COMMUNICATION USING AN UNDERWATER SONAR

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Abstract

"The oceans are considered to host a substantial part of human and industrial resources, namely oil and gas, whose industry will move to ever deeper waters, and where renewable energy continue to be harvested from the seas in offshore wind farms, but also increasingly through tidal, currents and wave energy converters. Furthermore, minerals such as cobalt, nickel, and copper, rare earth, silver and gold will be mined from the sea floor (deep sea mining). To this end, new offshore and port infrastructure will need to be built, monitored and maintained or repaired.

Many offshore operations can be carried out by professional divers, sometimes in dangerous missions. The dependency on such kind of work represents an actual threat to the offshore industry. The extensive use of unmanned underwater vehicles (AUVs/ROVs) could solve this problem. However, such vehicles are usually customized only for performing specific tasks and are difficult to operate. This typically makes their deployment rather expensive.” [1]

Out of this SWARMs targeted five main objectives:

1. To develop an environment characterization and coordination system
2. Design the necessary infrastructure for monitoring and controlling underwater industrial operations
3. Apply communication concepts ensuring smooth functioning while also exploring new, innovative technologies
4. Define and apply a methodology for designing new operations
5. Test, validate and demonstrate the SWARMs platform solution in relevant and environmentally controlled scenarios

This thesis will be about to establish wireless communication with the sonar, underwater wireless communication. In that environment it is a lot of disturbance noise, inter-symbol interference (ISI), the impact of the Doppler effect and it is low bandwidth and all these parameters affect the communication and the ability of transmitting data [2][3][4].
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1 Introduction

This project is made in conjunction with the research project SWARMs, which is an industry-led project with the goal to expand the use of underwater and surface vehicles to simplify the ideas, planning and implementation of deep-sea and offshore operations and missions. This will reduce the operational costs, increase the safety of tasks and of involved individuals, and expand the offshore sector \[5\][6].

- "Enabling AUVs/ROVs to work in a cooperative mesh thus opening up new applications and ensuring re-usability by promoting heterogeneous standard vehicles that can combine their capabilities, in detriment of further costly specialised vehicles.” \[5\]
- "Increasing the autonomy of AUVs/USVs and improving the usability of ROVs for the execution of simple and complex tasks, contributing to mission operations sophistication.” \[5\]

The general goal of this project is to develop an integrated platform for new generations of independent aquatic and underwater operations. Then it is possible to do:

- Corrosion prevention in offshore installations
- Monitoring of chemical pollution
- Detection, inspection and tracking of plumes
- Berm building
- Seabed Mapping

In this thesis, the main target is to establish wireless communication with an underwater sonar \[7\][8] using LabView \[9\][10][11]. To assist the progress of wireless communication with the sonar, there are some environmental limitations that have to be considered. Underwater communication is limited by the fact that there is low bandwidth and and a lot of disturbance noise, intersymbol interference (ISI), the impact of the Doppler effect and all these parameters affect the communication and the ability of transmitting data. Which modulation technique is the most efficient to use when it comes to send data wireless underwater and which antenna is the best suitable?
2 Background

2.1 Wireless communication and modulation techniques

Communication using waves is not something new. Waves, as in electromagnetic waves, exist in the nature and as in electronic discharge. Due to the early theories the lightning were electromagnetic waves and it has been proven by experiment that the invisible radio waves were of the same nature as the electromagnetic waves. That was the beginning of using radio waves for communication and it was the beginning of wireless communication. Guglielmo Marconi [12] says to be the inventor of radio communication [13]. Reginald Fessenden [14][15] were also an important person when it comes to radio communication and also then underwater communication. Reginald Fessenden is foremost known for his developing work launching radio technology, counting the groundwork of amplitude modulation (AM) radio. When it comes to modulation of radio waves there are also phase modulation (PM) and frequency modulation (FM). [16] It is important to modulate the signal so that the signal that is send, from the sender, is interpreted in the same way when received by the receiver. A modulated signal is demodulated at the receiver.

Related to terrestrial communication, underwater wireless communication is commonly done by using acoustic waves instead of electromagnetic waves, radio waves, or optical when it comes to long-range communication and the amount of data sent is limited [17]. Radio waves or optical is to prefer when sending big amount of data and it is demanding around the clock, high-data-rate communication networks that works in real time. The speed that acoustic waves travels with in the ocean is approximately 1500 m/s [18], so that long-range communication involves high latency, and that will be a problem for real-time response, synchronization, and multiple-access protocols.

Let’s compare the submarine communication systems with Internet, then the submarine communication system uses the frequency between 3 to 30 Hz [19], extremely low frequency (ELF) [20], and the Internet uses 2,4 to 5 GHz to send data. Therefore it is possible to send large amount of data. So far it has been difficult to use electromagnetic waves or optical for wireless communication underwater, especially in seawater and when the distance between the sender and receiver increases and also when the communication is done vertical.[21][22]

Underwater communication is neither something new. When the submarines started being used before world war one they had to be able to communicate with boats and other submarines and also be able to navigate and avoid collision with icebergs, rocks and land. They were using the Fessenden telegraph oscillator [23], an early version of a sonar. It was invented by Reginald Fessenden, with development starting in 1912 at the Submarine Signal Company of Boston [24].

A Fessenden oscillator is an electro-acoustic transducer [25]. It was the first equipment that successfully could manage acoustical echo ranging, with the same principle as is shown in figure 23. It has similar operating principle as a dynamic voice coil loudspeaker [26]. It was a very early type of transducer and it was adequate of generating underwater sounds and gathering their echoes [27]. It was transmission and reception of analogue data. Due of its comparably low operating frequency, it has been replaced by piezoelectric [28][29] devices in modern transducers, see figure 1.

Figure 1: Piezoelectric principal and Piezoelectric frequency response (courtesy to Omegatron [30][31])
In this study it is digital data that is transmitted and received wireless and with variably distances between the sender and receiver. When it comes to transmitting digitally represented data wireless there are three major category’s of digital modulation techniques:

- Amplitude-shift keying (ASK) [32]
- Frequency-shift keying (FSK) [32]
- Phase-shift keying (PSK) [32]

It is necessary to modulate transmitted digital data so that the receiver interprets the sent signal from the transmitter in right way [33]. To transform a digital signal in to a analogue signal is a process where the digital signal is transformed into its corresponding analogue signal. This is for converting the digital signal, that have discrete amplitude at discrete instants of time, into a continuous signal [34]. This can be important if the medium/channel is band pass and/or if there are multiple users that needs to share the medium, see figure 2.

![Figure 2: Medium/channel is band pass and/or multiple users (courtesy to Professor Natalija Vlajic [33])](image)

The modulation is a process where digital data or low-pass analogue data is converted to a band-pass, higher-frequency, analogue signal, see figure 3.

