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State-of-the art and perspectives of underwater optical wireless communications

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ABSTRACT
In scientific, military, and industrial sectors, the development of robust and efficient submarine wireless communication links is of enormous interest. Underwater wireless communications can be carried out through acoustic, radio frequency (RF), and optical waves. Underwater optical communication is not a new idea, but it has recently been considered because seawater exhibits a window of reduced absorption both in the visible spectrum and long-wavelength UV light (UV-A). Compared to its bandwidth limited acoustic counterpart, underwater optical wireless communications (UOWCs) can support higher data rates at low latency levels. Underwater wireless communication networks are important in ocean exploration, military tactical operations, environmental and water pollution monitoring. Anyway, given the rapid development of UOWC technology, documents are still needed showing the state of the art and the progress made by the most current research. This paper aims to examine current technologies, and those potentially available soon, for Underwater Optical Wireless Communication and to propose a new perspective using UV-A radiation.

Section: RESEARCH PAPER

Keywords: Underwater communication; visible light communications; optical wireless communication; bidirectional communication; LED; photo detector

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1. INTRODUCTION

Underwater wireless communication (UWC) has many potential applications in the military, industrial and scientific research fields but, for practical applications, significant data bandwidth is required [1]-[3]. Generally, underwater wireless communication takes place via acoustic waves due to their relatively low attenuation. They are the normal choice in almost all commercially available submarine transmission systems.

Unfortunately, acoustic systems have low bandwidth and high latency. Therefore, they are not suitable for bandwidth-hungry underwater applications such as image and real-time video transmission. However, as acoustic transmission is the only technology capable of supporting large transmission distances, extensive studies are being conducted to improve the performance of acoustic communication channels [4]-[8]. Anyhow, acoustic underwater communication is susceptible to malicious attacks [9]. Consequently, complementary technology capable of achieving secure broadband underwater communications is required.

Wireless communication via radio frequency waves (RF) is the most widespread technology in terrestrial communications. Sadly, this technology is not suitable for underwater applications. In water, radio frequency waves are strongly attenuated, especially in seawater where the propagation medium is highly conductive [10].

For short distance communications, underwater wireless optical communication (UOWC) can be a viable alternative to that achievable via acoustic waves. This technology, even with all its limitations, can be of great use in specific applications. Although not widely used yet, this article provides the state of the art in wireless underwater optical communication. Table 1. shows a comparison of acoustic underwater wireless communication technologies vs. underwater wireless optical communication.

Optical communication is defined as communication at a distance using light to carry information. An optical fibre is the most common type of channel for optical communications, as well as the only medium that can meet the needs for enormous bandwidth in such an information age. Replacing the channel

Table 1. Comparison of underwater wireless communication technologies.

Parameter	Acoustic	Optical
Attenuation	0.1 – 4 dB/km	0.39 dB/m (ocean) 11 dB/m (turbid)
Speed	1500 ms^{-1}	2.3 × 10^8 ms^{-1}
Data Rate	kbps	Gbps
Latency	High	Low
Distance	> 100 km	≤ 500 m
Bandwidth	1 kHz–100 kHz	150 MHz
Frequency	10–15 kHz	5 × 10^{14} Hz
Power	10 W	mW – W

from an optical fiber to free space, we achieve Free Space Optical Communications [11].

Visible light communication (VLC) is a communication technology in which the visible spectrum is modulated to transmit data. Due to the propagation distance of the light emitting diodes (LEDs), the VLC is a technology for short-range communication. Pang et al. [12] first introduced the concept of using LEDs for wireless communication.

Visible-Light Communication (VLC) technology was developed to provide both lighting and data transfer with the same infrastructure [13]-[16]. VLC techniques transmit information wirelessly by rapidly pulsing visible light using Light Emitting Diodes (LEDs). Generally, the information data is overlaid on the LED light without introducing flickering. The exhaustion of low-frequency bands to cope with the exponential growth for the high-speed wireless access is another reason for exploring new technologies. The visible light spectrum is unlicensed and hardware readily available, which can be used for data transmission. Furthermore, the exponential improvement in the high-power light emitting diodes is an enabler for high data rate VLC Network. As well as VLC, underwater optical wireless communications (UOWCs) systems are currently being studied [17]-[21]. In the UOWC systems, light sources are LEDs or Laser Diodes (LDs). Both are extremely interesting. LDs for their feature higher modulation bandwidth respect to LEDs. On the other hand, LEDs, compared to LDs, have higher energy efficiency, lower cost, and longer life. LEDs seem more suitable for applications where medium transmission bit rate is required.

Compared to acoustic communication, UOWC has great potential; with it, we can make communications with high bit rate and very low latency. Currently, the performance of UOWC systems is limited to short range applications [22]. Submarine optical communication systems are starting to be commercially available [23]-[25].

In the literature, numerous studies have addressed the problem of optical transmission in water through experiments. Unfortunately, there are objective difficulties in carrying out the experiments in a real underwater environment. Most of the experimental work is done within a controlled laboratory setup. In such configurations, sunlight which induces noise and which, in some cases, saturates the light detectors is neglected.

However, in-depth studies are still necessary to create systems that can be used in real operational scenarios. Researchers are needed to allow submarine optical transmission even over medium distances (greater than 500 m). Table 1 shows the performance features (benefits, limitations, and requirements) of acoustic and optical underwater communication [26].

While, Figure 1 compares the performance of acoustics, and UOWC, based on transmission range and data rate (bandwidth) [27].

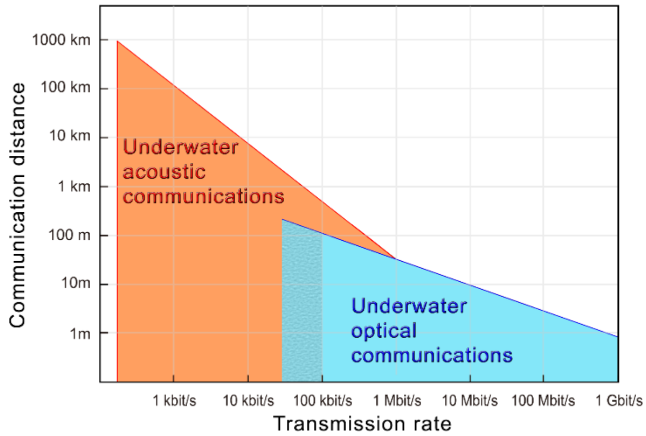

Figure 1. Compares the performance of acoustic, and UOWC, based on the transmission range and the data speed (bandwidth).

In order to provide a basic overview, we will go through and provide summary is to highlight the perspectives of UOWC technologies. The focus of this is to examine current technologies and those potentially available in the next few years, for UOWC.

The military sector where underwater optical wireless communication finds important applications, thanks to its intrinsic safety and the availability of higher bandwidth. One possible application is communication between divers. During military incursions with divers, it is very important for the command to have secure communications that are difficult to locate. Generally, underwater acoustic communications are easily detectable. In this scenario, UOWC is an excellent technology. It has the advantage that it is much more difficult to intercept. This application does not require long range and high band.

Figure 2 shows a typical UOWC military application scenario.

Another scenario is the one shown in Figure 3. It is a Dynamic Positioning Buoy [28], buoy capable of communicating with satellite and/or with a terrestrial station and with optical surveillance station positioned on the seabed.

The surveillance station can be powered by nuclear batteries [29] and in real time control, through digital optical correlation [30]-[32], if something intrudes into the monitored area. In case of suspect object (e.g., a submarine) the image and related alert is sent back to the buoy and, from it, to the ground costal station via satellite link. This application can grand a very accurate underwater video surveillance. In addition, by using UV light for

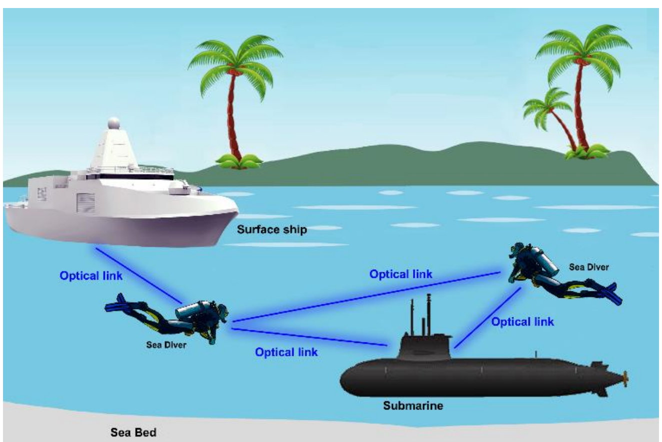

Figure 2. Typical military application scenarios of UOWC.

