Semester Project

Underwater optical communication

López Estepa, Pedro

Under supervision of K. Karakasiliotis and Prof. A. J. Ijspeert

Biologically Inspired Robotics Group

January 12, 2009

BIOLOGICALLY INSPIRED ROBOTICS GROUP (BIRG)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Abstract

This report presents the work accomplished during a Semester project at the BIRG Laboratory of EPFL. This project aims at implementing an underwater optical communication system between a robot and a surface platform for video transmission. Firstly we present the fundamental physics of different waves; then we discuss and compare the pros and cons for adopting different communication carriers (acoustic, radio and optical) and the final choice in optical communication. To establish an underwater communication system we develop an optical system, combining the Manchester modulation with 3 Watt high power light emitting diode, emitting light in blue part of visible spectrum. This report shows the design and experimental results in air and underwater.

Acknowledgement

I would like to dedicate this project to my parents and my brother for their love and support and providing me with the best.

Great thanks go out to Kostantinos Karakasiliotis for his advice, guidance and support.

I would also like to thank Dr. Alessandro Crespi for providing invaluable help.

I would also like to thank Prof. Auke Jan Ijspeert for giving the great opportunity of do a project in the EPFL.

I would also like to thank all members' BIRG group for their help.

Last but not least, I would like to thank Paola for her practical and emotional support.

Contents

List of Figures

Page

List of Tables

List of Abbreviations

Abbreviation	Full Description
AM	Amplitude Modulation
APD	Avalanche PhotoDiode
BR	Bit Rate
BW	BandWidth
dB	deciBel
COTS	Commercial Off-The-Shelf
FOM	Figure of merit
FOV	Field Of View bandpass
FSO	Free Space Optics
FPGA	Field Programmable Gate Array
GHz	Giga Hertz
Kbps	Kilo bits per second
LED	Light Emitting Diode
LOS	Line Of Sight
NEP	Noise Equivalent Power
NRZ	Non Return to Zero
PCX	Plano Convex
nm	Nanometre
SNR	Signal-to-Noise Ratio
TIA	TransImpedance Amplifier

List of Symbols

Symbol	Unit	Description
BW	HZ	Effective noise bandwidth
c	m^{-1}	Beam attenuation parameters
D_0	m	Receiver aperture diameter
D_1	m	Depth
D_2	m	Diameter of the collecting optics
E	$watts/m^2$	Downwelling irradiance
F	unit less	Excess noise noise factor
G_{det}	unit less	Detector current gain
I_{dark}	A	Multiplied dark current
I_{dc}	A	Non-multiplied dark current
K	m^{-1}	Attenuation of diffuse light
L_{fac}	unit less	Factor describing directional dependence underwater radiance
L_{sol}	$W/(m^2\text{-}sr)$	Solar radiance
P_{gb}	W	Optical power of background
P_t	W	Transmitter power
q	C	Electron charge
r	m	Communications range
R	unit less	Underwater reflectance of the downwelling irradiance
S	A/watt	Radiant sensitivity of the detector
ϕ	º	Angle between the optical axis of the receiver and the line-of-sight between the transmitter and receiver
θ	º	Half angle transmitter beam width
$\Delta\lambda$	m	wavelength bandpass

Chapter 1

Introduction

1.1 Problem overview

Wireless underwater communication is a challenging task. Most commonly used methods, which are well established for digital communication in air, do not work in water.

Conventionally, underwater communications are achieved using an acoustic method. Acoustic communication is the most versatile and widely used technique in underwater environments due to the low attenuation of sound in water. This is especially true in thermally stable, deep-water settings. On the other hand, the use of acoustic waves in shallow water can be adversely affected by temperature gradients, surface ambient noise, and multipath propagation due to reflection and refraction. The much slower speed of acoustic propagation in water, about 1500 m/s, compared with that of electromagnetic and optical waves, is another limiting factor for efficient communication and networking.

Available radio modules operate in the GHz range, the attenuation in water for high frequency radio, especially in electrically more conductive salt water, is extremely high. A way around this is using ultra low frequency longwave radio, for which the attenuation is manageable, but the maximum bandwidth is significantly limited.

Optical communication systems can have shorter ranges because of greater attenuation of light propagating through water, they may provide higher bandwidth (up to several hundred Kbps) communications as well as covertness. The development of high brightness blue LED sources, and laser diodes suggest that high-speed optical links can be viable for short-range application.

In this project, I review the physical fundamentals and engineering implementation for efficient underwater communication via optical waves. Underwater systems have severe power, and size constraints compared to land or air based systems. The primary focus of the project was to design the full communication system:

- Transmitter
    - Light emitting source
    - Signal modulation
    - Driver
    - Lens

- Receiver
    - Light receiver device
    - Signal treatment circuit
    - Lens

The secondary focus of this project was to construct the communication system and design and obtain experimental results in air and underwater.

1.2 Outline

This report is organized as follows: Chapter 2 presents the optical communication basic parameters and principles. Chapter 3 shows the basic components of underwater optical communication. Chapter 4 presents the design and circuitry of the final design. Chapter 5 shows the experimental results in air and underwater. Chapter 6 concludes our work. Chapter 7 presents further possible work. Chapter 8 presents the additional material and the bibliography.

Chapter 2

Optical communication

In this Chapter we show the optical characteristics, in air and underwater conditions. The intention of this chapter is provide the theoretical base for analyzing our final design and be able to develop it thought these parameters.

2.1 Free space optics communication concepts

Free space optics (FSO) is a line-of-sight (LOS) link that utilizes the use of lasers or light emitting diodes, LEDs, to make optical connections that can send/receive data information.

FSO has attractive characteristics of dense spatial reuse, low power usage per transmitted bit, and relatively high bandwidth. LED's, lasers, photodetectors are available today cheaply and in large volumes.

The main disadvantage of FSO communication is that the transmission medium is uncontrolled. The effects of atmospheric distortions, scintillation, weather and attenuation can only be minimized or compensated by the transmitter/receiver hardware.

Issues for FSO communications are listed in the Table 2.1

Absorption	Gradual loss in intensity of any kind of flux through a medium due to wavelength dependent particle absorption in the medium.
Alignment Issues	LOS beams are very narrow which causes major issues with alignment. Tracking is required for moving links and even on some stationary links.
Multi-Path dispersion	The path a photon takes is ideally a straight line, but due to scattering the photon may be redirect several times causing the light pulse to spread in time.
Physical Obstructions	Living organisms that enter into the beams path causing dropping of bit or total loss of connection.
Scattering	Light being redirected by particle roughly same size as than the propagating wavelength.
Scintillation & Turbulence	Variation of the refractive index along the propagation path caused by temperature and density variations leading to large variations in signal strength on the receiver photodetector

Table 2.1 Issues for FSO communication[5]

2.2 Optical water parameters

To consider the design of underwater optical communications systems for propagation of light in water and the light noise background, we must first develop two basic light-in-water attenuation parameters.

The first of these is the beam attenuation coefficient, designated by c, which describes the attenuation of a collimated beam of light.

$$I_t = I_0 \exp(-cz) \qquad \text{(Equation 2.1)}$$

where I_0= the original light irradiance (watts/m^2)

I_t= the transmitted irradiance

z= the path length.

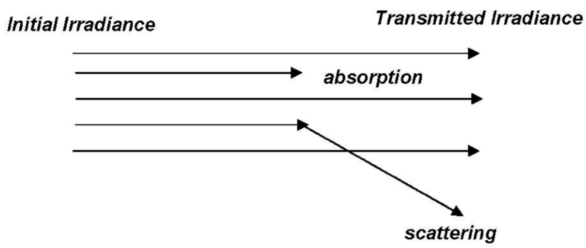


Figure 2.1 Illustration of beam attenuation coefficient

This parameter is wavelength dependent with the minimum value in the optical transmission window of water around 490 nm for clear ocean water and has a values of ~0.02 m^{-1}.

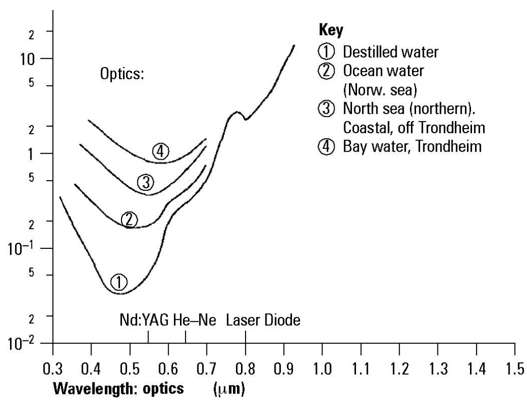


Figure 2.2 Spectral attenuation coefficient for optical radiation[2]

The second of the basic light in water attenuation parameters is designated by K and describes the attenuation of diffuse light.

$$I_t = I_0 \exp(-Kz) \qquad \text{(Equation 2.2)}$$

where I_0= the original light irradiance (watts/m^2)

I_t= the transmitted irradiance

z= the path length.

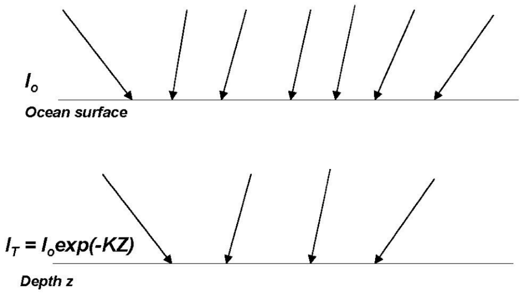


Figure 2.3 Illustration of diffuse attenuation coefficient[2]

This parameter is especially useful for calculating the attenuation of sunlight in ocean waters for background noise calculations. Values of K are classified according the so-called Jerlov water types, which range from the clear ocean(O) and coastal water types(C).

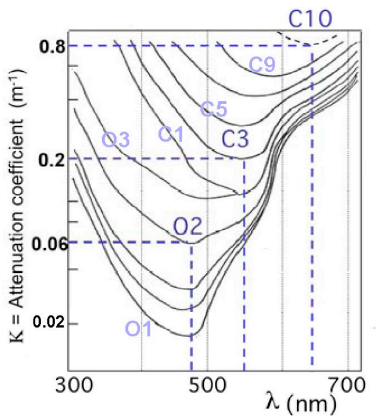


Figure 2.4 Jerlov ocean and coastal K spectra[2]

This parameter is also wavelength dependent with the maximum transmission shifting from about 490 nm in the blue portion of the spectrum for the clearest ocean water with a minimum value of K about 0.002 m^{-1}.

2.3 Evaluation criterion optical communication

The main parameters in underwater communications are shown in the evaluation criterion for optical communication: Signal-to-noise (SNR), noise equivalent power (NEP) and bit rate (BR).

The SNR is defined as the ratio of a signal power to the noise power corrupting the signal

$$SNR = \left[\frac{P_t}{\tan^2\theta} \frac{e^{-3Kr}}{4r^2} \frac{D^2 \cos\phi}{NEP} \right]^2 \qquad \text{(Equation 2.3)}$$

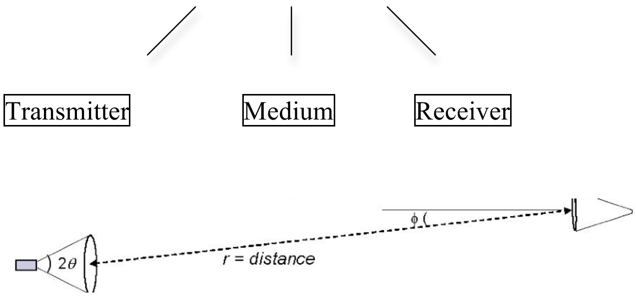


Figure 2.5 Illustration of SNR equation

This equation assumes the beam pattern of the transmitter is a constant for angles up to the 3-dB (halfway) point and zero beyond that angle.

The BR is related to SNR

$$BR = BW \log_2(1 + SNR) \qquad \text{(Equation 2.4)}$$

where BW is the system bandwidth and the other terms are defined as above.

The NEP is given by a summation of several noise terms. The first of these terms is the ambient light background shot noise. To calculate this noise term we first calculate the upwelling solar radiance (L_{sol})

$$L_{sol} = \frac{ERL_{fac} \exp(-KD)}{\pi} \qquad \text{(Equation 2.5)}$$

The optical power on the detector is given by

$$P_{gb} = \frac{\pi^2 D^2 (FOV)^2 \Delta\lambda L_{sol}}{16} \qquad \text{(Equation 2.6)}$$

The NEP of the solar background shot noise is given by

$$P_{bg\_sn} = \frac{\sqrt{2qSP_{bg}BW_{en}F}}{S} \qquad \text{(Equation 2.7)}$$

Likewise, the NEP of the signal shot noise is given by

$$P_{sig\_sn} = \frac{\sqrt{2qSP_{sig}BW_{en}F}}{S} \qquad \text{(Equation 2.8)}$$

where P_{sig} is Optical power of signal.

The NEP of dark current shot noise is given by

$$P_{dark\_sn} = \frac{\sqrt{(2qI_{dark}G_{\det}{}^{2}F + 21I_{dc})BW_{en}}}{SG_{\det}} \qquad \text{(Equation 2.9)}$$

The NEP of the preamplifier is given by

$$P_{amp\_n} = \frac{I_{n\_amp}\sqrt{BW_{en}}}{SG_{\det}} \qquad \text{(Equation 2.10)}$$

where I_{n_amp} is the preamplifier current noise density.