![Figure 3: To the left: Digital-to-analogue modulation. To the right: Analogue-to-analogue modulation (courtesy to Professor Natalija Vlajic [33])](image)

To be able to modulate the signal that is to be send an additional signal is added, the carrier signal, to the transmitted signal and the carrier signal will act as the base for the signal that includes the wanted information. The added signal is an analogue sin wave. A Sine wave has three parameters, amplitude, frequency and phase, that is possible to varying to represent digital data, 0 and 1. Depending on what the implementation is going to be used for the different modulation techniques has advantages and disadvantages. ASK is very simple to implement but it is sensitive to interference by disturbance noise and noise usually affect the amplitude.

\[
s(t) = \begin{cases} 
A_0 \cos(2\pi f_c t), & \text{binary 0} \\
A_1 \cos(2\pi f_c t), & \text{binary 1}
\end{cases}
\]  

(1)
The frequency spectrum, when it comes to ASK, were the information is stored is maybe easiest explained mathematical and then by using trigonometry and angle transformation formulae [35]. It is explained mathematically how two cosine waves are multiplied with each other:

\[ \cos A \cdot \cos B = \frac{1}{2} (\cos(A - B) + \cos(A + B)) \]

It is the carrier signal: \( v_c(t) = \cos(2\pi f_c t = \cos(\omega_c t)) \), where \( 2\pi f_c = \omega_c \), see figure 4

Then it is the digital signal: \( v_d(t) \) that is two cosine waves multiplied with each other, see figure 4.

This will result in the modulated signal \( v_{\text{ASK}} \), see figure 4:

\[
v_{\text{ASK}}(t) = v_c(t) \cdot v_d(t) = \cos \omega_c t \cdot \left[ \frac{1}{2} + \frac{2}{\pi} \cos \omega_0 t - \frac{2}{3\pi} \cos 3\omega_0 t + \frac{2}{5\pi} \cos 5\omega_0 t - \ldots \right] = \\
\frac{1}{2} \cos \omega_c t + \frac{2}{\pi} \cos \omega_c t \cdot \cos \omega_0 t - \frac{2}{3\pi} \cos \omega_c t \cdot \cos 3\omega_0 t + \ldots = \\
\frac{1}{2} \cos \omega_c t + \frac{1}{\pi} [\cos(\omega_c - \omega_0) t + \cos(\omega_c + \omega_0) t] - \frac{1}{3\pi} [\cos(\omega_c - 3\omega_0) t + \cos(\omega_c + 3\omega_0) t] + \ldots
\]

Figure 4: ASK (courtesy to Professor Natalija Vlajic [33])

In figure 5 it is shown in which spectrum the information is stored in when it comes to ASK.

Figure 5: The frequency spectrum (courtesy to Professor Natalija Vlajic [33])

The information will be stored in \( \omega_c - \omega_{d_{\text{max}}} \), \( \omega_c \) and in \( \omega_c + \omega_{d_{\text{max}}} \).

ASK is more suitable to transmit digital data over optical fibre where you can shield the optical fibre by cabling it. FSK is less sensitive to interference by disturbance noise, for example voltage spikes, noise, can be ignored. The receiver looks for specific frequency changes, see formula (2), of a number of intervals, see figure 7.

\[
s(t) = \begin{cases} 
A_0 \cos(2\pi f_1 t), & \text{binary 0} \\
A_1 \cos(2\pi f_2 t), & \text{binary 1} 
\end{cases}
\]

Figure 6: \( f_1 < f_2 \) (courtesy to Professor Natalija Vlajic [33])
The frequency spectrum for FSK differs in comparison with ASK. The digital signals look like: 

\[ v_d(t), \text{see figure 7, and it is modulated with } \omega_1 \text{ and } v'_d(t) = 1 - v_d(t), \text{ see figure 7, and it is modulated with } \omega_2. \]

This will result in the modulated signal \( v_{FSK} \), see figure 7:

\[
v_{FSK}(t) = v_d(t) \cdot v'_d(t) = v_d(t) \cdot (1 - v_d(t)) = \cos \omega_1 t \cdot v_d(t) + \cos \omega_2 (1 - v_d(t)) = \\
\frac{1}{2} \cos \omega_1 t + \frac{1}{\pi} \left[ \cos (\omega_1 - \omega_0) t + \cos (\omega_1 + \omega_0) t \right] - \frac{1}{3\pi} \left[ \cos (\omega_1 - 3\omega_0) t + \cos (\omega_1 + 3\omega_0) t \right] + ... + \\
\frac{1}{2} \cos \omega_2 t + \frac{1}{\pi} \left[ \cos (\omega_2 - \omega_0) t + \cos (\omega_2 + \omega_0) t \right] - \frac{1}{3\pi} \left[ \cos (\omega_2 - 3\omega_0) t + \cos (\omega_2 + 3\omega_0) t \right] + ...
\]

Compared to ASK, FSK need more bandwidth to be able to control and get the right information, that is transmitted. The wanted information is in \( \omega_1 - \omega_{d_{max}}, \omega_1, \omega_2 \) and in \( \omega_2 + \omega_{d_{max}} \). The FSK frequency spectrum is double in compared with ASK. FSK is suitable for over voice lines, in high-frequency, radio transmission for example.

Then there is the third modulation technique, PSK. The phase of the carrier signal is varied to represent binary 1 or 0, see formula (3). The amplitude and frequency is constant throughout each bit interval, see figure 9. For example binary 1 = 0° phase and then binary 0=180° (\( \pi \text{rad} \)) phase. PSK is the same as multiplying the carrier signal by 1 when information is 1 and with -1 when the information is 0. If only two different phases are used during modulation it is also called binary PSK or 2-PSK, see figure 9.

\[
s(t) = \begin{cases} 
A_0 \cos(2\pi f_c t), & \text{binary 1} \\
A_1 \cos(2\pi f_c t + \pi), & \text{binary 0}
\end{cases} \Rightarrow s(t) = \begin{cases} 
A_0 \cos(2\pi f_c t), & \text{binary 1} \\
-A_1 \cos(2\pi f_c t), & \text{binary 0}
\end{cases}
\]

Figure 7: FSK (courtesy to Professor Natalija Vlajic [33])

In figure 8 it is shown in which spectrum the information is stored in when it comes to FSK.

Figure 8: The frequency spectrum for FSK (courtesy to Professor Natalija Vlajic [33])

Figure 9: PSK (courtesy to Professor Natalija Vlajic [33])
The demodulator has to determine the phase of the received sinusoidal signal due to some reference phase, see figure 10. That makes PSK more complex when it comes to signal detection compared to both ASK and FSK, but PSK is less sensitive to disturbance noise then ASK and it uses the same bandwidth as ASK, see figure 11. If the environment is of a type that it will provide low bandwidth it is more efficient to use PSK then FSK when it comes to data-rate transmission.

In figure 10 there is the digital signal $v_d(t)$, the carrier signal $v_c(t)$ and those two signal will result in the modulated signal $v_{PSK}(t)$.

![Figure 10: PSK example (courtesy to Professor Natalija Vlajic [33])](image)

When it comes to detection of received signal trigonometry and angle transformation formulae [35] help to explain mathematical when cosine wave is multiplied with itself: $\cos^2 A = \frac{1}{2} (1 + \cos 2A)$. If the received/modulated signal $\pm A \cos(2\pi f_c t)$ is multiplied by $2 \cdot \cos(2\pi f_c t)$ the result will be:

$$2A\cos^2(2\pi f_c t) = A[1 + \cos[4\pi f_c t]]$$ as binary 1, and

$$-2A\cos^2(2\pi f_c t) = -A[1 + \cos[4\pi f_c t]]$$ as binary 0.