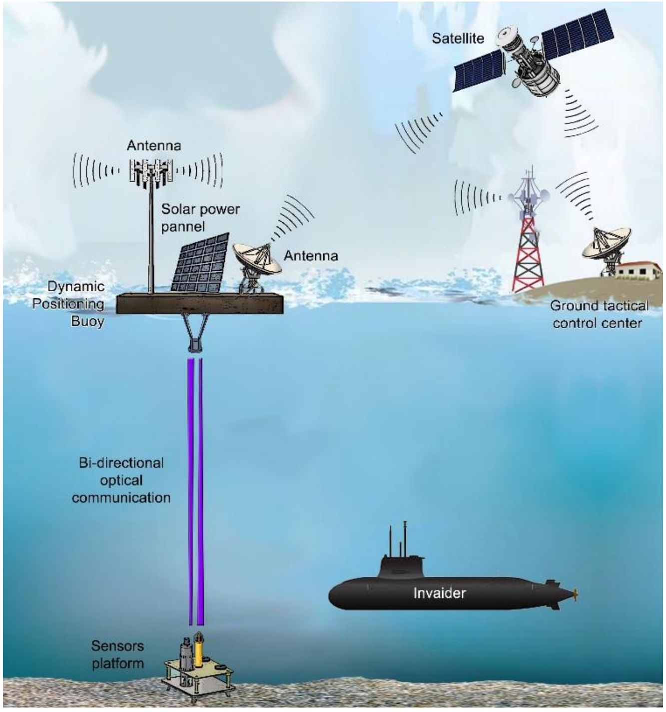

Figure 3. Underwater video surveillance scenario.

underwater optical wireless communication, the intruder has a hard time realizing that he has been detected.

In UOWC the link between transmitter and receiver can be mainly of two types [20],[26]:

- Point-to-point line-of-sight (point-to-point LOS);
- Diffuse line-of-sight (diffuse LOS) configuration.

The point-to-point LOS configuration, shown in Figure 4 (a), uses “collimated” light sources. In this arrangement, the receiver is positioned in such a way as to detect the light beam directly pointed in the direction fixed by the transmitter. In contrast, the diffuse LOS configuration uses light sources with a large divergence angle. This allows for greater flexibility in the reciprocal positioning of the transmitter and receiver, see Figure 4 (b).

Especially in military applications, where it is necessary to communicate between moving units, the diffuse line of sight configuration (diffuse LOS) must be used.

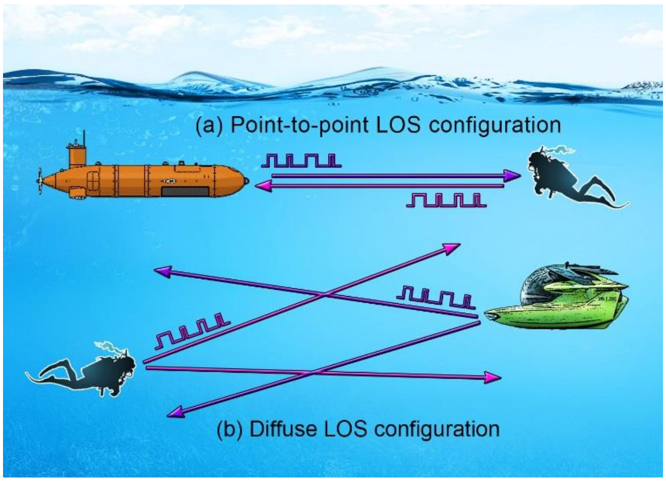

Figure 4. Examples of different underwater optical wireless link configuration.

Theoretically, in a UOWC system we could use any light source as a transmitter [33]. However, the limitations of power, size and switching speed imposed by the practical use of the system restrict the selection to two possible choices: laser diodes (LD) and light emitting diodes (LED)

Laser diodes (LD) make it possible to develop UOWC systems with a high modulation bandwidth and a high transmission power density. They generally have small angles of divergence and therefore a strong directionality. They are used in point-to-point LOS.

In most underwater communications between moving objects, it is not easy to achieve perfect alignment between transmitter and receiver. In this scenario, for a realistic application of the laser diodes, beam expansion or active alignment systems are required. This greatly complicates the design of the system. Furthermore, such systems are not very economical and often not very reliable.

Nowadays, high-brightness LEDs are available, and they represent a valid alternative to the use of laser diodes. The use of LEDs as light sources for UOWC systems offers many advantages such as long life, low energy consumption. In addition, LEDs with large divergence angles make alignment problems less stringent. Generally, LEDs are used in the diffuse LOS configuration.

By means of LEDs, it is possible to create simple and compact UOWC systems. Unfortunately, due to the large divergence angles and low modulation bandwidth, LEDs are only applicable for short-range transmissions and for applications where relatively low transmission speeds are required.

As receivers, a variety of sensors is potentially usable in UOWC [34]-[36]: Photodiode, PIN photodiode, Avalanche photo diode, Silicon photomultipliers.

2. OPTICAL TRANSMISSION IN THE AQUATIC MEDIUM

Beer’s law is commonly used to relate the absorption of diffuse light to the properties of the medium through which the light is traveling. When applied to a liquid medium, it states that the irradiance (*E*) decreases exponentially as a function of wavelength (λ) and distance (r) [37],[38]. Mathematically, we can write

$$E(\lambda, \mathrm{r}) = E_0 \cdot \exp[-K_\mathrm{d}(\lambda) \cdot r] \,, \tag{1}$$

where E_0 is the initial irradiance (in watts per square meter).

In a medium with attenuation coefficient $K_\mathrm{d}(\lambda)$, after traveling a distance r, the residual irradiance is $E(\lambda, r)$. In (1), we assume that K_d is constant along r.

The aquatic medium contains many different elements, dissolved or suspended. These components cause the spectral attenuation of the radiation. In particular, the concentration of chlorophyll is a very significant parameter for the use of optical radiation in submarine communications [39]-[41]. For this reason, a relationship between the attenuation coefficient K_d and the chlorophyll concentration was determined.

Underwater, the light shows less attenuation in the blue/green wavelength range. However, although light attenuation in seawater is minimum in the blue-green region, the optimal wavelength for underwater optical link is conditioned from the inherent optical properties of the water, which can largely vary in different geographic places.

Generally, coastal, and oceanic waters are classified according to the Jerlov water types [42]-[45]. For Jerlov coastal water types

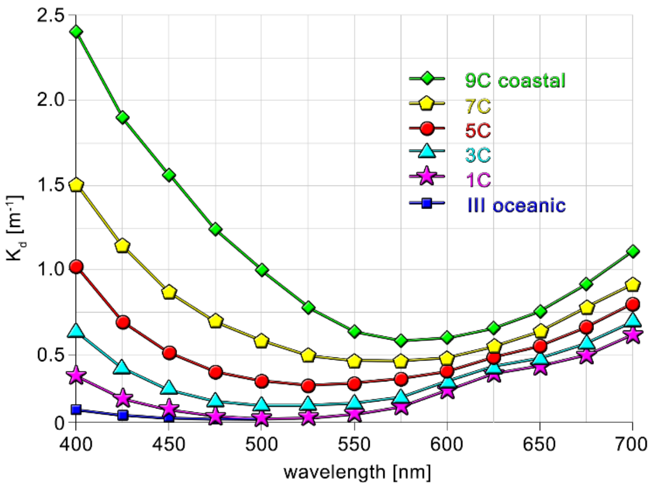

Figure 5. Diffuse light attenuation coefficient (K_d) vs. wavelength for Jerlov water types. Data from Tables XXVI and XXVII in Ref. [46].

1C, 3C, 5C, 7C, 9C and oceanic water type III, diffuse attenuation coefficients are shown in Figure 5.

Observing the Figure 5, we see that the optical signals are absorbed in water. However, seawater exhibits relatively little absorption in the blue/green region of the visible spectrum. Therefore, using wavelengths in this spectral region, high-speed connections can be attained according to the type of water. Minimum attenuation is centred near 460 nm in clear ocean waters and shifts to higher values for coastal waters.

Seawater light transmission model is shown in Figure 6.
The optical power reaching the receiver can be written as [47]-[50]:

$$P_{\mathrm{Rx}}=P_{\mathrm{Tx}}\cdot\eta_{\mathrm{Tx}}\cdot\eta_{\mathrm{Rx}}\cdot\exp\left[-\frac{K_{\mathrm{d}}(\lambda)\cdot z}{\cos\theta}\right]\cdot\frac{A_{R_x}\cdot\cos\theta}{2\,\pi\cdot z^2(1-\cos\theta_0)}, \quad (2)$$

where P_{Tx} is the transmitted power, η_{Tx} and η_{Rx} are the optical efficiencies of the Tx and Rx correspondingly, K_{d} (λ) is the attenuation coefficient, z is the perpendicular distance between the Tx plane and the Rx plane, θ_0 is the Tx beam divergence angle, θ is the angle between the perpendicular to the Rx plane and the Tx- Rx trajectory, and A_{Rx} is the receiver aperture area.