Finally the total NEP is given by

$$NEP_{tot} = \sqrt{P_{bg\_sn}{}^{2} + P_{sig\_sn}{}^{2} + P_{dark\_sn}{}^{2} + P_{amp\_n}{}^{2}} \qquad \text{(Equation 2.11)}$$

Knowing NEP_{total} we are able to calculate SNR and BR. In these underwater optical systems bandwidths of up to several hundred kbps may be achieved.

2.4 Figure of merit for underwater platform

The use of figure of merit (FOM) for underwater communication has primarily just focused on:

- Power of the transmitter
- Loss of the medium
- Sensitivity of the receiver

$$FOM_{System} = FOM_{Tx} \cdot FOM_{Environment} \cdot FOM_{Rx} \quad \text{(Equation 2.12)}$$

Firstly the FOM_{Tx} is determined by

$$FOM_{tx} = \frac{\frac{bit}{\sec} Range\Omega}{Power_{tx}} \left(\frac{AmpHour_{Platform} Density_{HwO} Mass_{platform} Volume_{platform} SurfaceArea_{platform}}{AmpHour_{Txsystem} Density_{Tx} Mass_{Tx} Volume_{Tx} SurfaceArea_{Tx}} \right)$$

(Equation 2.13)

The first term $\frac{\frac{bit}{\sec} Range\Omega}{Power_{tx}}$ is appropriate if the power and space constraints of the platform are not considered. Bits per second times range is the bit rate length product discussed above. Ω is the solid angle of the emitter, for isotropic acoustic system this can be 4π. The $Power_{Tx}$ is the amount of power that is supplied to the transmitter, thus it is the amount of power that is devoted to making using optical or acoustic power to send information.

The second term $\left(\frac{AmpHour_{Platform} Density_{HwO} Mass_{platform} Volume_{platform} SurfaceArea_{platform}}{AmpHour_{Txsystem} Density_{Tx} Mass_{Tx} Volume_{Tx} SurfaceArea_{Tx}} \right)$ express the impact of weight and size of the system on the overall platform. Where $AmpHours_{Platform}$ is the number of available Amp Hours in a power-limited system, $Volume_{Platform}$ and $Surface_{Platform}$ are the available volume and surface area of the platform. $Amps_{Txsystem}$ is the total electrical current in amps, including computational power for signal processing.

Secondly the $FOM_{Environ}$ is determined by

$$FOM_{Environ} = f(Wavelength, absorption, scattering, etc...) + Solar\_Background \quad \text{(Equation 2.14)}$$

This term expressed in dB/m is independent of the physical characteristic of the transmitter and receiver platforms, but does consider their relative physical positions in the environment and the impact of water type and time of day (solar background).

For the optical systems the absorption and scattering model gives the magnitude of the function *f* for attenuation-limited systems. The effects of solar background are dependent on the geometry, but are basically the reduction in SNR due to shot noise on the receiver.

Finally the FOM_{Rx} is determined by

$$FOM_{tx} = \frac{bitrate \cdot Aperture_{FOV}}{Power_{Rx}} \left(\frac{AmpHour_{Platform} Density_{HwO} Mass_{platform} Volume_{platform} SurfaceArea_{platform}}{AmpHour_{Rxsystem} Density_{Rx} Mass_{Rx} Volume_{Rx} SurfaceArea_{Rx}} \right)$$

(Equation 2.15)

The FOM is similar to the transmitter, instead of considering the solid angle of the emitted beam, the field of view (FOV) of the Aperture is considered. A certain amount of optical energy per bit is required to have a detectible signal and is equivalent to the bit-rate divided by the receiver power.

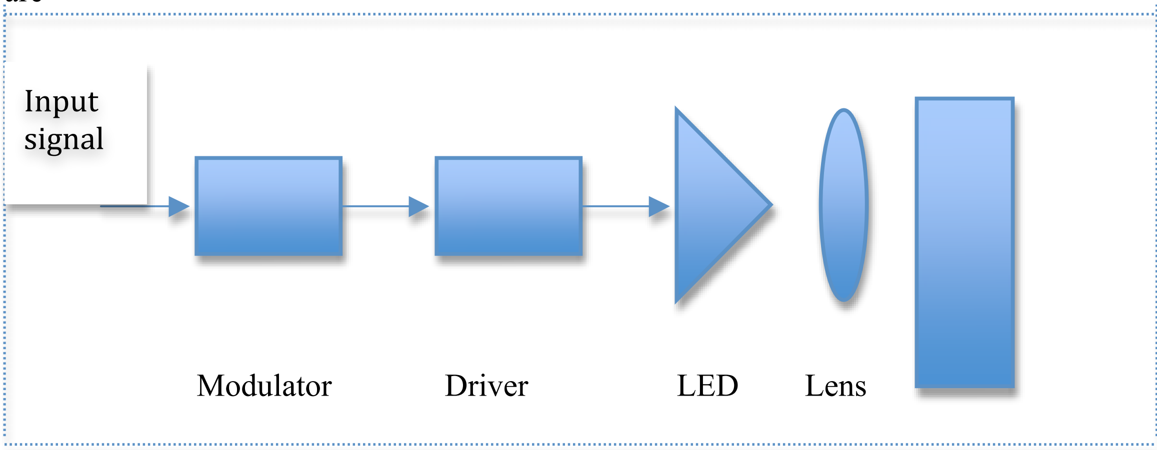
Chapter 3

Basic components and budgets of underwater optical communication

In this Chapter we present the basic components of an optical communication system, the intention of this chapter is to show the temporal line followed during the project. The first analysis of the communication before the design. The budgets knowledge is the first step ot design of a communication system.

3.1 Transmitter

The basic components of the underwater optical communication transmitter are



Platform window

Figure 3.1 Components of underwater communication transmitter

For the transmitter we have the modulator which modulates of the input signal. This modulation can be software or hardware.

The driver is necessary to transmit the signal to the LED in the right frequency and amplitude.

Newly developed high power LEDs emit substantial light and are typically very inexpensive. Currently, LEDS can emit up to several watts of power into an angle of several tens of degrees.

The lens collimated allow efficiently collimate the light into a determinate beam with more precision.

The transmitted light beam exits through the platform window into the water.

3.2 Receiver

The basic components of the underwater optical communication transmitter are

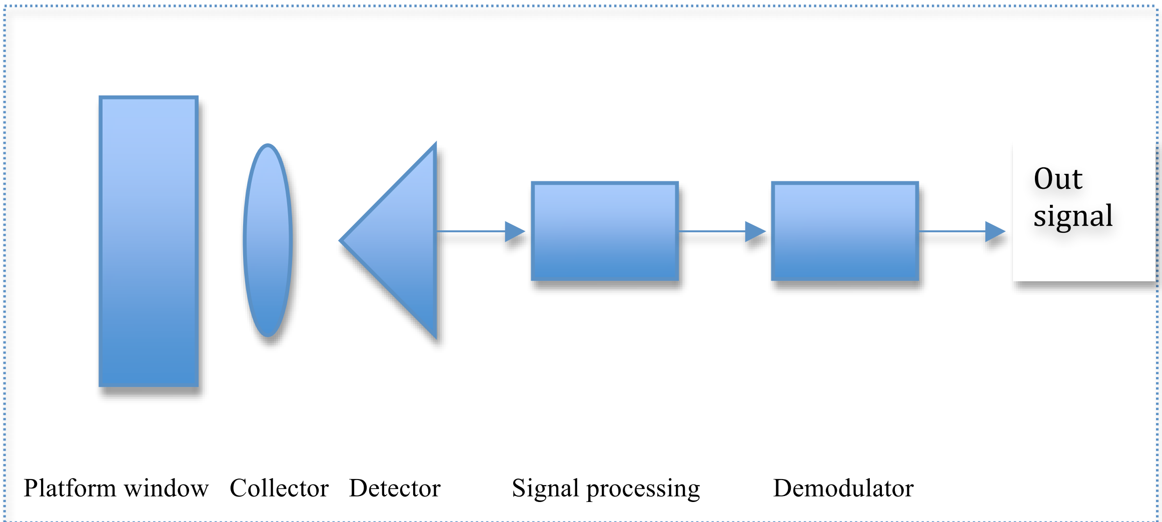


Figure 3.2 Components of underwater communication receiver

At the receiver, located on another platform, the beam enters the platform window after being attenuated by the water medium.

The received light, after the window, going through the collection optics onto the detector.

The detector is a photodiode**,** a type of photodetector capable of converting light into either current or voltage, depending upon the mode of operation. COTS photodiodes such as avalanche photodiodes (APDs) can be used as detectors, which can respond to pulses as narrow as several nanoseconds. The photodiode needs to have a balance between speed and sensitivity.

The signal processing stage takes the current from the photodiode. This is preamplified by a transimpedance amplifier (TIA). After that, the signal is filtered, amplified and processed.

The demodulator realizes the demodulation of the input signal. This modulation can be software or hardware.

3.3 Underwater optical link budget

After exposin a basic description of an underwater optical communication, we can show the budgets in this kind of systems. Weather, wavelength of the LED, distance between emitter and receiver, underwater currents, scattering, attenuation, absorption, detectors and data rates are just a few of the things that must be considered.

The main motivation of this project was to build an underwater link model, after analyzing the different communication types the conclusion was that the optical communication is the most useful in this case, however, as described above, scattering and variable optical qualities need be considered. These varying properties change with time and location which in turn could affect the amount of light lost.

The main optical properties that can influence communication are summarized in the diagram below.

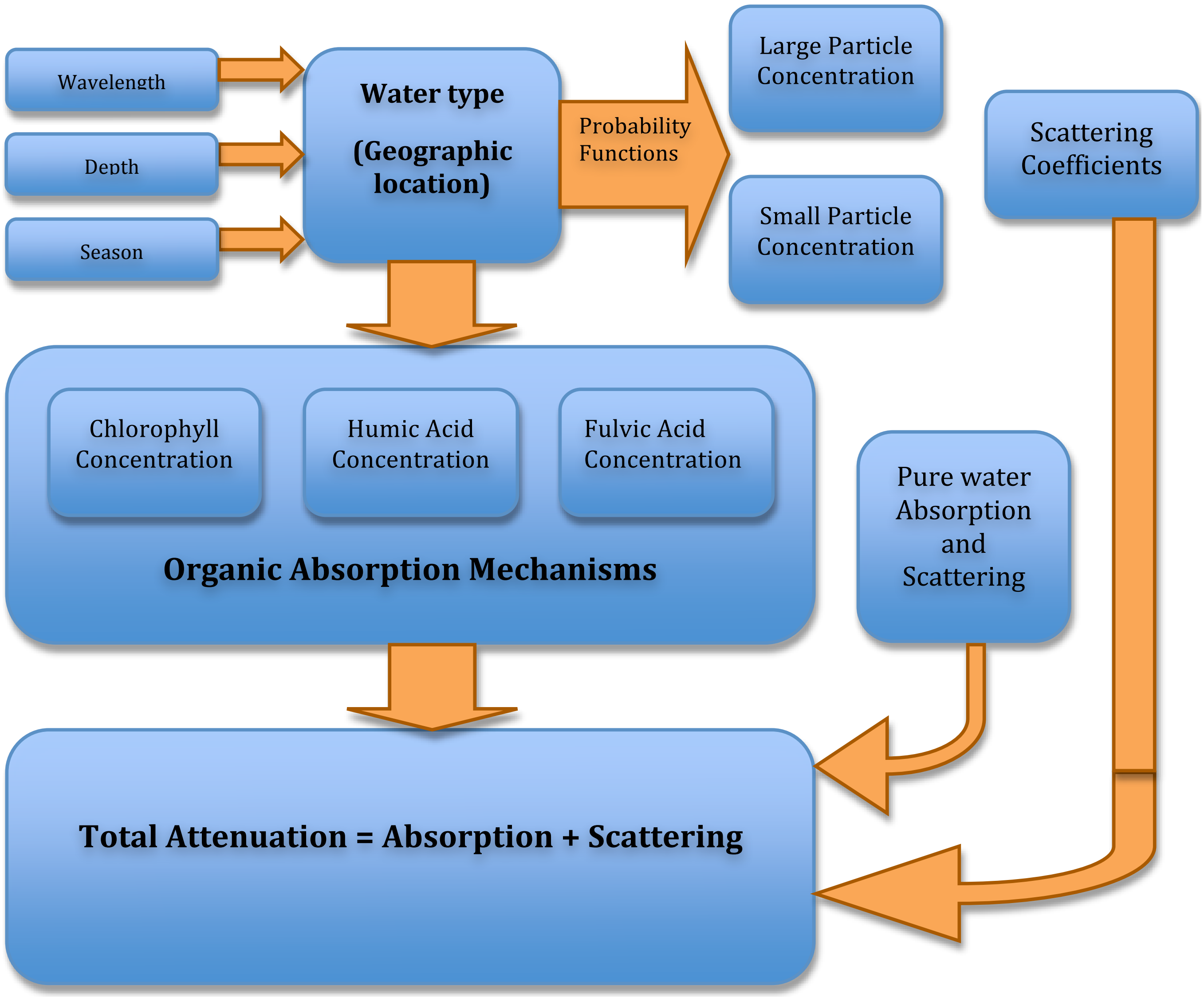


Figure 3.3 Functional bock diagram of the total attenuation underwater[5]

These parameters will be used to construct a power link budget for a theoretical underwater optical link. Furthermore the optical properties of the water will affect the performance of the hardware used.

In addition to these optical parameters, the communication systems are important for building a comprehensive model of the optical system.