To be able to determine the original baseband signal (i.e. the original binary sequence) it is easiest done by using low-pass filter to remove the oscillating part, see figure 12 [33]

![Figure 12: PSK with low-pass filter (courtesy to Professor Natalija Vlajic [33])](image)

In figure 13 the result is shown by using a low-pass filter to remove the oscillating part.

![Figure 13: PSK example, the result by using low-pass filter (courtesy to Professor Natalija Vlajic [33])](image)
If the modulation theory [36] is used to calculate the data rate, in bits per second (bps), and if baseband signal $x(t)$ has the bandwidth $[37]$ of $W_c/2$, see figure 14, and then the modulated signal $x(t)\cos(2\pi f_c t)$ has the bandwidth $W_c$ Hz, see figure 14.

![Figure 14: To the left: Data rate. To the right: The modulated data rate (courtesy to Professor Natalija Vlajic [33])](image)

If the bandpass channel has a bandwidth $W_c$ [Hz] then it have the baseband channel $W_c/2$ [Hz] available so, according to Nyquist Law [36], it is theoretical to support transmission of $2 \cdot (W_c/2) = W_c$ [pulses/second], see figure 14. Whit more advanced technique it is possible to recover the factor 2 in supported data-rate.

More phase shifts. If the phase shifts is doubled, $90^\circ = \pi/2$ rad, it is possible to generate 4 signals and each is representing 2 bits. Then you have 4-PSK, even called Quadrature PSK (QPSK).

$$s(t) = \begin{cases} 
A\cos(2\pi f_c t), & \text{binary 00} \\
A\cos(2\pi f_c t + \frac{\pi}{2}), & \text{binary 01} \\
A\cos(2\pi f_c t + \pi), & \text{binary 10} \\
A\cos(2\pi f_c t + \frac{3\pi}{2}), & \text{binary 11}
\end{cases}$$

(4)

This is visualized in figure 15.

![Figure 15: QPSK: visualized in frequency and constellation diagram (courtesy to Professor Natalija Vlajic [33])](image)

Now the data rate has increased without increasing the bandwidth use and depending on the quality of the apparatus that is used, in capability to analyse small differences in phase, 4-PSK can simply be extended to n-PSK.

To increase the data rate even more a new technique has been developed, it can be seen as a combination of ASK and PSK, and it is called Quadrature Amplitude Modulation, [38][39][40]. In QAM the original information signal stream is divided into two sequences that contains of odd and even symbols, see figure 16, even called “two-dimensional” signalling [41]. Let these signals be $B_k$ and $A_k$, there $A_k$ is for in-phase comparison and is modulated by $\cos(2\pi f_c t)$ and $B_k$ is for quadrature-phase comparison and is modulated by $\sin(2\pi f_c t)$.

![Figure 16: Original signal is split in to two sequences of odd and even symbols, $B_k$ and $A_k$ (courtesy to Professor Natalija Vlajic [33])](image)
The both signals are added together, \( Y(t) = A_k \cos(2\pi f_c t) + B_k \sin(2\pi f_c t) \), and is sent through the channel, see figure 17.

![QAM transmission](image)

Figure 17: QAM transmission (courtesy to Professor Natalija Vlajic [33])

Now the data rate have increased to 2 bits per bit-interval.

In figure 18 an example of QAM is shown.

![QAM example](image)

Figure 18: QAM example (courtesy to Professor Natalija Vlajic [33])

By using trigonometry and the angle transformation formulae [35] we got \( \cos^2(A) = \frac{1}{2}(1 + \cos(2A)) \), \( \sin^2(A) = \frac{1}{2}(1 - \cos(2A)) \) and \( \sin(2A) = 2\sin(A)\cos(A) \) and that is good to know and take use of in QAM demodulation. Because by multiplying \( Y(t) \) by \( 2 \cdot \cos(2\pi f_c t) \) and then filtering the resulting signal with a low-pass filter \( A_k \) is recovered. To recover \( B_k \) \( Y(t) \) is multiplied by \( 2 \cdot \sin(2\pi f_c t) \) and the resulting signal is also filtered by a low-pass filter, see figure 19.

![QAM modulation](image)

Figure 19: QAM modulation (courtesy to Professor Natalija Vlajic [33])
Signal constellation, constellation diagram [42], is used to visualize possible symbols, depending on what modulation design, that can be selected in a 2-D plane. The X-axis is corresponding to the in-phase carrier $\cos(\omega_c t)$. The projection of the point on the X-axis shows the maximum amplitude of the in-phase component, see figure 20. The Y-axis is then related to the quadrature carrier $\sin(\omega_c t)$ and the projection of the point on the Y-axis shows the maximum amplitude of the quadrature component, see figure 20. The length of the line that can be draw from the point to the origin is the maximum amplitude of the signal element, combination of X and Y components, see figure 20. The angel that is between the line and the X-axis is the phase of the signal element, see figure 20.

![Figure 20: QAM Constellation (courtesy to Professor Natalija Vlajic [33])](image)

Depending on which modulation technique is used the result differs, see figure 21.

![Figure 21: Constellation diagram comparison (courtesy to Professor Natalija Vlajic [33])](image)

As mentioned earlier so can QAM be seen as a combination between ASK and PSK and that can be described like this: $Y(t) = A_k \cos(2\pi f_c t) + B_k \sin(2\pi f_c t) = (A_k^2 + B_k^2)^{\frac{1}{2}} \cos(2\pi f_c t + \tan^{-1} \frac{B_k}{A_k})$ and the result is visualized by constellation digram in figure 22.

![Figure 22: 4-level QAM (courtesy to Professor Natalija Vlajic [33])](image)
2.2 Underwater communication techniques and suitable antennas

Sound Navigation And Ranging, Sonar, is a technique that uses sound propagation (usually underwater) to navigate, communicate with or detect objects on or under the surface of the water, such as other vessels [7][8]. There are several different techniques to use depending on what the user is going to use it. Passive and active are two of these techniques. Active is sending sound and waiting for the echo, see figure 23. That was this method that Reginald Fessenden was the inventor of.

![Active Sonar](image)

**Figure 23: Active Sonar (courtesy to Georg Wiora [43])**

Passive is listening after sounds [44]. In this thesis the sonar is of active type. The control of the system is done with a roboRIO [45] from National Instrument that is programmed using the LabView programming suite the on-board dual-core ARM real-time CortexA9 processor and customizable Xilinx field-programmable gate array, FPGA [46][47]. The sonar is connected to EvoLogics [48][49] underwater modem to be able to communicate. To be able to receive the signal that have been sent it is necessary to have an antenna and it also important then that the antenna is designed so that it can receive the signal that have been sent [18][50]. If it is in a special environment that the signals will be sent, as underwater, it is important do design the antenna so that is suitable for that environment [51][52][53].

