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# Prospects and Problems of Optical Diffuse Wireless Communication for Underwater Wireless Sensor Networks (UWSNs)

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## 1. Introduction

The aim of this paper is to highlight the prospects and problems of optical wireless communication for applications in the field of Underwater Wireless Sensor Networks (UWSNs). The necessity of wireless underwater connections, especially in UWSN, has dramatically increased in the last few years for a wide range of applications, from environmental monitoring to surveillance. The problem of wireless underwater communication is a challenging field of investigation since common terrestrial devices, equipped with radio wireless links, cannot be employed underwater and current underwater available technologies, mainly based on acoustical solutions, still pose problems due to low propagation speed of sound in water and low data-rate.

In the last years, the interest towards optical wireless communication has increased both for terrestrial (Akella et al., 2005) than for underwater applications (Doniec et al., 2010) since it allows to overcome some of the problems of acoustical communication (Akyildiz et al., 2005). In fact low data rate and low propagation speed require specific solutions and make it difficult the integration of underwater technologies with current available terrestrial modules. Transferring the paradigm of Smart Dust (V. Hsu & Pister, 1998) to UWSNs, largely unaffected by WSN revolution, is a challenge that can open great opportunities since current underwater solutions are still of large dimension, expensive and power-consuming.

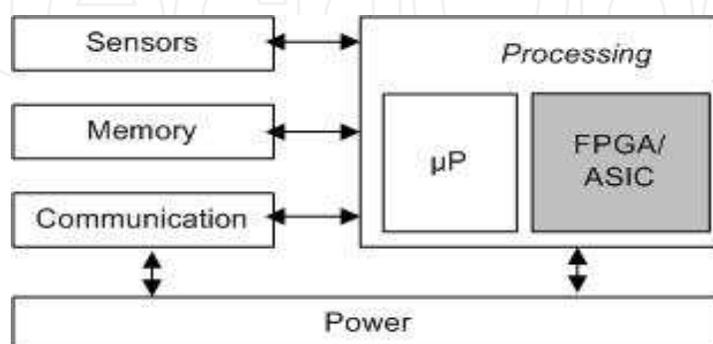


Fig. 1. Wireless Node Structure equipped with FPGA

This paper highlights the relatively less explored and innovative possibility of optical underwater communication as an interesting and feasible alternative solution for underwater networking targeting small, low-cost and low-power devices. In particular it focuses both the problems related to specific characteristics of the underwater channel targeting the interface with current terrestrial technologies available for Wireless Sensor Network (WSN) such as the one developed at DIBE WiseLab (Akyildiz et al., 2005) depicted in Fig.1 .

The goal of our work is to build a prototype of an UWSN based on optical communication among nodes. The optical PHY and MAC Layers have been developed considering the characteristics of IEEE 802.11 Infrared (IR) PHY layer and the compatibility with the current IEEE 802.15.4 protocol for terrestrial Wireless Sensor Networks (WSNs). This can be considered as a first step which, of course, should be followed by modifications and adaptation of the upper layers.

The network architecture can be organized as a three or bi-dimensional underwater network in which each node floats at different depths trying to maintain a fixed position with a good approximation, for instance by an anchorage to the sea bed (as detailed in Chapter 11). The nodes should be designed of slight dimensions (between 15 and 20 cm), they should be densely deployed, maintaining a distance between 10 and 30 meters from each other. As detailed in the next paragraph, each node should be able to communicate, by using only a wireless optical communication link, to the neighbors and, by using a multi hop path, to a base station placed on the water surface.

The interesting aspects which are reported in this work are related to:

- the use of optical communication (the adaptation of current available protocols, the choice of modulation, the adaptation to water channel variability, etc ...);
- the interface with current technology for WSN;
- the design and implementation of circuits for diffuse generation and reception of light impulses targeting low-cost and low-power components;

