VHDL Modules and Circuits for Underwater Optical Wireless Communication Systems

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Abstract: Underwater wireless optical communication has been used for establish a link between mobile vehicles and/or fixed nodes because light, especially in the blue/green region, allows to achieve higher data-rate than acoustical or electromagnetic waves for moderate distances. The here proposed work has the aim to pave the way for diffuse optical communication allowing to support optical communication in an Underwater Wireless Sensor Network of dense-deployed fixed nodes for specific application, such as monitoring and surveillance, for shallow, coastal and inland water in the case of moderate/limited area. In particular, taking into account already developed protocols for optical wireless communication, the focus is on the hardware implementation of different flexible modules to support both point-to-point and directional communication targeting the use of these technologies in the field of Underwater Wireless Sensor Network and the integration with current terrestrial technologies for Wireless Sensor Network. After a careful analysis of benefits and problems related to optical transmission underwater, design considerations are proposed with the description of the implemented modules. The use of light impulse for communication is motivated by the possibility of targeting high data-rate, low-cost and small dimension components. This paper describes an overall vision of the system: a HDL implementation of flexible modules for the management of optical communication (based on IEEE 802.15.4 and IEEE 802.11 standard) which target the interface with current terrestrial technology for Wireless Sensor Networks; the design and implementation of circuits for underwater optical point-to-point and planar communication. The preliminary results and design consideration are reported considering also future possible developments.

Key–Words: Underwater Wireless Communication, Optical Communication, Physical (PHY) Layer, Medium Access Control (MAC) Layer, Wireless Sensor Networks

1 Introduction

The growing need for underwater systems applied to observation and monitoring has considerably stimulated the interest in advancing the technologies for underwater wireless communication applied both for point-to-point communication than to support Underwater Wireless Sensor Networks (UWSNs) [1] [2].

Current technologies are mainly based on the use of acoustic communication and makes use of Autonomous Underwater Vehicles (AUVs), UWSNs, submarines, ships, buoys, and divers. These equipments are mainly developed to have a large operative area and can achieve long distance communication (in the range of kilometers), but still suffer from some limitations: they are very expensive, very limited in terms of data-rates transmission and they have usually very large dimensions. Especially as regards the aspects related to networking, they are often subject to a wide range of problems due to acoustic communication, especially considering that the propagation of acoustic waves is not very fast in water (1500 m/s) [1]. The Wireless Sensor Network (WSN) paradigm, where miniaturized nodes cooperate to build a distributed network for sensing the environment, has greatly improved terrestrial technologies in the last few years but it is difficult to transfer most of the know-how developed for terrestrial devices to their underwater counterparts due to the particular characteristics of underwater world. In particular, wireless underwater communication still pose a wide range of problems [4]: the use of acoustic communication is the most common but it has low data-rate, high power consumption and problems related to low propagation speed.

The work presented in this paper explores the possibility of using optical communication in Underwater Wireless Sensor Networks (UWSNs) by designing flexible modules, devoted to manage optical communication, which target the integration of existing available terrestrial technologies for WSN with optical circuits specifically implemented to support the generation and reception of light impulses.

The use of the alternative solution of optical communication, despite reaching shorter distances because of attenuation and scattering, reduces the problem of low-speed diffusion and low data-rate of acoustical signals. Optical underwater communication has been investigated considering:

- the high data-rate, which can range from Mb/s to Gb/s, if laser is employed;
- the possibility of using relatively low-power components and circuits equipped with LEDs and photodiodes;
- the possibility of targeting relatively small dimensions and low costs for the communication system;

This paper is organized as follows: a brief overview of the main aspects of underwater optical communication and applications of an optical UWSN, a presentation of the current developed modules and circuits followed by conclusion and future developments.

2 Applications

Optical underwater communication is an effective alternative to current underwater technology especially in some particular environments such as, for instance, shallow, coastal and fresh inland waters where the use of this approach is useful to overcome all the shortcomings related to the use of acoustic communication and to allow a wide adoption of underwater monitoring systems [10][4]. In particular the possibility of transferring high amount of data in a limited amount of time reducing power consumption can support the use of cameras and thus the collection and transmission of short video and pictures for a reliable monitoring and surveillance supported by images (benthic animals, different picture plankton and fish species. etc...).

Small dimensions and low-cost components allow to establish a dense deployed networks performing an effective fine grained sampling in the area of interest. The use of limited dimension imaging sensors could be used to collect different pictures of plankton and fish species to compare the efficacy of remote monitoring against the usual approach, which is performed by bringing samples to the laboratory. It could be possible, for instance, to perform pollution monitoring and frequent data collection (water temperature, specific conductivity, pH, turbidity, and possibly oxygen concentration) and, by using a high-data rate optical link, periodically deliver data reducing the time devoted to transmission and network congestion. The possibility of providing a high-data optical wireless link, in fact, can support a more efficient environmental monitoring: an underwater device can be equipped with the needed sensors for measuring the fresh water environment, including water temperature, specific conductivity, pH, turbidity, and possibly oxygen concentration.

3 The State of the Art of Underwater Optical Communication

In this paragraph will be briefly investigated the state of art related to underwater wireless communication. In addition researches related to Free Space Optical (FSO) communication will be presented with a brief introduction to the most important current standards for optical communication which have been taken into account for the development of the optical modules described the next paragraph.

Currently the use of wireless communication is very common in a wide range of terrestrial devices. In particular, one of the most innovative application is related to Wireless Sensor Network (WSN), as well detailed in [12], where a large number of small nodes communicate and work together to perform a specific task.

Specific applications include habitat monitoring, object tracking, nuclear reactor control, fire detection, and traffic monitoring where a large number of wireless nodes is scattered in a region where it is meant to collect data.

The progress and new developments in WSNs paradigm was clearly addressed by the Smart Dust project [19], which explored whether an autonomous sensing, computing, and communication system can be packed into a cubic-millimeter mote (a small particle or speck) to form the basis of integrated, massively distributed sensor networks. This research led to new opportunities to observe and act on the world by using a large number of small sensing self-powered nodes, which gather information or detect special events and communicate in a wireless fashion.

Also in the underwater world the application of wireless communication can have an important role. Underwater wireless communication systems find applications in oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications. Moreover, unmanned or autonomous underwater vehicles (UUVs, AUVs), equipped with sensors, will enable the exploration of natural undersea resources and gathering of scientific data in collaborative monitoring missions number of sensors and vehicles that are deployed to perform collaborative monitoring tasks over a given area.

Transferring the paradigm of WSNs to Underwater Wireless Sensor Networks (UWSNs) is a challenge that can open great opportunities. In fact, at the moment, current underwater wireless sensor nodes, in comparison with the terrestrial ones, are still very expensive, power-consuming and their dimensions are not reduced as for terrestrial ones.

Even if acoustic communication is the technology more frequently used for these applications, as well detailed in the next Paragraph 3.1, it is still an open field of research. In addiction are also proposed systems based on electromagnetic communication or optical waves.

Figure 1: Terrestrial [23] vs. underwater [22] nodes

3.1 Underwater Acoustical Communication

Since for the characteristics of the underwater channel technologies based on Radio Frequencies cannot be employed, acoustic waves, which can propagate well in seawater and can reach far distances, are widely used in underwater communication. As discussed in the introduction, although there are many recently developed solutions for WSNs, the unique characteristics of the underwater acoustic communication channel, such as limited bandwidth capacity and variable delays, require very efficient and reliable new data communication protocols and UWSNs nodes are still an open field of research [4][1]. The main limitations due to acoustic communication, which will be described, can be summarized as follows:

- The available bandwidth is severely limited;
- The underwater channel is severely impaired, especially due to multi-path and fading;
- Propagation delay in underwater is five orders of magnitude higher than in radio frequency (RF) terrestrial channels, and extremely variable;
- High bit error rates and temporary losses of connectivity (shadow zones) can be experienced, due to the extreme characteristics of the underwater channel;

The problem of underwater acoustic communication is still investigated in order to improve performances and overcome the current limitations. Some of the most interesting researches are here illustrated.

In [39] a high bit rate acoustic Link for video transmission over an underwater channel is investigated. To achieve this objective two approaches are proposed: the use of efficient data compression algorithms and the use of high-level bandwidth efficient modulation methods. In this paper the aim is to support a communication up to 64 Kb/s in order to provide acoustic transmission capability needed for near real-time video. In this case the focus is on the use of high-level bandwidth-efficient modulation methods. An experimental system, based on discrete cosine transform, Huffman entropy coding for video compression and and variable rate M-ary QAM has been implemented. Phase coherent detection is accomplished by decision-directed synchronization and adaptive equalization. System performance is demonstrated experimentally, using 25000 symbols/sec at a carrier frequency of 75 kHz over a short vertical path. The results were obtained using modulation methods of 16, 32 and 64-QAM, thus achieving bit rates as high as 150 kbps, which are proposed as sufficient for real-time transmission of compressed video.
In [42] a preliminary study for a Low Power Acoustic Modem for dense underwater sensor networks is proposed. This work is interested in bringing the benefits of terrestrial sensor networks underwater to the underwater world targeting: an efficient wireless communication, dense deployments (each sensor may have eight or more neighbors), self-configuration and local processing, and maximizing the utility of any energy consumed.

The datalink and PHY layers, written entirely in Java, use frequency-division multiple access (FDMA) with binary and 4-FSK (frequency shift keying) in any frequency band supported by the computers sound card and can run at any bit rate supplied by the user. Besides being able to adapt to channel conditions, this software modem offers the advantage of being far less costly than current hardware devices, such as the Benthos 013424 LF (9-14 kHz) omni-directional modem at $\$8800/pair$ as of April 2009, and of being easily configurable.

In [42] a Reconfigurable modem (rModem) is designed to simplify the experimental studies of new underwater acoustic sensor network algorithms on all layers with the possibility of cross layer optimization. rModem provides a unified simulation and rapid prototyping environment by exploiting Simulink tools.

Also network network topology has been widely investigate [1] because it is, in general, a crucial factor in determining the energy consumption, the capacity and the reliability of a network. The following scenarios in the field of Underwater Acoustical Wireless Sensor Networks (UW-ASNs) can be considered:

- Static two-dimensional UW-ASNs for ocean bottom monitoring. These are constituted by sensor nodes that are anchored to the bottom of the ocean. Typical applications may be environmental monitoring, or monitoring of underwater plates in tectonics;

- Static three-dimensional UW-ASNs for ocean column monitoring. These include networks of sensors whose depth can be controlled and may be used for surveillance applications or monitoring of ocean phenomena (ocean biogeochemical processes, water streams, pollution).

- Three-dimensional networks of autonomous underwater vehicles (AUVs). These networks include fixed portions composed of anchored sensors and mobile portions constituted by autonomous vehicles.

3.2 Underwater Electromagnetic Communication

The obstacle in using radio for underwater communication is the severe attenuation due to the conducting nature of seawater. In particular the attenuation is very high for high-frequency radio waves and, since the current terrestrial technology (such as Wireless Sensor Network) is often based on high-frequency in the range of GHz, it's impossible to use terrestrial devices in underwater applications.

Extremely low frequency radio signals have been used in military applications: Germans pioneered electromagnetic communication in radio frequency for submarines during World War II, where the antenna was capable of outputting up to 1 to 2 Mega-Watt (MW) of power. An extremely low frequency (ELF) signal, typically around 80 Hz at much lower power, has been used to communicate with naval submarines globally today. This is possible mainly because most of the transmission paths are through the atmosphere [43].

Some interesting studies and products related to the use of electromagnetic waves underwater are here reported. In [44] a theoretical analysis and experiments show that radio waves within a frequency range 1 to 20MHz is able to propagate over distances up to 100 m by using dipole radiation with transmission powers in the order of 100 W. This will yield high data rates beyond 1 Mbps which allows video images to be propagated at standard camera frame rates (25Hz) [45]. The antenna design in such case is very different from that of the antennas used for conventional service in the atmosphere: in fact, instead of having direct contact with seawater, the metal transmitting and receiving aerials are surrounded by waterproof electrically insulating materials. This way, an EM signal can be launched from the transmitter into a body of seawater and picked up by a distant receiver.

