented in 4.4a and 4.4b. These results indicate the occurrence of similar patterns, as with the air pump. When the mixer operated on lower speeds, the bubbles created caused inconsistencies in the signal, while higher speeds caused it to disappear completely. In the presence of ambient light, the minimum light received raised as more bubbles were created. This lead to a point where the ambient light



(a) The light intensity plot when bubbles were created using a hand mixer. Without lights on.

(b) The light intensity plot when bubbles were created using a hand mixer. With lights on.

Figure 4.4: Bubbles created by a hand mixer

reaching the receiver became bigger than the threshold and all of the received light counted as positive signals.

4.2.5 Test case 5: Color

The influence of the color of the water on underwater optical communication was tested. In order to achieve that, the water was colored using red and yellow food colors. The colors were completely dissolved in the water and left no additional particles floating in it. The colors were gradually added to the water and the approximate increase in attenuation compared to the baseline test was recorded. These findings can be seen in the figure 4.5. Overall 6 ml of food coloring was used on 12 l of water. Besides the increase in attenuation, no other noticeable change occurred while testing.

4.2.6 Test case 6: Air bubbles in colored water

The air bubble test was conducted with the now colored water. Compared to before, there was a noticeable drop in the performance of the system. The percentage of outliers for the whole test rose to 30% for the test in the dark and 60% for the test in the light. Meanwhile the same statistic for minutes 1 and 5 remained at 5% for both tests. The amount of errors also rose compared to the test with clear water. In figures 4.6c and 4.6d can be seen how the test in dark had more errors, but with less time between them compared to the test in the light. Compared to figures 4.4b and 4.3e, the opposite effect of having ambient light be present while air bubbles are present can be seen in4.6d. This

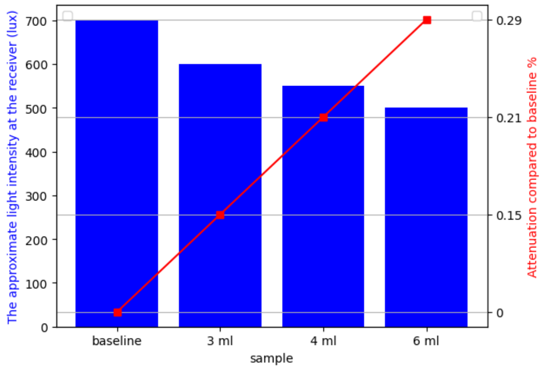


Figure 4.5: x-axis, The amount of food coloring used. The total dissolved solids in the samples are as follows: 3ml = 0.25 ml/L, 4ml =0.33 ml/L , 6 ml = 0.5 ml/L. y-axis left, the approximate expected light to reach the receiver. y-axis right, the approximate increase in attenuation compared to the baseline case.

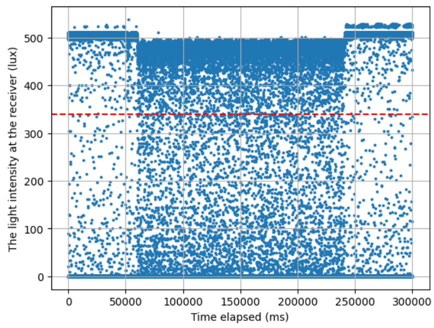
could be due to the air-water barrier becoming more difficult to pass as the liquid is more reflective.

4.2.7 Test case 7: Turbidity

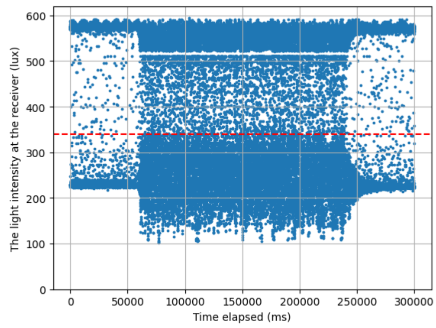
Although a big part of water turbidity is the color of the water, the water in the testbed couldn't truly be considered to be turbid, as it lacked any suspended solids floating around in it. For that reason, dirt was mixed with the colored water to achieve true turbidity. Two concentrations of dirt in water were tested. For the first concentration, 5 g of dirt was added to the water, and for the second one, an additional 5 g was added to the mix. This lead to the approximate dirt concentrations being 0.4 and 0.8 g/L and the approximate turbidity of 30 and 60 NTU. The water samples can be seen in figure 4.7a along with the dirt used in figure 4.7b.

As the particles making up dirt are heavier than water, when leaving the mixture to stay without motion for a long enough time, most of the dirt settles down at the bottom and the effect on communications is minimal. For this reason, the following test was conducted to find the impact of turbidity. First, the water in the testbed was thoroughly stirred in order to get all of the dirt particles floating in the water. Immediately after that, the 5 minute test timer was started.