Antennas are as old as communication with radio waves. The design of the antenna depends on the wavelength of the transmitted signal. In linear media the wavelength, \( \lambda \), of sinusoidal waveform that travels at constant speed, \( v \), can be described by \( \lambda = \frac{v}{f} \) and \( f \) is the frequency of the sinusoidal waveform, see figure 24.

![Wavelength](image)

**Figure 24: Wavelength (courtesy to Richard F. Lyon [54])**

Sinusoidal waves can be described mathematically as a function

\[
y(x, t) = Acos\left(\frac{2\pi x}{\lambda} - 2\pi ft\right) = Acos\left(2\pi \left(\frac{x}{\lambda} - ft\right)\right) = Acos\left(\frac{2\pi}{\lambda} (x - vt)\right)
\]

where \( y \) is the value of the wave at any position \( x \) and time \( t \), and \( A \) is the amplitude of the wave. They can also be described in terms of wave number \( k \) (2 times the reciprocal of wavelength) and angular frequency \( \omega \) (2 times the frequency)

\[
Acos(kx - \omega t) = Acos(k(x - vt))
\]
The relationship between wavelength and wave number to velocity and frequency can then be written as

\[ \begin{align*}
  k &= \frac{2\pi}{\lambda} = \frac{2\pi f}{v} = \frac{\omega}{v} \\
  \lambda &= \frac{2\pi}{k} = \frac{2\pi v}{\omega} = \frac{v}{f}
\end{align*} \]

Acoustic systems have been a standard technique for underwater communications as they are generally good for long range communications (up to tens of kilometres) [51][55][56]. But this technique is inadequate for real time and broadband underwater wireless sensor networks because of high latency, low protection against disturbance noise and low data rate [55].

The design for electromagnetic wave antennas [57] for transmission and receiving in air has to differ with the design of the antennas for transmission and receiving in water. To be able to design antennas for underwater equipment it is important to understand the effect of the conductivity, \( \sigma \), on the antenna material when the propagating medium is fresh or sea water [55][58]. It is also important to understand that a electromagnetic wave can not travel as fast in water as in air, so the wavelength will differ from air to water, see figure 25.

![Figure 25: To the left refraction (courtesy to Arne Nordmann [59]) and to the right wavelength is decreased (courtesy to Brews Ohare [60]) and that because of entering a slower medium](image)

The wavelength of a electromagnetic wave in vacuum is calculated \( \lambda = \frac{c}{f} \) where \( c \) is the speed of light. The speed in water will be affected by the factor \( \sqrt{\epsilon_r \mu_r} \), where \( \epsilon_r \) is the relative permittivity and \( \mu_r \) is the relative permeability [18]. The speed in water can then be expressed by \( c_{\text{water}} = \frac{c}{\sqrt{\epsilon_r \mu_r}} \) and that gives \( \lambda = \frac{c_{\text{water}}}{f} = \frac{c}{\sqrt{\epsilon_r \mu_r} \cdot f} \).
By using Maxwells equations [18][61] it is possible to predict the propagation of electromagnetic waves in water. The strength of the electric field $E_x$ and the strength of the magnetic field $H_y$ for a linearly polarized plane wave generated in the $z$ direction can be explained by $E_x = E_0 e^{j\omega t - \gamma z}$, see figure 26, and $H_x = H_0 e^{j\omega t - \gamma z}$, see figure 27, and in figure 28 it is shown how it looks like for a dipole antenna.

The angular frequency, $\omega$, can be expressed by $\omega = 2\pi f$. The propagation constant, $\gamma$, is expressed by $\gamma = \sqrt{j\omega \mu (j\omega \epsilon + \sigma)} = \alpha + j\beta$, where $\alpha$, the real part, is the attenuation constant and is expressed by $\alpha = \frac{\omega}{\sqrt{\mu \epsilon}} \sqrt{1/2(\sqrt{1 + (\sigma/\omega \epsilon)^2}} - 1)$ and $\beta$, the imaginary part, is the phase constant and is expressed by $\beta = \frac{\omega}{\sqrt{\mu \epsilon}} \sqrt{1/2(\sqrt{1 + (\sigma/\omega \epsilon)^2}} + 1) = \frac{2\pi}{\lambda}$. If attenuation will increase it will lead to reducing the effects of multi-path propagation.
Depending on which type of communication that is desirable and depending on what will be sent and what speed is needed there are some different antennas that can be used. Among the first antennas to be tested for wireless underwater communication was a dipole antenna [64]. Dipole means that the antenna is constructed by two terminals or “poles” and in those flows a radio frequency currency. That currency together with a added voltage will create an electromagnetic/radio signal that is to be radiated, see figure 29.

Figure 29: Dipole antenna (courtesy to Cadmium [65])

As mentioned earlier, when an electromagnetic wave spreads in a not solid medium it is attenuated. The attenuation increases with the frequency and with the conductivity of the medium. When it comes to conductive medium it is this $\sigma/\omega\epsilon$ that is used to divide mediums into three categories. If $\sigma/\omega\epsilon \ll 1$ it is a good medium, if $\sigma/\omega\epsilon \approx 1$ it is a poor conductor or semiconductor and if $\sigma/\omega\epsilon \gg 1$ it is a good conductor [18][55].

When using a dipole antenna and want to be able to accomplish as long range communication as possible it is important to use lower frequency, below 100 MHz [66].

Loop antennas is another antenna that also is used when it comes to underwater communication and the loop antenna has an advantage of depending on the magnetic field of the electromagnetic waves [18]. The main advantage is that the loop antenna is not affected by interference from man-made electrical signals [18], such as disturbance noise from electrical engines. To be able to design and construct compact communication systems the antenna has to be able to be made much smaller [67][68]. Also when it comes to be able to communicate wireless underwater in comparatively high-speed, and in this study, in short-range the J-antenna has been studied [55]. The examples that was raised in that study was short-range communication between AUVs or that the AUV is approaching a docking station for downloading the data that has been collected during the underwater mission.

The J-antenna has the shape of the letter J, see figure 30 [69], and there are also exists some different designs of the J-antenna, see figure 30 [70]. The J-antenna is also known as a vibrator antenna and it is commonly used wire antenna [18].

Figure 30: Model of J-antenna (courtesy to ZyMOS [69]) and some different designs of the J-antenna (courtesy to Crcwiki [70])

The J-pole antenna is an omnidirectional monopole antenna. To be able to solve the antenna matching to the feed-line there is a quarter wave parallel transmission line stub [68][71]. When it comes to determining the dimensions of the antenna for use underwater, specifically seawater, conductivity is very important to consider.
To be able to handle even higher data rate and at the same time keep the power requirement relatively low and keep the costs down another technique had to be developed. Due to this requirements the outcome was Ultra-wide band, UWB [72][73]. New and more advanced technique with specific requirements needs new and more advanced antenna, UWB antenna [74][63]. When it comes to UWB technology and it is used in air it should have bandwidth range of 3.1 GHz to 10.6 GHz. In that range is practical efficiency and satisfying omnidirectional radiation patterns the critical requirements. To be able to realizing the UWB multi-band communication system one of the crucial components is just the UWB antenna. It is a challenge to design a UWB antenna that deliver high performance when the current narrowband antennas exists. It is supposed to cover wide bandwidth, to produce an omnidirectional radiation pattern, be compact in size and have a simple configuration [74].