Recently, in September 2006, the first commercial underwater radio-frequency (RF) modem in the world, model S1510, was released by Wireless Fibre Systems [46]. Its data rate is 100 bps, and communication range is about several tens of meters. In January 2007, a broadband underwater RF modem, model S5510, came into birth. It supports 1-10 Mbps within 1 meter range [46]. Due to the propagation property of EM waves, EMCOMM is an appealing choice only for very short range applications. One example is the communication between autonomous underwater vehicles (AUVs) and base stations, where the AUVs can move within the communication range of a base station to offload data and receive further instructions [43].

3.3 Underwater Optical Wireless Communication

Underwater optical communication has been investigated both through theoretical studies [24] [4] [25] and in experimental tests [26], mainly developed in USA, Canada and Australia.

Currently, there are not many research activities on underwater optical communication, and few commercial optical modems are available specifically for underwater communication. As well detailed in the next paragraphs, recent interests in underwater sensor networks and seafloor observatories have greatly stimulated the interest in short-range high-rate optical underwater communication. For example, in [28][29], an optical modem prototype is designed for deep seafloor observatories; in [30] and [31], a dual mode (acoustic and optic) transceiver is used to assist robotic networks. Lab testings has shown that very high data rates can be achieved within a short range. For example, a laboratory experiment for underwater optical transmission achieves 1 Gbp/s rate over a 2-m path in a water pipe [32].

In the next paragraphs different underwater systems based on optical communication will be presented focusing both on point-to-point than on diffusive optical communication.

3.3.1 Point-to-point Communication

In [33] a low power and low cost underwater optical communication system is proposed by using inespensive devices that include: a light-emitting diode (LED) source, a silicon-based photodetector receiver, and off-the- shelf communication technology utilizing the IrDA protocol. The aim is to provide a solid, robust communication link and rejects ambient external light noise because, considering the applications for external submersible or ROV, lights could be an interference source. The proposed configuration uses an asynchronous serial communication rate of 14.4 kbs, but maximum baud rate supported can be higher, according to the IrDA protocol. In this case a higher data-rate would require a lower capacitance photodiode, which has less light-gathering capacity and would reduce the effective range of the device, which is already limited to 5 meters.

Also in [34] an underwater communication system has been implemented for a swarm of submersibles. It based on an optical communication transceiver, small in size, combining the IrDA physical layer with 3 Watt high power light emitting diodes, emitting light in the green and blue part of the visible spectrum. As in the previous example, the approach is to use the IrDA physical layer modulation replacing the infrared light emitting diodes (LEDs) with high power green or blue LEDs, and also the photodiode with a type which is sensitive in the visible part of the spectrum. The prototype transceiver costs approximately $\$45$ per unit and, on this low hardware level, no link management or higher level error correction is done. The wide angular coverage, the uniform emission footprint and very high light intensity allow for either omnidirectional coverage up to 2 metre radius with only five transmitters, when using simultaneously transmitting expensive LEDs that consume 2W or, with additional lenses, long range directional links having a collimated beam (up to 5 meters).

In [26] and [35] a low-cost medium-range optical underwater modem is proposed. The components used in this system are low cost costs (in the order of $\$10$) A sophisticated detection algorithm is exploited (based on spread spectrum) to maximize the communication range. Tests have been performed up to 10 meters and a data-rate of 310bps has been achieved.

In [30] and [31] the underwater wireless sensor network AquaNodes is described. In this application the use of optical communication is shown as an efficient solution for data muling in the network proposed by CSIRO ICT Centre (Australia) and MIT CSIAL (USA). This research proposes a network where data exchange is performed by connecting, both optically and acoustically, previously deployed static nodes and mobile (AUVs) vehicles, so that the characteristics of the two communication strategies can be exploited. Each device is provided with an optical modem, which can perform a transmission up to 300 kb/s in a range below 8 meters. This approach clearly shows that the use of an optical communication system allows for a considerable reduction in terms of energy consumption with respect to a multi-hop acoustic transmission and a resulting increase of operational life of the system. Moreover, considering this work, the use of optical modems instead of acoustic ones for short range communications leads to a remarkable reduction of costs, since the cost of an optical modem is of the order of $\$50$ node against approximately $\$3000$ node of an acoustic modem.

In [36] is illustrated a careful analysis by modeling the underwater channel based on underwater optics. Through this analysis, it is showed that a single color LED is very weak in a wavelength dependent underwater channel and, to overcome this problem, a multi-wavelength adaptive scheme combined with rate adaptive transmission is proposed taking inspiration from already developed algorithms. The proposed system can adapt to the channel by considering the change in power for each wavelength band, and controlling the data rate.

In [37] a short range underwater optical communication link is established by using an open source free space modem proposed by the project RONJA. which consists of three modules: a transmitter, a receiver, and an interface to the source. The design was not optimize and was less robust than expected. While successful 10 Mbps operation was demonstrated and the universal twisted pair boards and transmitter boards worked according to the standards, the receivers had problems capturing the signal. In this work the focus was mainly on the design and implementation of circuits for transmission and reception. The design of the transmitter is based on Cyan or Green Light and and two lens are used to collimate the light from the LED. The receiver too is equipped with lens to condense the photonic area down to the size of the detector area. The used equipment is very expensive and difficult to use in real applications; as reported, the experimental results achieved 10 Mb/s at a distance up to 5 meters.

A commercial product targeting optical underwater communication, from Ambalux (http://www.ambalux.com), includes high-bandwidth transceivers, which allow a point-to-point transmission at a data rate of 10Mbs up to 40m, depending on environmental conditions. A set of tests based on this commercial products has been described in[38], where a solution for omni-directional communication is also proposed in order to improve the efficacy of the connection with an underwater untethered vehicle. This approach, however, is not suitable for a dense UWSN or small and low power devices, where nodes are deployed with low accuracy and concerns on system size and energy consumption are addressed.

3.3.2 Diffusive underwater optical communication

In these paragraph are reported some researches related to the use of diffusive underwater optical communication for different applications.

In [40] the point-to-point optical communication system developed by Ambalux (http://www.ambalux.com) is used to perform a wide number of tests with the aim of paving the way for a future underwater omni-directional wireless optical communication systems. The LEDs used in the test emitted light in the green and blue light spectrum and were tested in a pool and in a tank filled with lake water. The primary objective of these tests was to get profiles of the behaviors of such communication systems with respect to water characteristics such as turbidity levels, prior to building an omni-directional optical communication. The results of the tests indicated that turbidity level, viewing angle and separation distance plays a significant role in the behavior of blue light in water. In particular, the aim was to define a threshold viewing angle (TVA), the minimum viewing angle at which communication is lost when one of the communication devices is rotated with respect to a virtual axis that contains the segment represented by the center of gravities of the two devices when they are aligned.

On the basis of the previous studies, two geometric forms were modelled: icosahedron and spherical hexagon. The icosahedron was retained because of its simplicity in geometry and its ability to provide complete free space coverage using the selected LED. In [38], the previous illustrated configuration has been tested to implement a high bandwidth optical networking for underwater untethered tele-robotic operation. A rate of 4 Mb/s was achieved in hemispherical configuration up to 5 meters. Experimentation in the field achieved initially 115 Kb/s over a distance of 15 metres. A second experiment, after the modification of the transmitter and the receiver software, was attempted: in this case the transmission was increased to 1.5 Mb/s and the first wireless underwater video pictures were transmitted. Despite the originally anticipated different kinds of turbidity (fish, plankton, rocks or other objects) in the water, the experiment still received video feedback of the anchor of a floating laboratory at around 15 metres deep in the bottom of the lake.

In [29] an optical modem technology for seafloor observatories is illustrated and problems related to design and implementation of a system for underwater optical wireless communication are focused. The idea is to implement an optical modem system which should provide sufficient bandwidth to allow transmission of compressed high resolution video (i.e., 2-10 Mbit/s for studio quality video), allowing nearly unrestricted motion on the part of the mobile sensor (UUV), and working at ranges below 100 m. In this case, the design of the system have been developed considering the following aspects: (1) selection of a transmission light source (wavelength, power, beamwidth), (2) selection of a detector (field of view, quantum efficiency, gain), and (3) selection of an aiming and tracking strategy. As regards transmission light source, LEDs are suggested to be used for the transmitters as they are switchable at high rates, can be reasonably collimated, and are easily arrayed to increase transmit power. High intensity blue LEDs such as those fabricated from Gallium Indium Nitride (InGaN) on a silicon carbide (SiC) substrate can provide on the order of 10 mW each and they can be configured in arrays to increase the total radiant flux (optical power). The light from one or more LEDs can be collimated with a lens to focus its beam. While their bandwidth is low by optical standards (30 ns rise time), a 100 ns bit duration meets the design goal of 10 Mbit/s. LED transmitters provide significant flexibility as well: both OOK and PPM are possible with the same hardware. As regards the receiver, in this work a photomultiplier tube (PMT) is chosen for the detector because it provides higher sensitivity and less noise than photodiodes (including avalanche or PIN types) although the tube size can be a limiting factor in certain conditions. Considering the aiming and tracking strategies, three possible configurations for optical communications between a fixed node and a free-swimming vehicle are suggested in this paper:

1. Pointed transmission (Tx) and reception (Rx) with acoustic or optical aiming is the most efficient scenario from an optical transmission standpoint. The transmitter consists of several

collimated LEDs or a laser diode, and the receiver is a PMT. This method requires a search and acquisition mode by both the Rx and Tx which consumes time and energy (regardless of whether the aiming is acoustic or optical);

2. Directional-Tx to omni-directional-Rx scenario can be accomplished with a hemispherical PMT detector and either a laser diode or a hemispherical array of LEDs. In this case, the aiming problem is one-sided and could be accomplished via acoustics or with optics;

3. Omni-directional Tx and Rx which is the mechanically simplest solution. This can be accomplished using the large area PMT detector with a moderate output-power blue laser diode or LED and diffusing optics. The diffusing optics can be done either with discrete reflective and refractive elements or with a high transmission scattering medium.

Taking into account the previous proposed theoretical studies, some optical systems have been implemented and tested, as reported in [28]. The omni-directional light source used was blue-green (470nm) to take advantage of the low attenuation in seawater at those wavelengths, and produced a uniform light field over a 2π steradian hemisphere. Six commercially available 470nm (blue) light emitting diodes (LED) were arranged in a hemispherical geometry and encapsulated in a weekly scattering potting material to provide some diffusion of the light field over the full hemisphere of operation. The receiver consisted of a large-aperture, hemispherical photomultiplier tube (PMT) chosen for its high sensitivity, low noise and high speed. Apertures and mirrors have been used to obtain a 91 m path length in a 15 m deep pool and to prevent reflections from the surrounding walls from contaminating the results. A 100 meter bench test has been performed to verify the range and geometry calculation using neutral density filters to simulate the attenuation of water.

In the same work ([28]) different tests are performed to validate the concept of omni-directional free water optical communication in the range of 10 meters. In particular, the power spectrum of the received signal during the transmission of a pulse train at different repetition rates is reported: 1.25 MHz, 5 MHz and 10 MHz.

In [47] the concept of underwater laser sensor network is illustrated as a new approach for broadband communication in the underwater environment based on the blue-green laser has been proposed. In this paper the applications of the underwater sensor network in the undersea exploration are discussed with the difficulties in the traditional the underwater acoustic sensor network. A basic of prototype of underwater laser sensor network is described: it includes the architecture of laser sensor node and protocol stack for underwater laser sensor network, but it does not shown implementation or interesting practical results.