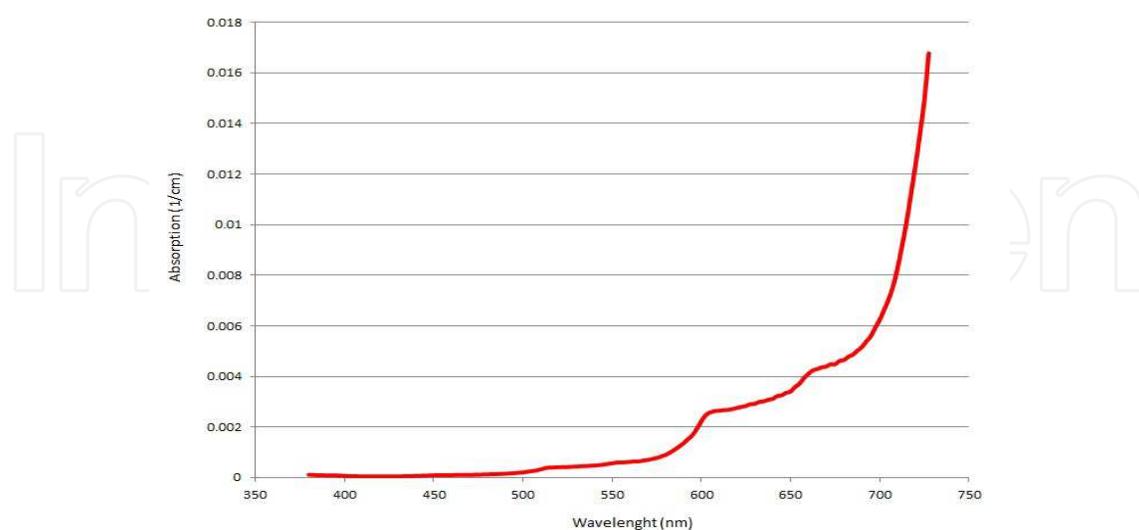


Fig. 2. Underwater Attenuation of Light from experimental data

	Acoustic	Electromagnetic	Optical
Nominal speed ( <i>m/s</i> )	$\approx 1,500$	$\approx \textit{light - speed}$	$\approx \textit{light - speed}$
Power Loss	$0.1\text{dB}/\textit{m}/\text{Hz}$	$\approx 28\text{dB}/1\text{km}/100\text{MHz}$	$\sim \textit{turbidity}$
Bandwidth	$\approx \textit{kHz}$	$\approx \textit{MHz}$	$10 - 150\text{MHz}$
Frequency band	$\approx \textit{KHz}$	$\approx \textit{MHz}$	$10^{14} - 10^{15}\text{Hz}$
Antenna size	$\approx 0.1\text{m}$	$\approx 0.5\text{m}$	$\approx 0.1\text{m}$
Effective range	$\approx \textit{km}$	$\approx 10\text{m}$	$\approx 10 - 100\text{m}$

Table 1. Comparison of Different Technologies for Underwater Wireless Communication

## 2. Underwater Wireless Communication: physical 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 ( $\sim\text{km}$ ). 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)(Lanbo et al., 2008). Compared to acoustic communication it offers a practical choice for high-bandwidth communication and it propagates faster in the water ( $2.255 \times 10^8$ ).

Nevertheless it is affected by different factors to take into account for an efficient design. 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.

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

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. A comparison between different wireless underwater technologies for underwater communication is illustrated in Table 1.

## 3. Wireless Underwater Communication Systems: analysis of the state of art

In this chapter will be briefly investigated the state of art related to underwater wireless communication.

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 Networks (WSNs), as well detailed in (Akyldiz et al., 2001) (Puccinelli & Haenggi, 2005), where a large number of small nodes communicate and work by using an optical wireless link.

### 3.1 Underwater Acoustical 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 (Akyldiz

et al., 2001) (Akyildiz et al., 2005) (Lanbo et al., 2008). 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.

Considering low-power and low-cost devices and targeting short-medium distances, the most important available products are described in (Yan et al., 2007) (Singh et al., 2006) and they can reach data-rate in the order of Kb/s.

### **3.2 Underwater Electromagnetic Communication**

As regards Electromagnetic Communication, 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 (Shelley, 2005).

In (Al-Shamma'a et al., 2004) 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) (Lucas et al., 2004). 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 (Fibre, 2008). 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 (Fibre, 2008). 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 (Shelley, 2005).

### **3.3 Optical Underwater Wireless Communication**

Underwater optical communication has been investigated both through theoretical studies (Jaruwatanadilok, 2008) (Lanbo et al., 2008) (Kedar, 2007) and in experimental tests (Feng Lu, 2009)(Hanson & Radic, 2008), 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

sea floor observatories have greatly stimulated the interest in short-range high-rate optical underwater communication.

### 3.3.1 Point-to-point Communication

In (Tivey et al., 2004) a low power and low cost underwater optical communication system is proposed by using inexpensive components. It is based on IrDa protocol and the adaptation to underwater channel is performed by replacing Infrared Communication with light generated by LEDs. Also in (Shill et al., 2004) an underwater communication system has been implemented for a swarm of submersibles. It combines 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 (Feng Lu, 2009) and (Lee et al., 2008) a low-cost (in the order of \$10) medium-range optical underwater modem is proposed. 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 (Vasilescu et al., 2007) and (Vasilescu et al., 2005) 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 (Ito et al., 2008a) 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 (Hanson & Radic, 2008) the work is motivated by the need to demonstrate error-free underwater communication at qualitatively higher data rates than previously reported with either optical or acoustic methods. In this case a Laser source is used and an error-free underwater

optical transmission measurements at 1 Gbit/s over a 2 m path in a laboratory water pipe.

In (Chancey, 2007) a short range underwater optical communication link is established by using an open source free space modem proposed by the project RONJA. Unfortunately, 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 (Ambalux, 2008), includes high-bandwidth transceivers, which allow a point-to-point transmission at a data rate of 10Mbps up to 40m, depending on environmental conditions. A set of tests based on this commercial products has been described in (Baiden & Bissiri, 2007), 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.

Recently an underwater optical wireless modem (AquaOptical)(Doniec et al., 2009) has been implemented. It is designed for integration in robotic application and allows to support a wireless communication of 2 Mb/s up to a range of 30m.

### **3.4 Diffusive underwater optical communication**

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

In (Baiden et al., 2009) the point-to-point optical communication system developed by Ambalux (Ambalux, 2008) 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 (Baiden & Bissiri, 2007), 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 (Fair et al., 2006) 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 (Farr et al., 2005). 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  $2\pi$  steradian hemisphere. Six commercially available 470nm (blue) light emitting diodes (LED) were arranged in a hemispherical geometry and encapsulated in a weakly 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 (Farr et al., 2005) 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.

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 (Liu & Ge, 2006) 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.

The here described devices show that the use of optical communication can be a feasible solutions for underwater wireless communication. In the comparison with the here proposed works, the aim of this paper is to illustrate the problems and possible solutions for the application of optical wireless communication in order to support a UWSN of dense deployed nodes as detailed in Chapter 1 and 11.