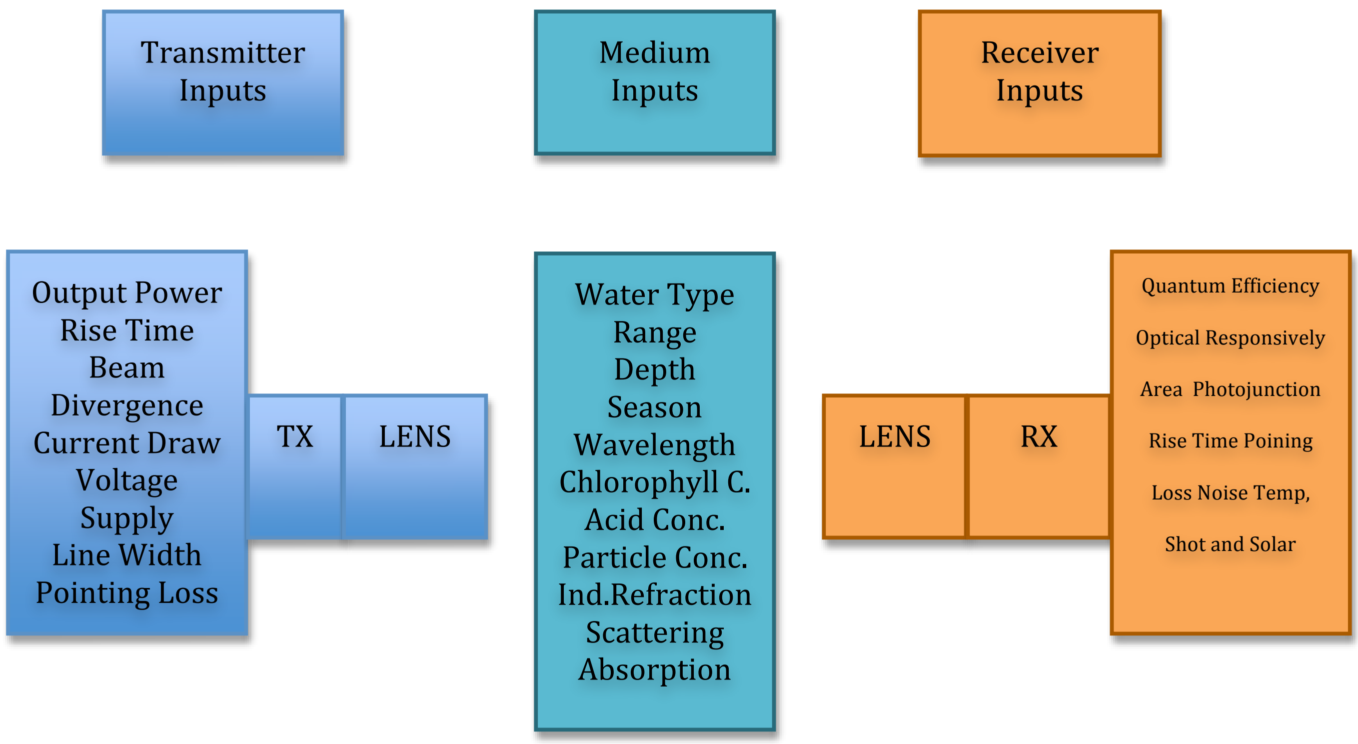


Figure 3.4 Block diagram Link Budget[5]

According to these budgets, in the chapter 4, we will make specific choices for the components describes in the paragraphs 3.1 and 3.2.

Chapter 4

Design and circuitry

The basic idea of this project was to create a fast but relatively inexpensive way to realize an underwater video transmission. There were two parts to the project. The first part is the system is the electrical circuits including receiver and transmitter. The second part is the mechanical/optical enclosures that house the lens and copper boxes containing the receiver and transmitter circuits.

4.1 Transmitter

The main problem, in an optical transmitter design, is the upper frequency at which the light source can be modulated. Several factors limit it, these include the time constants (frequency response) of the driving circuitry, the physics of the diode itself, and the characteristics of the medium. All these factors must be solved through a summary between modulation, driving and light source.

The final transmitter design for an underwater optical communication is below.

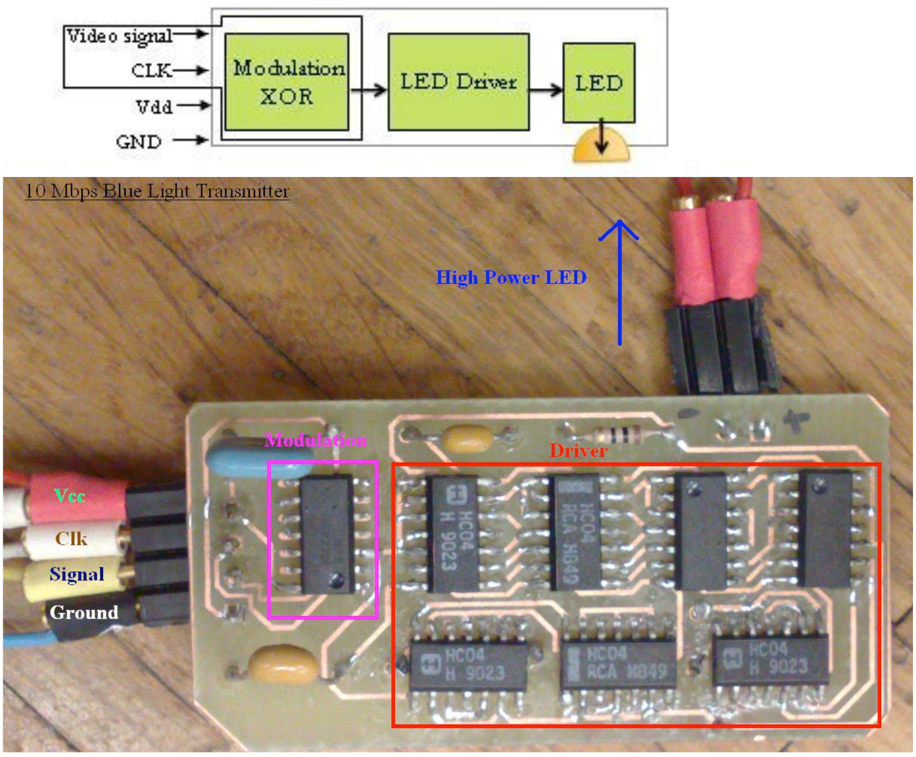


Figure 4.1 Transmitter Block Diagram (Up)-Transmitter final design (down)

The full circuit diagram and part list are in Appendix A and B respectively.

The signal arrives from the camera FPGA, we consider this signal whit a high quality so it's not necessary filter it and amplify it. Before the signal is transmitted is necessary modulate it by a MM74HC86M XOR Gate with a clock signal and drive it by stacking seven 74HC04 ICs. The signal is then ready for transmission via the blue LED.

4.1.1 Modulation

Optical modulation is one of the keys for realizing such high performance optical network. Digital communications employing LED as optical carriers generally having carrier frequencies in the Megahertz range that permit enough high modulation bandwidths for video transmission.

The optical modulation is used to modulate a beam of light, converting the electrical signal array into the light signal array and including information into the signal.

One type of optical modulation categorization, is according to the way of obtaining the modulation of intensity of a light beam:

- Direct modulation: Modulate the current driving the light source.
- External modulation: Modulation performed by a light modulator.

The easiest way to realize the modulation is direct modulation obviously, but for high frequency there are problems with

Depending on the parameter of a light beam, which is manipulated, the modulation may be categorized into:

- Amplitude modulation
- Phase modulation
- Polarization modulation

The first step to choose the right modulation is defining the main characteristics of our communication. In our project the main reason to use modulation is lose of signal detection, through the transmitter is in moving always, we are not going to know if we are receiving a '0' or we lost the signal.

So, after study and analyze the papers [9-10], the conclusion is that we need a simple modulation to have the maximum efficiency in the transmission. The minimal number of code data is two, and the most efficiency, easy and useful, as we can see in a commercial model [11], is Manchester [12].

We propose a modulation based on Manchester coded in order to reduce the low power optical fluctuation [12], it is possible implement it through Hardware and because or signal come from a FPGA that could give us the clock signal necessary for the modulation.

The data '1' and '0' of Manchester code have '10' and '01' patterns, respectively, it has less optical power fluctuation than IRZ scheme.

Data	Manchester Code
0	01
1	10

Table 4.1 Manchester Codification

The Manchester code is obtained by the combination of the non-return-to zero (NRZ) data and clock; it can be easily generated with an exclusive OR (XOR) gate.

Data	Clock	Code signal(D⊕C)
0	0	0
0	1	1
1	0	1
1	1	0

Table 4.2 System Codification

In our system we use a clock with the double frequency to realize the modulation and 50% duty cycle.

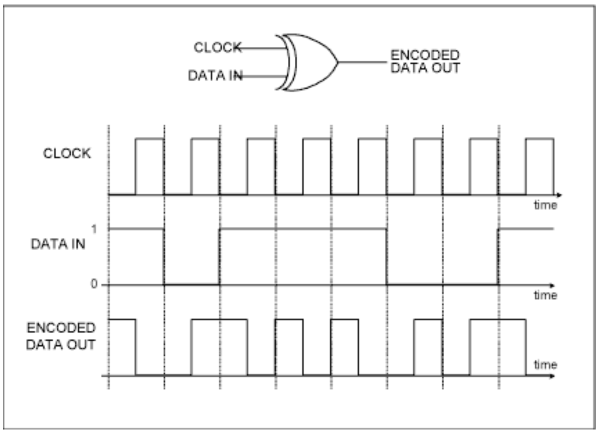


Figure 4.2 System Codification

The design for the modulation is below. To build the design, the commercial XOR gate chosen was MM74HC86M.

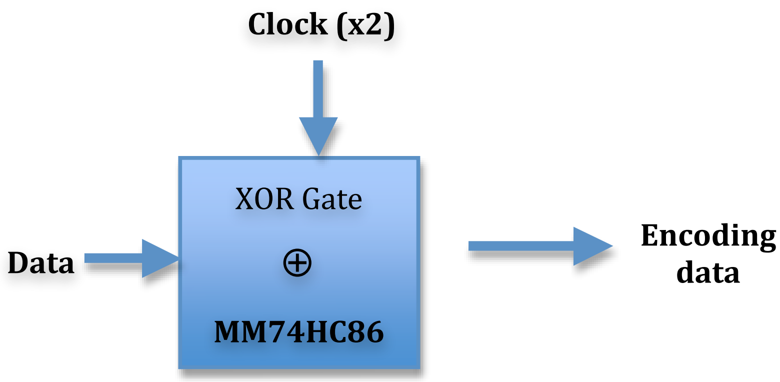


Figure 4.3 Codification block diagram

The MM74HC86 EXCLUSIVE OR (XOR) gate utilizes advanced silicon-gate CMOS technology to achieve operating speeds similar to equivalent LS-TTL gates while maintaining the low power consumption and high noise immunity characteristic of standard CMOS integrated circuits. These gates are fully buffered and have a fan-out of 10 LS-TTL loads. The 74HC logic family is functionally as well as pin out compatible with the standard 74LS logic family. All inputs are protected from damage due to static discharge by internal diode clamps to V_{CC} and ground. The electronic characteristics are

- Typical propagation delay: 9 ns
- Wide operating voltage range: 2-6V
- Low input current: 1 μA maximum
- Low quiescent current: 20 μA maximum (74 Series)
- Output drive capability: 10 LS-TTL loads
- Package type: SOIC 14

The voltage range is appropriate for our design; in our case we will use 5 V. The low input current is necessary to have a low power in the transmitter and the delay is acceptable. The election of SOIC 14 is because all the transmitter was build in SOIC technology.

4.1.2 LED

The main reason to choose as light source of a LED is because LED is an omnidirectional light source, and in our communication system the transmitter is in moving. In our case we will use a high-powered LED. Recently, high-powered LEDs have been commercialized for applications requiring high efficient.

For the election of the LED we must consider that for optical communication purpose the following aspects should be considered:

- Optical wavelength
- Optical output power
- Reliability
- Beam parameter
- Luminous flux

Superflux LEDs are a revolutionary, energy efficient and ultra compact new light source, combining the lifetime and reliability advantages of Light Emitting Diodes with the brightness of conventional lighting.

There are three LED wavelengths that could be considered for underwater applications, Blue, Cyan and Green

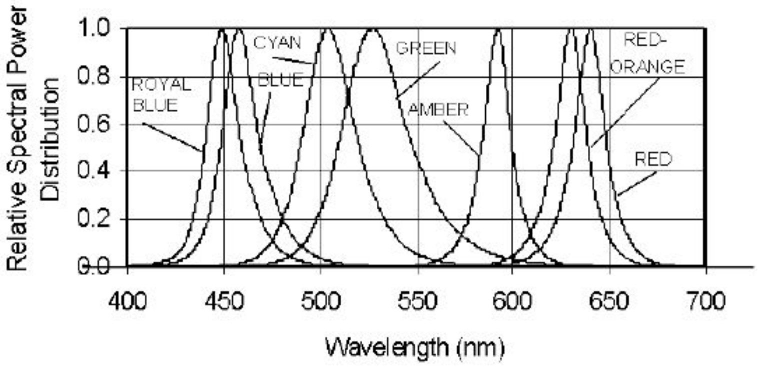


Figure 4.4 Relative intensity vs. wavelength

The wavelength chosen is blue, because presents a minimal absorption value underwater.

In many LED applications the characteristics of the output beam are not that important; however in an optical communications system the ability to collimate a beam is very important. The Superflux LEDs have a similar setup as a typical LED, but adding a good lens with the epoxy is possible forming a collimated beam with minimal distortion.