4 Optical Wireless Underwater Communication Aspects

Due to the impossibility of using Radio Frequencies (RF), traditionally wireless underwater communication employs acoustic waves because sound propagates well in water and its range can be very long ($\sim$km). However, it has several disadvantages such as narrow bandwidth and latency in communication due to the slow speed of acoustic wave in water. For instance, at ranges of less than 100 m the data transmission rates of these systems in shallow littoral waters are $\sim$10 kb/s.

Experimental tests have shown that an alternative feasible solution is optical communication especially in blue/green light wavelengths, even if limited to short distances (up to 100 m)[4]. Compared to acoustic communication it offers a practical choice for high-bandwidth communication and it propagates faster in the water (2.255 x 10^8).

Nevertheless it is affected by different factors to take into account for an efficient design [8]. The attenuation of a light beam between two points can be described as in 1 where d_1 and d_2 are the positions of the points.

$$A = e^{-k(d_1-d_2)} \left(\frac{d_1}{d_2}\right)^2 \tag{1}$$

In the first term, k is defined as $k = a(\lambda) + b(\lambda)$ and it is dependent by the wavelength: a is the term related to the absorption of water while b models the scattering which depends both on light wavelength and turbidity. The second term, instead, models the quadratic attenuation.

4.1 Wireless optical modulation techniques

In this chapter some considerations about underwater wireless communication are proposed. In particular, since present underwater communication systems involve the transmission of information in the form of sound, electromagnetic (EM), or optical waves the advantages and limitations of each of these techniques are illustrated. The problem of modulation for wireless optical communication has been investigated in literature both for terrestrial [53] than for underwater applications [52]. In this paragraph, after a brief description of the most important available techniques, a comparison of the different available techniques will be carried out taking into account the peculiarity of the underwater environment.

As well detailed in literature [53] basic modulation techniques mainly contain three formats, such as Amplitude Modulation (ASK), Frequency Modulation (FSK) and Phase Modulation (PSK).

In particular is here considered the Amplitude-shift keying(ASK). It is a form of modulation that represents digital data as variations in the amplitude of a carrier wave. The amplitude of an analog carrier signal varies in accordance with the bit stream (modulating signal), keeping frequency and phase constant. The level of amplitude can be used to represent binary logic 0s and 1s. For low-cost optical communication system this modulation with direct detection techniques (IM/DD) is preferred to reduce the complexity of the implementation, since in this mode of operation, the intensity or power of the optical source x(t) is directly modulated by varying the drive current while at the receiver, a photodetector is used to generate a photocurrent y(t) which is proportional to the instantaneous optical power incident upon it. It is possible to think the carrier signal as an ON or OFF switch where 0 is represented by the absence of a carrier, thus giving OFF/ON keying operation.

4.1.1 Pulse Position Modulation

Pulse-Position Modulation (PPM) can be considered in order to further improve the anti-disturbance capacity of information transmission and it proposed in different systems both for terrestrial [54] than for underwater systems [4].

Pulse Position modulation is a well-known orthogonal modulation technique, in which M message bits are encoded by transmitting a single pulse in one of 2^M possible time-shift. PPM scheme, at each time interval is T_s and $L = 2^M$ time-shifts constitute a PPM frame. At the transmitter end, the signal will be launched by the light pulse to form a specific time slot, and in the receiver end, the photoelectric diode detects the light pulse and then to judge its time slot to evaluate his position and resume the signal. In L-PPM system, a block of input bits is mapped on to one of distinct waveforms, each including one "on" chip and M-1 "off" chips. A pulse is transmitted during the "on" chip, it can be defined as [52]:

$$P_m = \begin{cases} i_s & t \in [m-1]T_f/L, mT_f/L \\ 0 & else \end{cases} \quad (2)$$

Considering the characteristics of the different modulation the Table 1 can be proposed for a comparison between different techniques (R_B is the baseband signal bandwidth).

4.1.2 Various improved forms of PPM modulation

Since the characteristics of PPM appeared to be interesting for a wide range of applications some alternative and modified PPM modulations are here described taking into account advantages and disadvantages. In particular the following modulation are considered:

1. Differential Pulse Position Modulation (DPPM);
2. Pulse Interval Modulation (PIM);
3. Dual Header Pulse Interval Modulation (DH-PIM);

The **DPPM** can be considered a simple improvement of PPM modulation. To get the corresponding DPPM signal of a PPM modulation all the "0" times slot behind the "1" of the PPM . In comparison with the PPM, the DPPM symbol has no serious symbol synchronous requirements it can provide a higher power utilization and bandwidth utilization. For a fixed L,L-DPPM is less average-power efficient than LPPM because it has a higher duty cycle. However, for a fixed-average bit rate and fixed available bandwidth, it can be used a higher L with DPPM, resulting in a net improvement in average power efficiency.

An other interesting modulation is the **PIM**: while the PPM modulation indicates the information by the location of the light pulse, the PIM modulation indicates the information by the interval between two optical pulses. PIM modulation still divides a frame into L time-shifts, each log L bits binary information is encoded as the number of time slot between the two adjacent light pulses.

DH-PIM is an improved PIM modulation, and also it is a most complicated modulation technique. It has been frequently used for atmospheric laser communications modulation in recent years. Each DH-PIM symbol consists of a header and a number of empty information slots.

4.1.3 BER vs. SNR

Considering the previous described modulations it is interesting to evaluate can be based on the evaluation

Modulation	Implementation Complexity	Sensitivity to multi-path delay	Required transmitted power	Bandwidth
OOK	simple	general	P_{R-OOK}	$2R_B$
FSK	most complex	most anti-sensitive	$\frac{1}{2}P_{R-OOK}$	$\|f_1-f_0\|+2R_B$ (2 FSK)
DPSK	more complex	more sensitive	$\frac{1}{8\sqrt{\ln 2}}P_{R-OOK}$	$2R_B$ (2 DPSK)
PPM	simple	general	$\frac{2}{P_{R-OOK}}$	$\frac{L}{log_2 L}R_B$ (L-PPM)

Table 1: Comparison of Various Modulations [52]

of the Bit Error Rate versus SNR. The following results are mainly based on [52] [49]. For OOK demodulation format a threshold is used to compare the received voltage to decide "1" or "0". In AWGN channel model, the received voltage is

$$p(t) = \begin{cases} i_s + n_{c(t)}, & \text{"1"} \\ n_{c(t)}, & \text{0"} \end{cases} \quad (3)$$

where $n_{c(t)}$ is the Gaussian process. For the data "1", the probability density of $x(t)$ is:

$$p_1(x) = \frac{1}{\sqrt{2\pi\sigma}} exp(\frac{-(x-i_s)^2}{2\sigma^2}) \quad (4)$$

for the data bit "0" the probability density of x(t) is:

$$p_0(x) = \frac{1}{\sqrt{2\pi\sigma}} exp(\frac{-x^2}{2\sigma^2}) \quad (5)$$

By fixing the the judgment threshold to $\frac{1}{2}i$, the bit error rate is defined as:

$$p_e(ook) = \frac{1}{2} erfc \frac{i_s}{2\sqrt{2}\sigma} = \frac{1}{2} erfc \frac{\sqrt{S}}{2\sqrt{2}} \quad (6)$$

where erfc is the complementary error function. According to [35], in additive Gaussian noise channel, the bit error rate of 2FSK coherent modulation and 2DPSK coherent modulation are given by the following equations:

$$p_e(FSK) = \frac{1}{2} erfc \sqrt{\frac{S}{4}} \quad (7)$$

$$p_e(DFSK) = erfc \sqrt{\frac{S}{2}} (1 - \frac{1}{2}\frac{S}{2}) \quad (8)$$

For the L-PPM modulation in the Gaussian white noise channel, there are many performance evaluation methods for the BER as suggested in [55]. The following formula is used in [49]:

$$p_e(L-PPM) = \frac{1}{L}[\frac{1}{2} erfc(\frac{1-k}{2\sqrt{2}\sqrt{LS}})] + \quad (9)$$

$$+ \frac{L-1}{2}[erfc(\frac{k}{2\sqrt{2}\sqrt{LS}})] \quad (10)$$

A simulation, carried out in [49] on the basis of the previous formulas, shows the Bit Error Rate with different SNR condition and 4 PPM and 8 PPM is employed for PPM scheme and is reported in Figure 2.

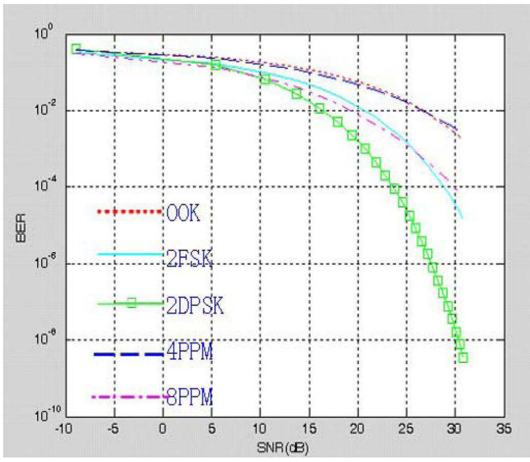

Figure 2: The BER performance of different modulation schemes with SNR [49]

4.1.4 Power Consumption

Also problems related to power consumption has been investigated in literature [33] [52] since they are crucial in underwater devices. Small and light systems are desirable in order to improve underwater system performance and considerations about power consumption are important in the choice of modulation. The following considerations can be carried out for the different modulations:

1. for the Frequency Shift Key (FSK) modulation a specific frequency carrier wave for digital "1", and a different frequency carrier wave for digital "0" are generated. In this case the optical transmit power required as the transmitting duration is always on and it appears to be inefficient for applications on power-constrained devices.

2. the Phase Shift Key (PSK) modulator generates an in phase signal for digital "1" and an out of phase signal for a digital "0". In this case the PSK demodulator are complex since the different coherent demodulation are needed to compare the current phase with the previous phase and it can be inefficient for power-constrained devices.

3. the On-Off Keying (OOK) and Pulse Position Modulation (PPM) do not use completely the frequency or phase information, but the design of the receiver and the transmitter is simple. The data throughput of PPM modulation is smaller than OOK modulation, but the required receive power is just:
$$\frac{1}{\sqrt{\frac{L}{2}log_2L}}$$
of OOK modulation at the same error rate performance. It means that PPM could transmit longer distance than OOK at the same transmitting power condition.

If P represent the smallest pulse width, the comparison of different modulation techniques, taking into account the Maximum rate, the Transmit power and the Complexity of modulation is shown in Table 2

5 System Description

5.1 Design consideration

The here proposed work has the aim to implement and design modules for the management of optical communication in a Underwater Wireless Sensor Network (UWSN), targeting the interface with current terrestrial technologies (in particular those based on IEEE 802.15.4).

The here proposed hardware architecture is to be considered as a preliminary step since it supplies a hardware structure which can be, eventually, easily adapted to different systems or integrated with additional functions for different standards. In particular this design can be easily modified or integrated on further considerations related to the telecommunication protocol or future experimental tests.

The trade-off between optimization and flexibility motivated the following choices:

- each functional block, taking inspiration from the IEEE802.15.4 protocol, has been implemented independently, by separating the management of the PHY layer, the transmission and reception of data and the interface to the MAC Layer;
- each module, both for Layer management and the transmission and reception of data, has been divided in sub-module (combinational logic or Finite State Machine (FSM)) specifically devoted to a task in order to simplify the adaptation or modification of the implemented functionalities;
- the interface between modules and sub-modules is managed by using FIFO Buffers and control units supporting the coordination and the exchange of information.

Currently the PHY Layer and a functions subset of the MAC Layer have been described by using an Hardware Description Language (HDL), in particular VHDL (Very High Speed Hardware Description Language), as suggested in [5] [6] .