#### **4. Application of underwater optical wireless communication**

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. In particular the possibility of transferring high amount of data in a limited amount of time reducing power consumption can support the transmission of short video and pictures for a reliable monitoring and surveillance. Small dimensions and low-cost components allow to establish a dense deployed networks performing an effective fine grained sampling in the area of interest. 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.

#### **5. Design consideration for a diffuse optical underwater communication**

The design of underwater optical systems for underwater networking should takes into account different aspects which are illustrated in the next paragraphs:

- the Physical(PHY) Layer to manage the transmission and reception of data by using devoted circuits;
- the Medium Access Control(MAC) Layer to manage the possibility of more than one devices to communicate each others;
- the aspects related to the circuits design and implementation (such as choice of the Led and photodiodes and their collocation on a surface).

In the next paragraph some design consideration for each of the previous aspect will be presented and our design and implementation results will be briefly illustrated. The here described system is an based on a previous implementation illustrated in (Anguita et al., 2010) (Anguita et al., 2008) (Anguita et al., 2009) and it implements PHY and MAC Layer modules which have been described by using an Hardware Description Language (HDL), in particular VHDL (Very High Speed Hardware Description Language), as suggested in (Pang et al., 2007) (Dasalukunte & Owall, 2008) and well detailed in Chapter 6.3.

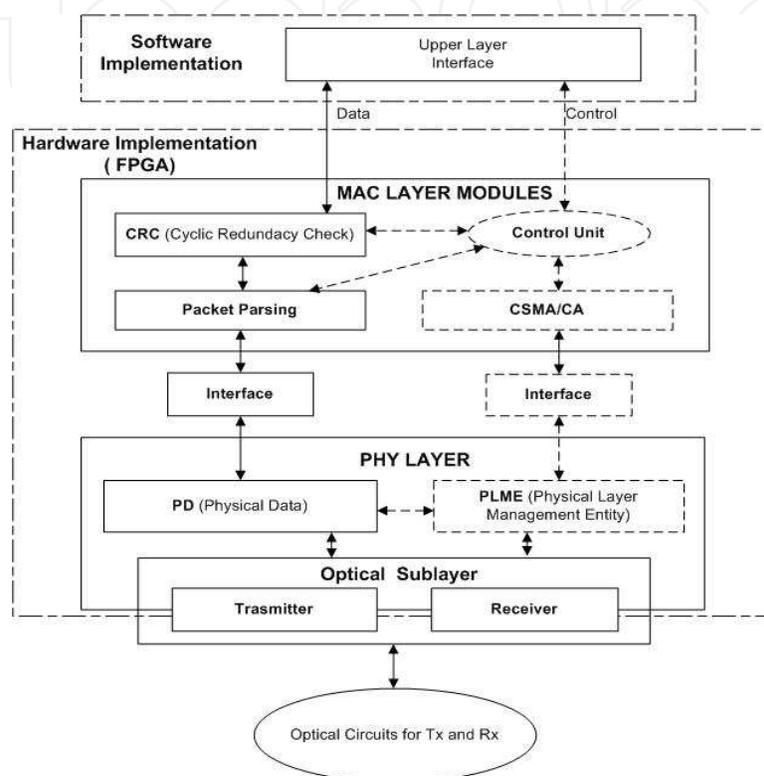


Fig. 3. General block diagram of the Optical Transmission System

## 6. The Physical Layer

The Physical Layer has to support:

1. the transmission and reception of data by using optical communication;
2. the interface with a MAC Layer of the communication stack by providing the services required by the upper layers.

In particular, the design should take into account the peculiarity of underwater channel and focus on the following elements:

1. efficient wireless optical modulation techniques;
2. adaptation to underwater channel variability;
3. adaptation to data-rate communication requirements;
4. interface with current standard used for WSN (i.e. IEEE 802.15.4).

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 2. Comparison of Various Modulations Techniques

### 6.1 Wireless optical modulation techniques

As well detailed in literature (Ghassemlooy et al., 2007) (Park & Barry, 1995) (Kahn & Barry, 1997) basic modulation techniques mainly contain three formats, such as Amplitude Modulation (ASK), Frequency Modulation (FSK) and Phase Modulation (PSK).

Taking into account previous reported studies (Lee et al., 2008), 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 (IEEE 802.11 IR) than for underwater systems (Lee et al., 2008).

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 (Meihong, Xinsheng & Zhangguo, 2009):

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

Considering the characteristics of the different modulation the Table 2 can be proposed for a comparison between different techniques ( $R_B$  is the base-band signal bandwidth).

Since the characteristics of PPM appeared to be interesting for a wide range of applications some alternative and modified PPM modulations can be considered such as Differential Pulse Position Modulation (DPPM), Pulse Interval Modulation (PIM) and Dual Header Pulse Interval Modulation (DH-PIM).

#### 6.1.1 BER vs. SNR

Considering the previous described modulations it is interesting to evaluate the Bit Error Rate versus SNR. The following results are mainly based on (Meihong, Xinsheng & Zhangguo, 2009) (Meihong, Xinsheng & Fengli, 2009). 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:

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

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

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

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

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

where  $\operatorname{erfc}$  is the complementary error function. According to (Lee & Kahn, 1999), in additive Gaussian noise channel, the bit error rate of 2FSK coherent modulation and 2DPSK coherent modulation are given by the following equations:

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

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

For the L-PPM modulation in the Gaussian white noise channel, there are many performance evaluation methods for the BER as suggested in (C.X.Fan et al., 2001) (Ma, 2003) (Malik et al., 1996). The following formula is used in (Meihong, Xinsheng & Fengli, 2009):

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

in order to show the Bit Error Rate in different SNR conditions. The 8-PPM is reported to be a good choice to reduce the BER.