So, after the election of blue Superflux LED, the next step was to choose the power. The first design was realized with a 1.6 Watt Superflux LED B32180. Is the minimal value possible for a transmission, and we can't forget the emplacement of the transmitter, an underwater robot, for this reason the electronic power is essential. But the results weren't appropriates, because the maximum distance was 2 cm. The possible development was design a lens system to focus the light, but the transmission location doesn't allow locate a big system. For this reason we decided change the LED to 3Watt Superflux LED with a commercial lens and try develop the lens system in a future project.

So Finally, the Superflux LED use in the final design was LXHL-PB09. The next table shows the different between the final LED and the previous one

Model	Power Dissipation (W)	Current (forward) (mA)	Vf (V)	Typical Luminous flux (lm) Φ_{ϖ}
B32180	1.6	400	4	11
LXHL-PB09	3	700	3.7	23

Table 4.3 LED comparison

The bad point is the power dissipation, but in the future we will try developing the lens system to use a low power one.

So the final election is the LXHL-PB09 LED with the physic characteristics

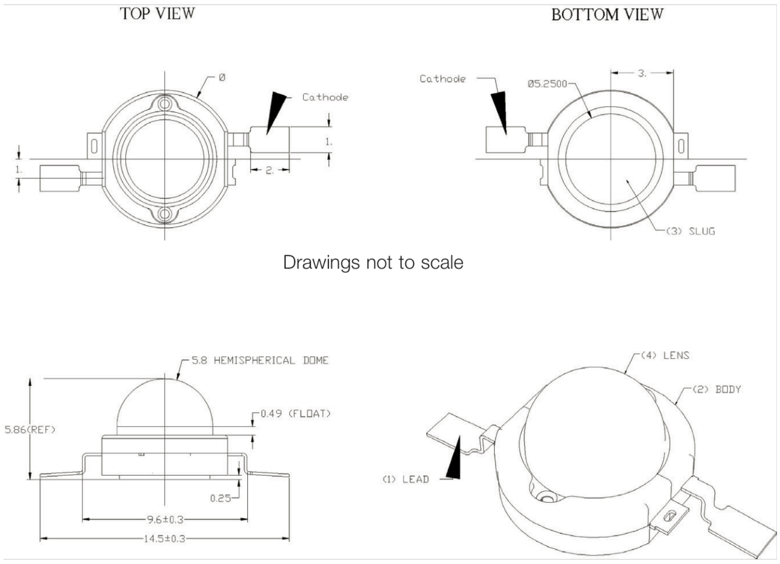


Figure 4.5 LED physical descriptions

Finally the complete LED characteristics

Optical Characteristics at 700mA, Junction Temperature, T_J = 25ºC Continued

Radiation Pattern	Color	Dominant Wavelength[1] λD, Peak Wavelength[2] λP, or Color Temperature[3] CCT Min.	Typ.	Max.	Spectral Half-width[4] (nm) $\Delta\lambda_{1/2}$	Temperature Coefficient of Dominant Wavelength (nm/ºC) $\Delta\lambda_D / \Delta T_J$	Total Included Angle[5] (degrees) $\theta_{0.90V}$	Viewing Angle[6] (degrees) 2θ 1/2
	Blue	460nm	470nm	490nm	25	0.04	160	140

Electrical Characteristics at 700mA, Junction Temperature, T_J = 25ºC

Color	Forward Voltage V_F [1] (V) Min.	Typ.	Max.	Dynamic Resistance[2] (Ω) R_D	Temperature Coefficient of Forward Voltage[3] (mV/ºC) $\Delta V_F / \Delta T_J$	Thermal Resistance, Junction to Case (ºC/W) $R\theta_{J-C}$
Blue	3.03	3.70	4.47	0.8	-2.0	13

Table 4.4 LED complete characterizations

According with the thermal indications in the datasheet was necessary include a dissipater in the design with for thermal dissipation.

4.1.3 Driver

According to the LED, it is necessary design a high frequency driver with an output current of 700 mA. There are different possibilities a commercial module or a custom one.

It's possible to use a commercial module, the line of 2008 PowerPuck drivers exhibit very high efficiency and require no external current-limiting resistors or additional heat sinking. The main characteristics are below

Specifications

Output Current, 2008B-350 . . . . 350mA[1]
Output Current, 2008B-700 . . . . 700mA[1]
Output Current, 2008B-1000 . . . . 1000mA[1]
Operating Temperature . . . . -40-+85°C
Storage Temperature . . . . -40-+125°C

Absolute Maximum Ratings

Input Voltage, DC Model. 32V
Output Voltage 32V

Typical Characteristics

Output tolerance (within specified temp. range) . . . . ±5%
Efficiency 95%
Input Voltage Minimum . . . . $5V_{DC}$
Input Margin (350mA unit[1], add to LED $V_{f\ MAX}$) . . . . $2V_{DC}$

The main advantage is that this design is built for the LED use in our design, so the efficiency is maxim. But there are several disadvantages; the first one is that this project is an academic one, so it's interesting try to design a module like this. The second one is referral to the transmitter emplacement; in the robot we can't have 32 V for input voltage and the input voltage minimum is so high. Without these limits the most efficient and appropriate is use this module.

The other possibility is design a driver . One possibility is using a MOSTET[2]. Other type is driven using a moderate power FET [13](field effect transistor) and appropriate logic. Its possible drive by a high speed MOS transistor with low input capacitance in order to achieve sharp turn-on edges that can be easily detected by the receiver.

All these drive system are right for a general optical communication, without limit of external current input. Our problem is again the transmitter emplacement where we have power limit. For these reason we decided use an hex inverters array, exactly the MM74HC04.

The MM74HC04 inverters utilize advanced silicon gate CMOS technology to achieve operating speed similar to LS-TLL gates with the low power consumption of standard CMOS integrated circuits. The package is below.

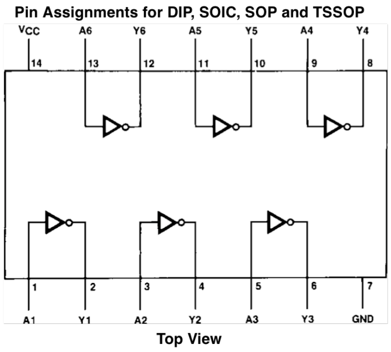


Figure 4.6 Hex inverter package diagram.

The electric characteristics are below

Absolute Maximum Ratings (Note 1)

(Note 2)

Supply Voltage (V_{CC})	−0.5 to +7.0V
DC Input Voltage (V_{IN})	−1.5 to V_{CC} +1.5V
DC Output Voltage (V_{OUT})	−0.5 to V_{CC} +0.5V
Clamp Diode Current (I_{IK}, I_{OK})	±20 mA
DC Output Current, per pin (I_{OUT})	±25 mA
DC V_{CC} or GND Current, per pin (I_{CC})	±50 mA
Storage Temperature Range (T_{STG})	−65°C to +150°C
Power Dissipation (P_D)	
(Note 3)	600 mW
S.O. Package only	500 mW
Lead Temperature (T_L)	
(Soldering 10 seconds)	260°C

We are going to need 700 mA to drive the High-powered LED, so if each pin supply 25mA, we are going to need 28 inverters equal to seven packages. So the design is seven hex inverters in parallel like the figure.

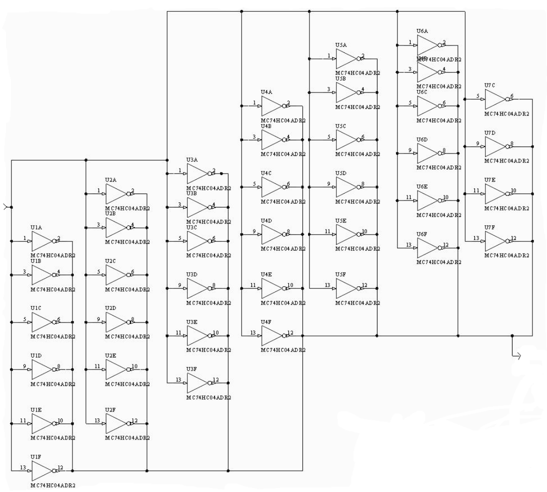


Figure 4.7 Receiver Driver Schematic

4.1.4 Lens

The lenses are for our system like antennas for microwaves, the gain dependent on LED geometry and size. The main problem is again the transmitter emplacement, we can include big lens in the transmitter because it is located in the underwater robot.

If the transmitter broadcast angle and the receiver FOV are both narrow, the SNR of the received pulse is higher but the pointing accuracy of transmitter and receiver is critical. If, however, the transmitter broadcast angle and/or the receiver FOV is wide, pointing is less critical; SNR is lower with the transmitted photons spread out into a wider angle and some covertness could be lost. However, this is probably not an issue with these short communications.

For this reason, we improve the effectiveness of the optical system with a Fraen acrylic concentrator on the LED to create a cone of light with an internal angle of 30 degrees. This increases distance ate the expense of transmission angle. The reduction in the transmission angle can be solved including more photodiodes or developing a lens system in the receiver.

The lens use to the final design is FHS-HMB1-LL01-z.

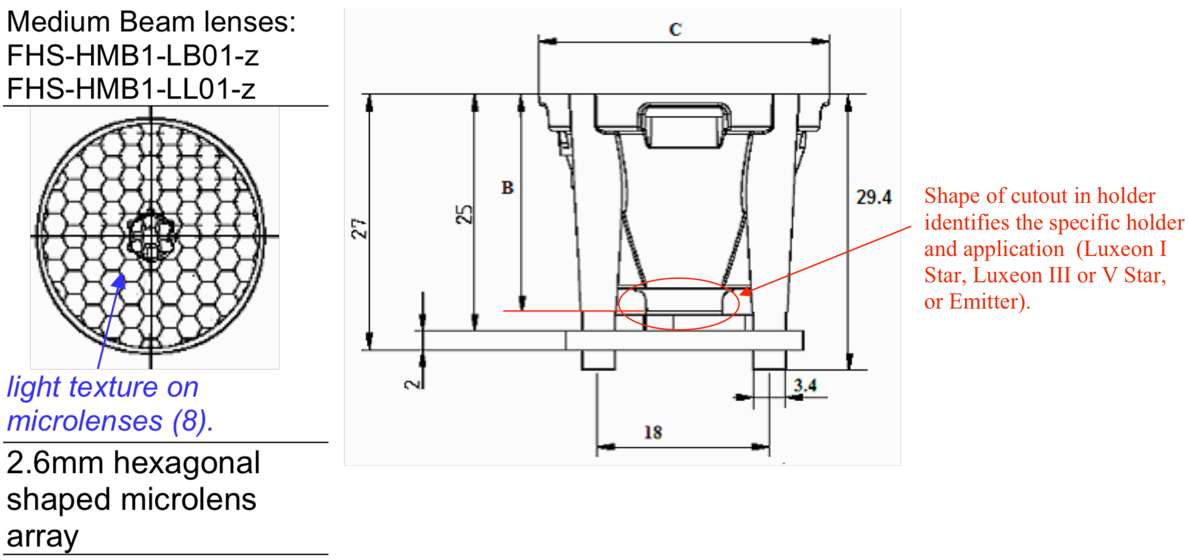


Figure 4.8 FHS-HMB1-LL01-z scheme

So after apply the lens we are going to obtain a signal with a luminous

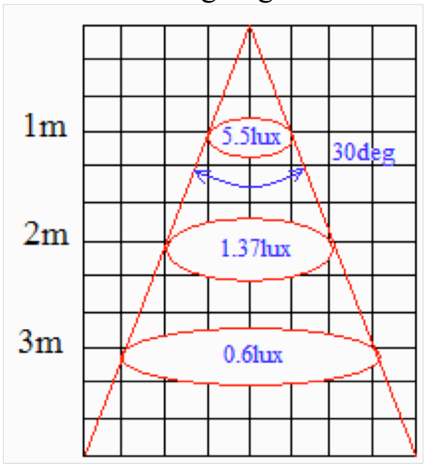


Figure 4.9 Luminous characteristic lens

4.2 Receiver

The receiver detects the light via the photo detector. The low current signal triggers a dual gate transistor (NTE415), which takes the current from the 12 V rail and transmits it to the NE592 video amplifier. The NE592 cleans the incoming rounded signal to a square wave. Pin 8 of the NE592 is the other part of the differential output and carries the data stream through a pre-amp circuit consisting of a pair of common emitter connected transistor. The signal is then sent to a 4th Butterworth low pass filter (LT1568IGN) and a high frequency amplifier.