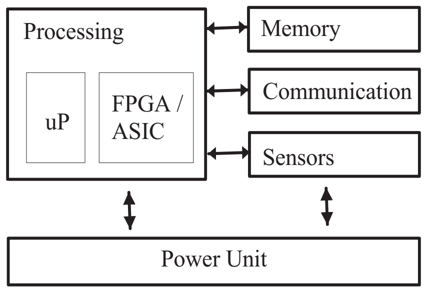

Figure 3: WSN node overview

The system then has been interfaced to a software for testing purposes. The description of each module has been carried out by using an Hardware Description Language because:

1. it could easily integrated in WSN nodes (Figure 3) developed for terrestrial application equipped by a Field Programmable Gate Array (FPGA), such as the one developed by the WISE Laboratory at DIBE [7];

2. it could be used for the implementation of an ASIC/ASIP specifically devoted to manage optical communication. In this case the implementation of a prototype on FPGA is to be considered as a passage for simulation and optimization

	OOK	FSK	DPSK	4-PPM	8-PPM
Maximum rate	$\frac{1}{2P}$	$\frac{1}{2P}$	$\frac{1}{2P}$	$\frac{1}{2P}$	$\frac{3}{8P}$
Transmit power	Middle	Higher	Highest	Low	Lowest
Complexity of modulation	Low	Higher	Highest	Lower	Lower

Table 2: Transfer rate versus implementation complexity [49]

whose aim is then to build a specific CHIP for the management of the optical communication.

The design approach has been bottom-up, starting from the management of the circuits for transmission and reception to the MAC Layer, and based on a modular approach. The here proposed work targets the interface with current terrestrial technologies and it is inspired to IEEE 802.15.4 for WSN and IEEE 802.11, which supports an optical PHY Layer based on InfraRed (IR) [9].

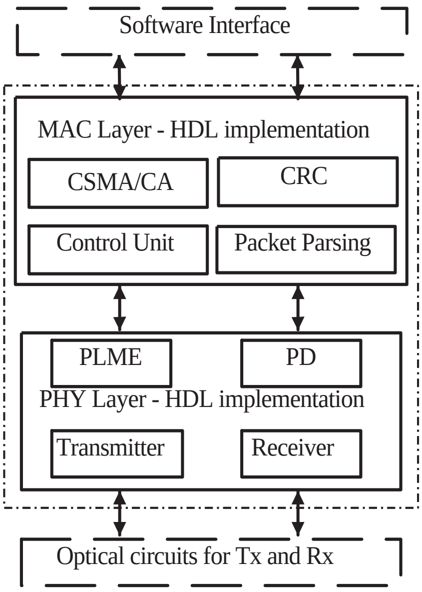

Figure 4: HDL modules overview

It is a preliminary step since it supplies a hardware structure which can be, if necessary, easily adapted to different systems or integrated with additional functions for different standards and protocols. This flexibility is based on a modular design and well defined interfaces between each modules.

5.2 Physical Layer Structure

The PHY Layer structure, depicted in Figure 5, is composed of 4 principal modules described in the following paragraphs.

The **Transmitter** generates the transmission on the physical channel managing a LED circuit. It can

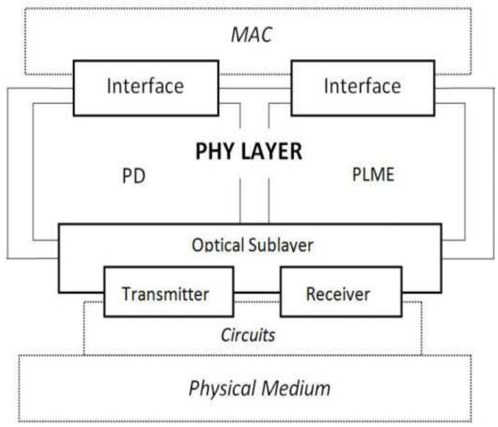

Figure 5: Physical Layer Structure

generate a synchronization signal or a transmission signal based on PPM modulation in which bits are encoded by the position of the light pulse in time slots. The duration of the time slot is fixed by the value of the input prescaler and the modulation can be a 4 or 16 PPM.

The **Receiver** manages the output of the receiver circuit. It has been designed to synchronize automatically with the transmitter baud rate: it determines how many clock cycles is the duration of the time slot chosen by the transmitter by counting 32 transitions of the input. This value is the output prescaler and it is used to decode the following PPM transmission. The receiver detects the modulation (4 or 16 PPM) and performs also a clock correction in order to maintain synchronization.

The **Physical Layer Management Entity (PLME)** provides the layer management service interfaces through which layer management functions may be invoked.

The **Physical Data (PD)** service enables the transmission and reception of PHY protocol data units (PPDUs) across the physical channel.

5.3 Implementation Results

As detailed in the previous paragraphs, each module has been simulated to test its behavioral correctness

Module	Slices	%
PHY Layer	866	45
Trasmitter	154	8
Receiver	231	12
PLME	173	9
PD	308	16

Table 3: Implementation on Xilinx Spartan-3 FPGA

by using $XilinxISE^{TM}$ simulation tools since the project has been developed on Xilinx Tools. In this paragraph the results regarding the implementation of the PHY Layer module described in the previous Paragraphs are illustrated considering also ACTEL technology and the use of $LiberoIDE$ integrated tool.
In particular the implementation on the following devices have been targeted:

1. a Xilinx Spartan III;

2. a Actel IGLOO AGLN250;

The Xilinx Spartan III has been chosen because it commonly integrated in low-cost student board which offer useful interfaces for experimental tests, illustrated in the next chapter.

The IGLOO AGL250 has been chosen because it is a low-cost and low-power FPGA used for high volume applications, such as sensor nodes, where power and size are key decision criteria having the advantages of flexibility and quick time-to-market in low-power and small footprint profiles.

5.3.1 Xilinx Spartan III implementation

The Digilent Board is a powerful, self-contained development platform equipped with a Spartan-3 FPGA from Xilinx (Xilinx Spartan3 XC3S200-FT256) The Spartan III has 200K System Gates, 4.320 equivalent logic cells and a 50 MHz clock.
The 4-digit seven-segment display on the board have been used to show the the value of some parameters (for instance the value of prescaler) with the 8 available LEDs. A dedicated program in $C\#$ to manage the interface to the PHY Layer has been implemented: it allows to performs a test of transmission and set different parameters of the PHY Layer. Since the PHY Layer VHDL description is developed in standard VHDL by using a modular approach, when an implementation on a specific device is targeted it is possible to perform an optimization by replacing some modules with core-generated blocks of code. In this case a better result in terms of occupied area can be achieved.

In Table 3 the results of the implementation on Xilinx Spartan-3 FPGA are reported in terms of slices. The Configurable Logic Blocks (CLBs) of Spartan-3 FPGA Family constitute the main logic resource for implementing synchronous as well as combinatorial circuits. Each CLB comprises four interconnected slices. These slices are grouped in pairs. Each pair is organized as a column with an independent carry chain. Both the left-hand and right-hand slice pairs use these elements to provide logic, arithmetic, and ROM functions. Besides these, the left-hand pair supports two additional functions: storing data using Distributed RAM and shifting data with 16-bit registers.
The maximum frequency that can be achieved by the system is 40 MHz. A preliminary test has been performed in air at the maximum data-rate supported by the Serial Port RS-232 of the Board (in the order of 10 kb/s). by using a simple circuit composed by a LED and a Photodetector (Figure 6).

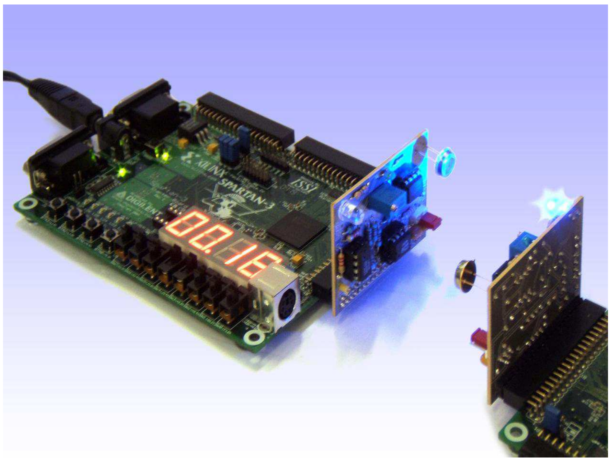

Figure 6: Preliminary Test on Air

5.3.2 IGLOO Low Power

As detailed in the previous paragraph, the possibility of the integration of a low-power FPGA in a Wireless Sensor Node is an interesting opportunity for the management of the underwater wireless optical communication. Considering the current available devices, the Actel IGLOO low-power FPGA appears to be an effective solution. By using the Actel Libero Integrated Design Environment, as for the implementation on Xilinx, some optimizations has been carried out. The target FPGA is a IGLOO nano Devices (AGLN250) with 250.000 system gates (6.144 equivalent core cells) and up to 71 I/O pins.
The implementation results are reported in Table 4. The maximum clock rate achievable is up to 20 MHz which can easily support a communication in the or-

Module	Core Cells	%
PHY LAYER	2405	40
Trasmitter	347	6
Receiver	735	12
PLME	442	7
PD	881	15

Table 4: Implementation on IGLOO Devices (AGLN250)

der of Mb/s.

5.4 Medium Access Control Design

The MAC Layer hardware design is based on a modular approach similar to that used for PHY Layer implementation. The MAC Layer handles the access to the PHY Layer through the PD and the PLME, while it manages different services for the Upper Layers, similarly to the PLME in the PHY Layer.

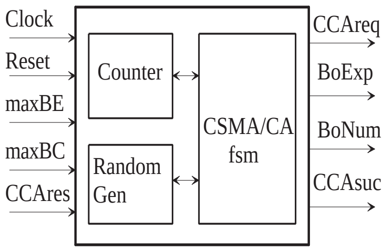

Figure 7: CSMA-CA implementation

Currently the following functions have been implemented:

1. Packet parsing and addresses verification;
2. Cyclic Redundancy Check (CRC): to check the integrity of transferred data;
3. a module to manage the transmission and reception of the MAC Payload to the upper layer;
4. the CSMA/CA mechanism for channel access.

The competition for channel access is based on a CSMA/CA protocol in which a device, when it wishes to transmit data, waits for a random number of backoff periods before detecting the channel. If the channel is busy, the device increases the number of attempts by one and checks if the maximum number of attempts has been reached. If the limit is exceeded, the device generates a channel access error and reports this event to upper layers. If the number of attempts is below the limit, the device repeats this procedure until it access the channel successfully or the number of attempts exceeds the limit.

The previous described mechanism has been implemented in hardware by using a dedicated module composed by a random number generator, for the calculation of the random delay, a counter and an other module, based on a FSM, to manage the CSMA/CA algorithm as depicted in Figure 7.

5.4.1 Considerations on implementation

The previous reported results show that the structure and functionalities of this VHDL description of the optical PHY Layer can be easily implemented on low-cost and low-power FPGA allowing also the integration with other modules to describe the MAC Layer and the interface with upper layers. This work has taken inspiration from different hardware implementation [57] but, since the implemented protocol has been adapted to optical communication, in particular taking into account the characteristics of IEEE 802.15.4 protocol, it is not easy to make a detailed comparison with implementation results reported in literature.

The examples of VHDL description and hardware implementation are common in literature for different reasons. In general these implementations [56] [58] propose better performances or reduced power consumption by using dedicated hardware.

This design has been mainly oriented to define and describe a flexible hardware architecture that can be easily adapted, improved or also modified taking into account deeper consideration about the protocol and possible alternative choices related both to telecommunication aspects than to implementation ones.

The current implementation of this optical PHY Layer can be considered a good starting point for adding new functionalities up to the complete implementation of an dedicated optical module which would manage, in connection with the here implemented PHY Layer, the MAC Layer adding further functionalities as briefly described in the following paragraph.

6 Test of the Communication System

The previous described modules have been synthesized and implemented on a Xilinx Spartan-3 FPGA and a dedicated program in $C\#$ is used to manage the interface to the Digilent Spartan 3 Board: it allows to perform tests of transmission and set different parameters of the PHY and MAC Layer (Figure 8).