### 6.1.2 Power Consumption

Also problems related to power consumption has been investigated in literature (Tivey et al., 2004) (Meihong, Xinsheng & Zhangguo, 2009) 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.

	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 3. Transfer rate versus implementation complexity from (Meihong, Xinsheng & Fengli, 2009)

- 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.
- 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:

$$\frac{1}{\sqrt{\frac{L}{2} \log_2 L}}$$

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 3.

## 6.2 Adaptation to underwater channel

As well detailed in theoretical studies (Jaruwatanadilok, 2008) (Giles & Bankman, 2005) (Smart, 2005) optical underwater transmission is deeply influenced by turbidity and the received power is highly dependent by the wavelength of transmitted signal and the dimensions of the particles and substances dissolved in water.

To overcome this problem the use of different wavelengths for transmission can improve SNR. By using visible optical communication, this results in having different colours which can be used to generate the transmitted signal. This solution has been successfully explored in (Ito et al., 2008a) where it is shown, by comparing theoretical and experimental results, that the better wavelength lies around 420 nm (blue) and increase in presence of turbidity (Chancey, 2007).

The design of the PHY Layer should take into account the possibility of switching from one colour to another considering underwater conditions; the design can be based on different parameter such as the evaluation of decrease or improvement of SNR or comparison between different transmission lines. By using a system equipped with different wavelength LEDs for transmission it could be possible to evaluate in parallel the performance of each transmission line (Diana & Kahn, 1999). The modules described in the following paragraphs, as for the channels in radio based transmission, allow the management of different transmission lines by using an ad-hoc parameter. Currently the evaluation of an automatic system is under evaluation taking into account the previous reported works.

The transmission system has to consider also the adaptation of the transmission data-rate which can be motivated both by the evaluation of underwater channel conditions and by the information which has to be transmitted. If a PPM modulation is used for the transmission the impulse duration has also a strong influence on the power consumption since power consumption increase when LEDs for transmission are activated.

An approximate evaluation of power consumption (Energy/bit) can be based on the following formula:

$$E = P \times t_{pulse} \times pulses/bit \quad (10)$$

with P the input power to the LED,  $t_{pulse}$  the time for each pulse and taking into account the number of pulses per bits.

### 6.3 PHY Layer HDL modules implementation

The PHY Layer has been completely described by using an Hardware Description Language (HDL), while a small subset of functions of the MAC Layer for testing purposes have been implemented by a software interface. The description of each module has been carried out by using an Hardware Description Language because:

1. it could easily integrated in WSN nodes 1 developed for terrestrial application equipped by a Field Programmable Gate Array (FPGA), such as the one developed by the WISI Laboratory at DIBE (WiseLab, 2010);
2. it could be used for the implementation of an ASIC/ASIP specifically devoted to manage the transmission and reception of data by using the optical. In this case the implementation of a prototype on FPGA is to be considered as a passage for simulation and optimization whose aim is then to build a specific CHIP for the management of the optical communication.

The used HDL Language is VHDL (Very High Speed Hardware Description Language). It is defined in IEEE as a tool of creation of electronics system because it supports the development, verification, synthesis and testing of hardware design, the communication of hardware design data and the maintenance, modification and procurement of hardware.

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 functions of the **Transmitter** are in synthesis:

1. the generation of a synchronization signal which is used by the transmitter in order to synchronize the impulse duration which can defined by the user;
2. a transmission signal based on PPM modulation (4 or 16 PPM) in which bits are encoded by the position of the light pulse in time slots.

The synchronization is performed by alternating 32 presences and absences of a pulse in consecutive time slots, allowing the receiver to calculate the pulse duration chosen for the following transmission of data.

The choice of PPM is based on the evaluation of the performance of different modulation schemes for underwater optical wireless communication illustrated in the previous chapter. Although most reported underwater communication systems use OOK modulation technique because of its simplicity for implementation, the proposed results argue that OOK has the disadvantages in power efficiency and control capacity of the error rate for underwater optical

channel. DPSK has good error control capability and high bandwidth, but it consumes large power and it is more complex to implement in embedded devices.

The frame format is organized as described in 4. As usual it is composed by different fields which have the following functions:

1. a Preamble composed by:
  - a field **SYNC** which is used to perform the synchronization, composed by 64 slots (32 alternating impulse of a prefixed duration), and SFR (Start Frame Delimiter) to indicate the end of the synchronization.
  - a field **DR** which is used to identify which modulation is chosen (in this case 4-PPM or 16-PPM).
2. a **Frame Length** used to communicate the number of byte in the PSDU (Physical layer Standard Data Unit) transmitted by using PPM modulation;
3. a Physical layer Standard Data Unit (**PSDU**) which is composed by the data transmitted to MAC Layer;

Preamble			Header	
SYNC	SFD	DR	Frame Length	PSDU
64 slot	4 slot	3 slot	7 bit	0-127 byte

Transmitted by PPM

Fig. 4. Frame Format

The **Receiver** has been designed to synchronize automatically with the transmitter baud rate: it determines how many clock cycles lasts a time slot for 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 by using two different methods. The first one is based on clock modification considering the truncating error made during mean calculation of the time slot duration. The second one modifies system operations by verifying that the input value is constant for the entire duration of the time slot. These methods are carefully described in the following paragraphs. The possibility of modify the duration of a single impulse can support the adaptation to different external circuits and the automatic variation of impulse duration.