The transmitted power is limited by the energy that can be used by the transmitter apparatus. It must be as small as possible. In this way, it is possible to have low power supply; very useful in underwater applications.

Equation (2) shows that for the same energy used by the transmitter, if you want to increase the transmission distance, it is essential, among other things, to improve the efficiency of the transmitter and of the receiver.

Obviously, the transmission distance can also be increased by using reception systems capable of capturing, theoretically, even the single photon.

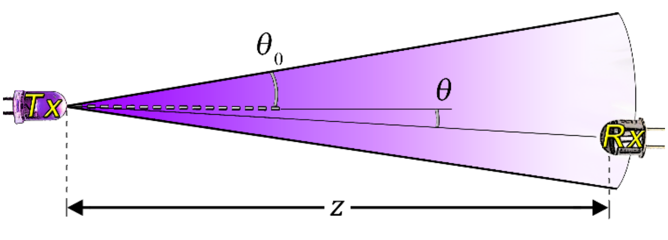

Figure 6. Seawater light transmission model.

As for light sources, technology offers increasingly efficient and reliable devices. Current light sources (Laser Diode and LED) have excellent efficiency, high reliability, low power consumption and low cost. On the contrary, as far as the receiver is concerned, there is still a lot of research work to be done.

Generally, the detected light from the receiver is small and disturbed by noise, especially if the transmission is not over a very short distance. For this reason, new error-corrected modulation systems that are relatively immune to noise must be studied, especially if we want to use submarine optical transmission with high bitrate.

3. BASIC COMPONENTS OF UOWC

An UOWC link can be schematized in three parts, the transmitter unit (Tx), the underwater channel and the receiver module (Rx). The schematic in Figure 7 shows the components of a typical system.

3.1. The Transmitter (TX)

For UOWC systems, the function of the transmitter is to transform the electrical signal in optical one, projecting the carefully aimed light pulses into the water. As already mentioned, the optical light sources are based on LED or LD one [51]–[58].

The transmitter consists of four principal components: a modulator and pulse shape circuit, a driver circuit, which converts the electrical signal into an optical signal suitable for transmission and a lens to realize the optical link configuration.

A critical parameter in optical transmission is the modulation scheme used. Different modulation schemes can be used in UOWC systems. Each varies in complexity, implementation cost, bandwidth, power consumption, noise robustness, and bit error rate (BER). Table 2 shows a summary on UOWC modulation schemes.

Typical RF modulating schemes are not applicable in VLC.

Recent UOWC studies have tried to characterize the performance of communication systems using different modulation techniques to increase together the data transmission rate and the link distance [59]–[66]. Table 1 summarizes the main modulation schemes that can be used in the UOWC [67].

3.2. The Receiver (Rx)

The receiver has the task of capturing the transmitted optical signal and transforming it into an electrical signal.

In many applications, it is important to select a specific wavelength that impacts on the light detector [86]. The light

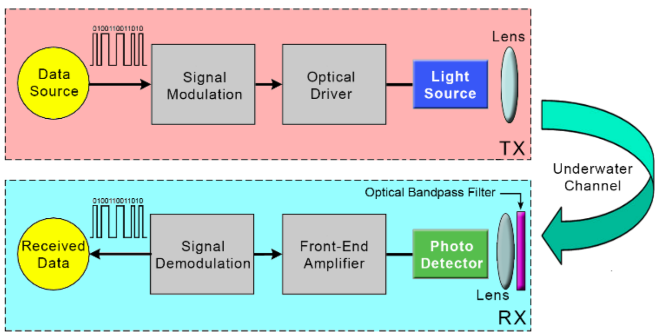

Figure 7. Schematic of a typical UOWC link. The transmitter (Tx) is composed of a modulator, optical driver, light source, and projection lens. The receiver (Rx) is made of optical bandpass filter, photodetector, Low noise electronics and demodulator.

Table 2. Summary on UOWC modulation schemes.

Modulation	Drawbacks	Advantages	Ref.
OOK-NRZ	Low energy efficiency	Simple and Low cost	[68]-[70]
PPM	High requirements on timing Low bandwidth utilization rate More complex transceivers	High power efficiency	[71]-[75]
PWM	Low power efficiency	Very good noise immunity	[20], [58]
DPIM	Error spread in demodulation Complex modulation devices	High bandwidth efficiency	[58], [76], [77]
PSK	High implementation complexity High cost	High receiver sensitivity	[78]-[80]
QAM	High implementation complexity High cost	High system spectral efficiency Better rejection on noise	[80]-[82]
PolSK	Short transmission distance Low data rate	High tolerance to underwater turbulence	[83], [84]
SIM	Complex modulation/demodulation devices and suffers from poor average power efficiency	Increase system capacity Low Cost	[85], [86]

coming on the receiver should have no noise introduced by sunlight and the presence of other light sources [87]. To try to solve this problem, the wavelength band (the one transmitted) is selected by using a narrow optical band-pass filter [88],[89].

When the receiver receives the transmitted optical signal, this provides to transform it into an electric signal by using photo detectors. There are many different types of photo detectors currently commonly used, e.g., the photodiodes. These devices, for their characteristics of small size, suitable material, high sensitivity, and fast response time, are commonly used in optical communication applications. There are two types of photodiodes: the PIN photodiode and the Avalanche Photodiode (APD).

Unfortunately, due to the high detection threshold and high noise intensity, linked to Trans-Conductance Amplifier, that limit their practical application, photodiodes are not advisable for long distance UOWC systems. For traditional detection devices and methods, due to the exponential attenuation of the water, the optical communication distance is less than 100 m [43],[90]. This constraint severely limits the performance of UOWC systems. Especially for the management of AUVs and remote-control vehicles (ROV) [91]-[95].

Recent research is focused on the possible application of Single Photon Avalanche Diodes (SPADs) technology to UOWC systems. The Avalanche Photodiodes have a similar structure to that of the PIN photodiodes and operate at a much higher reversed bias. This physical characteristic allows to a single photon to produce a significant avalanche of electrons. This way of operation is called the single-photon avalanche mode or even the Geiger's mode [96]-[98]. The great advantage of SPADs is

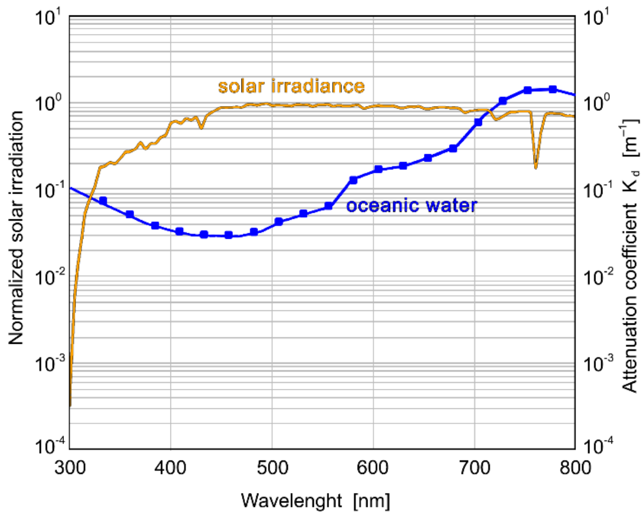

Figure 8. Solar irradiance and oceanic water diffuse light attenuation coefficient abortion. The curves show that the minimum of the optical absorption of water is aligned with the maximum of solar radiation. Since sunlight is an important source of noise, the best ratio propagated signal on solar radiation is obtained using radiation cantered around 385 nm.

that their detectors do not need to a Trans-Conductance Amplifier. This intrinsically leads that optical communications realized with this kind of diodes could provide high detection, high accuracy, and low noise measurements [99]-[108].

4. UNDERWATER COMMUNICATIONS BY UV-A RADIATION

In the literature, almost all studies do not consider the presence of sunlight. It is inevitable that UOWC systems are exposed to sunlight. Furthermore, it should be noted that the optical absorption spectrum of seawater aligns with the maximum amplitude of the solar spectrum, see Figure 8 [109].

Generally, solar intensity decreases with depth. By examining how light is absorbed in water, see Figure 5, we see that the best wavelengths to use in UOWC are 450-500 nm for clear waters and 570-600 nm for coastal waters.

This same attenuation is also true for the solar spectrum. Figure 9 shows how sunlight penetrates seawaters.

In the presence of sunlight, the receivers see very high white noise and can often go into saturation. This problem is particularly important with SPADs. Of course, in real applications, the viewing direction of the photo-sensor is also important. An upward facing detector is exposed to sunlight a few orders of magnitude greater than when facing downward or to the side.

All this, in many practical applications, makes it difficult to use the spectrum of visible light.

For this reason, submarine communication systems that use UV-A band communication channels are extremely interesting.

We must also observe two other important characteristics of optical communication that uses near ultraviolet.