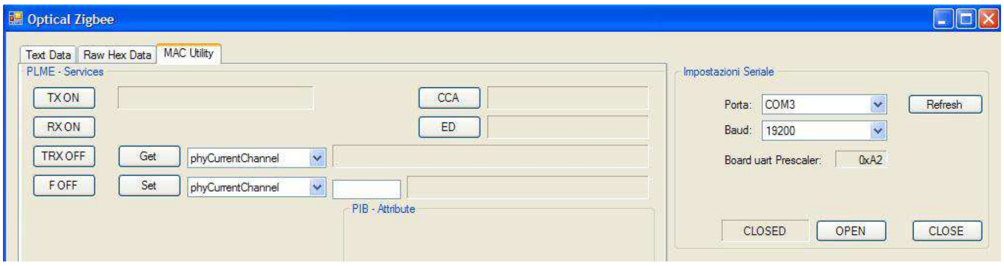

Figure 8: User interface to optical PHY and MAC Layers

The VHDL description is developed in generic standard VHDL and it is planned an integration in a WSN node by using an Actel IGLOO low-power FPGA which appears to be an effective solution for its low-power and reduced costs.

Some circuits implementation and experimental tests have been carried out. They are the basis to implement a diffuse optical communication which could support a dense network of small nodes able to exchange data at high data-rate (in the order of Mb/s). In general our approach has focused the possibility of using low-cost and low-power components.

In the next paragraph a point-to-point transceiver is described and then a 2-d structure for planar communication is proposed.

For point-to-point transceiver tests have been performed both in air than underwater by using a specifically designed tank. The tank (Figure 9) consists of a 2 meters long waterproof pipe built of high-density polyethylene black plastic.

The transmitter generates an impulse of light of a fixed duration (250 ns) which allows to support a transmission at 1Mb/s in the case of an 16-PPM modulation or at 2Mb/s in the case of a 4-PPM. The choice of LED wavelength has been done to maximize the power of received signal as illustrated below (Figure 17).

Particular attention has been posed on the circuit for the reception, since the reciprocal distance of the underwater devices cannot be fixed in advance and the receiver has to maintain his functioning in all the coverage area of the transmitter.

The receiver has been designed considering different blocks: a photodiode; a transresistance amplifier, to have a conversion from current to voltage; a bandpass filter to eliminate noise below 10 kHz and above 20 MHz; an Automatic Gain Control (AGC), based on a Linear Technology LT1006, used to amplify the signal received by the first part of the circuit and to automatically increase or decrease the gain according to the signal amplitude; a comparator, to determine the output value by fixing a threshold.

Figure 9: Experimental set-up

7 Experimental Test Bed

The tests have been performed at the Hardware Laboratory of DIBE (Department of Biophysical and Electronic Engineering).

The air test have been carried out by using single guides to fix the reciprocal position of a transmitter and a receiver and different electronic equipments (such as oscilloscopes) to perform the appropriate measurements.

The underwater tests, instead, have been performed by using a specifically designed and implemented tank. The tank (Figure 10) consists of 2 meters long waterproof pipe built of high-density polyethylene black plastic. Its width and depth are 20 centimeters and it has been filled with more or less 50 liters of liquid. It has been equipped with a tap at the basis so to recycle the same water for tests on different systems. The water used for the tests was clear distilled water or tap water.

Moreover, specific mechanical components has been designed to support tests with transmitter and receiver. The position of the receiver is fixed at the top of the tank while the position of the transmitter can be varied. A specific guide (Figure 11) has been designed

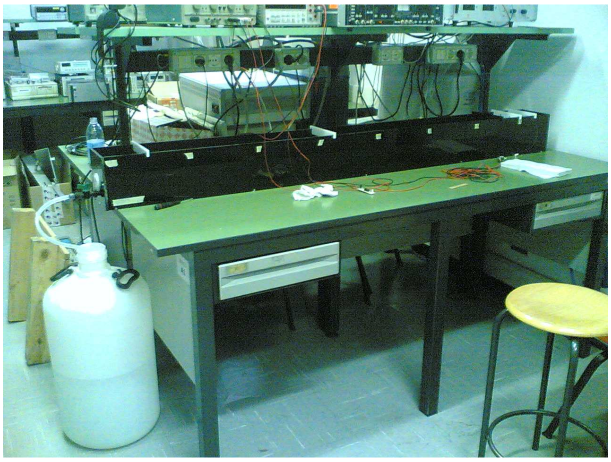

Figure 10: Tank for experimental tests

to allow the movement of the transmitter in the water: it can be moved step by step to reach the maximum length of the tank so that the measurements could be performed at different distances.

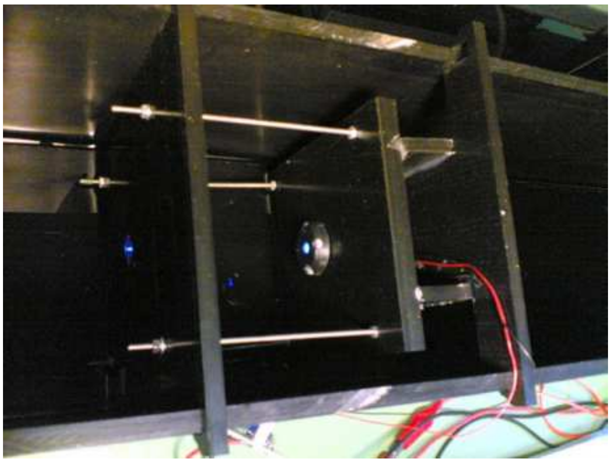

Figure 11: Mechanical guide for the transmitter

7.1 Preliminary Experimental Tests

The aim of this previous test has been to test the functionalities of the experimental testbed and it allow to show, by implementing a simple circuit, the different behavior of underwater light propagation at different wavelengths.
The transmission of light has been performed by using LEDs of different colors, each corresponding at a different wavelengths: blue, green and red.
The experimental test bed has a transmitter for the generation of light of different colors and a receiver (Figure 12) composed by:

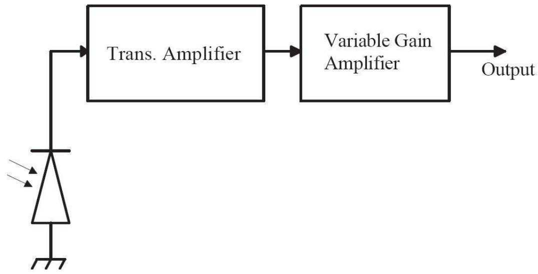

Figure 12: Receiver block description

1. a transresistance amplifier: to have a conversion from current to voltage (Figure 13);
2. an amplifier with a variable gain.

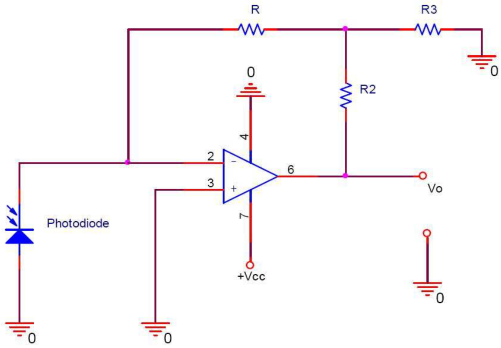

Figure 13: Transresistance amplifier

The transmitter and the receiver have been placed in the tank and the value V at the output has been measured for different distances. For each distance, the input current to the LEDs has been set to have at the receiver the same output voltage. This approach allows not to take into account the different spectral response of the photodiode for different wavelengths. In addition the output value due to the dark current of the photodiode has been measured in order to calculate the effective value of the received signal. In this case it is 1.52 V. The tests have been performed by using distilled water. Considering the same configuration of receiver and transmitter this test allows to shown the different behavior of each wavelength. The tests are reported in tables 5 and 6.

Considering the experimental results is possible to notice that, as expected, the value for each wavelength is different and, for the used water, the best wavelength appears to be the green one. The use of this circuits could be useful to perform experimental evaluation for different types of water. However, the proposed approach does not take into account the different spectral response of the photodiode for different wavelength and the different input current values used to maintain the same output at the receiver.

Distance (cm)	Blu	Green	Red
100	2.01 V	2.08 V	2.02 V
125	1.86 V	1.91 V	1.87 V
150	1.75 V	1.81 V	1.77 V
175	1.66 V	1.70 V	1.67 V

Table 5: Signal value at the receiver with distilled water

Distance (cm)	Blu	Green	Red
100	490 mV	560 mV	500 mV
125	340 mV	390 mV	350 mV
150	230 mV	290 mV	250 mV
175	140 mV	180 mV	150 mV

Table 6: Effective value

7.2 Communication test

The PHY Layer currently has been tested performing a point-to-point optical communication. In this case, due to the limitations of the serial interface between the Board and the PCs, the transmission rate has been reduced to the maximum data-rate supported by the Serial Port RS-232 of the Board (in the order of 10 kb/s) by using a preliminary version of the circuits (Appendix **??**).

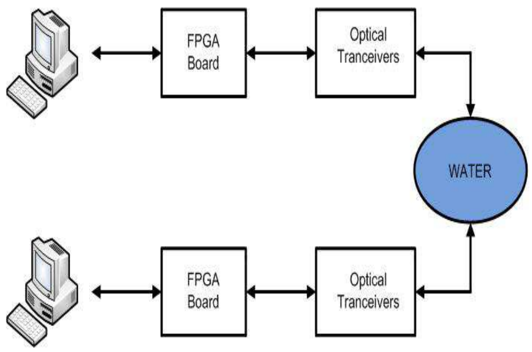

Figure 14: Experimental Test Bed configuration

The experimental set-up (Figure **??**) is composed of two PCs, for running the user interface, connected respectively to a Digilent S3 Board where the optical PHY layer has been implemented. Each Board is connected to the transmitter and receiver circuit placed in the of clear water. The parameters of the transmission have been set from the user interface.

The programs allows to transmit and receive a sequence of data which can be selected, for instance, from a file. By using the program interface is possible to set some parameters of the PHY Layer or to send a

Figure 15: Program interface utilities

primitive in order to display its value. Some particular of the interface utilities are shown in Figure 15.

By using the interface, for instance, it is possible to set the modulation (4-PPM or 16-PPM) and the value of prescaler which define the duration of a single impulse of light.

7.3 Point-to-point optical communication

7.3.1 Circuits Specification

The here described transceiver has been designed to support the generation and reception of light impulses on the basis of the following specifications.

The transmitter generates an impulse of light of a fixed duration: in this case, the impulse duration has been fixed at 250ns which allows to support a transmission at 1Mb/s in the case of an 16-PPM modulation or at 2Mb/s in the case of a 4-PPM.

Considering the application in clear water and the aspects regarding water absorption illustrated in the previous chapters, the impulse is generated by using a fixed wavelength determined as described in the next paragraph (Figure **??**). As regard the distance, the target is between 5 and 10 meters, since the aim is to support an Underwater Wireless Sensor Network of small and densely deployed nodes.

Particular attention has been posed on the circuit for the reception. In fact, since in the application targeted by this work the reciprocal distance of the underwater devices, in certain conditions, cannot be fixed in advance, the receiver has to maintain his functioning in all the coverage area of the transmitter and this condition has to be carefully evaluated in the design.

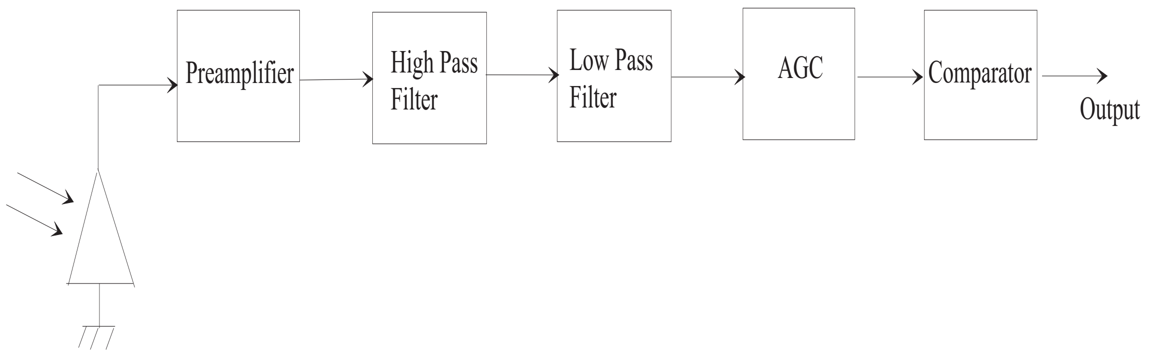

Figure 16: Receiver block description

7.3.2 Receiver

The receiver has been designed considering different blocks as illustrated in Figure 16.