Two different algorithms to maintain the synchronization have been implemented, since receiver and transmitter clocks could not be perfectly synchronised:

1. the automatic correction of time slot duration during the reception of data on the basis of the truncating error in the calculation of the time-slot period.
2. the dynamic correction by evaluating that the sampling should always be in the center of the transmitted impulse and modifying the sampling clock if this condition is not reached.

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

In this optical PHY Layer the PLME can manage the following services:

1. PLME-ED (Energy Detection) which reply by sending informations about the detect energy of the received signal (in this case the information can be received as input or a default value can be set if the detection is not supported);
2. PLME-GET read settings of the PHY Layer;
3. PLME-SET modify the settings of the PHY Layer;
4. PLME-CCA performs the CCA (clear channel assessment) and send the collected information to the MAC Layer;
5. PLME-SETTRX- STATE allows to change the internal operating state of the transceiver;
6. PLME-PPM is a specific service has been added to support the optical communication and the choice of a transmission based on 4 or 16-PPM;

The choice of the primitives, inspired to those of RF PHY Layer, have been adapted to optical communication in particular considering:

1. the management of the CCA (Clear Channel Assessment) which evaluates the current state of reception and the current state of the channel: the evaluation of this parameter is based on the state of the receiver, since, while the system is receiving, a transmission is not allowed, or on the evaluation of a period of time previously defined if;
2. the management of modulation by adding the possibility of choosing between 4-PPM and 16-PPM.
3. the adaptation of some attributes related to the state and function of the PHY Layer.

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

It is implemented by using 3 different sub-modules: the PDTR for the transmission, the PDREC for the reception and the PDSAP which allows coordination among internal sub-modules and the rest of the PHY Layer by implementing FIFO buffers. In addition it is interfaced to the MAC Layer. The PD manages four I/O interfaces to communicate through four FIFO buffers: two for upper layer (reading and writing) and two for PDTR and PDREC. This PD communicates to MAC Layer by using the same primitives structure performed in the PLME, with different codes, The operations performed by the PD does not require shared resources since the 3 modules, which have been easily optimized, can work in parallel.

The implemented PHY Layer are interfaced to the MAC modules described in the next paragraph.

## 7. The MAC Layer

### 7.1 Mac Layer Design Consideration

The previous described optical PHY Layer can be interfaced with an appropriate Multiple Access Control (MAC) module for providing addressing and channel access control mechanisms that make it possible for several network nodes to communicate within a multi-point network. As detailed in advance the idea is to support the interface with current terrestrial technologies developed for Wireless Sensor Networks based on IEEE802.15.4.

In this paragraph some considerations for the design of an hardware friendly MAC Layer are proposed taking into account the previous implemented optical PHY Layer and the current terrestrial technologies for WSN.

The current IEEE 802.15.4 standard proposes different MAC frame format (Beacon Frame format, Data and Acknowledgment frame format, MAC command frame format). The possibility of choosing the duration of the Mac Protocol Data Unit (MSPU) in the structure of the PHY Layer can easily allows the adaptation to the different format. The creation of the MSPU can be performed by using the hardware modules similar to those described in the previous paragraph (for instance in the description of the PD module).

The MAC Layer hardware implementation can be 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-SAP and the PLME-SAP, while the MAC Management Entity (MLME) should manage the different services for the Upper Layers, similarly to the PLME in the PHY Layer.

The use of optical communication allows to overcome the problems related to low propagation speed of acoustical communication which required complex access algorithms.

Considering power consumption, it is unlikely to have a continuous communication between nodes and the communication activity is not regular between the node. A good choice appears to be a competition for channel access based on a CSMA/CA protocol in which a device, when it wishes to transmit data, waits for a random number of back-off periods before sensing 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 reiterates this procedures until it either captures the channel successfully or the number of attempts exceeds the limit.

In particular, as concerns the parameters specifically related to the optical communication two main aspects will be considered:

1. the possibility of changing the wavelength of the emitter, by choosing different colors (blue, red or green) if water turbidity varies. It can be implemented, for instance, by using a mechanism such as the one described in (Ito et al., 2008b) by managing the corresponding parameters in the PHY Layer;
2. the possibility of choosing between a 4 or 16 PPM;
3. the support of an higher data rate in comparison with the Radio based technologies for WSN. For instance, the IEEE 802.15.4 can achieve 250 Kb/s and the implementation of the Optical Management modules on a dedicated FPGA or by using an ASIP/ASIC should target the synchronization with the Upper Layers of the node.

If the transmission and reception of data should be encrypted for reasons of security, and encryption module can be easily integrated in the design as suggested in (Dasalukunte & Owall, 2008).

## **7.2 MAC Layer HDL implemented modules**

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.

Currently the following functions have been implemented:

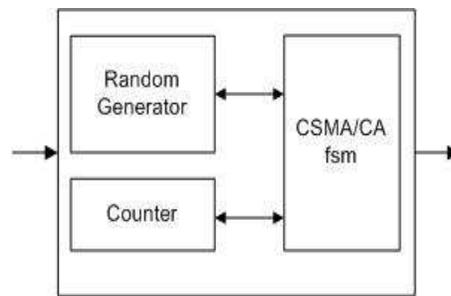


Fig. 5. CSMA-CA implementation

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 previous described CSMA/CA 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 5.