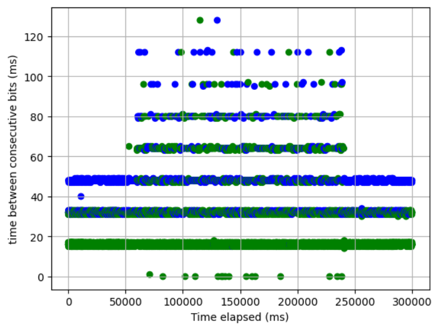
The light intensity plots for the measurements can be seen in 4.8. Despite the large changes to the light intensity, the amount of outliers remained relatively low for all tests



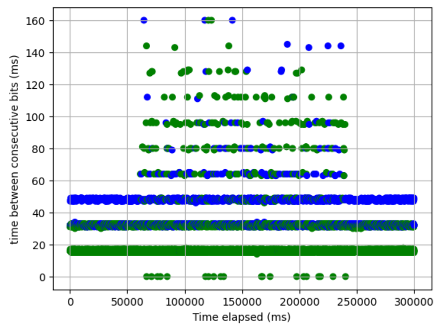
(a) The light intensity plot when the water was colored with 6 ml of food coloring and bubbles were used to disrupt the signal. Without lights on.



(b) The light intensity plot when the water was colored with 6 ml of food coloring and bubbles were used to disrupt the signal. With lights on.



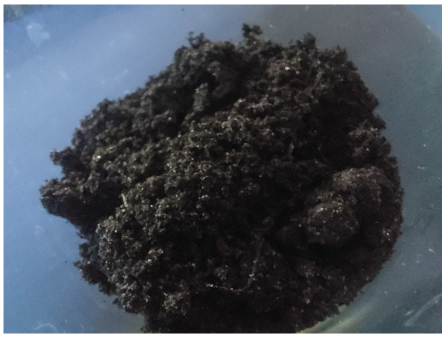
(c) The time between each consecutive bit. Colored water bubble. No lights. 10627 bits were received with the "1" to "0" rate of 0.28.



(d) The time between each consecutive bit. Colored water bubble. No lights. 11072 bits were received with the "1" to "0" rate of 0.3.

Figure 4.6: Colored water bubble measurements.

(a) The three water samples and their approximate turbidity in NTU. From left to right: 1) colored water with no dirt added to it. 2) 5 grams of dirt added to the colored water. 3) 10 grams of dirt added to the colored water.



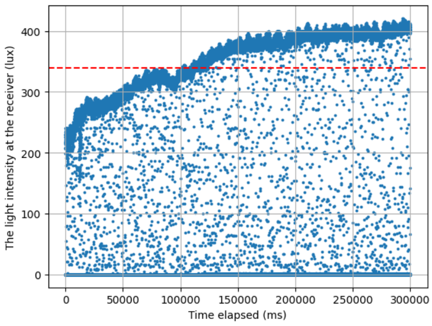
(b) The sample of dirt used to create turbidity.

Figure 4.7: Turbid water composition

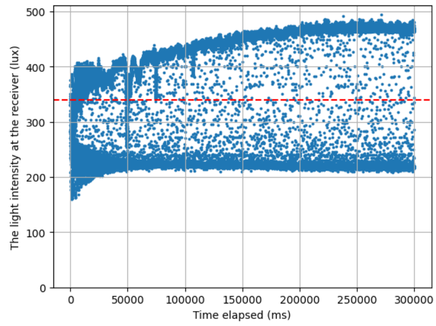
at around 10%. The static threshold of 340 lux was no longer suitable to accurately measure positive signals for all the tests, as the signal attenuation in the water had become too severe. Still, for each of the conducted tests, a separate threshold can be found, which when used will yield no errors. The signal strength recovered as time elapsed, but would not be reaching same levels as before the tests. Recovery started quickly, but slowed down in time.

4.2.8 Test case 8: Turbulence in turbid water

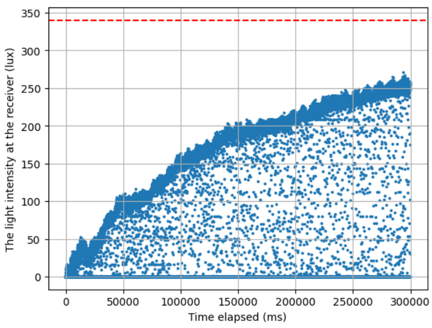
The same turbulence test as in section 4.1.2 was conducted, but this time with the more turbid water (60 NTU). Before the test, all of the dirt had settled down at the bottom of the testbed. The resulting data is seen in figure 4.9. As the mixer creating the turbulence was stationary, not all of the dirt was spun up. Still, while the mixer was on, the strength of the signal slowly lessened over time to the point of no longer triggering the threshold of 340. Despite that, when using the lower threshold of 1, all data was successfully received. After the mixer was stopped, the signal strength started to steadily recover. Overall, during the 3 minute period while the mixer was on, the light intensity at the receiver dropped by around 200 lux.