(1) This communication channel is not identifiable and difficult to intercept. It is particularly attractive for military applications.
(2) Using UV radiation makes it easier to maintain alignment between transmitter and receiver [111],[112].

An important application of UOWC is underwater communication from diver-to-diver. There are commercially available audio interphones that work quite well.

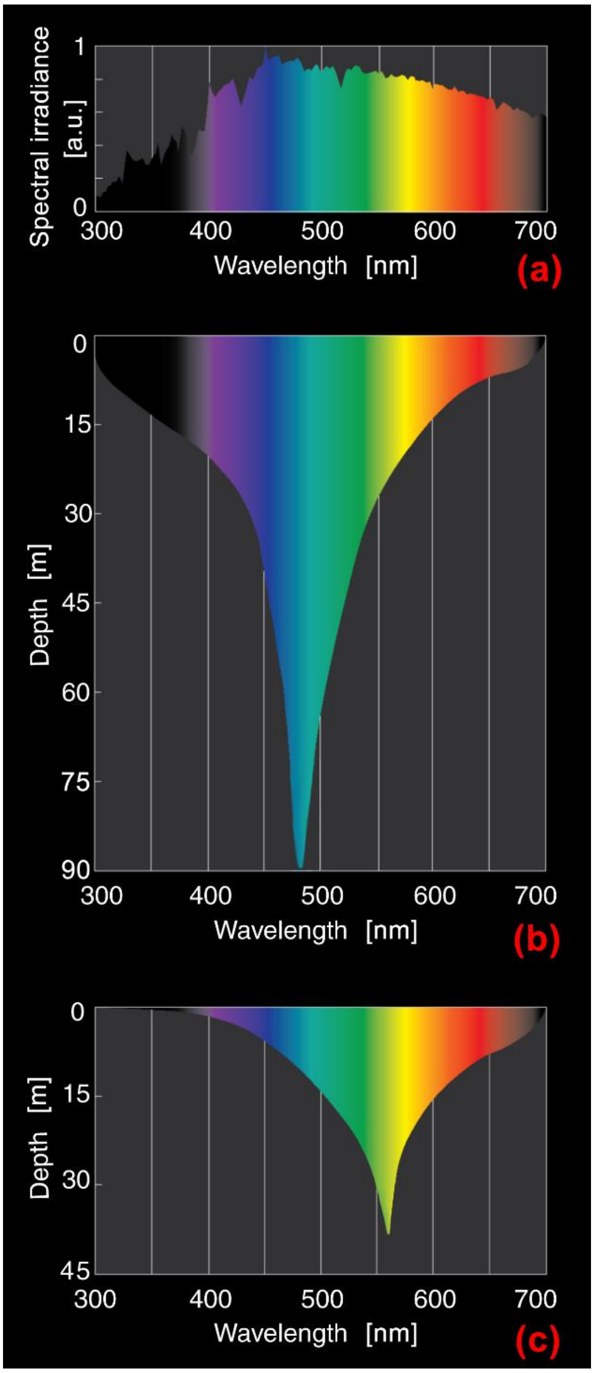

Figure 9. (a) Spectral irradiance of sunlight at the level of the sea; (b) light penetration in open ocean, (c) light penetration in coastal water. [110].

However, these systems in military tactical applications (such as raids by military divers) have the drawback of being easily identifiable.

In order to understand if a system capable of implementing a communication between divers that is not easily identifiable is feasible, some preliminary studies have been carried out.

In particular, we tried to understand if it is possible to create a compact UOWC system that requires few energy resources.

For this purpose, we tried to verify the feasibility of an optical communication made through a LED-to-LED link.

Due to the growing demand for high-power UV LEDs for commercial applications, cost-effective and efficient LEDs that emit in the near ultraviolet (UV-A) are currently available.

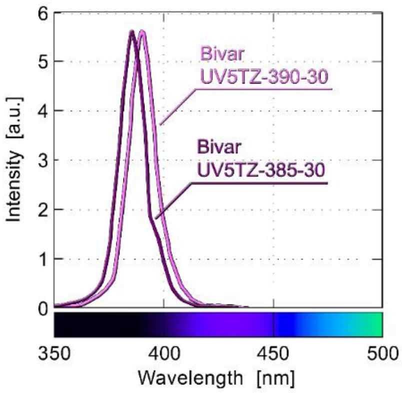

Figure 10. Spectral intensity of the LEDs used as Tx and Rx.

LEDs with emission in the range from 350 to 400 nm (UV-A) are light sources that allow you to work just beyond the visible light radiation. That is, in that region of the spectrum where most of the sunlight does not penetrate the water. This part of the spectrum is still quite close to the minimum attenuation in water. Therefore, it is useable in UOWC systems.

In addition to be excellent light sources, LEDs can be used both as temperature sensors [113] and as light detectors [114],[115]. LEDs can detect a narrow band of wavelengths, close to what they emit when used as a source.

In our experiment, we used a Bivar UV5TZ-385-30 LED as a transmitter and a Bivar UV5TZ-390-30 LED as a receiver [116]. Light intensities vs. the wavelengths of the LEDs used are shown in the Figure 10.

The two LEDs were inserted in a tank filled with real seawater (water taken from the Tyrrhenian coast - Anzio - Italy). The LEDs are placed at a distance of 50 cm and facing one towards the other.

The LED used as a transmitter was driven by the circuit shown in the Figure 11.

The LED driver shown in the figure has a restricted baud rate. The main reason is the limited switching speed of silicon devices. A maximum data rate of 100 kbps can be achieved with this driver. In any case, this speed of data transmission is more than enough to implement an excellent audio connection.

Obviously, if the driver is made with transistors made in GaN technology, data transmissions with speeds higher than 1 Mbps can be obtained [118].

Figure 12 shows the Rx LED Driver circuit.

Figure 13 shows the signal received by the LED used as light detector. The transmitter LED is polarized with 25 mA and switched with a frequency of approximately 80 kHz.

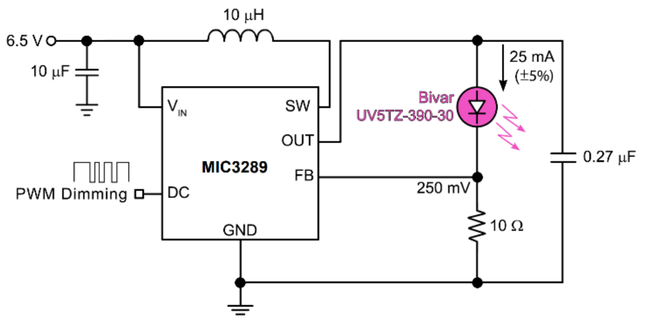

Figure 11. Tx LED driver circuit using MIC3289 PWM boost switching regulator [117].

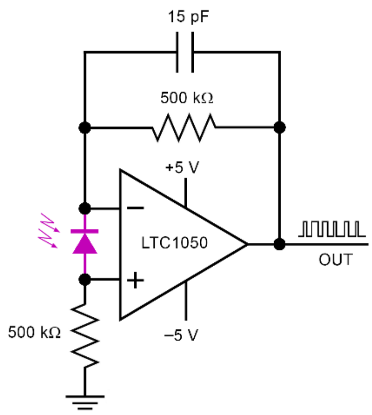

Figure 12. Rx LED Driver circuit using the LTC1050 Operational Amplifier [119].

The received signal, after traversing 50 cm of seawater, is "good". Obviously, further studies are needed to implement and characterize an underwater UV-A communication realized using the LED-to-LED link.

5. CONCLUSIONS

Recently many studies have been conducted to use UOWC technology to transmit information safely with high data rate in underwater environment. Today, UOWC systems usable in real operating conditions (with some exceptions) are not yet available. Therefore, a lot of research in this area has yet to be done. In particular:

- Currently, an inevitable phenomenon for UOWC Link is the misalignment between transmitter and receiver. To limit the impact of misalignments between transmitter and receiver, research is underway for the development of smart transceivers. However, the need to develop robust and reliable UOWC transceivers that do not require rigorous alignment is urgent.
- The design innovative modulation and coding schemes that can adapt the characterizations of underwater environment.
- Since most UOWC systems are integrated into a battery-powered platform, energy efficiency is therefore important. The systems must be designed with high energy efficiency.

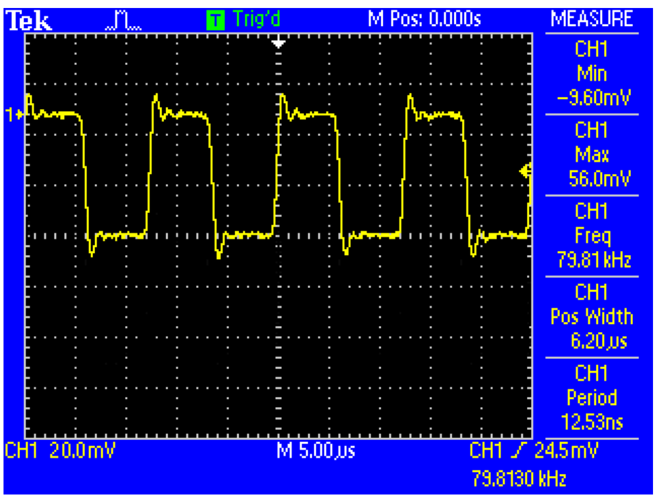

Figure 13. Receiver output signal. Rx implemented according to the circuit of Figure 12.