## 8. Implementation Results for PHY and MAC Layer

As a first step, the previous described modules have been synthesized and implemented on a Xilinx Spartan-3 FPGA in order to use a previously implemented testbed (Anguita et al., 2010). The second step, reported in this paper, has been the implementation an optimization of the previously described modules on an Actel IGLOO low-power FPGA in order to integrate the system in a WSN node (WiseLab, 2010)(Figure 1). A dedicated program in C# has been integrated from the previous version (Anguita et al., 2010) in order to manage the interface and to perform tests of transmission by setting different parameters of the PHY and MAC Layer (Figure 6).

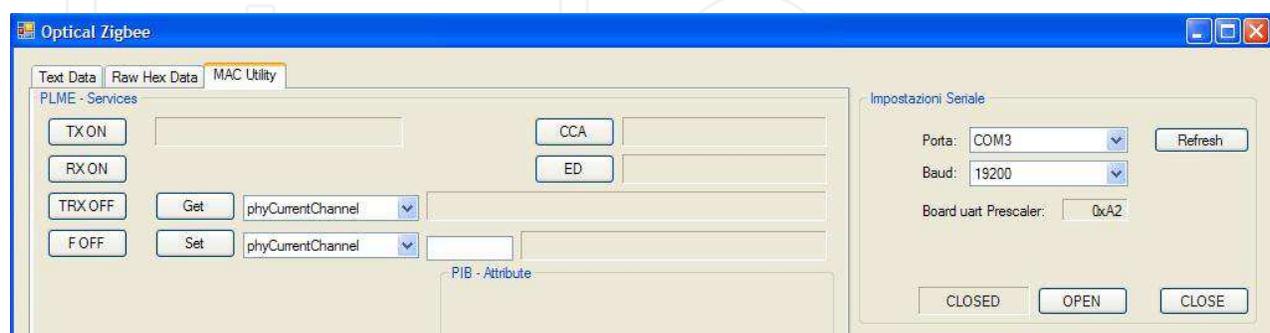


Fig. 6. User interface to optical PHY and MAC Layer

In Table 4 the results of the implementation on Actel IGLOO AGL250 are reported in terms of core cells. The maximum frequency that can be achieved by the system is 20 MHz which can support a transmission in the order of Mb/s.

Module	Core Cells	%
<b>PHY LAYER</b>	<b>2405</b>	<b>40</b>
<i>Trasmitter</i>	347	6
<i>Receiver</i>	735	12
<i>PLME</i>	442	7
<i>PD</i>	881	15
<b>MAC Layer</b>	<b>962</b>	<b>16</b>
<i>CSMA-CA</i>	601	10
<i>Packet Parsing</i>	238	4
<i>Others</i>	123	2

Table 4. Implementation on IGLOO Devices (AGLN250)

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

Table 5. Sensitivity for PDB-S5971 High-speed photodiodes and absorption coefficients

## 9. Wireless optical communication circuits

The implementation of an efficient diffuse underwater communication require the implementation of circuits for transmission and reception of light impulse. Considering the application of the communication system in a USWN the focus should be on using low-cost and low-power components targeting a low/medium distance up to 30 m. 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).

As regards the transceiver components, a careful evaluation should be performed. For the transmitter the use of LED seems to be more interesting for low cost and low power application, offering small, flexible, cheap devices which are easy to array. For the receiver, the use of PIN-photodiodes could be attractive taking into account their fast response, but also the use of photomultiplier tubes (PMT's) and avalanche photodiodes (APD's) could be consider. A presentation of both point-to-point than planar diffuse optical circuits, which have been implemented and tested, is proposed.

### 9.1 Point-to-point communication

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 8).

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

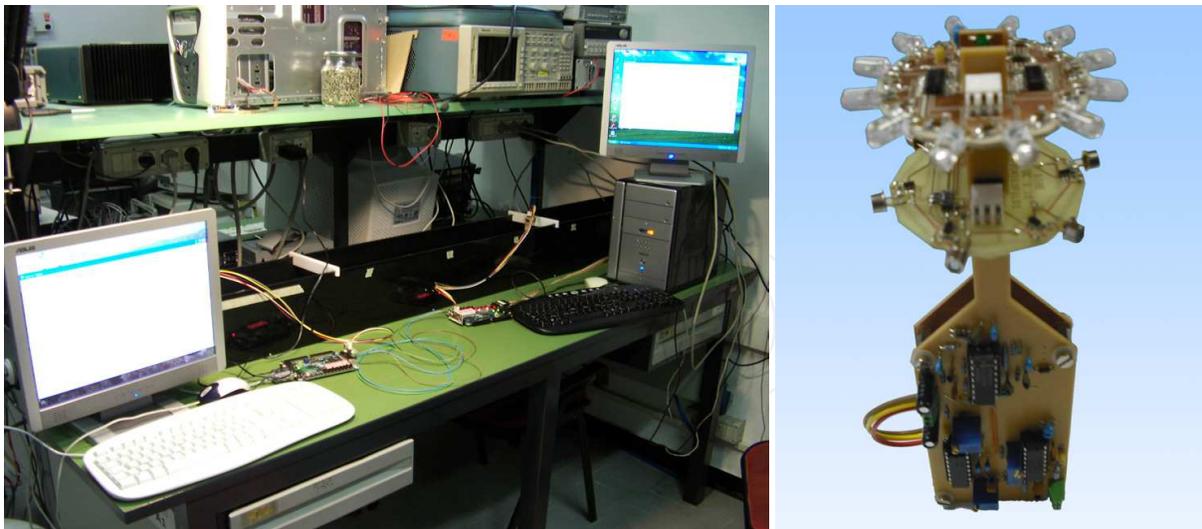


Fig. 7. Experimental set-up for point-to-point tests (a) - Bidirectional Transceiver (b)

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.