In figure 31 it is shown the basic idea of a UWB antenna.

![UWB antenna diagram](image)

In water the bandwidth is not in a range of 3.1 GHz to 10.6 GHz, but even though that it is a known fact it have been studies made on using UWB communication system for underwater communication with suitable antennas. Most common is a dipole antenna and variations of the dipole antenna, for example bow tie antennas [63][75].

Also to improve the communication and to increase the transmission range multiple-input and multiple-output (MIMO) are introduced and used, see figure 32.

![MIMO communication system](image)

The MIMO method is for multiplying the capacity of a radio link using multiple antennas for transmitting and receiving to achieve multipath propagation [77][78]. This technique has became an crucial component in terms of wireless communication.
In the beginning MIMO was multiple antennas at the transmitter and receiver. Then it was developed for more modern usage and now more MIMO refers to a more practical technique to be able to send and receive more than one data signal at the same time over the same communication channel, multipath propagation. This technique differs essentially from the smart antenna technique and have been developed to increase the performance of a single data signal, for example as beam-forming and diversity. In wireless communications, multipath is the propagation phenomenon that results in radio signals arriving to the antenna on the receiving side by two or more paths. Causal factors to multipath includes disturbance noise from the atmosphere, reflection and refraction caused by the ionosphere, and reflection from water and objects on land like mountains and buildings. Multipath propagation can be described mathematical. By using the method of the response of an impulse that is used for studying linear systems a mathematical model can be made. A single impulse/signal is to be transmitted a time 0, an ideal Dirac pulse of electromagnetic power, \( x(t) = \delta(t) \) [79].

Because of existing multiple electromagnetic paths will the receiver receive more than one signal and they will possibly differ in time of arrival and the received signal then can then be described by \( y(t) = h(t) = \sum_{n=0}^{N-1} \rho_n e^{j\phi_n} \delta(t - \tau_n) \), and it is shown in figure 33.

Figure 33: Mathematical model of the multipath impulse response (courtesy to I Cantalamessa [80]).

\[ N \] is the number of received signals and that is the same as the number of electromagnetic paths and it is possible that \( N \) is a large number. The \( n^{th} \) impulse has a time delay that is \( \tau_n \). The convoluted amplitude, that means in magnitude and phase, is represented by \( \rho_n e^{j\phi_n} \) of the received signal. All these parameters is affected by the time. If all functions is rewritten so they are dependent on the time the result would be \( \tau_n = \tau_n(t), \rho_n = \rho_n(t) \) and \( \phi_n = \phi_n(t) \). The time between the first and last received signal is called the multipath time [81], \( T_M \), and it is represented by \( T_M = \tau_{N-1} - \tau_0 \).

In a linear, time constant systems, the multipath phenomena can be characterised by the channel transfer function \( H(f) \), that is defined by the impulse response \( h(t) \) as the continuous time Fourier transform [82].

\[
H(f) = \mathcal{F}(h(t)) = \int_{-\infty}^{\infty} h(t) e^{j2\pi ft} dt = \sum_{n=0}^{N-1} \rho_n e^{j\phi_n} e^{j2\pi f\tau_n}
\]

The Fourier transform of Dirac pulse is a convoluted exponential function, the last term in the equation above, an eigenfunction [82] of every linear system.
The characteristic of the transferring channel with the presence of peaks and valleys, notches, is now achieved. It can be shown that the average distance, in Hz, between two, in sequence, valleys or peaks, is approximately inversely proportional to $T_M$. This described coherence bandwidth is accordingly defined as $B_C \approx \frac{1}{T_M}$ [83] and is shown in figure 34 [80].

![Figure 34: Mathematical model of the multipath channel transfer function (courtesy to I Canta-lamesa [80]).](image)

Let’s take a digital transmission and the data stream that have been sent over the communication channel have been changed because of being effected by noise, interference, distortion or bit synchronization error, the number of changed bits is the number of bit errors. If the number of bit errors is measured during an amount of time and it is divided by the total numbers of transmitted bits during this studied time interval, the result will be the bit error rate (BER) [84][85]. Bit error rate is often expressed in percentage.

To improve the bit error rate without requiring more energy consumption to be able to carry out the transmission were error-correcting codes, such as turbo codes, TC, developed by Claude Berrou [86][87]. In the scientific paper by Claude Berrou, Alain Glavieux and Punya Thitimajshima [87] where turbo codes first is described is also the turbo codes encoder and decoder in figure 35 explained.

![Figure 35: Turbo encoder and Turbo decoder (courtesy to Anton Petrov [88][89])](image)

When MIMO was introduced there were also a new technique developed to encode digital data that was transmitted on multiple carrier frequencies and that was Orthogonal frequency-division multiplexing, OFDM [2][90]. Together with OFDM is an implementation of the fast Fourier transform, FFT [91][92][2] algorithm on the receiver side, and the inverse on the sender side, will make an efficient modulator and demodulator. An example of a transmitter and receiver is shown in 36

![Figure 36: OFDM transmitter and receiver (courtesy to Oli Filth [93][94])](image)

To get the OFDM carrier signal must all orthogonal sub-carriers be summed. Each sub-carrier will be independently modulated to get the baseband data [95]. Due to that non-linear behaviour have been observed in several digital communication systems [96] PSK is a suitable modulation technique, because it is less sensitive to non-linearities due to the constant envelope constellation.
One drawback is that PSK is less bandwidth efficient than other communication signals like QAM, QAM is also a suitable modulation technique. Both techniques is suitable when parallel transmission is desirable [95]. This complex baseband signal can be used to modulate a main RF carrier. The input signal, \( s[n] \), is representing a serial stream of binary digits. By inverse multiplexing \( s[n] \), the serial stream is divided into \( N \) parallel streams. Each parallel stream is then mapped to a stream of symbols by a suitable modulation technique, PSK or QAM. Depending on which modulation that is used the streams can vary in bit-rate.

To eliminate inter-symbol interference, ISI, in multipath fading channels, a guard period of length

\[
T
\]

will make them orthogonal over every symbol period. This is represented by:

\[
\frac{1}{T} \int_{0}^{T} (e^{j2\pi k_{1}t/T})^* (e^{j2\pi k_{2}t/T}) dt = \frac{1}{T} \int_{0}^{T} e^{j2\pi (k_{2} - k_{1})t/T} dt = \delta_{k_{1}k_{2}}
\]

where \( * \) stands for the complex conjugate operator and \( \delta \) is the Kronecker delta [97].

To eliminate inter-symbol interference, ISI, in multipath fading channels, a guard period of length \( T_{g} \) is added at the start of every symbol [95][98]. The guard period is a cyclic copy and it will result in that it will extend the length of the waveform to appurtenant symbol, periodic addition. This periodic addition will, in the interval \(-T_{g} \leq t < 0\) will be the same as the signal in the interval \((T - T_{g}) \leq t < T\).