- Possibility of using different colored light sources at the same time to increase data transfer speed and / or allow simultaneous use by multiple users.
- Development of new underwater communication channel modeling. When environmental conditions deviate from ideality, the light signal rapidly degrades. It is essential to study the propagation of the light beam with models that simulate real conditions as much as possible (even in "difficult"" environments). All this to allow the optimization of transmission and reception techniques, both in terms of transmitter and sensor used as receiver.

Furthermore, we have presented a preliminary study to verify the feasibility of a simple, economical and reliable communication system that uses UV-A radiation. The possibility of using near ultraviolet radiation should favor the development of UOWC systems that can also be used in the presence of solar radiation.

Finally, almost all the studies available in the literature are conducted by simulation or by laboratory experiments. Studies in real marine environment are needed.

The interest in UOWC is mainly outside the academic field. In fact, the possibility to use UOWC is based on future military applications for secure Under Water Telephones (UWTs), necessary for allowing secure communications between vessels and submarines, considering the possibility to use both direct and spread light channels. In addition, the usage of Point-to-Point optical communications can allow a better usage of torpedoes, not specifically for their guidance, but for reporting sonar information back to the base station with a high rate, even in case of not wire-guided solution.

REFERENCES

[1] I. F. Akyildiz, D. Pompili, T. Melodia, Underwater acoustic sensor networks: research challenges, Ad Hoc Networks 3(3) (2005), pp. 257 – 279.
DOI: 10.1016/j.adhoc.2005.01.004

[2] C. M. G. Gussen, P. S. R. Diniz, M. L. R. Campos, W. A. Martins, F. M. Costa, J. N. Gois, A survey of underwater wireless communication technologies, J. of Commun. and Info. Sys. 31(1) (2016), pp. 242–255.
DOI: 10.14209/jcis.2016.22

[3] M. F. Ali, D. N. K. Jayakody, Y. A. Chursin, S. Affes; S. Dmitry, Recent Advances and Future Directions on Underwater Wireless Communications, Archives of Computational Methods in Engineering, pp. 1-34. 2019.
DOI: 10.1007/s11831-019-09354-8

[4] E. Demirors, G. Sklivanitis, G.E. Santagati, T. Melodia, S. N. Batalama, High-Rate Software-Defined Underwater Acoustic Modem with Real-Time Adaptation Capabilities, IEEE Access (6) (2018), pp. 18602-18615.
DOI: 10.1109/ACCESS.2018.2815026

[5] D. Centelles, A. Soriano-Asensi, J. V. Martí, R. Marín, P. J. Sanz, Underwater Wireless Communications for Cooperative Robotics with UWSim-NET, Appl. Sci. 9 (2019), 3526.
DOI: 10.3390/app9173526

[6] M. J. Bocus, A. Doufexi, D. Agrafiotis, Performance of OFDM-based massive MIMO OTFS systems for underwater acoustic communication, IET Communications 14(4) (2020), pp. 588-593.
DOI: 10.1049/iet-com.2019.0376

[7] E. Demirors, G. Sklivanitis, G.E. Santagati, T. Melodia, S. N. Batalama, High-Rate Software-Defined Underwater Acoustic Modem with Real-Time Adaptation Capabilities, IEEE Access 6, 2018, pp. 18602–18615.
DOI: 10.1109/ACCESS.2018.2815026

[8] D. Centelles, A. Soriano-Asensi, J. V. Martí, R. Marín, P. J. Sanz, Underwater Wireless Communications for Cooperative Robotics with UWSim-NET, Appl. Sci. 9(3526) (2019).
DOI: 10.3390/app9173526
[9] M. C. Domingo, Securing underwater wireless communication networks, IEEE Wireless Communications, 18, no. 1, 2011, pp. 22-28.
DOI: 10.1109/MWC.2011.5714022
[10] X. Che, I. Wells, G. Dickers, P. Kear, X. Gong, Re-evaluation of RF electromagnetic communication in underwater sensor networks, IEEE Commun. Mag. 48, no 12, 2010, pp. 143–151. DOI: 10.1109/MCOM.2010.5673085
[11] M. A. Khalighi, M. Uysal, Survey on Free Space Optical Communication: A Communication Theory Perspective, IEEE Communications Surveys & Tutorials 16(4) (2014), pp. 2231-2258. DOI: 10.1109/COMST.2014.2329501
[12] G. Pang, T. Kwan, Chi-Ho Chan, H. Liu, LED traffic light as a communications device, in Proceedings 1999 IEEE/IEEJ/JSAI International Conference on Intelligent Transportation Systems (Cat. No.99TH8383), 1999, pp. 788-793.
DOI: 10.1109/ITSC.1999.821161
[13] Z. Ghassemlooy, L. N. Alves, S. Zvanovec, M. A. Khalighi, Visible light communications: theory and applications, CRC press, Boca Raton, FL, USA, 2017.
DOI: 10.1201/9781315367330-3
[14] A. Al-Kinani, C. X. Wang, L. Zhou, W. Zhang, Optical wireless communication channel measurements and models, IEEE Commun. Surv. Tutor. 2018, 20, 2018, pp. 1939–1962.
DOI: 10.1109/COMST.2018.2838096
[15] S. U. Rehman, S. Ullah, P. H. J. Chong, S. Yongchareon, D. Komosny, Visible Light Communication: A System Perspective - Overview and Challenges, Sensors vol.19, no. 5, 2019, 1153. DOI: 10.3390/s19051153
[16] G. Schirripa Spagnolo, L. Cozzella, F. Leccese, S. Sangiovanni, L. Podestà, E. Piuzzi, Optical Wireless Communication and Li-Fi: a New Infrastructure for Wireless Communication in Saving Energy Era, 2020 IEEE International Workshop on Metrology for Industry 4.0 & IoT, Roma, Italy, 2020, pp. 674-678.
DOI: 10.1109/MetroInd4.0IoT48571.2020.9138180
[17] G. Schirripa Spagnolo, L. Cozzella, F. Leccese, Underwater Optical Wireless Communications: Overview, Sensors, 20, 2261, 2020.
DOI: 10.3390/s20082261
[18] G. Schirripa Spagnolo, L. Cozella, F. Leccese, A Brief Survey on Underwater Optical Wireless Communications, 2020 IMEKO TC-19 International Workshop on Metrology for the Sea, Naples, Italy, October 5-7, 2020, pp. 79-84. Online [Accessed 01 September 2021]
https://www.imeko.org/publications/tc19-Metrosea-2020/IMEKO-TC19-MetroSea-2020-15.pdf
[19] H.M. Oubei, C. Shen, A. Kammoun, E. Zedini, K.H. Park, X. Sun, G. Liu, C.H. Kang, T.K. Ng, N.S. Alouini, Light based underwater wireless communications, Japanese Journal of Applied Physics, 57, no. 8S2, 08PA06, 2018.
DOI: 10.7567/JJAP.57.08PA06
[20] Z. Zeng, S. Fu, H. Zang, A survey of underwater optical wireless communications, IEEE Commun. Surv. Tutorials, 19, no. 1, pp. 204–238, 2017.
DOI: 10.1109/COMST.2016.2618841
[21] B. Cochenour, K. Dunn, A. Laux, L. Mullen, Experimental measurements of the magnitude and phase response of high-frequency modulated light underwater, Appl. Opt. 56(14) (2017), pp. 4019-4024.
DOI: 10.1364/AO.56.004019
[22] D. Anguita, D. Brizzolara, G. Parodi, Building an Underwater Wireless Sensor Network Based on Optical: Communication: Research Challenges and Current Results, 2009 Third International Conference on Sensor Technologies and Applications, Athens, Greece, 2009, pp. 476-479.
DOI: 10.1109/SENSORCOMM.2009.79
[23] BlueComm Underwater Optical Communication. Online [Accessed 01 September 2021]
https://www.sonardyne.com/product/bluecomm-underwater-optical-communication-system/
[24] SA Photonics - Neptune™ FSO. Onlin [Accessed 01 September 2021]
https://www.saphotonics.com/communications-sensing/optical-communications/
[25] Shimadzu, MC100 Underwater Optical Wireless Communication Modem. Online [Accessed 01 September 2021]
https://www.shimadzu.com/news/g16mjizzgbhz3--y.html
[26] H. Kaushal, G. Kaddoum, Underwater Optical Wireless Communication, IEEE Access 4 (2016), pp. 1518–1547. DOI:10.1109/ACCESS.2016.2552538
[27] Hamamatsu, Underwater optical communications. Online [Accessed 01 September 2021]
https://www.hamamatsu.com/eu/en/applications/underwater-optical-communication/index.html
[28] Introduction to Dynamic Positioning (DP) Systems. Online [Accessed 01 September 2021]
https://safety4sea.com/wp-content/uploads/2019/12/USCG-introduction-to-dynamic-position-systems-2019_12.pdf?__cf_chl_jschl_tk__=pmd_R1lflkpH3ZcKQcOPTpdg.KHcD0hZ2GGCbGdxtKvgYgE-1630499591-0-gqNtZGzNAjujcnBszQi9
[29] I. Hamilton, N. Patel, Nuclear Batteries for Maritime Applications, Marine Technology Society Journal 53(4) (2019), pp. 26-28. DOI: 10.4031/MTSJ.53.4.5
[30] H. Ma, Y. Liu, Correlation based video processing in video sensor networks, In International Conference on Wireless Networks, Communications and Mobile Computing 2, pp. 987-992, Maui: HI, USA, 3-16 June 2005.
DOI: 10.1109/WIRLES.2005.1549547
[31] G. Schirripa Spagnolo, L. Cozzella, F. Leccese, Phase correlation functions: FFT vs. FHT, ACTA IMEKO 8(1) (2019), pp. 87-92. DOI: 10.21014/acta_imeko.v8i1.604
[32] M. Darwiesh, A. F. El-Sherif, H. S. Ayoub, Y. H. El-Sharkawy, M. F. Hassan, Y. H. Elbashar, Hyperspectral laser imaging of underwater targets, J. Opt 47, 2018, 553.
DOI: 10.1007/s12596-018-0493-7
[33] M. Kong, Y. Chen, R. Sarwar, B. Sun, Z. Xu, J. Han, J. Chen, H. Qin, J. Xu, Underwater wireless optical communication using an arrayed transmitter/receiver and optical superimposition-based PAM-4 signal, Opt. Express 26, no. 3, 2018, pp. 3087-3097. DOI: 10.1364/OE.26.003087
[34] S. Donati, Photodetectors: devices, circuits and applications, Wiley-IEEE Press; 2nd edition (January 7, 2021)
[35] S. Gundacker, A. Heering, The silicon photomultiplier: fundamentals and applications of a modern solid-state photon detector, Phys. Med. Biol. 65, 2020, 17TR01.
DOI: 10.1088/1361-6560/ab7b2d
[36] M. A. Khalighi, H. Akhouayri, S. Hranilovic, Silicon-Photomultiplier-Based Underwater Wireless Optical Communication Using Pulse-Amplitude Modulation, Journal of Oceanic Engineering 45(4), 2020, pp. 1611-1621.
DOI: 10.1109/JOE.2019.2923501
[37] H.R. Gordon, Can the Lambert-Beer law be applied to the diffuse attenuation coefficient of ocean water?, Limnology and Oceanography, 34(8) (1989), pp. 1389-1409.
DOI: 10.4319/lo.1989.34.8.1389
[38] F. Campagnaro, M. Calore, P. Casari, V. Sanjuan Calzado, G. Cupertino, C. Moriconi, M. Zorzi., Measurement-based simulation of underwater optical networks, OCEANS 2017 - Aberdeen, Aberdeen, 2017, pp. 1-7.
DOI: 10.1109/OCEANSE.2017.8084671
[39] C.F. Bohren, D.R.; Huffman, Absorption and Scattering of Light by Small Particles, Wiley: New York, NY (USA), 1988.
DOI: 10.1002/9783527618156
[40] F. A. Tahir, B. Das, M. F. L. Abdullah, M. S. M. Gismalla, Design and Analysis of Variation in Chlorophyll and Depth for Open