The receiver has been implemented by using the following component: Si PIN photodiode Hamamatsu S5971 - high-speed photodiodes, with  $1\text{mm}^2$  surface area. To evaluate the better wavelength for the transmitter Table 5 has been compiled considering the absorption coefficients for clear water and the photodiode sensitivity reported in the component datasheet. The output current of the photodiode is proportional to:

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

where  $S$  is sensitivity and  $P$  is the power in watts,  $d$  the distance and  $k$  the absorption coefficient. Figure 8 shows how the output current varies according to distance for different wavelengths of light, by using the equation 11.

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 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 crucial 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).

The receiver circuit has been tested in air and in water. Tests in clear water allows to receive correctly the transmitted sequence generated by the system (Figure 7) up to 2 meters: a more accurate evaluation of the BER is planned for turbid water. Considering the limitation of the available testbed, tests in air been performed at different distances: a reception of the transmitted sequence is possible starting from few centimeters, since the AGC avoids saturation, up to 10 meters, while below light impulses are not clearly detected. Even if the AGC stage has to be modified to allow the reception in case of higher distances, considering that our

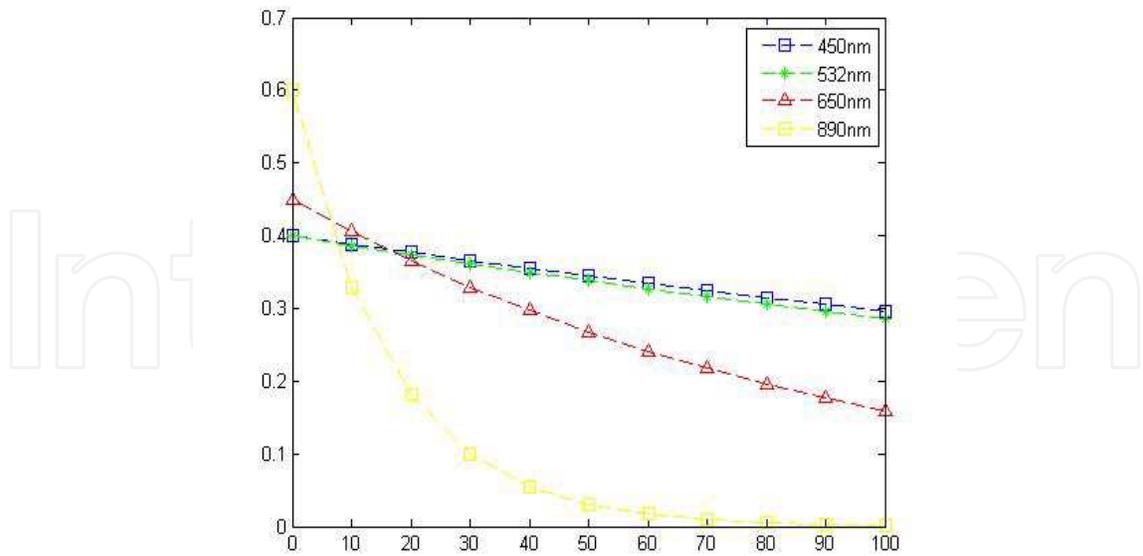


Fig. 8. Comparison between different wavelengths

target is up to 10-15 meters underwater, the tested circuit is a good starting point for further improvements.

The cost of the components is less than 30 euros, very cheap in comparison with some acoustic modem.

### 10. Design Consideration and Implementation of Planar Optical Circuits

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. Taking into account some previous works (Akella et al., 2005), in this paragraph some considerations regarding the design and implementation of a circular transceiver are reported with a preliminary implementation description.

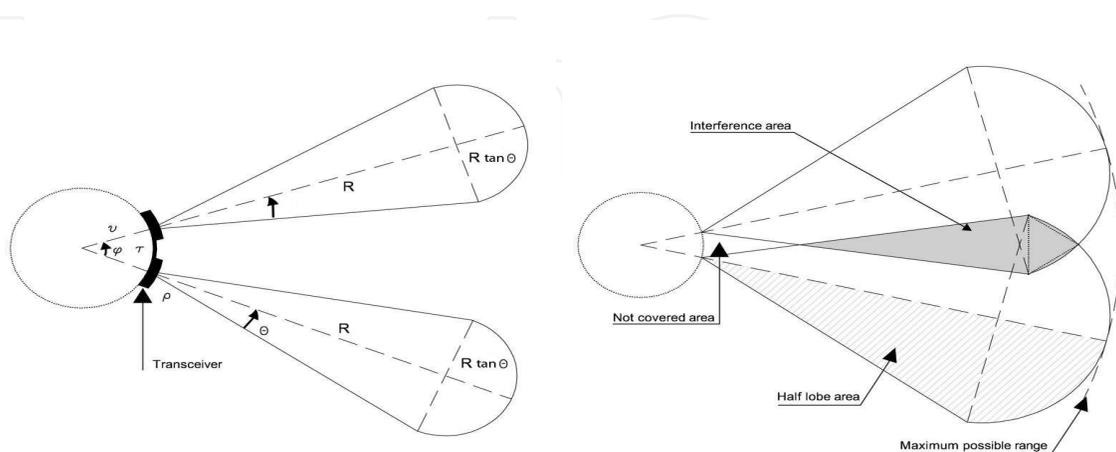


Fig. 9. Transmitter disposed to cover a 2-D circular area with (a) and without overlap (b)