The OFDM signal with the periodic addition can then be represented by:

\[
\nu(t) = \sum_{k=0}^{N-1} X_{k} e^{j2\pi k t/T}, \quad -T_{g} \leq t < T
\]

For every modulated sub-carrier is using \( M \) different symbols and there are \( N \) sub-carriers used will the OFDM symbol alphabet consists of \( M^{N} \) combined symbols.

The OFDM signal that have been filtered by a low-pass filter is represented as:

\[
v(t) = \sum_{k=0}^{N_{1}} X_{k} e^{j2\pi k t/T}, \quad 0 \leq t < T,
\]

where \( X_{k} \) are the data symbols, \( N \) is the number of sub-carriers and \( T \) is the duration of every OFDM symbol. The low-pass signal, \( v(t) \), has a real part and a complex part. If the real part of \( v(t) \) is used it can be transmitted at a baseband wire-line applications, as for example DSL. When it comes to wireless application the signal \( v(t) \) is complexed. Therefore is the transmitted signal transformed to the carrier frequency, \( f_{c} \). The transmitted signal can then be represented by:

\[
s(t) = \Re \left\{ \nu(t) e^{j2\pi f_{c} t} \right\} = \sum_{k=0}^{N-1} |X_{k}| \cos \left( 2\pi f_{c} \left( t + \frac{k}{N} \right) + \arg[X_{k}] \right)
\]

If the time between every sub-carrier is \( \frac{1}{T} \) it will make them orthogonal over every symbol period.
The guard period will result in that time overhead is added and that will decrease the system overall spectral efficiency. Therefore should the time span for the guard be extended. $T_w$ will then be $T = T_s + T_g$, $T_s = NT$ and $N$ is the number of sub-carriers.

The Volterra method is also used to explain the non-linearities in communication systems [96]. In communication system power amplifiers operate near saturation due to limited power resource.

$$y_n = \sum_{p=1}^{P} \sum_{\tau_1}^{N_p} \cdots \sum_{\tau_p}^{N_p} h_p(\tau_1, \cdots, \tau_p) \prod_i^{p} z_{n-\tau_i}$$

The baseband represented by the Volterra model

$$y_n = \left\lfloor \frac{z_n}{2^p} \right\rfloor N_{2p+1} \sum_{\tau_1}^{N_{2p+1}} \cdots \sum_{\tau_{2p+1}}^{N_{2p+1}} h_{2p+1}(\tau_1, \cdots, \tau_{2p+1}) \prod_{i=1}^{p} z_{n-\tau_i} \prod_{j=p+1}^{2p+1} z_{n-\tau_j}$$

Multidimensional orthogonal polynomials represented by the Volterra model. They are formed as products of one dimensional orthogonal polynomials, $P_{\tau_i}(z_i)$, where $\tau_i$ is the degree of the polynomial and $z_i = z_{ni-1}$. $Q^{(p)}_{\tau_1 \cdots \tau_k}(z_n) = \prod_{q=1}^{k} P_{\tau_q}(z_{nq})$

where $\tau_1 + \cdots + \tau_k = p$, $z_n = (z_{n1}, \cdots, z_{nk})$, the superscript $(p)$ specify the degree of $Q$ and all $\tau_1, \cdots, \tau_k$ are definite.

Multiple copies of a data stream is sent on multiple transmitting antennas. It is sending the data stream in an environment with scattering, reflection, refraction and at the receiver the data stream is more affected by noise. The possibility to send on multiple antenna but receive on only one or optional multiple antenna were studied. Space-time coding, STC, were a technique that improved error rate over single-antenna system [99]. STC were designed based upon trellis codes, convolutional code [100]. It were developed to simpler block codes [101], Alamouti space-time coding [102], and this to increase the link reliability. This techniques were later even more developed to space-time block-codes, STBC [103].

A matrix is used to represent STBC and describe it mathematically. Every modulated symbol is represented by $s_{ij}$, $i$ is representing a time slot and $j$ is representing one antenna’s transmissions over time. Every row is a new timeslot and every column is an new antenna

$$\begin{bmatrix}
    s_{11} & s_{12} & \cdots & s_{1NT} \\
    s_{21} & s_{22} & \cdots & s_{2NT} \\
    \vdots & \vdots & \ddots & \vdots \\
    s_{T1} & s_{T2} & \cdots & s_{TNT}
\end{bmatrix}$$

During studies of STBC it was shown that the most effective design of STBC is done by using orthogonal design. That means that the vectors representing any pair of columns taken from the coding matrix is orthogonal. This will simplify the decoding at the receiver. The decoding will be simple, linear and optimal. When designing STBC it is based on the stated diversity criterion developed by Tarokh [104] and the diversity criterion were formed by using space-time trellis codes [104]. The diversity criterion is described like this: lets consider the possibility of the maximum-likelihood of that the receiver decides incorrectly to support a signal that looks like $c = c_1 c_2^\tau c_3^{\tau^2} \cdots c_T^{\tau^T} e_1^\tau e_2^{\tau^2} e_3^{\tau^3} \cdots e_T^{\tau^T}$ and the transmitted signal looks like

$$c = c_1^1 c_2^2 \cdots c_T^{\tau_T}, c_1^1 e_2^{\tau^2} \cdots c_T^{\tau_T} e_T^{\tau_T}.$$ This will result in a matrix that looks like

$$B(c, e) = \begin{bmatrix}
    e_1^\tau - c_1^\tau & e_1^\tau - c_2^\tau & \cdots & e_1^\tau - c_T^\tau \\
    e_2^\tau - c_1^\tau & e_2^\tau - c_2^\tau & \cdots & e_2^\tau - c_T^\tau \\
    \vdots & \vdots & \ddots & \vdots \\
    e_T^\tau - c_1^\tau & e_T^\tau - c_2^\tau & \cdots & e_T^\tau - c_T^\tau
\end{bmatrix}$$
It has been shown that orthogonal STBC can manage the maximum diversity that is allowed by this criterion.
The simplest matrix were developed by Alamouti [101] and it were designed for a system with two transmitting antennas and the resulting coding matrix looks like \[ \begin{bmatrix} c_1 & c_2 \\ -c_2^* & -c_1^* \end{bmatrix} \], Alamouti code, and were * stands for complex conjugate. This is the only standard STBC that is able to manage full code-rate [104]. If there are \( T \) time-slots and the block is encoding \( k \) symbols is the code-rate \( r = \frac{k}{T} \). It takes two time-slots to transmit two symbols.

When it comes to decoding orthogonal STBC is one especially beneficially detail that maximum likelihood decoding can be managed at the receiver, but this is only possible with linear processing. To be able to consider a decoding method, when it comes to wireless communication, was a new model needed. At the time \( t \), is the signal \( r_{jt} \) received by the antenna \( j \) and it is represented by

\[ r_{jt}^i = \sum_{i=1}^{n_T} \alpha_{ij} s_i^t + n_{jt}^i \]

\( \alpha_{ij} \) is the path gain from the transmitting antenna \( i \) to the receiving antenna \( j \). \( s_i^t \) is the signal that is transmitted by the transmitting antenna \( i \) and \( n_{jt}^i \) is a sample of additive white Gaussian noise, AWGN [105].