Ocean Underwater Optical Communication, Wireless Personal Communications, pp. 1-19, 2020.
DOI: 10.1007/s11277-020-07275-5

[41] S. K. Sahu, P. Shanmugam, A study on the effect of scattering properties of marine particles on underwater optical wireless communication channel characteristics, In OCEANS 2017: Aberdeen UK.
DOI: 10.1109/OCEANSE.2017.8084720

[42] N. G. Jerlov, Irradiance, ch. 10 in Optical Oceanography (Elsevier, 1968), pp. 115–132.
DOI: 10.1016/S0422-9894(08)70929-2

[43] J. W. Giles, I. N. Bankman, Underwater optical communications systems. Part 2: basic design considerations, MILCOM 2005 - 2005 IEEE Military Communications Conference, Atlantic City, NJ, USA, 2005, pp. 1700-1705 3.
DOI: 10.1109/MILCOM.2005.1605919

[44] J. Sticklus, P. A. Hoeher, R. Röttgers, Optical Underwater Communication: The Potential of Using Converted Green LEDs in Coastal Waters, IEEE Journal of Oceanic Engineering, 44, no. 2, pp. 535-547, April 2019.
DOI: 10.1109/JOE.2018.2816838

[45] M.G. Sticklus, C.D. Mobley, Inherent optical properties of Jerlov water types, Applied optics, 54, no. 17, 2015, pp. 5392-5401.
DOI: 10.1364/AO.54.005392

[46] N. G. Jerlov, Marine Optics, Elsevier Oceanography Series, 276, 1976.
DOI: 10.1016/S0422-9894(08)70795-5

[47] L. K. Gkoura, G. D. Roumelas, H. E. Nistazakis, H. G. Sandalidis, A. Vavoulas, A. D. Tsigopoulos, G. S. Tombras, Underwater Optical Wireless Communication Systems: A Concise Review, Turbulence Modelling Approaches - Current State, Development Prospects, Applications, Konstantin Volkov, IntechOpen, 26 July 2017.
DOI: 10.5772/67915

[48] R. A Khalil, M. I. Babar, N. Saeed, T. Jan, H. S. Cho, Effect of link misalignment in the optical-Internet of underwater things, Electronics 9(4) (2020), 646.
DOI: 10.3390/electronics9040646

[49] S. Arnon, D. Kedar, Non-line-of-sight underwater optical wireless communication network, J. Opt. Soc. Am. A 26(3) (2009), pp. 530–539.
DOI: 10.1364/JOSAA.26.000530

[50] S. Arnon, Underwater optical wireless communication network, Optical Engineering, 49, no. 1, 015001, January 2010.
DOI: 10.1117/1.3280288

[51] T. Wiener, S. Karp, The Role of Blue/Green Laser Systems in Strategic Submarine Communications, IEEE Trans. Commun. 28, 1980, pp. 1602–1607.
DOI: 10.1109/TCOM.1980.1094858

[52] C. Shen, Y. Guo, H. M. Oubei, T. K. Ng, G. Liu, K. H. Park, K. T. Ho, M. S.; Alouini, B.S. Ooi, 20-meter underwater wireless optical communication link with 1.5 Gbps data rate, Opt. Express, 24, 2016, pp. 25502–25509.
DOI: 10.1364/OE.24.025502

[53] T. Wu, Y. Chi, H. Wang, C. Tsai, G. Lin, Blue Laser Diode Enables Underwater Communication at 12.4 Gbps, Sci. Rep., 7, 2017, 40480.
DOI: 10.1038/srep40480

[54] P. Tian, X. Liu, S. Yi, Y. Huang, S. Zhang, X. Zhou, L.; Hu, L. Zheng, R. Liu, High-speed underwater optical wireless communication using a blue GaN-based micro-LED, Opt. Express 25 (2017), 1193.
DOI: 10.1364/OE.25.001193

[55] J. Sticklus, P.A. Hoeher, R. Röttgers, Optical Underwater Communication: The Potential of Using Converted Green LEDs in Coastal Waters, IEEE J. Ocean. Eng., 44, 2018, pp. 535–547.
DOI: 10.1109/JOE.2018.2816838

[56] L. Grobe, A. Paraskevopoulos, J. Hilt, D. Schulz, F. Lassak, F. Hartlieb, C. Kottke, V. Jungnickel, K.D. Langer, High-speed visible light communication systems, IEEE Commun. Mag., 51, 2013, pp. 60–66.
DOI: 10.1109/MCOM.2013.6685758

[57] K. Suzuki, K. Asahi, A. Watanabe, Basic study on receiving light signal by LED for bidirectional visible light communications, Electron. Commun. Jpn., 98, 2015, pp. 1–9.
DOI: 10.1002/ecj.11608

[58] C. Gabriel, M. A. Khalighi, S. Bourennane, P. Léon, V. Rigaud, Investigation of suitable modulation techniques for underwater wireless optical communication, In Proceedings of the International Workshop on Optical Wireless Communications, Pisa, Italy, 22 October 2012; pp. 1–3.
DOI: 10.1109/IWOW.2012.6349691