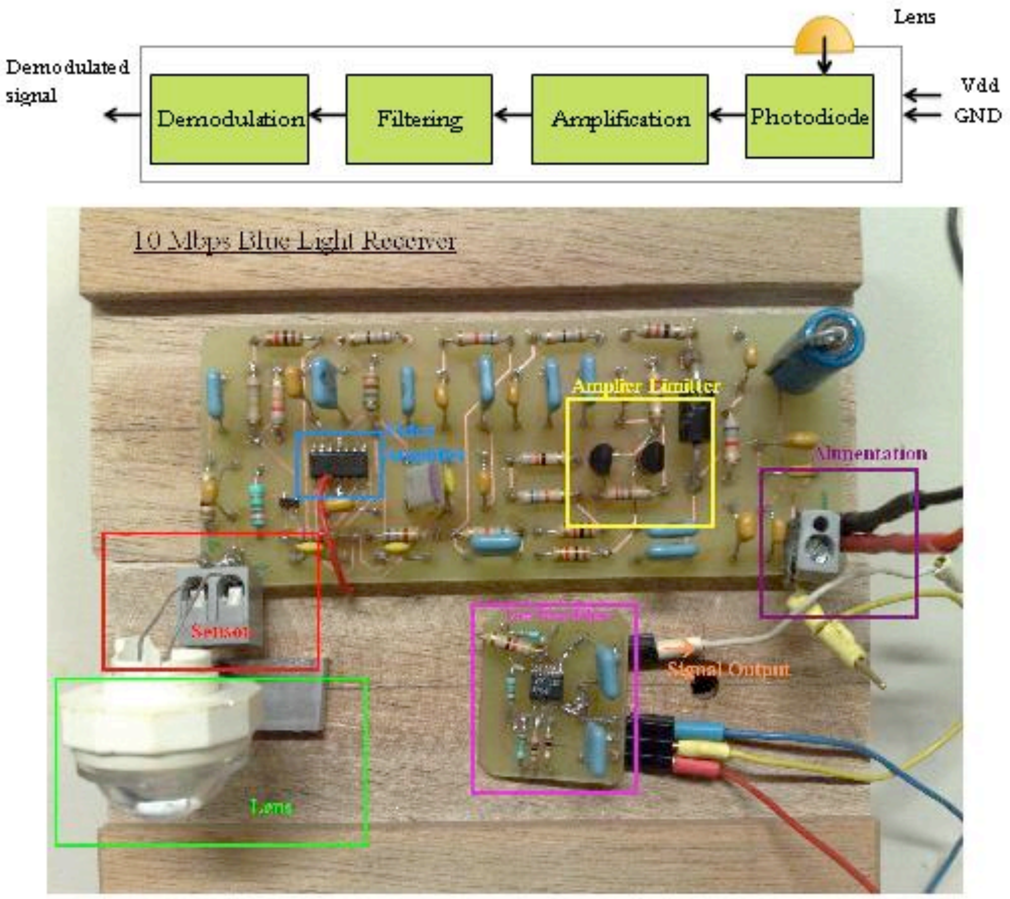


Figure 4.1 Receiver Block Diagram (Up)-Receiver final design (down)

4.2.1 Photodiode

We tested several different photo diodes PDB-C158, BPW21 and SLD-70BG2, and got the best results with the diode SLD-70BG2, which has a good trade off between speed and sensitivity.

The planar photodiode is designed to operate in either photoconductive or photovoltaic modes. This diode incorporates a BG filter that rejects infrared wavelengths and approximates the response of the human eye. High sensitivity and low dark current allow use in low irradiance applications. The photodiode measures 3.6 mm X 3.6 mm (0.140” X 0.140”) and is supplied on a ceramic base with a clear epoxy dome package.

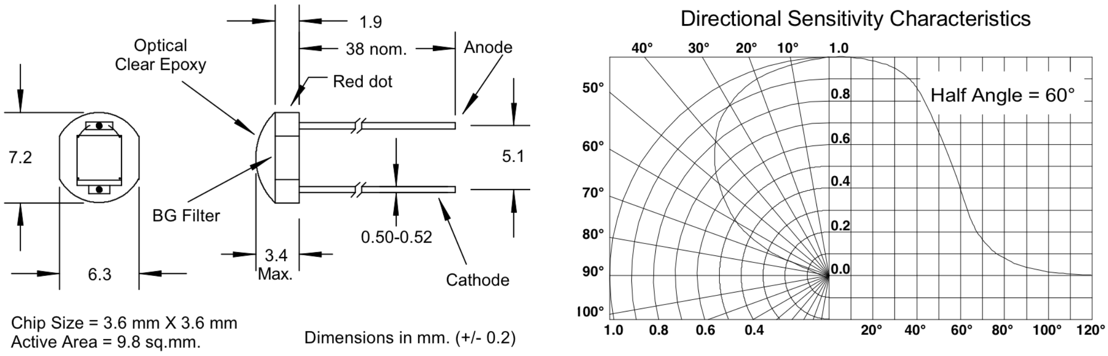


Figure 4.11 Photodiode dimensions & sensitivity

The electrical characteristics of the photodiode

Electrical Characteristics (T_A=25°C unless otherwise noted)

Symbol	Parameter	Min	Typ	Max	Units	Test Conditions
I_{SC}	Short Circuit Current	40	55		µA	V_R=0V, Ee=25mW/cm^2 (2)
V_{OC}	Open Circuit Voltage		0.40		V	Ee=25mw/cm^2 (2)
I_D	Reverse Dark Current:					
	SLD-70BG2A			100	nA	V_R=100mV, Ee=0
	SLD-70BG2B			100	nA	V_R=5V, Ee=0
	SLD-70BG2C			20	nA	V_R=5V, Ee=0
	SLD-70BG2D			5	nA	V_R=5V, Ee=0
	SLD-70BG2E			1	nA	V_R=5V, Ee=0
C_J	Junction Capacitance		180		pF	V_R=0V, Ee=0, f=1MHz
t_R	Rise Time		4		µs	V_R=5V, R_L=1kΩ (3)
t_F	Fall Time		6		µs	V_R=5V, R_L=1kΩ (3)
TC_I	Temp. Coef., I_{SC}		+0.2		%/°C	(2)
V_{BR}	Reverse Breakdown Voltage	50			V	I_R=100µA
λ_P	Maximum Sensitivity Wavelength		550		nm	
λ_R	Sensitivity Spectral Range	400		700	nm	
$\theta_{1/2}$	Acceptance Half Angle		60		deg	(off center-line)

Specifications subject to change without notice. 103184 REV 0

Table 4.5 Electrical characteristics photodiode

In the final design, we will implement a design with five photodiodes to increase the reception area, like in the figure 4.12.

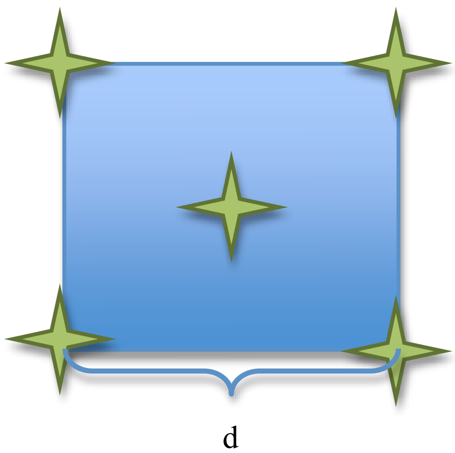


Figure 4.12 Photodiode location system

The final value of the parameter “d” will depend in the maximum angular coverage of the emitter and it could be useful in a future application to control the position of the surface platform

4.2.2 Signal treatment

The low current signal triggers a dual gate transistor (NTE415), which takes the current from the 12 V rail and transmits it to the NE592 video amplifier.

The NE592 cleans the incoming rounded signal to a square wave. Pin 8 of the NE592 is the other part of the differential output and carries the data stream through a pre-amp circuit consisting of a pair of common emitter connected transistor.

The signal is then sent to a 4^{th} Butterworth low pass filter (LT1568IGN). The LT®1568 is an easy-to-use, active-RC filter building block with rail-to-rail inputs and outputs. The internal capacitors of the IC and the GBW product of the internal low noise op amps are trimmed such that consistent and repeatable filter responses can be achieved. With a single resistor value, the LT1568 provides a pair of matched 2-pole Butterworth lowpass filters with unity gain suitable for I/Q channels.

By using unequal-valued external resistors, the two 2-pole sections can create different frequency responses or gains. In addition, the two stages may be cascaded to create a single 4-pole filter with a programmable response. Capable of cutoff frequencies up to 10MHz, the LT1568 is ideal for antialiasing or channel filtering in high-speed data communications systems.

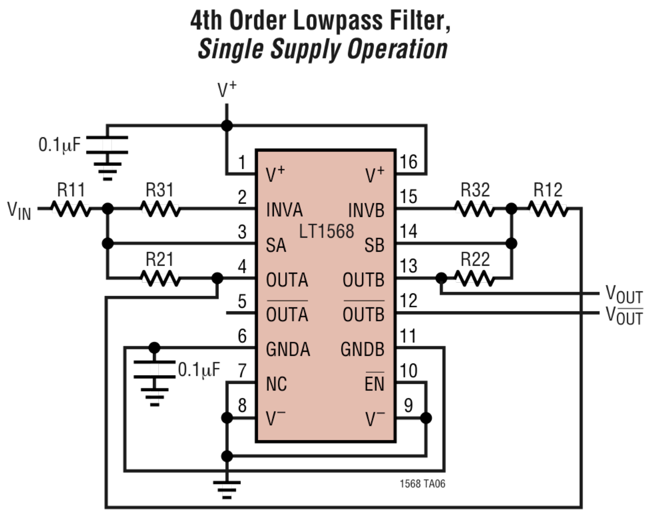


Table 4. Resistor Values in Ohms, 4th Order Lowpass Butterworth, Gain = 1

f_{CUTOFF} (MHz)	R11, R21	R31	R12, R22	R32
1	1.05k	1.58k	1.82k	887Ω
2	523Ω	787Ω	909Ω	432Ω
3	348Ω	523Ω	590Ω	294Ω
4	255Ω	383Ω	432Ω	215Ω
5	205Ω	309Ω	348Ω	174Ω
6	169Ω	255Ω	280Ω	143Ω
7	143Ω	221Ω	232Ω	124Ω
8	124Ω	196Ω	196Ω	107Ω
9	107Ω	174Ω	169Ω	97.6Ω
10	97.6Ω	158Ω	143Ω	88.7Ω

Figure 4.13 4^{th} Order Lowpass Filter Butterworth

After the filtering, it could be possible realize an amplification. In our case, we don’t know the power restrictions in the surface platform, we decided don’t realize this stage because the high frequency amplifier requires more power than the other receiver’s part.

4.2.3 Demodulation

The easiest way to demodulate the signal is to use a microcontroller. Due to time restrictions and since demodulation can easily be a part of the future work concerning the software of our communication, it is not implemented in this current work.

4.2.4 Lens

Plano-Convex (PCX) Lenses have a positive focal length making them ideal for collecting and focusing light in imaging applications. They are also useful in a variety of applications involving emitter, detectors, lasers and fiber optics.

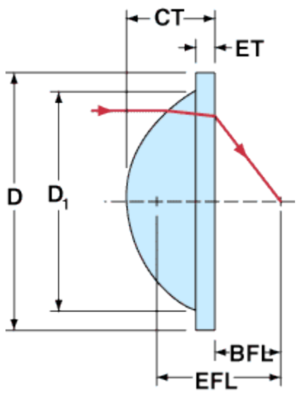


Figure 4.15 Plano Convex Lenses

Available in a wide variety of diameters and focal lengths, our election was diameter equal to 1 mm and Center Thickness (CT) equal 0.5 mm. We are going to use one for each photodiode.

This election is the most important in the final results, because the final signal reception is completely depended on the lens system. For this reason we decided use a standard one to analyze the results and include the improvement of this system in the future work, because the main point of this project was the physical electrical layer and improve this point is studying the results for different diameters.

Chapter 5

Experimental data

Six experiments were carried out to measure the maximum range and coverage of the optical digital link in air and underwater. The range is defined as the maximum distance between transmitter (LED) and receiver (photodiode). Furthermore, experiments were carried out to investigate how transfer rate and duty cycle behave at distances greater than the range of the link. The experiment setup and the individual results are outlined in the following sections.

5.1 Hardware setup

In order to avoid any unwanted interference, sender and receiver were physically separated and the used wires were short as possible.

For transmission, a high frequency pulse generator was connected to the optical transmitter, which generate a byte stream. The transmitter was powered by a laboratory power supply. The receiver circuit was powered by a laboratory power supply too, and connected to an oscilloscope, which analyzed the received stream.

The closest distance between emitter and receiver unit was between the LED and the photo diode. The receiver system was fixed and to measure the range, only the LED was moved.

For the experiments in air, the LED and the photo diode were aligned horizontally, and positioned on a table with a possible reflecting surface, but it was the best possibility. The experiments was carried out in normal indoor lighting conditions, mainly fluorescent tubes.

For the underwater experiments, we had an important limitation, we haven't a platform to submerge the system underwater. For this reason, the experiment was carried out in a rectangular pool with white wall, which 0.01 meters deep, 0.60 meter width, 1.10 meters length and thickness 5 mm in each wall as figure 5.1 shows.

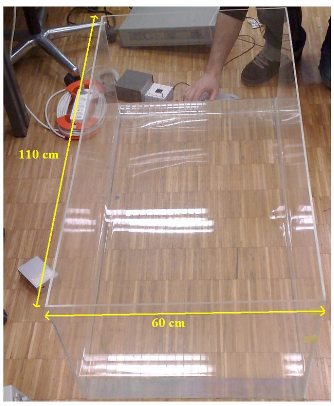


Figure 5.2 Emitter coverage in air.

The receiver and emitter were out of water, in the walls surface to decrease effects of the reflecting. We realize the experiments with clear water with no visible pollution. With these conditions, we can do only two distances experiments, with 0,6 meter and 1,1 meter. The experiment was realized with the same environmental light with the experiments in air.

5.2 Air results

The range in this context means the maximum distance between transmitter and receiver, which still allows error-free transmission of data. For these experiments we use a (460 nm) blue emitter, with a forward voltage of 3.7V and a current of 600mA. The region of interest for the behaviour of transfer rate and error range is from 40 cm and 200 cm.