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  $2\rho$ :

$$\tau = \frac{2\pi r - 2n\rho}{n} \quad (12)$$

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

$$\varphi = 360^\circ \frac{\tau}{2\pi r} \quad (13)$$

The coverage area  $L$  of a single transmitter can be given by (Akella et al., 2005):

$$L = R^2 \tan(\vartheta) + 0.5\pi R \tan(\vartheta)^2 \quad (14)$$

Two cases can happen for the effective coverage area  $C$  of a single transmitter, based on the value of  $\varphi$ ,  $\theta$ ,  $R$ , and  $r$ :

1. if coverage area of the neighbor transmitter do not overlap (Figure 9):

$$R \tan(\vartheta) \leq (R + r) \tan(0.5\varphi) \quad (15)$$

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 (Figure 9):

$$R \tan(\vartheta) > (R + r) \tan(0.5\varphi) \quad (16)$$

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 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  $30^\circ$  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.

## 11. Future Research Directions

Starting from the previous described results, the creation of an innovative long survival optical Underwater Wireless Sensor Network (UWSN) could be targeted. It will be 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 thanks 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.

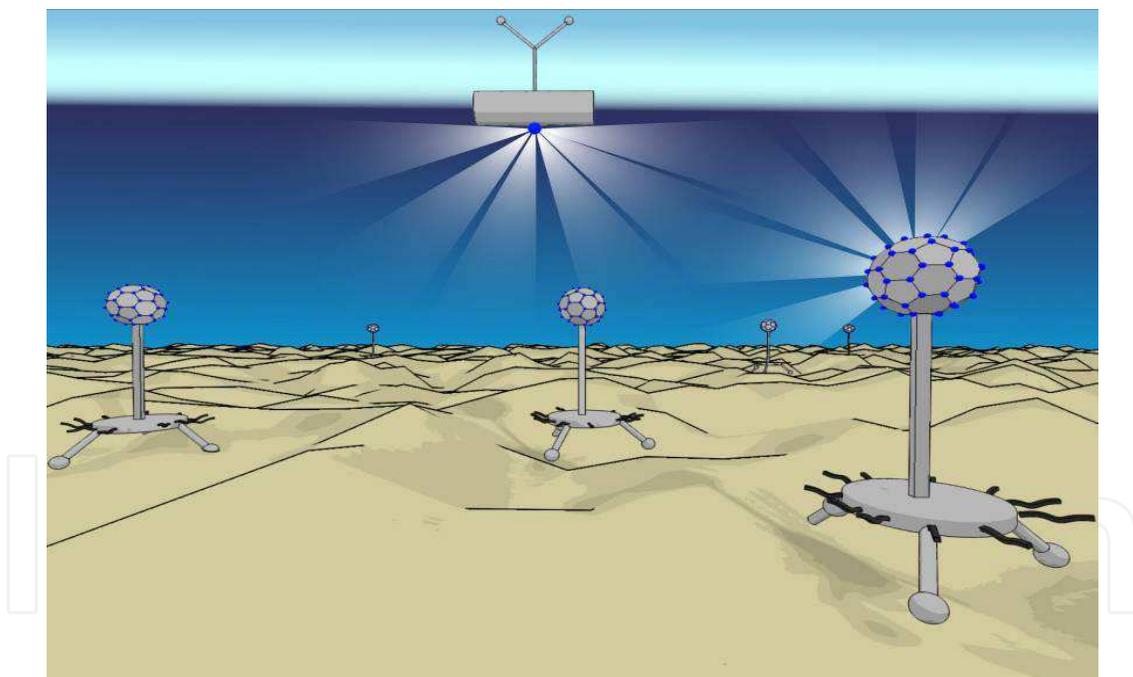


Fig. 10. optical UWSN Concept

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 (D.Zhu, 2010). The delicate equilibrium between energy harvesting, storage and consumption is to be 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 thanks 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 10.

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## **Wireless Sensor Networks: Application-Centric Design**

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Over the past decade, there has been a prolific increase in the research, development and commercialisation of Wireless Sensor Networks (WSNs) and their associated technologies. WSNs have found application in a vast range of different domains, scenarios and disciplines. These have included healthcare, defence and security, environmental monitoring and building/structural health monitoring. However, as a result of the broad array of pertinent applications, WSN researchers have also realised the application specificity of the domain; it is incredibly difficult, if not impossible, to find an application-independent solution to most WSN problems. Hence, research into WSNs dictates the adoption of an application-centric design process. This book is not intended to be a comprehensive review of all WSN applications and deployments to date. Instead, it is a collection of state-of-the-art research papers discussing current applications and deployment experiences, but also the communication and data processing technologies that are fundamental in further developing solutions to applications. Whilst a common foundation is retained through all chapters, this book contains a broad array of often differing interpretations, configurations and limitations of WSNs, and this highlights the diversity of this ever-changing research area. The chapters have been categorised into three distinct sections: applications and case studies, communication and networking, and information and data processing. The readership of this book is intended to be postgraduate/postdoctoral researchers and professional engineers, though some of the chapters may be of relevance to interested master's level students.

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