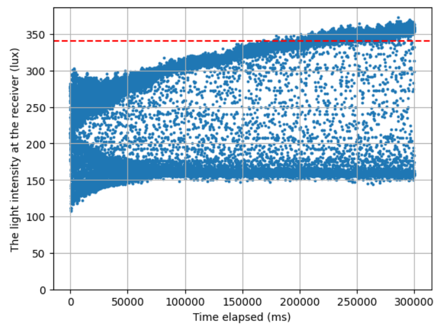
(a) The light intensity plot for the test. Turbidity around 30 NTU with no lights. The average light intensity of a positive signal when the dirt is fully settled was around 500 lux.



(b) The light intensity plot for the test. Turbidity around 30 NTU with lights. The average light intensity of a positive signal when the dirt is fully settled was around 550 lux.

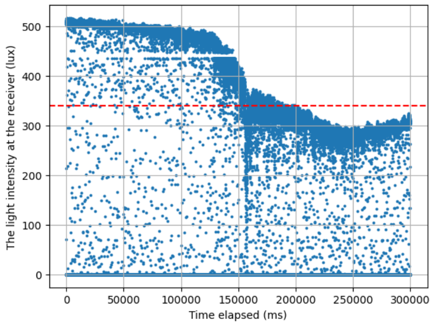


(c) The light intensity plot for the test. Turbidity around 60 NTU with no lights. The average light intensity of a positive signal when the dirt is fully settled was around 500 lux.

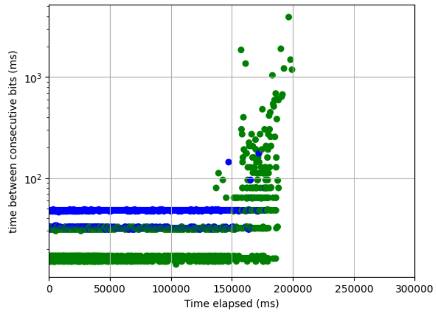


(d) The light intensity plot for the test. Turbidity around 60 NTU with lights on. The average light intensity of a positive signal when the dirt is fully settled was around 550 lux.

Figure 4.8: Tests in turbid water. Before each test, the water was thoroughly stirred.



(a) The light intensity plot for the test. Turbidity around 60 NTU with no lights. The mixer was off on minutes 1 and 5. During minutes 2-4 the power of the mixer steadily increased.



(b) The time between each consecutive bit. Turbidity around 60 NTU with no lights, threshold at 340. All of the last bits that were received were "0"-s indicating the superiority of shorter light signals. Note that the y-scale is logarithmic.

Figure 4.9: Turbulence in turbid water (60 NTU).

4.3 Conclusions

From the measurements, the following observations were made.

1. Using shorter flashes of light to send information is preferred, as the longer flashes are more fragile to disruptions. Furthermore, using shorter flashes enables faster communications, as more information can be sent during the same time window.

2. Water flow by itself in clear water was not be able to disrupt communications while testing. Although when suspended particles were present, it started to play a bigger role.

3. Air bubbles in the path of the light will heavily increase the variance in the signal strength and will result in lost data.

4. Creating turbidity by changing the color of the water increases the attenuation of the signal. Additionally, the effect of air bubbles on communication becomes more severe.

5. Even a relatively low amount of suspended particles floating in the water will have a huge impact on signal strength, but these particles will eventually settle down if no movement is induced and their impact will be minimal.

6. It is important to set a suitable threshold for a positive signal. If no additional light sources are expected to be present, accepting any received signal as positive will be enough.

In the conducted benchmark, an optical communications system was tested under various underwater conditions, primarily by analyzing changes in signal strength over a distance of 40 cm.

5

Summary

In this thesis, an overview of the current state of the wireless underwater communications was given. The three most popular techniques of acoustic, optical and radio wave underwater communication were discussed in more detail. This included such categories such as the data transmission speed, possible communication distance and environmental friendliness, along with the advantages and disadvantages of each technique in more detail. Additionally, other up-and-coming approaches taken for wireless underwater communication were briefly discussed.

The later part of the thesis focused on benchmarking a simple optical wireless underwater communications system in different water conditions. These included cases like susceptibility to turbulent water flow, air bubbles in the way of the light beam, water color and turbidity. The results were mainly analysed by looking at the changes to the light intensity that the receiver was able to pick up during a set testing period. Some of the conclusions made include the high impact of suspended particles floating in the water on communications and the importance of choosing the right threshold for light intensity to be considered positive.

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