The maximum-likelihood detection rule [99] is to express the decision variables

\[ R_t = \sum_{t=1}^{n_T} \sum_{j=1}^{n_R} r_{jt}^i \alpha_{i(i)} j \delta_t (j) \]

\( \delta_t (j) \) is the sign of \( s_i \) in the \( k \)th row of the coding matrix and \( \epsilon_k(p) = q \) stands for that \( s_p \) is the \( (k, q) \) element of the coding matrix. This is for \( i = 1, 2, \ldots, n_T \) and then decide on constellation symbol \( s_i \) so that it will satisfy this

\[ s_i = \arg \min_{s \in A} \left( |R_t - s|^2 + \left( -1 + \sum_{k,l} |\alpha_{kl}|^2 \right) |s|^2 \right) \]

\( A \) is the constellation alphabet. This linear decoding scheme will result in maximal diversity. By using optimal decoding it will result in that the bit-error rate (BER) of this STBC will be the same as the maximal ratio combining, MRC [106][107], of the \( 2n_R \)-branch. This is a result of the perfect orthogonality between the symbols after receive processing, there are two copies of each symbol transmitted and \( n_R \) copies received.
3 Related Work

When it comes to underwater communication Reginald Fessenden [14][15] was among the first developers of that kind of communication. It was transmission and reception of analogue data. When it comes to transmission and reception of digital data wireless and when the bandwidth is limited it is more complicated, especially if it is big amount of data that are being sent. Rodionov A.Yu, Unru P.P, Kirianov A.V, Dubrovin F.S and Kulik S.Yu did a study in 2016 and managed to establish good horizontal wireless underwater communication and managed to send data about 10 km, [108].

Due to the low bandwidth underwater it is important to find a modulation technique that maximize the amount of data sent over the limited bandwidth channel and still manage keep up good noise rejection and signal distortion performance. S. Monaco wrote about a technique in 2002 that had been developed to be able to maximize data sent on limited bandwidth channel. This technique is called triangular modulation, TM [109].

Phase shift keying, PSK [32], is also a good modulation technique that is less sensitive to disturbance noise and is good to use when bandwidth channel is limited [110][32]. PSK has also been developed further to be able to increase the data rate of sent data when bandwidth is limited [41].

Antennas are as old as communication with radio waves. The design of the antenna depends on the wavelength of the transmitted signal.

Acoustic systems have been a standard technique for underwater communications as they are generally good for long range communications (up to tens of kilometres) [51][55][56]. But this technique is inadequate for real time and broadband underwater wireless sensor networks because of high latency, low protection against disturbance noise and low data rate [55].

The design for electromagnetic wave antennas for transmission and receiving in air has to differ with the design of the antennas for transmission and receiving in water. To be able to design antennas for underwater equipment it is important to understand the effect of the conductivity, $\sigma$, on the antenna material when the propagating medium is fresh or sea water [55][58]. It is also important to understand that a electromagnetic wave can not travel as fast in water as in air, so the wavelength will differ from air to water, see figure 25 [59][60].

When using a dipole antenna and want to be able to accomplish as long range communication as possible it is important to use lower frequency, below 100 MHz [66].

Loop antennas is another antenna that also is used when it comes to underwater communication and the loop antenna has an advantage of depending on the magnetic field of the electromagnetic waves [18]. The main advantage is that the loop antenna is not affected by interference from man-made electrical signals [18], such as disturbance noise from electrical engines.

To be able to design and construct compact communication systems the antenna has to be able to be made much smaller [67][68]. Also when it comes to be able to communicate wireless underwater in comparatively high-speed, and in this study, in short-range the J-antenna has been studied [55]. To be able to handle even higher data rate and at the same time keep the power requirement relatively low and keep the costs down another technique had to be developed. Due to this requirements the outcome was Ultra-wide band, UWB [74]. New and more advanced technique with specific requirements needs new and more advanced antenna, UWB antenna [74][63].

To improve the bit error rate without requiring more energy consumption to be able to carry out the transmission were error-correcting codes, such as turbo codes, TC, developed by Claude Berrou [86][87]. In the scientific paper by Claude Berrou, Alain Glavieux and Punya Thitimajshima [87] where turbo codes first is described is also the turbo codes encoder [88] and decoder [89] explained, see figure 35.

Considering the limitation of bandwidth, scattering, reflection, refraction and man made noise when it comes to underwater communication were another technique tried out with multiple-inputs and multiple-output, MIMO [77][78]. In the beginning it were multiple transmitting antennas and multiple receiving antennas. This techniques were developed to have multiple transmitting antennas but only have one or optional number of receiving antennas.
When MIMO were introduced there were also a new technique developed to encode the digital data that were transmitted on multiple frequencies and that technique were called orthogonal frequency-division multiplexing, OFDM [2][90]. Together with OFDM is an implementation of the fast Fourier transform, FFT [91][92][2] algorithm on the receiver side, and the inverse on the sender side, will make an efficient modulator and demodulator. Due to that non-linear behaviour have been observed in several digital communication systems [96] PSK is a suitable modulation technique, because it is less sensitive to non-linearities due to the constant envelope constellation. One drawback is that PSK is less bandwidth efficient than other communication signals like QAM, QAM is also a suitable modulation technique. Both techniques is suitable when parallel transmission is desirable [95]. This complex baseband signal can be used to modulate a main RF carrier.

To be able to transmit on multiple antennas and receive on one or optional numbers of antenna were the space-time coding, STC [100], introduced. STC were then further developed to space-time block-codes, STBC [103].

The sonar that will be used in this study comes from DeepVision [7][8]. DeepVision have specialized in development of high performance and low price side scan sonar systems. EvoLogics is a company that have specialized in underwater communication and have developed modems specialized for underwater communication [48][49].

National Instruments have developed a software platform, LabView, to use so that the user have the opportunity to develop different embedded systems and also developed hardware to connect to your computer to test the program that has been created in LabView [10][11][9]. The control of the system in this study is done with a roboRIO[45] from National Instrument that is programmed using the LabView programming suite the on-board dual-core ARM real-time CortexA9 processor and customizable Xilinx FPGA [46][47].
4 Problem formulation

Is it possible to establish wireless communication using an underwater sonar using LabView? Due to the fact that this thesis were performed on a test rig, 38 [111], that communicated wirelessly, using a constructed motherboard 39 [111], using LabView, is it possible to establish wireless communication?