The first experiment is focused to find the most adequate rate, for this we measure the received signal depending the emitting frequency. Figure 5.1 shows the results.

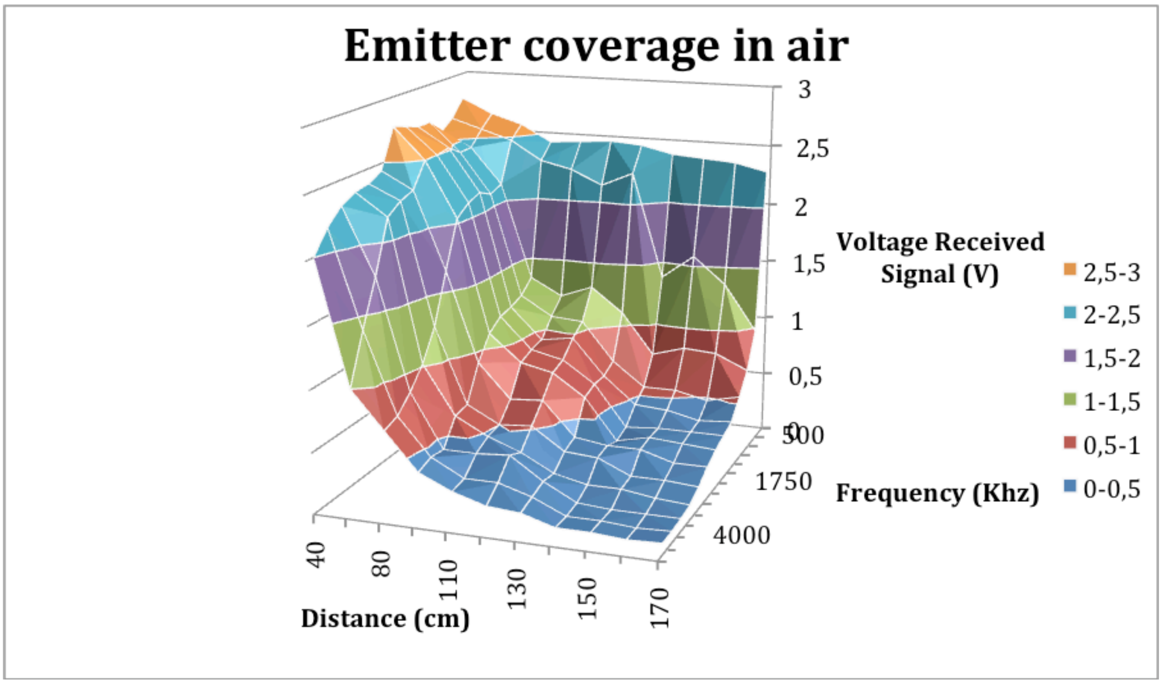


Figure 5.2 Emitter coverage in air.

As expected, the range decreases with the frequency. The final election of the frequency will depend of different factors; one of them is the type of modulation. The modulation efficiency will influence in the decision between rate and range of application. If we use a type of modulation like Manchester modulation, we will emitting in a half of the frequency really, it's for this reason we will be more interested in this case in develop the rate before than the range. In other case, if we implement a communication protocol, we can dispose around the maximum efficiency in communication. This is going to focus the system development in other way.

For the maximum analyzed rate (2Ghz), we decided to study the duty cycle influence depending of the distance between emitter and receiver. Figure 5.2 shows the results.

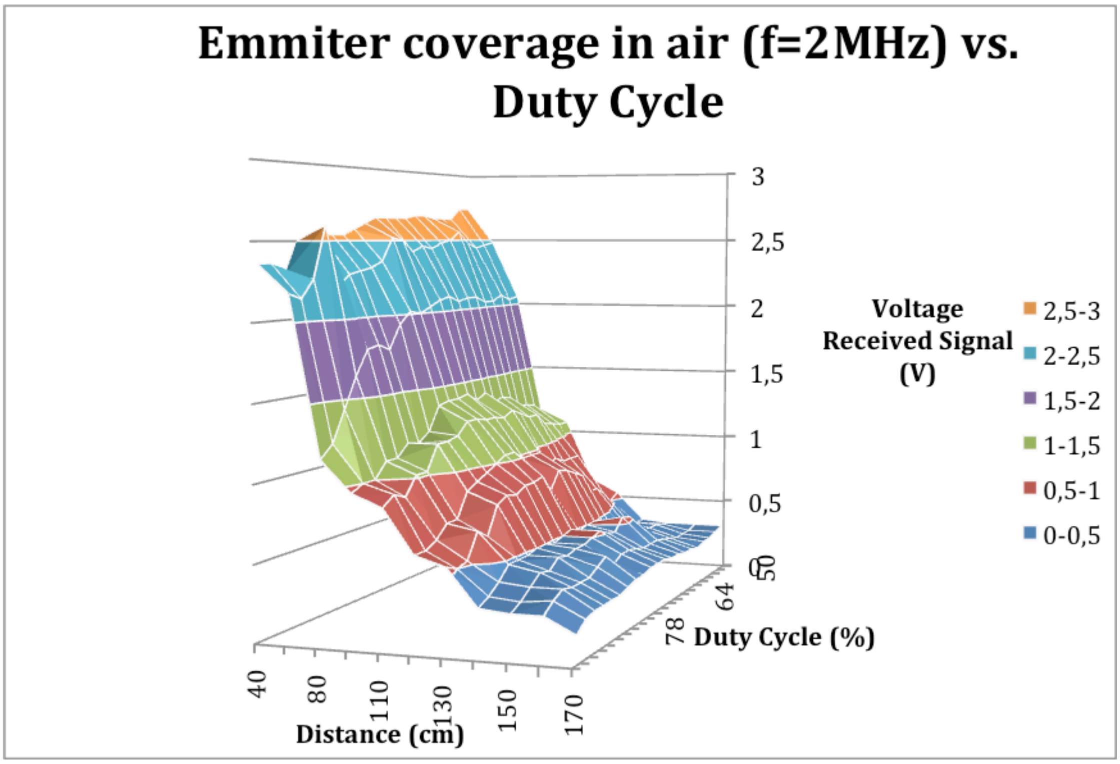


Figure 5.3 Emitter coverage in air (f=2MHz) vs. Duty Cycle

The analyze of Duty Cycle influence is focused to find the better transmission with the minimal power consumption in the emitter, what it's mean, with more duty cycle we have better results due to we are emitting a signal with more 1 than 0, more light in any case. The high power rating permits it to be used in a low duty cycle mode, allowing an intense pulse of light generated for a short period of time, but in our case we have a big power restriction in the receiver that prohibit this case. The problem to include high duty cycle is the power consumption in the transmitter, less than high power rating but enough to be considered.

The results in our experiment show that we have an optimal value around 70-80, more pronounced in longer distances.

5.3 Underwater results

The problems that we have limit the truthfulness of these experiments, but the final results are logic because all the experiments were realized in the same situation, so we can take conclusion of them.

The same experiments as described before were conducted in water, but only in the two distances that we dispose. The first experiment is focused to find the most adequate rate, for this we measure the received signal depending the emitting frequency. Figure 5.4 shows the results.

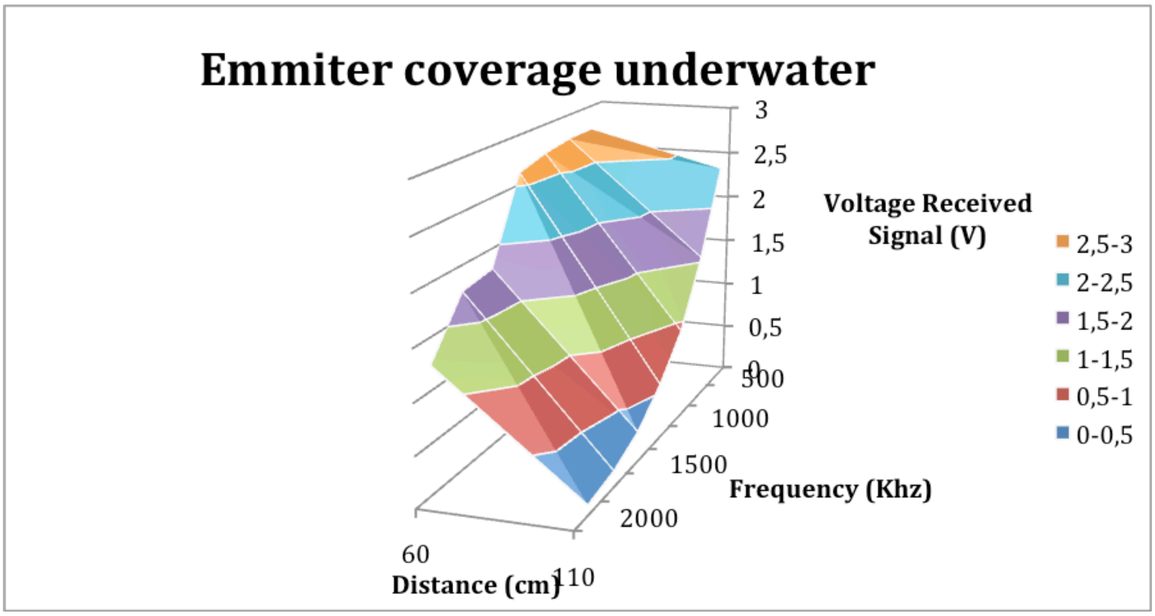


Figure 5.4 Emitter coverage underwater

To our surprise, the received signal increased, even though there should be absorption and coupling losses in water, and losses in the wall. The increased intensity at the receiver can be explained in the reflexion by the bright pool walls. We also expect less high frequency noise disturbing the receiver in the outdoor environment, because underwater the attenuation in high for this range.

The important result is that clear water attenuation in fresh water does not have a big impact on the range of optical communication in a short range.

For 1 MHz and 2MHz, we decided to study the duty cycle influence depending of the distance between emitter and receiver. Figures 5.5 and 5.6 shows the results.