The block diagram consists of:

- Photodiode;
- Transresistance amplifier: to have a conversion from current to voltage;
- High pass filter: to eliminate noise below 10 kHz;
- Low pass filter: to eliminate noise above 20 MHz;
- Automatic Gain Control: it is used to amplify the signal received by the first part of the circuit and to automatically increase the gain when the signal amplitude is small and decrease the gain when the amplitude is higher;
- Comparator: to decide the value of the output by fixing a threshold.

The receiver has been implemented by using the following component: Si PIN photodiode Hamamatsu S5971 - high-speed photodiodes, with $1mm^2$ surface area. To evaluate the better wavelength for the transmitter, as suggested in [30], Table 7 has been compiled considering the absorption coefficients for clear water collected by Pope [**?**] and the photodiode sensitivity reported in the component datasheet. The output current of the photodiode is proportional to:

$$S \times e^{-k(d)} \times P \qquad (11)$$

where S is sensitivity an P is the power in watts, d the distance and k the absorption coefficient. Figure **??** shows how the output current varies according to distance for different wavelengths of light, by using the equation 11.

Wavelength of emitted light	Photodiode Sensitivity	Absorption Coefficient
450nm (blue)	0.37 A/W	9.2 x $10^{-5}cm^{-1}$
532nm (green)	0.39 A/W	4.4 x $10^{-4}cm^{-1}$
650nm (red)	0.42 A/W	3.4 x $10^{-3}cm^{-1}$
890nm (infrared)	0.63 A/W	6.0 x $10^{-2}cm^{-1}$

Table 7: Sensitivity for PDB-S5971 High-speed photodiodes and absorption coefficients

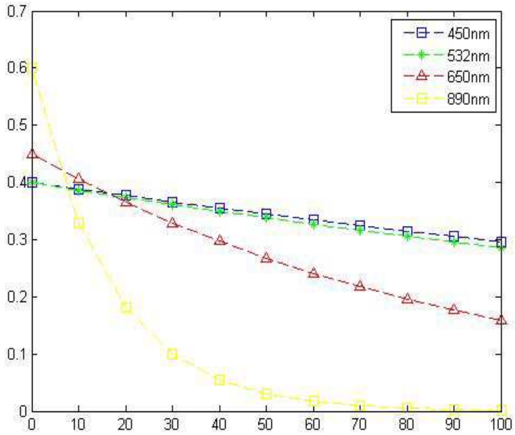

Figure 17: Comparison between different wavelengths

Due to the severe attenuation in water, the output current for infrared is less than for blue/green light at 10m, even if the sensitivity of the Photodiode is higher for infrared. It is possible to note that that red light outperforms green light up to 1.5/2 m but blue and green are better beyond. Taking into account the previous results, also considering that the attenuation is strongly influenced by turbidity, the better choice appear to be blue or green light. These considerations are very important because the system performance is determined by the detector when signal attenuation along a wireless link is considered. It is important for the receiver to detect low-level optical signals maintaining a Signal-to-Noise Ratio (SNR) sufficiently large to yield an acceptable Bit Error Rate (BER).

For the AGC stage the circuit depicted in Figure 18 been designed and implemented.

The circuit is used to support the automatic gain control. It has been implemented by using a low power consumption device produced by Linear Technology LT1006 and the operational amplifier AD600. By using the OrCad simulator, some tests have been performed on this configuration. It never reaches saturation for the presence of a strong impulse and, on the other hand, amplifies low level signal. It allows the receiver to avoid the saturation in case of excessive proximity of the transmitter LED. Instead, when the light impulse detected by the receiver is small, it allows a good amplification.

7.3.3 Transmitter

The transmitter is a circuit that allows to drive a Blue LED in order to generate light impulse of 250 ns. In this case the Everlight Electronics LED, DLE-038-045 is used. It has typical luminous intensity of 1630 mcd, a wavelength peak around the 428 nm and a field of view of 30^o. The implemented transmitter have been used both for the tests in air than for the tests in the tank of water.

7.3.4 Tests of the receiver circuit

The received circuit has been tested in air and in water by using the transmitter, by measuring the output voltage at the AGC stage output, by using a waveform generator which allows to generate trains of impulses. The tests have been performed at different distances both in air than in water considering the limitation of the available testbed. In Table 8 and 9 the measured values are reported. The reported results show that the use of the AGC allow to avoid saturation when the transmitter and the receiver are practically in contact while the amplification at higher distances could be improved. Nevertheless it allows to receive a signal up to 4 meters.

Distance	Output
1 cm	6,20 V
5 cm	6,10 V
50 cm	4,90 V
100 cm	3,20 V
150 cm	2,60 V
175 cm	2,30 V

Table 8: Measured signal values in water

Distance	Output
1 cm	6,40 V
5 cm	6,10 V
10 cm	5,30 V
100 cm	4,00 V
150 cm	3,20 V
200 cm	2,90 V
250 cm	2,40 V
300 cm	2,10 V
350 cm	1,70 V
400 cm	1,20 V

Table 9: Measured signal values in air

7.4 Design consideration for directional communication

The possibility of targeting the connection between more than two devices leads to the necessity of implementing a directional, up to omni-directional, transceiver able to send and detect optical impulse.

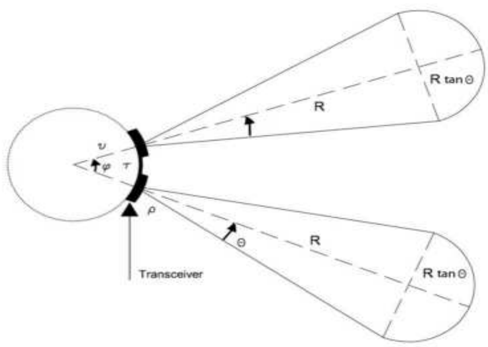

Figure 19: Transmitter disposed to cover a 2-D circular area

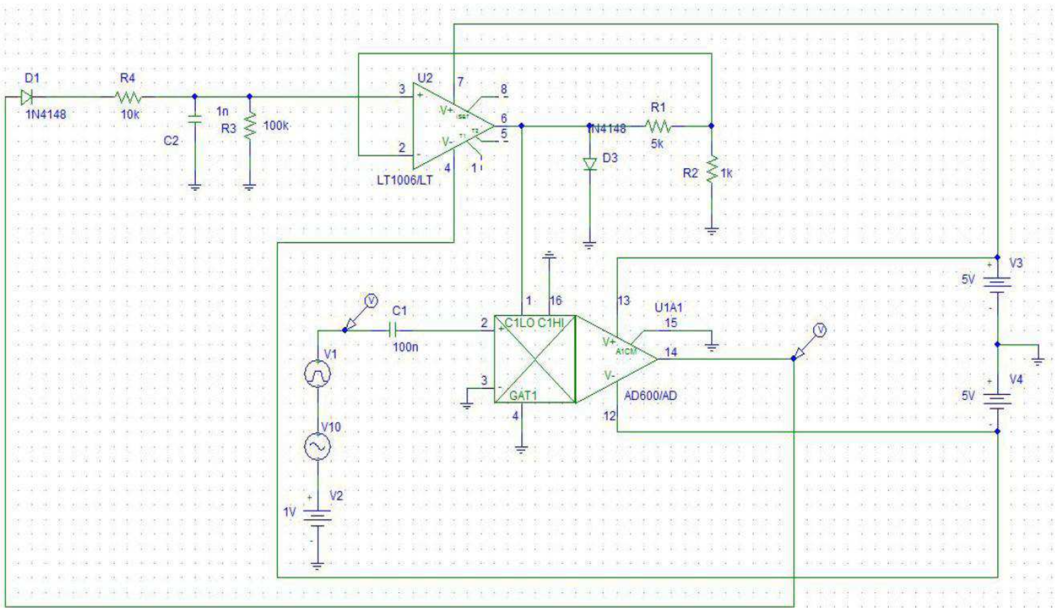

Figure 18: Receiver Automatic Gain Block Design

Taking into account some previous works, in this paragraph some considerations regarding the design and implementation of a circular transceiver are reported with a preliminary implementation description.

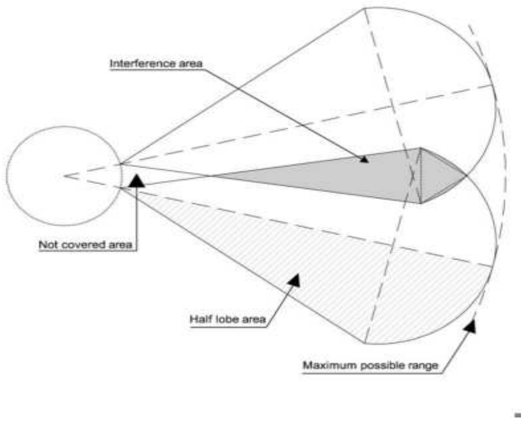

Figure 20: Transmitter disposed to cover a 2-D circular area(with overlap)

In particular the collocation of components (LED or photodiodes) on a 2D structure is considered. Assuming that n transmitter are placed at equal distance gaps on the circular node (radius r), considering that the diameter of a transmitter is 2ρ:

$$\tau = \frac{2\pi r - 2n\rho}{n} \tag{12}$$

The angular difference between any two neighboring transceiver is given as:

$$\varphi = 360^0 \frac{\tau}{2\pi r} \tag{13}$$

The coverage area L of a single transmitter can be given by:

$$L = R^2 tan(\vartheta) + 0.5\pi R tan(\vartheta)^2 \tag{14}$$

Two cases can happen for the effective coverage area C of a single transmitter, based on the value of φ, θ, R, and r:

1. if coverage area of the neighbor transmitter do not overlap 19:

$$Rtan(\vartheta) \leq (R + r)tan(0.5\varphi) \tag{15}$$

In this case, the effective coverage area is equivalent to the coverage area, i.e. C=L.

2. Coverage area of the neighbor transmitter overlap 20:

$$Rtan(\vartheta) > (R + r)tan(0.5\varphi) \tag{16}$$

In this case, the effective coverage area is equivalent to the coverage area excluding the area that interferes with the neighbor transceiver. If I is the interference area that overlaps with the neighbor transmitter's coverage, then C = L-I. Considering that the target of our work is to have a directional or at least omni-directional a good design approach should minimize the interfere area.

If the target is to have a transmission and reception of data by using all the elements placed on the circular structure, the overlap is not a problem for the communication. But, since the final idea is to add the possibility of supporting also a directional communication in which a single LED could be activated, the idea is to minimize the interference between adjacent LEDs and receivers.

Taking into account the previous illustrated considerations, an implementation of the transmitter has been tested in order to evaluate the behavior of transmitter signal for a 2-d structure. This implementation targets the reduction of the overlap and the possibility of supporting also a directional transmission, by using only one or a reduced set of LEDs for generating the signal.