[59] H. M. Oubei, C. Shen, A. Kammoun, E. Zedini, K. H. Park, X. Sun, G. Liu, C. H. Kang, T. K. Ng, N. S. Alouini, Light based underwater wireless communications, Jpn. J. Appl. Phys., 57, 2018, 08PA06.
DOI: 10.7567/JJAP.57.08PA06

[60] J. Xu, M. Kong, A. Lin, Y. Song, X. Yu, F. Qu, N. Deng, OFDM-based broadband underwater wireless optical communication system using a compact blue LED, Opt. Comm., 369, 2016, pp.100–105.
DOI: 10.1016/j.optcom.2016.02.044

[61] C. Lu, J. Wang, S. Li, Z. Xu, 60m/2.5Gbps Underwater Optical Wireless Communication with NRZ-OOK Modulation and Digital Nonlinear Equalization, In Proceedings of the Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, USA, 5–10 May 2019; pp. 1–2.
DOI: 10.1364/CLEO_SI.2019.SM2G.6

[62] 802.15.7-2011—IEEE Standard for Local and Metropolitan Area Networks--Part 15.7: Short-Range Wireless Optical Communication Using Visible Light. IEEE 2011.
DOI: 10.1109/IEEESTD.2011.6016195

[63] N. Suzuki, H. Miura, K. Matsuda, R. Matsumoto, K. Motoshima, 100 Gb/s to 1 Tb/s based coherent passive optical network technology, J. Lightwave Technol., 36, 2018, pp. 1485–1491.
DOI: 10.1109/JLT.2017.2785341

[64] H. Ma, L. Lampe, S. Hranilovic, Integration of indoor visible light and power line communication systems, In Proceedings of the IEEE 17th International Symposium on Power Line Communications and Its Applications, Johannesburg, South Africa, 24–27 March 2013; pp. 291–296.
DOI: 10.1109/ISPLC.2013.6525866

[65] S. Dimitrov, H. Haas, Information rate of OFDM-based optical wireless communication systems with nonlinear distortion, J. Lightwave Technol., 31, 2012, pp. 918–929.
DOI: 10.1109/JLT.2012.2236642

[66] M. A. Khalighi, M. Uysal, Survey on free space optical communication: A communication theory perspective. IEEE Commun. Surv. Tutor., 16, 2014, pp. 2231–2258.
DOI: 10.1109/COMST.2014.2329501

[67] G. Napoli, J. V. M. Avilés, R. M. Prades, P. J. S. Valero, Survey and Preliminary Results on the Design of a Visual Light Communication System for Radioactive and Underwater Scenarios, In Proceedings of the 17th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2020), pp. 529-536.
DOI: 10.5220/0009889805290536

[68] S. Jaruwatanadilok, Underwater wireless optical communication channel modeling and performance evaluation using vector radiative transfer theory, IEEE Journal on selected areas in communications 26(9) (2008), pp. 1620–1627.
DOI: 10.1109/JSAC.2008.081202

[69] F. Akhoundi, J. A. Salehi, A. Tashakori, Cellular underwater wireless optical cdma network: Performance analysis and implementation concepts, IEEE Transactions on Communications 63(3) (2015), pp. 882–891.
DOI: 10.1109/TCOMM.2015.2400441

[70] Z. Wang, Y. Dong, X. Zhang, S. Tang, Adaptive modulation schemes for underwater wireless optical communication systems. WUWNet '12: Proceedings of the Seventh ACM International

Conference on Underwater Networks and Systems, November 2012 Article no. 40 pp. 1-2.
DOI: 10.1145/2398936.2398985
[71] X. He, J. Yan, Study on performance of M-ary PPM underwater optical communication systems using vector radiative transfer theory, ISAPE2012, 2012, pp. 566-570.
DOI: 10.1109/ISAPE.2012.6408834
[72] S. Tang, Y. Dong, X. Zhang, Receiver design for underwater wireless optical communication link based on APD, 7th International Conference on Communications and Networking in China, 2012, pp. 301-305.
DOI: 10.1109/ChinaCom.2012.6417495
[73] P. Swathi, S. Prince, Designing issues in design of underwater wireless optical communication system, 2014 International Conference on Communication and Signal Processing, 2014, pp. 1440-1445.
DOI: 10.1109/ICCSP.2014.6950087
[74] M. Chen, S. Zhou, T. Li, The Implementation of PPM in Underwater Laser Communication System, 2006 International Conference on Communications, Circuits and Systems, 2006, pp. 1901-1903.
DOI: 10.1109/ICCCAS.2006.285044
[75] S. Zhu, X. Chen, X. Liu, G. Zhang, P. Tian, Recent progress in and perspectives of underwater wireless optical communication, Progress in Quantum Electronics, 73, 2020, 100274.
DOI: 10.1016/j.pquantelec.2020.100274
[76] X. Mi, Y. Dong, Polarized digital pulse interval modulation for underwater wireless optical communications, OCEANS 2016 - Shanghai, 2016, pp. 1-4.
DOI: 10.1109/OCEANSAP.2016.7485450
[77] M. Doniec, D. Rus, BiDirectional optical communication with AquaOptical II, 2010 IEEE International Conference on Communication Systems, 2010, pp. 390-394.
DOI: 10.1109/ICCS.2010.5686513
[78] W. C. Cox, J. A. Simpson, J. F. Muth, Underwater optical communication using software defined radio over LED and laser based links, 2011 - MILCOM 2011 Military Communications Conference, Baltimore, MD, USA, 2011, pp. 2057-2062.
DOI: 10.1109/MILCOM.2011.612762
[79] M. Sui, X. Yu, F. Zhang, The Evaluation of Modulation Techniques for Underwater Wireless Optical Communications, 2009 International Conference on Communication Software and Networks, 2009, pp. 138-142.
DOI: 10.1109/ICCSN.2009.97
[80] B. Cochenour, L. Mullen, A. Laux, Phase Coherent Digital Communications for Wireless Optical Links in Turbid Underwater Environments, OCEANS 2007, 2007, pp. 1-5.
DOI: 10.1109/OCEANS.2007.4449173
[81] Y. Zhao, A. Wang, L. Zhu, W. Lv, J. Xu, S. Li, J. Wang, Performance evaluation of underwater optical communications using spatial modes subjected to bubbles and obstructions, Optics Letters 42(22) (2017), pp. 4699-4702.
DOI: 10.1364/OL.42.004699
[82] N. Saeed, A. Celik, T. Y. Al-Naffouri, M. S. Alouini, Underwater optical wireless communications, networking, and localization: A survey, Ad Hoc Netw., 94, 2019, 101935.
DOI: 10.1016/j.adhoc.2019.101935
[83] W. C. Cox, B. L. Hughes, J. F. Muth, A polarization shift-keying system for underwater optical communications, OCEANS 2009, Biloxi, MS, USA, 2009, pp. 1-4.
DOI: 10.23919/OCEANS.2009.5422258
[84] X. Zhang, Y. Dong, S. Tang, Polarization differential pulse position modulation. In Proceedings of UWNet '12: Seventh ACM International Conference on Underwater Networks and Systems November 2012 Article No.: 41, pp. 1–2
DOI: 10.1145/2398936.2398986
[85] G. Cossu, R. Corsini, A. M. Khalid, S. Balestrino, A. Coppelli, A. Caiti, E. Ciaramella, Experimental demonstration of high speed underwater visible light communications, 2013 2nd International Workshop on Optical Wireless Communications (IWOW), 2013, pp. 11-15.
DOI: 10.1109/IWOW.2013.6777767
[86] G. Cossu, A. Sturniolo, A. Messa, D. Scaradozzi, E. Ciaramella, Full-Fledged 10Base-T Ethernet Underwater Optical Wireless Communication System, IEEE Journal on Selected Areas in Communications, 36, no. 1, pp. 194-202, 2018.
DOI: 10.1109/JSAC.2017.2774702
[87] G. Schirripa Spagnolo, D. Papalillo, C. Malta, S. Vinzani, LED Railway Signal vs full Compliance with colorimetric Specification, Int. J. Transp. Dev. Integr., 1, no. 3, pp. 568–577. 2017.
DOI: 10.2495/TDI-V1-N3-568-577
[88] T. Hamza, M. A. Khalighi, S. Bourennane, P. Léon, J. Opderbecke, Investigation of solar noise impact on the performance of underwater wireless optical communication links. Opt. Express 24(22) (2016), pp. 25832-25845.
DOI: 10.1364/OE.24.025832
[89] J. Sticklus, M. Hieronymi, P. A. Hoeher, Effects and Constraints of Optical Filtering on Ambient Light Suppression in LED-Based Underwater Communications, Sensors 18(11) (2018), art. no. 3710.
DOI: 10.3390/s18113710
[90] T. J. Petzold, Volume Scattering Functions for Selected Ocean Waters (No. SIO-REF-72-78), Scripps Institution of Oceanography, La Jolla Ca Visibility Lab, 1972. Online [Accessed 1 September 2021]
https://apps.dtic.mil/dtic/tr/fulltext/u2/753474.pdf
[91] E. Petritoli, F. Leccese, M. Cagnetti, High accuracy buoyancy for underwater gliders: The uncertainty in the depth control, Sensors 19(8) (2019), art. No. 1831.
DOI: 10.3390/s19081831
[92] E. Petritoli, F. Leccese, High accuracy attitude and navigation system for an autonomous underwater vehicle (AUV), Acta IMEKO 7 (2018) 2, pp. 3-9.
DOI: 10.1109/10.21014/acta_imeko.v7i2.535
[93] F. Leccese, M. Cagnetti, S. Giarnetti, E. Petritoli, I. Luisetto, S. Tuti, R. Durovic-Pejcev, T. Dordevic, A. Tomašević, V. Bursić, V. Arenella, P. Gabriele, A. Pecora, L. Maiolo, E. De Francesco, G. Schirripa Spagnolo, R. Quadarella, L. Bozzi, C. Formisano, A Simple Takagi-Sugeno Fuzzy Modelling Case Study for an Underwater Glider Control System, 2018 IEEE International Workshop on Metrology for the Sea; Learning to Measure Sea Health Parameters (MetroSea), Bari, Italy, 2018, pp. 262-267.
DOI: 10.1109/MetroSea.2018.8657877
[94] M. Tabacchiera, S. Betti, S. Persia, Underwater optical communications for swarm Unmanned Vehicle Network, 2014 Fotonica AEIT Italian Conference on Photonics Technologies, Naples, Italy, 2014, pp. 1-3.
DOI: 10.1109/Fotonica.2014.6843839
[95] C. Lodovisi, P. Loreti, L. Bracciale, S. Betti, Performance analysis of hybrid optical–acoustic AUV swarms for marine monitoring, Future Internet, 10, no. 7, 2018, 65.
DOI: 10.3390/fi10070065
[96] F. Zappa, S. Tisa, A. Tosi, S. Cova, Principles and features of single-photon avalanche diode arrays, Sens. Actuators A Phys., 140, 2007, pp. 103–112.
DOI: 10.1016/j.sna.2007.06.021
[97] J. Kirdoda, D.C.S. Dumas, K. Kuzmenko, P. Vines, Z.M. Greener, R.W. Millar, M.M. Mirza, G.S.; Buller, D.J. Paul, Geiger Mode Ge-on-Si Single-Photon Avalanche Diode Detectors, In Proceedings of the 2019 IEEE 16th International Conference on Group IV Photonics (GFP), Singapore, 28–30 August 2019.
DOI: 10.1109/GROUP4.2019.8853918
[98] S. Donati, T. Tambosso, Single-photon detectors: From traditional PMT to solid-state SPAD-based technology, IEEE J. Sel. Top. Quantum Electron. 20(2014), pp. 204–211.
DOI: 10.1109/JSTQE.2014.2350836
[99] T. Shafique, O. Amin, M. Abdallah, I. S. Ansari, M. S. Alouini, K. Qaraqe, Performance analysis of single-photon avalanche diode underwater VLC system using ARQ, IEEE Photonics J. 9 (2017),