To assist the progress of wireless communication with the sonar/test rig, there are some environmental limitations that has to be considered. Underwater communication is limited by the fact that there is low bandwidth, a lot of disturbance noise, inter-symbol interference (ISI) and the impact of the Doppler effect. Due to the knowledge that the AUVs and ROVs is driven by electrical engines, that also produce disturbance noise and that will be added to the already existing disturbance noise, it is important to investigate how all these parameters will affect the communication and the functionality of the sonar.
5 Research questions

The main target for this study is to be able to establish wireless underwater communication with a sonar by using LabView. To be able to reach the main target of this work it is important to divide the main target into sub targets. So the sub targets will be:

1. Establishing wireless communication with a sonar, DeepVision[8], using LabView[9] and verify that the communication works

2. Test the wireless communication in different surroundings

3. Investigate how disturbance noise, from surroundings and added from electrical engines, affect the wireless communication and the functionality of the sonar

Due to the change of hardware, the sub targets ended up to be:

1. Establishing wireless communication with the constructed test rig 38 [111] by using the constructed motherboard 39 [111] and using LabView and verify that the communication works

2. Test the wireless communication in different surroundings

3. Investigate how disturbance noise, from surroundings and added from electrical engines, affect the wireless communication and the functionality of the sonar
6 Method

To begin with wireless communication using the sonar, using LabView and EvoLogics [48][49] underwater modem, has to be established and verified, and there will LabView be the program that verifies the communication and shows the results. When the wireless communication has been verified, the surroundings has to be varied so that the affect on the communication can be investigated and the result can be displayed. What happens if disturbance noise also will be added, electrical engines for example? How will that affect the wireless communication? Which modulation technique will be the most effective due to that it is wireless communication that will be used and there is limited bandwidth underwater and a lot of disturbance noise and that digital data is to be sent in real time? Phase Shift Keying (PSK) [32], and developed PSK techniques(n-PSK), is one method that is used when it is data that is to be sent wireless and bandwidth is limited. Maybe it also is possible to combine with triangular modulation (TM) [109] that also is good to use when bandwidth is limited. Data has been managed to be sent long distances horizontally. Is it possible to send data wireless long distance vertically? The control of the system is done with a roboRIO [45] from National Instrument that is programmed using the LabView programming suite the on-board dual-core ARM real-time CortexA9 processor and customizable Xilinx FPGA [46][47].

Due to that the sonar and the roboRIO had to be sent away to another location and that I instead became using hardware from an other Master Thesis [111] the method had to change. Wireless communication has still to be established, but now it were established with the test rig, 38 [111], by using the constructed motherboard 39 [111] connected to myRIO. The control of the system were done with a myRIO [112] from National Instrument using the LabView programming myRIO FPGA that is integrated into the Xilinx Zynq-7010 System on Chip (SoC) [46] [47]. Due to the fixed test rig it were not possible to increase the distance between transmitter and receiver to more than the length of the test rig. Both horizontally and vertically communication is still possible to test even if the distance is not very long between the transmitter and receiver.
7 Results

Instead of the sonar and the roboRIO the thesis were made using hardware from an Master thesis, [111], and myRIO [112] instead of roboRIO.

To be able to get the generated signals out to the transducer a specific hardware is necessary to access data acquisition platform, NI USB-7845R [113]. Unfortunately this hardware were missing so therefore it was not possible to perform complete tests to verify the communication.

The transducer allows for conversion between acoustic and electric energy in both transmission and reception. Piezoelectric devices were used to make the transducer elements 37 [111].

![Transducer elements](image)

Figure 37: Transducer elements (courtesy to Albin Barklund and Daniel Adolfsson [111])

Two sets of transducer elements were constructed and placed on a test rig 38 [111].

![Test rig](image)

Figure 38: Test rig (courtesy to Albin Barklund and Daniel Adolfsson [111])

To be able to have an interface between power supply, Data Acquisition (DAQ) platform and channel boards were a motherboard constructed 39[111].

![Motherboard](image)

Figure 39: Motherboard (courtesy to Albin Barklund and Daniel Adolfsson [111])
Also shown in the figure 39 is the channel boards and the power supply unit (PSU) and they were also constructed during the Master thesis, see figure 40[111].

![Channel board and PSU](image.png)

**Figure 40**: Channel board and PSU (courtesy to Albin Barklund and Daniel Adolfsson [111])

The channel board were constructed so that it transmits on digital output and receives on analogue input. So to be able to establish wireless communication by using LabView, myRIO and the constructed hardware, the analogue signal has to be transformed to a digital signal and then transmitted on digital output. To begin with the tests were made above water, but the software were constructed as the communication were made under water. The carrier signal is a pulse width modulated (PWM) signal that sends at 40 MHz. The data signal is a square wave signal that transmits 8 bit data at 20 MHz. To be able to call it communication the sender has to know that the receiver has received before transmitting again. So the sender count the transmitted bits and waits for the receiver to count the received bits and then sends again. The result of the test made above water is shown in figure 41

![Result of the communication test above water](image.png)

**Figure 41**: The result of the communication test above water

The result of the test made under water with now other disturbance is shown in figure 42, this is horizontal transmission, and in figure 43, this is vertical transmission

![Result of the communication test under water](image.png)

**Figure 42**: The result of the communication test under water, horizontal transmission
Figure 43: The result of the communication test under water, vertical transmission

The theory and the software is done to be tested when necessary hardware is accessible to verify or not verify that the wireless communication works.
8 Discussion

The wireless communication could not be verified. But I am convinced that it is possible to establish wireless communication using the test rig, the motherboard, myRIO and LabView. When that is accomplished I am also convinced that it is possible to establish wireless communication using the sonar from DeepVision and the under water modem from Evologics and the roboRIO and LabView. Both myRIO and roboRIO has the same FPGA and maximum frequency is 40 MHz. So if, in the future, it is desirable to investigate transmission over 40 MHz it is necessary to look after another hardware or develop their own.

At this time it desirable to test the communication with lower frequency on the PWM signal and square wave signal to see if it is possible to establish wireless communication and very it. So both signals need to be generated and then integrated on the FPGA.

When communication is verified, it is one step further in accomplish real-time wireless communication between the AUV/ROV, the transmitter, and for example the boat at the surface, receiver. It will be a small step, more testing and developing is needed before reaching the goal, but it is a step in the right direction.
9 Conclusion

Wireless communication were not verified, but I am convinced that it will be possible to establish wireless communication using LabView, myRIO or robobRIO, constructed motherboard or under water modem and used hardware, test rig or sonar. When communication is verified it is a step in the right direction to establish real-time wireless communication between the AUVs/ROVs, transmitter, and for example a boat at the surface, receiver.
10 Future work

First of all wireless communication has to be established and verified. I am convinced that is possible. After that, next step would be to verify that the data that is transmitted is the same data that is received. Then it would also be interesting do the tests with the sonar from DeepVision using the under water modem from Evologics and the roboRIO and compare the results. Then also do the test in the right environment, the oceans with salt water and also longer range with wireless communication. If there will be problem with the long range wireless communication, would it improve with using MIMO? How will the communication be affected by more disturbance noise from the surrounding? Which antenna is the most suitable and if different modulation techniques are used? How will the test results differ? At which frequency is the best communication established?
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References


[30] Wikipedia By Omegatron - The source code of this SVG is valid. This vector image was created with Inkscape by userOmegatron. This SVG electrical schematic was created with the Electrical Symbols Library CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3176486. (2017-03-23) Piezoelectric sensor. [Online]. Available: https://en.wikipedia.org/wiki/Piezoelectric_sensor


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