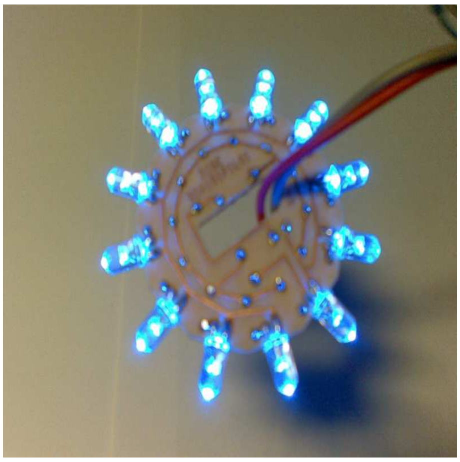

Figure 21: Circular LEDs configuration used for experimental tests

The LEDs disposition on a 2-d structure has been performed using 12 Ledman LL1503PLBL1-301 blue LED (with 30^o of FOV) disposed on a circular disk of 10 cm diameter. By using single receiver, equipped with a SFH-2013P photodiode, different measures have been considered at different distances, as reported in the Table 10. In particular, the profile of the received optical signal can be determined by considering the maximum value in a line-of-sight condition and the minimum value which is measured between a LED and another.

From the measurements reported in Table 10, it is shown that the difference between the minimum and the maximum achieved value is higher near the transmitter while it become less important when the distance between the transmitter and the receiver increases. On the basis of the values of Table 10, the previous structure can be considered acceptable as a base for the implementation of the 2-D transceiver. Currently a circular transceiver, equipped with LEDs and Photodiodes, is under construction.

Distance (cm)	Max Value	Min Value	Difference
80	7.2 V	6 V	1.2 V
100	6.5 V	5.5 V	1 V
150	5.5 V	4.7 V	0.8 V
200	4.9 V	4.6 V	0.3 V

Table 10: Signal values at the receiver

Component	Cost (euro)
LED	5.69
SFH-203P	5.25
AD600	12.57
PDB-C139	2.91
S5971	7.59
OPA357	0.51
LTC6244	1.61

Table 11: Cost of some components used for circuits implementation

7.5 Comparison with the state-of-the-art and conclusions

The optical communication modules illustrated in the previous chapter and the circuits tested and described in this chapter can be considered a first step for the implementation of an UWSN based on optical communication. The illustrated tests and simulations, completed only for a point-to-point communication, will lay down the foundation for an underwater directional or omni-directional optical communication system for an optical UWSN.

In this paragraph, a brief comparison with current optical underwater communication systems is proposed in order to highlight the novelty of our approach and to compare the achieved results.

A trade-off between circuits specifications and low-power and low-cost components have been targeted since the receiver and the transmitter can be used in a large number of devices where energy supply can be difficult. Information on the cost of the components is reported in Table 11.

In [37] a point-to-point underwater optical communication is implemented by using an off-the-shelve optical modem (http://ronja.twibright.com/) used for terrestrial wireless optical communication which allows two sources to transmit and receive data using a modulated beam of light up to 10 Mb/s. In this case the design of the transmitter is based on Cyan or Green Light and and two lens are used to collimate the light from the LED. The receiver too is equipped with lens to condense the photonic area down to the size of the detector area. In this work, focusing on point-to-point communication in an experimental environment, the possibility of using this equipment in real applications is not well addressed. Complex and costly lens and cases (up to 300 euro) and power-consuming components make it difficult to transfer this technology to small and low-cost underwater devices. In comparison the work illustrated in this paper proposes a low cost equipment (100 euro) and a communication up to 2 Mb/s managed by flexible modules which can be adapted both for point-to-point and for omni-directional communication.

In [38] [40] an high bandwidth optical communication is proposed as a support for untethered telerobotic operation. In this work the researches start from the necessity of supporting the real-time reception and transmission of video to support underwater activities such mining, construction, aquaculture. They use the previous described commercial optical modem from Ambalux Corporation (http://www.ambalux.com) and they adapt this system in order to support the generation of omni-directional optical transmission which should easily allow the interface with Underwater Vehicles moving in the range of the transmitter. In this case the focus is mainly on achieving an high bandwidth communication while the dimension and power-consumption of the components is not the main concern. The reported results [40] illustrates a communication of 1,5 Mb/s up to 15 meters between a fixed node and a mobile Vehicles.

In this work the approach is different from that proposed in this paper where the idea is to support a network of densely deployed underwater nodes. In this case the basic idea is to create a higher FOV in order to avoid problems of tracking or pointing between fixed nodes and mobile underwater vehicles. The achieved data-rate can be compared with the preliminary results achieved by the underwater optical wireless system proposed in this paper. As concern cost and power-consumption, it is not possible to make comparison because data regarding components are not reported in these papers.

In [26] an underwater wireless optical modem is presented for point-to-point optical communication targeting medium-short distances, from 5 to 10 meters. In this work the aim is to provide a much more cost-effective alternative for applications where the required communication range is modest, since existing acoustic modems often cost on the order $1.000 to $10.000, In this work the approach is similar to that proposed in this paper, but they focus on an individual transmitter-receiver pair. In this work the signal detection is based on direct sequence spread spectrum (DSSS), using a 32-chip Gold sequence while data communication beyond mere signal detection is achieved by using pulse position modulation (PPM). The cost of the proposed system is comparable with that proposed in this system (in the order of 10 euros), even if the data-rate is approximately 310bps in comparison with the here proposed system which allows a wireless communication up to 2 Mb/s.

In [30] [31] an underwater wireless sensor network which consists of static and mobile underwater sensor nodes is described. The nodes communicate point-to-point using a novel high-speed optical communication system and they broadcast using an acoustic protocol integrated in the TinyOS stack. The nodes have a variety of sensing capabilities, including cameras, water temperature, and pressure. The mobile nodes can locate and hover above the static nodes for data muling, and they can perform network maintenance functions such as deployment, relocation, and recovery. In this case the use of optical communication is limited to point-to-point activities. The modulation is based on a modified VFIR optical communication format the receiver gets a continuous sequence of pulses regardless of the data (as opposed to NRZ and its variants), and can be easily kept in syncronization.

As for our system they target the integration with an existing protocol and a limited range of operations (up to 5 meter). They employ an optical communication based on a green LED achieving a data rate of 320 kb/s. The system proposed in this paper, instead is based on a PPM modulation and implements a different method for synchronization. aiming at achieving higher data-rate. It targets the interface with current available terrestrial technologies for WSN with optical communication for connection between nodes.

In [28] diffuse optical transmission is proposed for a connection between AUV and seafloor underwater observatories. The ideal platform for exploring and monitoring these sites, especially during episodic events, is a remotely-piloted, unmanned, underwater vehicle (UUV) which is capable of sending back high-quality video or other high-rate sensor data. The combined requirement of remote-piloting and high data rates suggested the idea of a bidirectional optical wireless communications link capable of sending and receiving data at one to several Mbits per second. The implemented transmitter is composed by six commercially available 470nm (blue) light emitting diodes (LED) were arranged in a hemispherical geometry and encapsulated in a weekly scattering potting material to provide some diffusion of the light field over the full hemisphere of operation. The selected LEDs have sufficiently fast rise and fall times to switch up to a PRF of 10 Mb/sec. The receiver consisted of a large-aperture, hemispherical photomultiplier tube (PMT) chosen for its high sensitivity, low noise and high speed. A 10 m vertical dock test was performed in slightly turbid water of 10 m depth: the power spectrum of the received signal during the transmission of a pulse train at different repetition (1.25 MHz, 1OMHz, 5MHz) rates is reported.

This work focuses in particular the communication between Underwater Mobile Vehicles and a fixed node targeting application in sea floor observatories. The achieved distances and data-rate are interesting but it could be difficult to apply these results to low-cost and small devices where transmitters and receivers should be placed on the same small surface.

In [32] an error free optical transmission measurements at 1 Gb/s over a 2 m path in a laboratory water pipe is proposed but a high power consumption LD (laser diode) is used with the aim of showing different behavior in case of different water conditions. They employ different kind of water (clear ocean, coastal ocean, harbor water and Maalox suspension) to test the different frequency response. In this case the proposed system appears to be, at the moment, useful for theoretical consideration but further work will be required to develop practical high speed sources and detector. Even if the achieved data-rate is of a different order of magnitude in comparison with that proposed in this paper, nevertheless the cost and the power involved in this kind of device make this solution highly impractical for UWSN nodes.

In conclusion, taking into account the state of art of optical underwater wireless communication, different systems and applications have been illustrated and compared with the here proposed implemented modules. This paper proposes a new approach which, starting from the management of a point-to-point optical underwater transmission and reception of data, aims to support the communication in a UWSN by the design and implementation of a PHY and MAC Layer targeting the interface with current terrestrial technologies for WSN. The high-data rate exchange of data by using optical underwater communication (in the order of Mb/s) can support many emerging applications which involve, for instance, the recording and transmission of images and short video sequences. The use of optical communication for supporting an UWSN has been studied in literature and this paper proposes a first implementation approach. As regard the preliminary tests and simulation they appear to be a good starting point for the future developments.

7.6 Planar transceiver

Taking into account the previous circuits, a 2-d transceiver has been implemented. The LEDs disposition on a 2-d structure has been performed using 12 Ledman LL1503PLBL1-301 blue LED (with 30^0 of FOV) disposed on a circular disk of 10 cm diameter. The reduction of the overlap between the signal generated by each LED has been targeted so to allow the possibility of supporting also a directional transmission, by using only one or a reduced set of LEDs. The same approach has been considered for the placement of the photodiodes for the 2-d receiver. Tests of the transmitter have been carried out by using a single receiver, equipped with a SFH-2013P photodiode. Different measures have been considered at different distances. The profile of the received optical signal, determined by considering the maximum value in a line-of-sight condition and the minimum value which is measured between a LED and another, show that the generated light impulses is uniformly distributed on the surface. Tests on the receiver have shown a performance decrease in comparison with the point-to-point circuit due to the noise generated by the photodiodes which are not directly exposed to the light impulses. Nevertheless a reception up to 4 meters in air can be achieved.

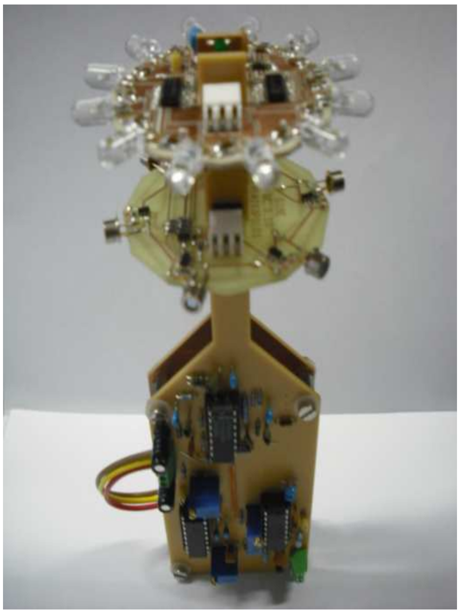

Figure 22: Circular transceiver configuration used for experimental tests (transmitter on the top)

8 Conclusion and Future Development

The here described work is to be considered as a first step targeting the implementation of an optical module interfaced with current terrestrial technology for WSN and circuits for optical communication in order to build an optical UWSN. The implemented circuits, even if under improvement, are a good starting point for an effective high data-rate and low-cost underwater communication. Next developments are aimed to implements new services in the MAC Layer and to perform communication tests with more than two nodes starting from a planar optical connection, while currently only point-to-point tests have been performed. In addition, the use of a limited number of LEDs for a directional communication, when the topology of the network has been fixed, and the possibility of changing the wavelength of the emitter, by choosing different colors (blue, red or green), if water turbidity varies, can be interesting to explore.

8.1 Near Future Goal

The optical wireless modules here described can be easily modified and integrated with additional functionalities.

In particular, the first step, will be focused on the implementation of the MAC Layer in order to integrate the here described PHY Layer, taking into account the previously illustrated design considerations.

The development of the MAC Layer, while, on one hand, is inspired to IEEE 802.15.4 protocol to support compatibility with current terrestrial technologies, on the other hand has to consider the aspects related to the management of optical communication. For instance, the following characteristics can be taken into account:

1. the possibility of choosing between a 4 or 16 PPM;
2. the possibility of managing circuits where choosing different wavelengths of the emitter, by using different colors (blue, red or green), in order to have a system adaptive to water turbidity. This property, for instance, can be implemented by using a mechanism to manage the corresponding parameters in the PHY Layer;
3. the possibility of an adaptive directionality of the communication system, by activating only some of the transducers, in order to spare energy and optimize the communication efficiency.