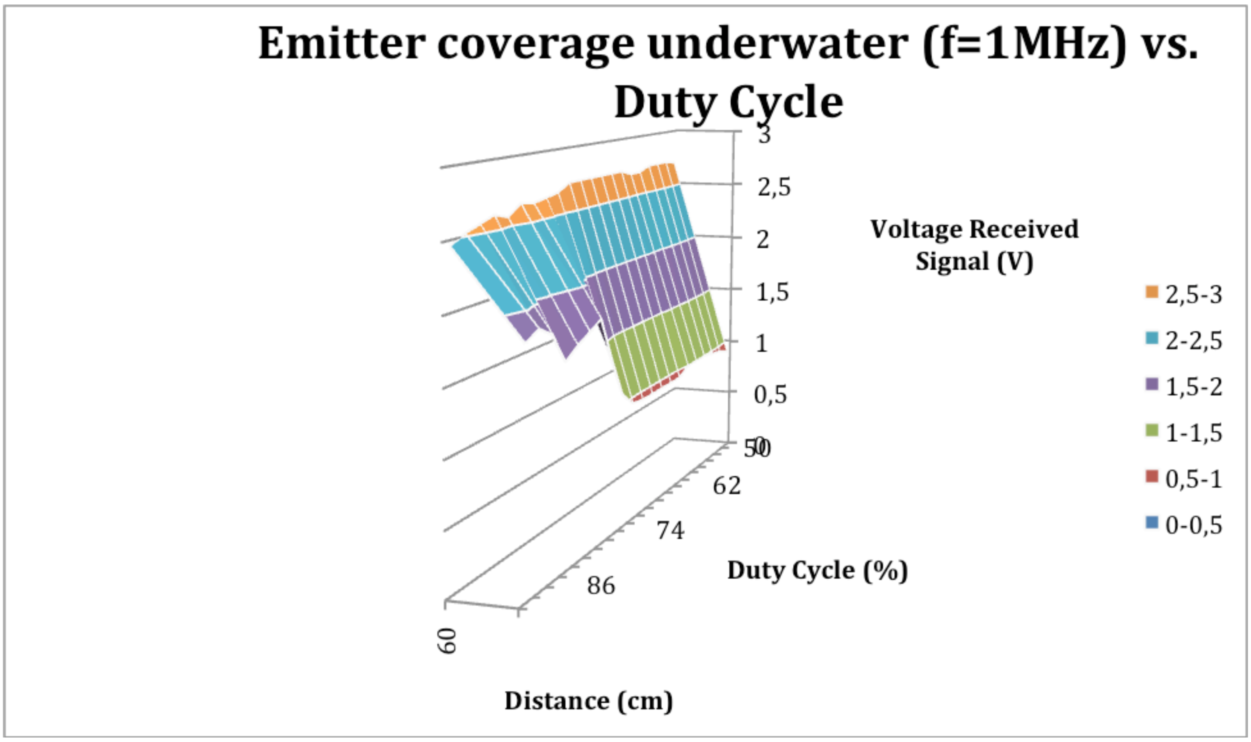


Figure 5.5 Emitter coverage underwater (f=1MHz) vs. Duty Cycle

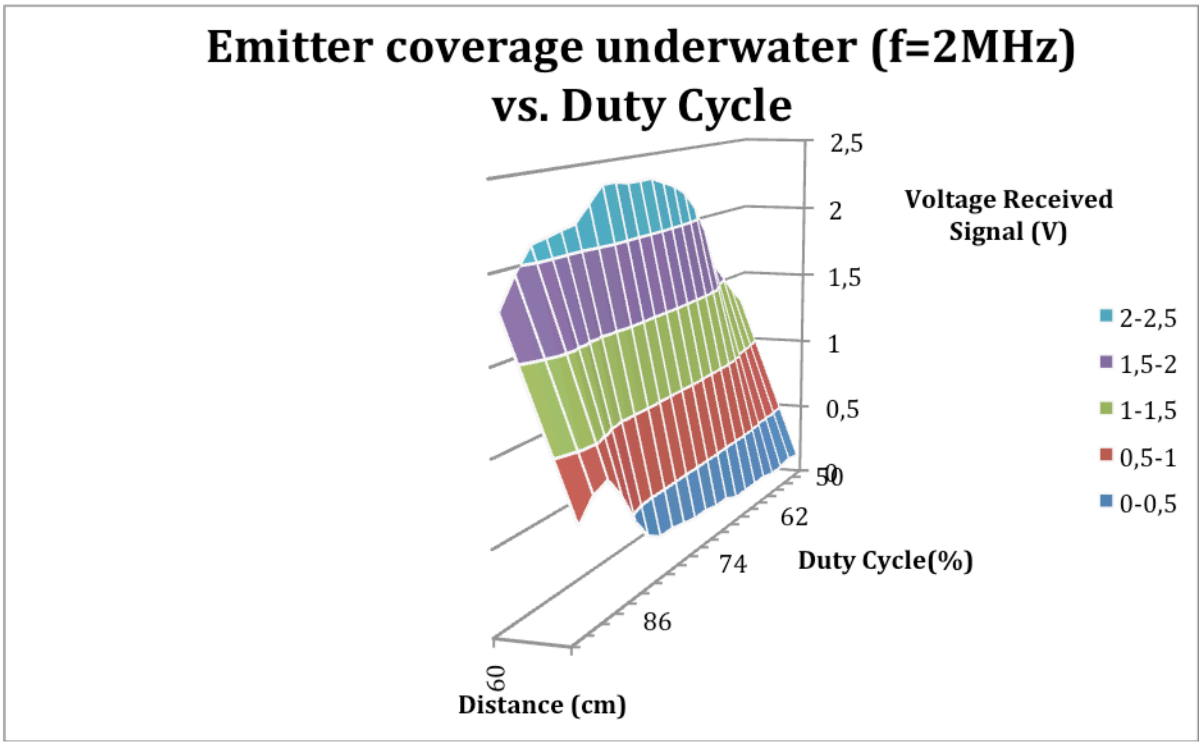


Figure 5.6 Emitter coverage underwater (f=2MHz) vs. Duty Cycle

The results in our experiment show that we have an optimal value around 68% in 60 cm communication and 86% in 110 cm communication. We can observe how it's more pronounced in longer distances the duty cycle influence in underwater too.

The last experiment realized, was study the perpendicular coverage of the emitter what it means more or less the angular range. We propose change the distance "d" of the figure 5.8, and analyze the received signal.

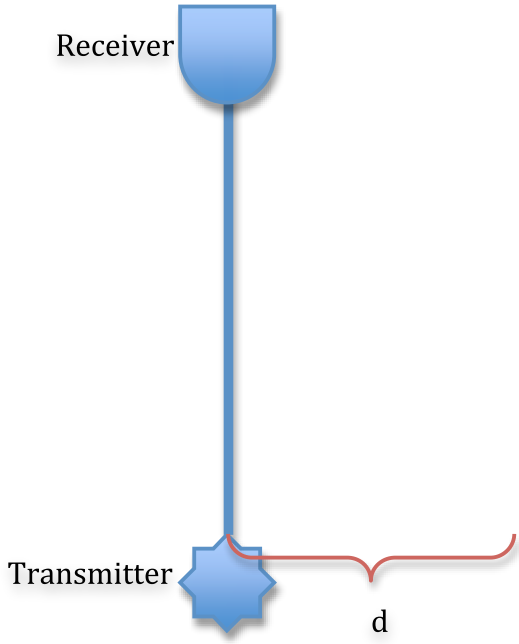


Figure 5.7 Experiment situation

The figures 5.8 and 5.9 show the results.

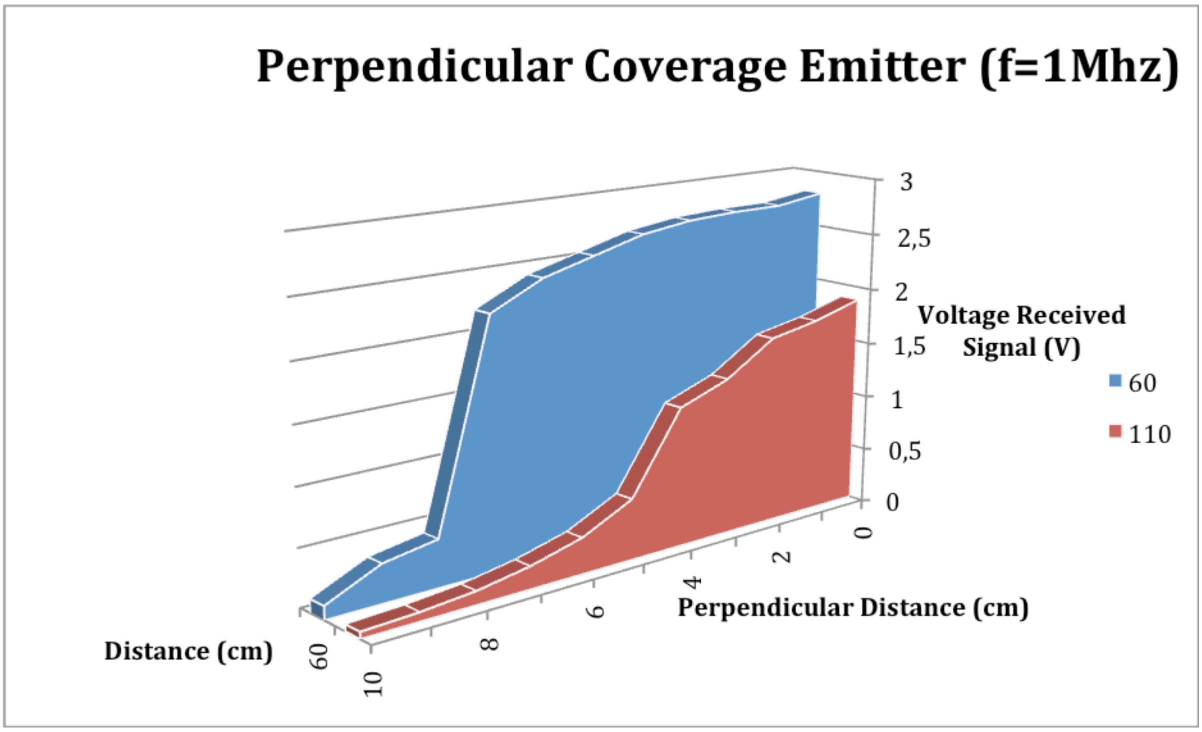


Figure 5.7 Perpendicular Coverage Emitter underwater (f=1Mhz)

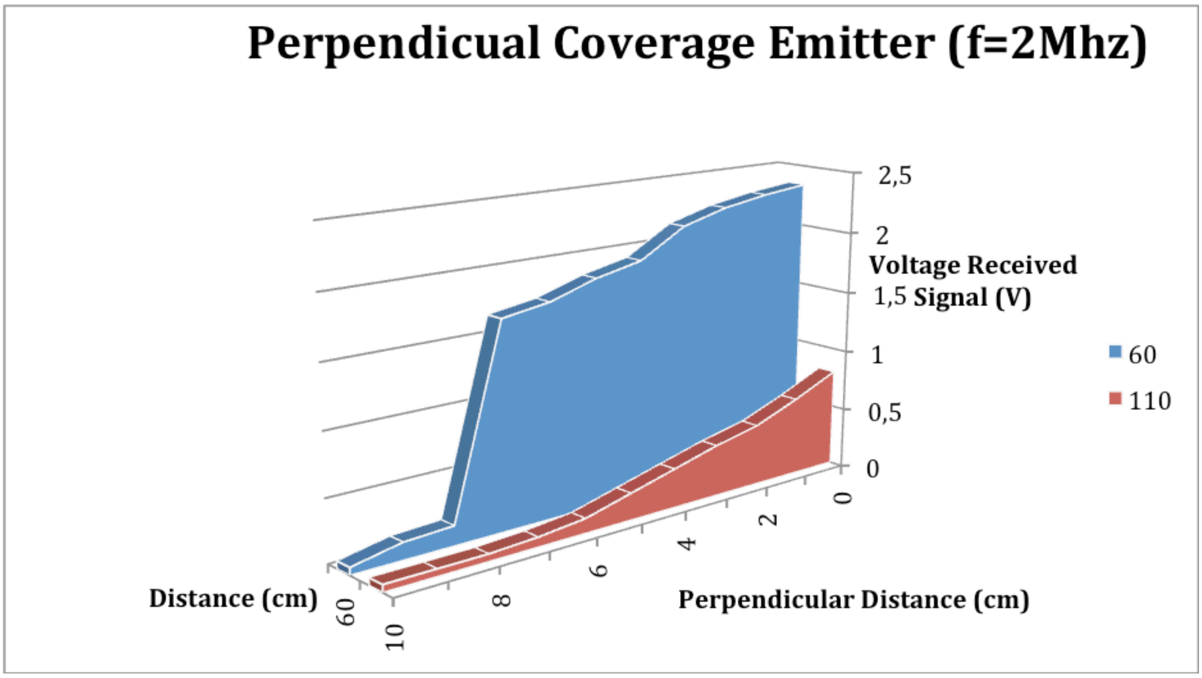


Figure 5.8 Perpendicular Coverage Emitter underwater(f=2Mhz)

As expected, the lens election is fundamental, because we lose the signal radically when the receiver is out of emitter range. It could be possible amplified the emitter range to 60º, but it suppose less signal in the received. We can't increase the power alimentation in the emitter, so the development must be centre in the receiver lens study and develop a system like we propose before in the Figure 4.14

Chapter 6

Conclusion

The presented optical communication system is suitable for underwater applications, since high frequency radio wave is highly absorbed in water, and acoustic communication systems are relatively low bandwidth. We can do a classification of the optical communication systems present in the bibliography in two groups. The first one present a limitation in size but normally the power supply isn't a handicap, for this reason it's possible implement the communication with a high-power LED. The second group present a limitation in power supply and limit the transmitted rate around 500 kHz and the range in less than one metre. Our main problem is that we cannot include our system in any of these groups, we have an important size limitation because our emitter is located in a small robot and we can't increase the range include big lens as it's usual to do. In the other way, we have a power limitation because the power supply must be inside the robot, and we can't include a 1A power supply. For these reasons our project is inside of a new optical communication field. With this situation, our system presents several limitations due to lack of study in this field and lack of time, but the main point is that we can say that according with the results, this communication is possible to be implemented, increasing the study of some points.

The experiments have shown that the range is not decreased while working in underwater, for the blue wavelength, and high power LED emitters can be used for high-speed optical communication with an appropriate lens.

The wide angular coverage, 30º because it's the used lens in the transmitter, doesn't allow more than 10 cm range around the perpendicular point of movement. So, to allow omnidirectional coverage it's necessary to include an improved lens system in the receiver and a system with several photo diodes to increase the detection range.

The power consumption of 3W in the transmitter is the maximum limit to include in the final emplacement, the robot. So for this reason, it's necessary an analysis about how was possible to increase the power consumption. Once the lens study was finished, it could be necessary to realize this analysis, because finally we must include a small battery and it could be a problem.

The results depending of the rate show that depending the final system necessities, we will define the adequate one. The experiments show that the system has a good response in the range between 500 kHz and 1.50 MHz, could be increase to 2 MHz if the lens system was more efficient. So here we have the most important conclusion, the main point to increase the full system must be realize a complete analysis about the lens system.

According with the initial project requirements, we have completed the electronic hardware fabrication, which means, design and build a full underwater communication system. There are two points from the initial requirements that aren't completed, the fabrication of an underwater platform to realize the underwater experiments and an analysis to determine the most efficient lenses system. We propose these points in the future work.

Chapter 7

Future work

According to the limitation showed in the conclusion, the complete analysis to find the most efficient lens system in the transmitter and the receiver is obligatory to improve the system. This was the first point in the future work, once we know the results and we have chosen the most efficience lens, the prototype used for experiments will be redesigned, to achieve smaller PCB dimensions, and to enable implementation on submersible. Several receivers will be used, to achieve omnidirectional and in the future could be a system to control the surface platform.

Once an optimal communication is build, we can improve other fields like the signal treatment in the receiver. Include a high frequency amplification after the filter, once we know the power specifications in the receiver, will be interesting to increase the signal. Other improvement could be increasing the receiver sensibility doing an impedance study in the receiver circuit.

Other important point in the future work is the optical coupling of the emitter and photoreceptors to the water, because is an open field. Especially if the wide opening angles and uniform emission footprints are required, coupling lenses have to be carefully designed, to avoid losses due to reflection, refraction, or occlusion. In other point, the radio interferences will be solved including a Faraday box in the receiver and emitter if it was necessary.

For the final system characterization, realize a full underwater characterization after these improvements will be necessary, including calculate the underwater communication parameters described in the chapter 2.

Finally, out of our project, it could be interesting to include the modulation and demodulation software, using a microcontroller. But this point is out of our project, because we are interested in the physical layer.

Chapter 8

Bibliography

[1] Smart, J.H., "*Underwater Optical Communications Systems Part1: Variability of Water Optical Parameters*," MILCOM 2005, 2005.