pp. 1–11.
DOI: 10.1109/JPHOT.2017.2743007
[100] R. Hadfield, Single-photon detectors for optical quantum information applications, Nat. Photon 3 (2009), pp. 696–705. DOI: 10.1038/nphoton.2009.230
[101] D. Chitnis, S. Collins, A SPAD-based photon detecting system for optical communications, J. Lightwave Technol., 32, 2014, pp. 2028–2034.
DOI: 10.1109/JLT.2014.2316972
[102] E. Sarbazi, M. Safari, H. Haas, Statistical modeling of single-photon avalanche diode receivers for optical wireless communications, IEEE Trans. Commun., 66, 2018, pp. 4043–4058.
DOI: 10.1109/TCOMM.2018.2822815
[103] M. A. Khalighi, T. Hamza, S. Bourennane, P. Léon, J. Opderbecke, Underwater wireless optical communications using silicon photo-multipliers, IEEE Photonics J., 9, 2017, pp. 1–10. DOI: 10.1109/JPHOT.2017.2726565
[104] Z. Hong, Q. Yan, Z. Li, T. Zhan, Y. Wang, Photon-counting underwater optical wireless communication for reliable video transmission using joint source-channel coding based on distributed compressive sensing, Sensors, 19, 2019, 1042. DOI: 10.3390/s19051042
[105] S. Pan, L. Wang, W. Wang, S. Zhao, An Effective Way for Simulating Oceanic Turbulence Channel on the Beam Carrying Orbital Angular Momentum, Sci. Rep. (9) (2019), pp. 1–8. DOI: 10.1038/s41598-019-50465-w
[106] M. Sait, X. Sun, O. Alkhazragi, N. Alfaraj, M. Kong, T.K. Ng, B.S. Ooi, The effect of turbulence on NLOS underwater wireless optical communication channels, Chinese Opt. Lett. 17 (2019), art. No. 100013.
DOI: 10.3788/COL201917.100013
[107] L. Zhang, D. Chitnis, H. Chun, S. Rajbhandari, G. Faulkner, D. O'Brien, S. Collins, A comparison of APD-and SPAD-based receivers for visible light communications, J. Lightwave Technol. 36 (2018), pp. 2435–2442.
DOI: 10.1109/JLT.2018.2811180
[108] C. Wang, H. Y. Yu, Y. J. Zhu, T. Wang, Y. W. Ji, Multi-LED parallel transmission for long distance underwater VLC system with one SPAD receiver, Opt. Commun., 410, 2018, pp.889–895. DOI: 10.1016/j.optcom.2017.11.069
[109] N. E. Farr, C. T. Pontbriand, J. D. Ware, L.-P. A. Pelletier, Non-visible light underwater optical communications, IEEE Third Underwater Communications and Networking Conference (UComms), Lerici, Italy, 2016, pp. 1-4.
DOI: 10.1109/UComms.2016.7583454
[110] J. Marshall, Vision and lack of vision in the ocean, Current Biology, Volume 27(11), 2017, pp. R494-R502.
DOI: 10.1016/j.cub.2017.03.012
[111] Xiaobin Sun, Wenqi Cai, Omar Alkhazragi, Ee-Ning Ooi, Hongsen He, Anas Chaaban, Chao Shen, Hassan Makine Oubei, Mohammed Zahed Mustafa Khan, Tien Khee Ng, Mohamed-Slim Alouini, Boon S. Ooi, 375-nm ultraviolet-laser based non-line-of-sight underwater optical communication, Optics express, 26(10) (2018), pp. 12870-12877.
DOI: 10.1364/OE.26.012870
[112] Xiaobin Sun, Meiwei Kong, Omar Alkhazragi, Chao Shen, Ee-Ning Ooi, Xinyu Zhang, Ulrich Buttner, Tien Khee Ng, Boon S. Ooi, Non-line-of-sight methodology for high-speed wireless optical communication in highly turbid water, Optics Communications, 461, 2020, 125264.
DOI: 10.1016/j.optcom.2020.125264
[113] G. Schirripa Spagnolo, F. Leccese, LED Rail Signals: Full Hardware Realization of Apparatus with Independent Intensity by Temperature Changes, Electronics 10 (2021), art. No. 1291. DOI: 10.3390/electronics10111291
[114] R. Filippo, E. Taralli, M. Rajteri, LEDs: Sources and Intrinsically Bandwidth-Limited Detectors, Sensors, 17, 2017, 1673.
DOI: 10.3390/s17071673
[115] G. Schirripa Spagnolo, F. Leccese, M. Leccisi, LED as Transmitter and Receiver of Light: A Simple Tool to Demonstration Photoelectric Effect, Crystals, 9, 2019, 531.
DOI: 10.3390/cryst9100531
[116] Bivar UV5TZ LEDs Datasheet. Online [Accessed 01 September 2021]
https://www.mouser.it/datasheet/2/50/biva_s_a0002780821_1-2262009.pdf
[117] MIC3289 datasheet. Online [Accessed 01 September 2021] https://ww1.microchip.com/downloads/en/DeviceDoc/mic3289.pdf
[118] C. S. A. Gong, Y. C. Lee, J. L. Lai, C. H. Yu, L. R. Huang, C. Y. Yang, The high-efficiency LED driver for visible light communication applications, Scientific reports, 6, no.1, 2016, pp.1-7.
DOI: 10.1038/srep30991
[119] LTC1050 Data sheet. Online [Accessed 01 September 2021] https://www.analog.com/media/en/technical-documentation/data-sheets/1050fb.pdf