The second step will be the integration with a current developed terrestrial node. A good starting point could be the use of the wireless node developed by the WISI Laboratory at DIBE (http://www.wiselaboratory.it/)which is equipped by an FPGA. One of most important aspect of the integration will be the interface with the upper layers taking into account the differences of the optical layers in comparison with the Radio based technologies for WSN. For instance, the IEEE 802.15.4 protocol can achieve different data rate and the implementation of modules on a dedicated FPGA or by using an ASIP/ASIC should target the adaptation and synchronization with the upper layers of the node.

According to the parameters illustrated in the previous paragraphs, the circuits for reception and transmission of data currently used for point-to-point communication will be disposed to perform a directional communication on a surface paving the way to an omni-directional implementation. In addition, an interested advance will take into account the possibility of adding LEDs of different colors (for instance blue, red and green) in order to support the adaptation to different turbidities: this hardware, in connection with MAC functionalities, will allow the nodes to exploit the shifting of the minimum attenuation window toward longer wavelengths, which occurs when the concentration of suspended particles increases.

8.2 Future Research Directions: Autonomous long survival UWSN for ambient monitoring

Starting from the previous described results, the creation of an innovative long survival optical Underwater Wireless Sensor Network (UWSN) could be targeted. It will able to sense, compute, communicate and cooperate in an underwater environment by using long-survival, low-cost and eventually disposable nodes. Innovative approaches could be developed to address:

1. wireless, adaptive and low-power optical underwater communication;
2. underwater energy scavenging and harvesting;
3. autonomous and self-governing behavior of the nodes in the underwater environment, including intelligent energy storing and utilization, to guarantee long-term operation under a wide range of conditions and avoid frequent and costly rescue procedures;

The first innovation will address the communication capabilities. Efficient optical communication could be implemented thank to a low-cost, efficient and omni-directional communication system, based on short wavelength LEDs, and able to exploit the minimum absorption wavelength window, shifting toward longer wavelengths in turbid waters. The optical communication, despite reaching shorter distances respect to acoustic communication, will allow to achieve high data rates with lower energy requirements. Finally, the implementation of adaptive directionality, by activating only some of the transducers will allow to spare energy and optimize the communication efficiency. Online nonlinear modeling and adaptation to the time-varying aquatic channel characteristics of the optical system can be used to advance the state-of-the-art and achieve effective and efficient Free Space Omni-directional Optical (FSOO) underwater communication.

The second innovative field of research could be underwater energy scavenging for self-supply or for increasing the lifetime of both each node and the entire network. While solar power can be exploited on the water surface and in shallow but clear waters, other techniques must be explored for producing and storing energy in a general underwater environment. Terrestrial energy scavenging for artificial artifacts and autonomous sensors relies mainly on exploiting environmental vibrations, converting mechanical energy in electrical energy. In the static underwater nodes, random movements forced by the water flow, underwater currents and noise, can be exploited to perform underwater energy scavenging. The delicate equilibrium between energy harvesting, storage and consumption is to addressed by developing adaptive behavior, to optimize the survivability of both the nodes and the entire network.

The third field of research should address the development of low-power, low-cost miniaturized nodes able to sense, compute, communicate and cooperate in an aquatic environment. The development of new nodes, with volumes that are orders of magnitude smaller than current generation equipments, will allow the development of new applications, where tiny and, eventually, disposable nodes will be able to perform 4D monitoring of aquatic environments. The increased density of the network, which will be possible thank to the miniaturization and low-cost of the nodes, will allow to compensate for the relatively short range of the underwater optical communication channel, which is, as shown, well below 100m. Furthermore, in settings where environmental issues are of limited concern, the use of low-cost disposable nodes will avoid frequent and costly rescue procedures, by simply adding new nodes to areas not covered by the network or to overcome the malfunctioning of old nodes.

The development of the previous described fields of research could lead to the implementation of low-cost optically communicating nodes, able to be deployed with low accuracy on the area of interest, and capable of self-configuring as a sensing network as depicted in Figure 23. This optical UWSN (Figure 23) will be able to perform data collection for ambient monitoring and to transmit the acquired, and eventually preprocessed, data to one or more Access Points (APs) or Base Stations (BSs), connected to the terrestrial data concentrator through conventional wireless (radio) channels. The optical UWSN could exploit multi-hop communication, in order to avoid the need of a fixed infrastructure, to achieve simpler and more cost-effective deployment, and to improve the survivability of the system. The BS could incorporate both the functionalities of a node and the functionalities of a conventional terrestrial WSN, using radio wireless communications, so to integrate with existing terrestrial WSNs and also allow long distance communication where needed.

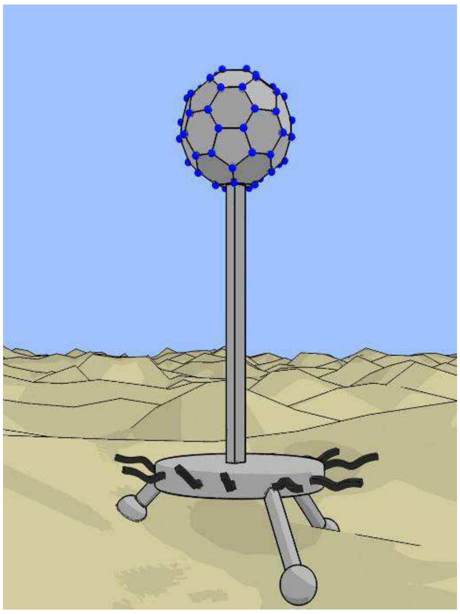

Figure 24: Single Node Concept

The main challenge in realizing an optical UWSN is the development of an innovative node (Figure 24): an autonomous, self-powered and low-cost (eventually disposable) sensing device. Each node could make use of FSOO communication in the upper end of the visible light spectrum, where minimum absorption and scattering occurs, and will adapt to the turbidity of the water environment by exploiting light sources of different wavelengths, according to colour and clarity of the water. Furthermore, FSOO could also allow non Line-Of-Sight (LOS) communication between nodes by exploiting light scattering and re-

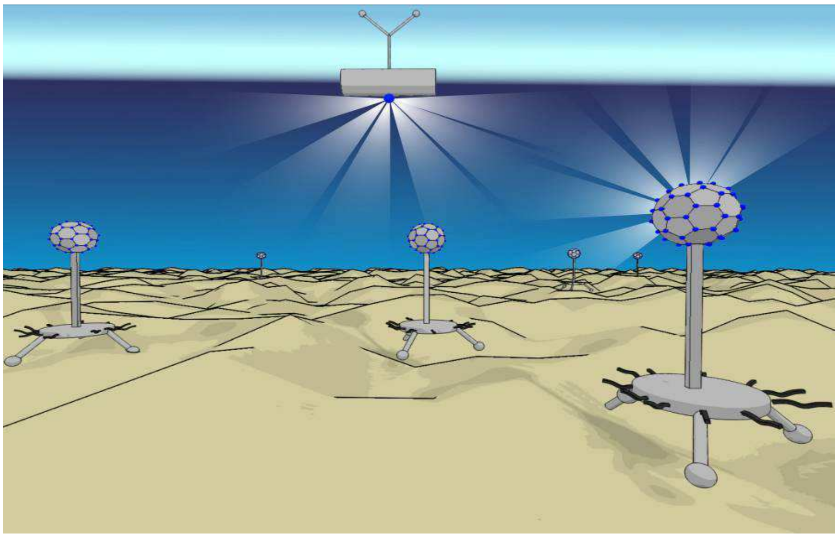

Figure 23: optical UWSN Concept

flection from the water surface. The use of an optical communication channel will allow the node to achieve data rates that are orders of magnitude higher than current generation UWSNs, which exploit acoustic channels. On one side, this approach will limit the total energy consumption by using very short communication time-frames and reducing the overall activity of the node; on the other side it will allow the transmission of moderately large quantities of data (e.g. still images or low-resolution video) at a sustained rate. In acoustic based networks, the discovering of the network topology (e.g. using triangulation) is a difficult task; on the contrary, the use of ad-hoc optical modulations and transmission protocols will allow, after the deployment of an optical UWSN, to easily compute the position of each node. The initial mapping of the node positions will allow not only to discover the network topology, but will also simplify the rescue procedure of faulty nodes and their recovery at the end of their life, especially if disposability cannot be exploited due to environmental reasons. Moreover, after discovering the network topology, each node will switch to more energy-preserving modulations and protocols for data transmission, exploiting also adaptive directionality when targeting node-to-node transmission.

Even if each node could sustain part of its operational life through conventional batteries, it could achieve longer operational life by harvesting energy from the environment mainly through mechanical energy conversion. Solar energy will also be considered as a viable option, because in some cases the nodes will be deployed in shallow and clear waters. The mechanical energy harvesting mechanism will exploit both advective flows, caused by river waters or wind, and orbital movement, caused by waves, through the use of piezoelectric materials. The mechanical energy scavenging will take advantage of both the main support of the optical communication system and additional whiskers mounted on the node body (Figure 24).

Environmental compatibility of the optical UWSN node will be guaranteed by its small dimension, respect to current-generation monitoring systems. While buoys for sea monitoring often surpass $10.000cm^2$ of water surface occupation and a buoyancy payload of several hundred kilos, this kind of nodes will not exceed a footprint of $100 - 200cm^2$. Furthermore, the communication will not interfere with the water fauna thank to the almost exclusive use of return-to-zero and short-pulse optical modulations for data transmission. In addition, in environmentally rich locations, the system could use a long-sleep operation mode, stopping transmission for several minutes so that the underwater fauna will not be attracted by lights, avoiding also heavy interference with data communication.

Each node should provide the flexibility to host a large sensor payload (Figure 25), able to target the identified environmental monitoring scenarios, according to user needs (for instance including cameras for image or short video recording). Both analog and digital interfaces can be easily developed for addressing the interfacing needs of a large number of COTS sensors for underwater applications.

In summary, future research direction could target a node architecture which will inherit the structure of the terrestrial counterparts, but will introduce new architectural blocks, which will be developed ad-hoc for the underwater environment. The optical commu-

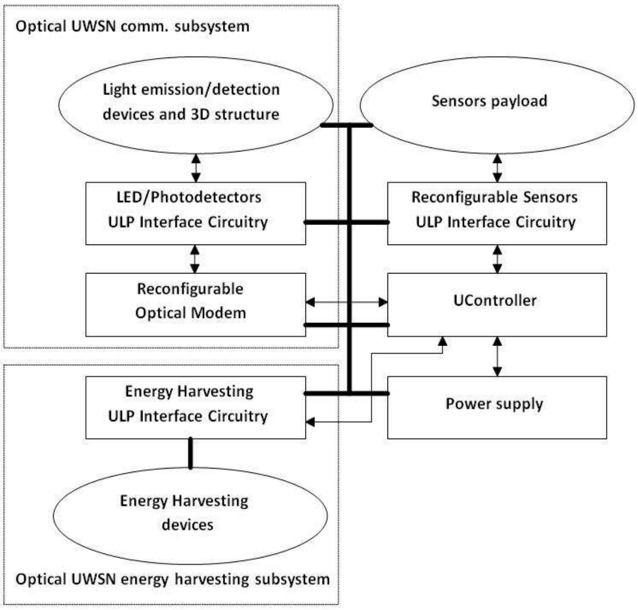

Figure 25: optical UWSN Node Architecture

nication subsystem which will consist of a reconfigurable device, able to adapt the light emission and detection to the varying water conditions and a carefully designed 3D structure able to emit and receive light omni-directionally. The energy harvesting subsystem which will be designed to extract energy from water flows and transform it to sustain a long operational life of the node.

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