[2] Giles J.W. and Bankman I.N. "*Underwater Optical Communications Systems Part2: Basic Design Considerations,"* MILCOM 2005, 2005.

[3] Schill F., Zimmer R. Uwe and Trumpf J. *"Visible Spectrum Optical Communication and Distance Sensing for Underwater Applications"* National ICT Austraila Ltd., Locked Bag 8001, Camberra ACT 2601, Australia.

[4] Jones J.C., Di Meglio A., Aid N., Sanchez A. and Wang L.S., *"The Use of Digital Signal Processors in Underwater Communication Systems".* SimoCo International, Cambridge, UK.

[5] Chancey M.A. *"Short Range Under Water Optical Communication Links"*

[6] Yoon S. and Qiao Ch. *"Cooperative Search and Survey using Autonomous Underwater Vehicles (AUVs)"*

[7] Joe J. and Toh S.H. *"Digital Underwater Communication Using Electric Current Method"* Singapore.

[8] Vasilescu I., Kotay K. and Rus D. *"Data Collection, Storage, and Retrieval with an Underwater Sensor Network"*

[9] Kazovsky L.G, Mavweater D.T, and Sadot D. "*Combined optical modulation formats and their applications"* Laser and Electro-Optics Society Annual Meeting, 1995. 8th Annual Meeting Conference Proceedings, Volume 1.

[10] Winzer P.J and Essiambre R.J. *"Advanced Optical Modulation Formats"* Proceeding of the IEEE Volume 94, Issue 5, May 2006 Page(s): 952-985.

[11] www.ronja.com

[12] Bong Kyu Kim, Heuk Park, Hwan Seok Chung, Sun Hyok Chang, Kwang Joo Kim, Sung Wong Park, Bin Yeong Yoon and Bong Tae Kim. *"Manchester Coding based Re-modulation Scheme for Optical Acces Network"* BcN Department, ETR,161, Gajeong-dong, Uuseong-gu, Daejeon 305-700, Korea.

[13] Farr N.,Chave A.D,Freitag L., Preisig J., White S.N., Yoerger D. and Sonnichsen F. *"Optical Modem Technology for Seafloor Observatories"* Woods Hole Oceanographic.

[14] Cochenour B., Mullen L. and Laux A. "*Phase Coherent Digital Communiactions for Wireless Optical Links in Turbid Underwater Environments*" Naval Air Systems Command. Patuxent River, MD 20634.

[15] Shaw A., Al-Shamma'a A.I., Wylle S.R and Toal D. "*Experimental Investigations of Electromagnetic Wave Propagation in Seawater*" Liverpool John Moores University, General Engineering Research Institute, Byrom Street, Liverpool L3 and University of Limerick, Dept. of Electronics and Computer Engineering, Limerick, Ireland.

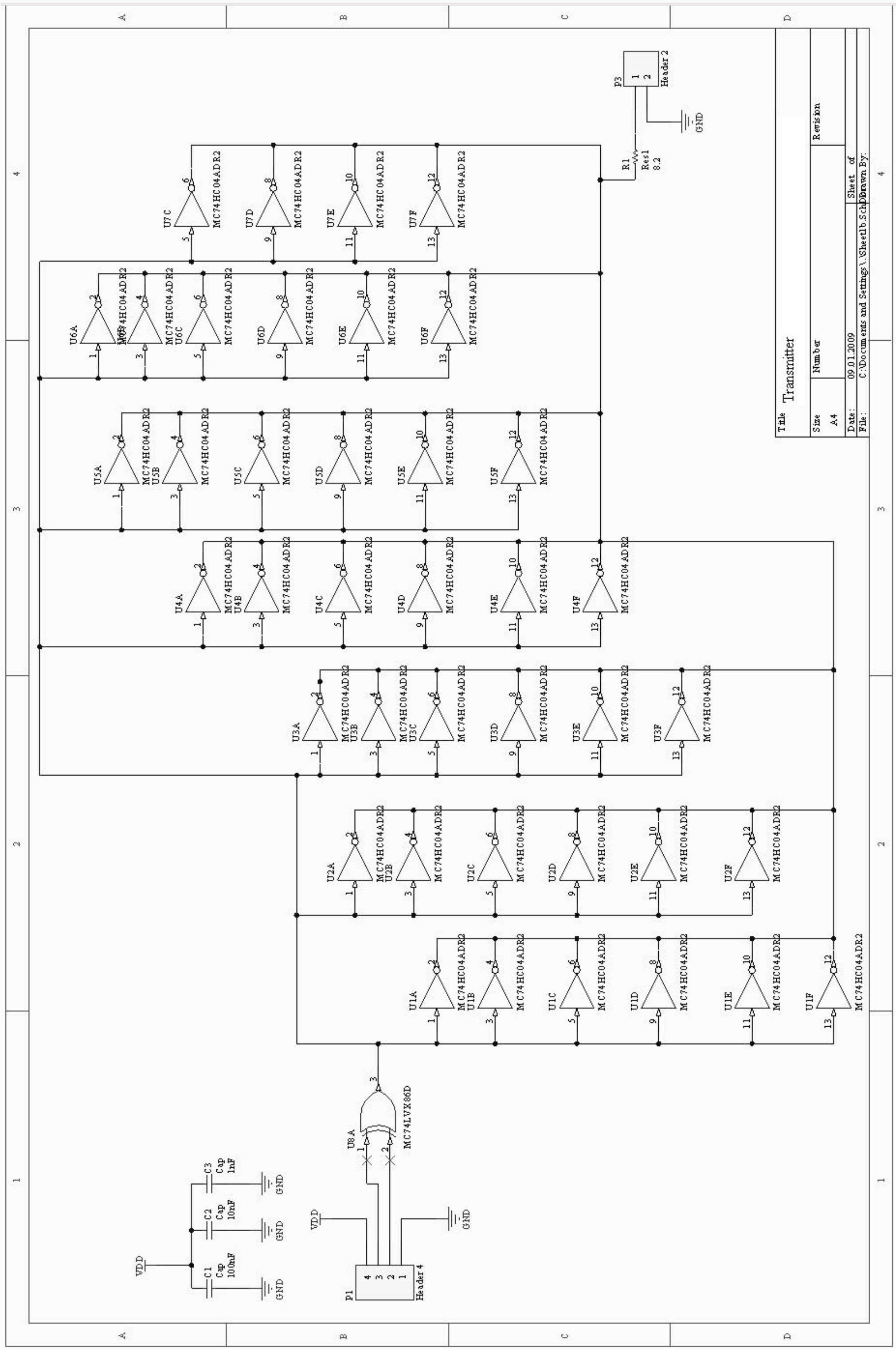
[16] Nasri N., Ben Hnia H., Kachouri A., Abdellaoui M. and Samet M. "*Modulation/Demodulation Techniques With FPGA's Architecture to improve OFDM Wireless Underwater Communication Transceiver*" LETI-ENIS R.Soukra-BP 3038. SFAX-TUNISIA and LETI-ENIS, ISECS-R. Menzel chaker Km 0.5 B.P.868.3018 SFAX-TUNISIA

[17] Luleds. Luxeon III Emitter, Technical Datasheet DS45, 2004

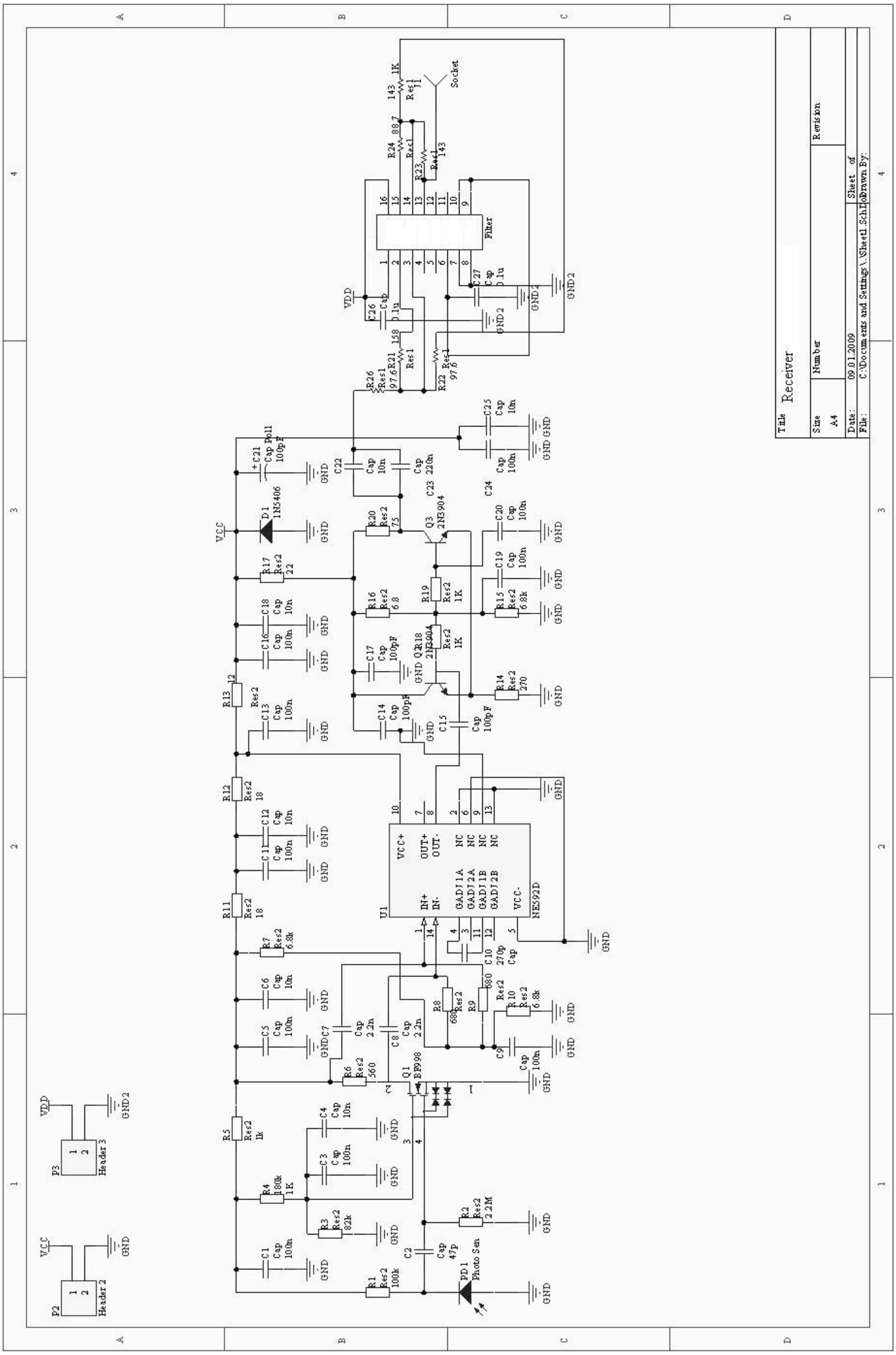
Appendix A

Circuit Diagrams

Transmitter



Receiver


Receiver
Title
Size
A4
Number
Revision
Date: 09.01.2009
Sheet of
Drawn By:
NE592D
Filter
Socket
BF998
2N3904
1N5406
Photo Sen
Header 2
Header 3
VCC
VDD
GND
GND2

Appendix B

Part List

Transmitter

Device	Value	Package	Quantity
LXHL-PB09			1
MM74HC86		SOIC14	1
MM74HC04M		SOIC14	7
RESISTOR	8.2	250mW pref. metallic	1
CAPACITOR	1n	Ceramic 50V	1
CAPACITOR	10n	Ceramic 50V	1
CAPACITOR	100n	Ceramic 50V	1

Table B.1 Transmitter Part List

Receiver

Device	Value	Package	Quantity
LT1568IGN		SSOP16	1
2N3904			2
1N5408			1
BF908			1
BPW43			1
NE592		DIL14	1
POLARICED_CAPACITOR	100u/16V		1
CAPACITOR	47p	Ceramic 50V	1
CAPACITOR	270p	Ceramic 50V	1
CAPACITOR	1n	Ceramic 50V	1
CAPACITOR	2.2n	Ceramic 50V	3
CAPACITOR	10n	Ceramic 50V	7
CAPACITOR	100n	Ceramic 50V	10
CAPACITOR	47p	Ceramic 50V	1
RESISTOR	12	250mW pref.metallic	1
RESISTOR	18	250mW pref.metallic	2
RESISTOR	22	250mW pref.metallic	1
RESISTOR	75	250mW pref.metallic	1
RESISTOR	180	250mW pref.metallic	1
RESISTOR	220	250mW pref.metallic	1
RESISTOR	270	250mW pref.metallic	2
RESISTOR	330	250mW pref.metallic	1
RESISTOR	390	250mW pref.metallic	1
RESISTOR	470	250mW pref.metallic	1

RESISTOR	560	250mW pref.metallic	2
RESISTOR	680	250mW pref.metallic	3
RESISTOR	820	250mW pref.metallic	1
RESISTOR	1k	250mW pref.metallic	4
RESISTOR	1.2k	250mW pref.metallic	1
RESISTOR	1.5k	250mW pref.metallic	1
RESISTOR	1.8k	250mW pref.metallic	1
RESISTOR	6.8k	250mW pref.metallic	4
RESISTOR	82k	250mW pref.metallic	2
RESISTOR	100k	250mW pref.metallic	3
RESISTOR	120k	250mW pref.metallic	1
RESISTOR	180k	250mW pref.metallic	1

Table B.3 Receiver Part List