Editorial

Underwater Optical Wireless Communications: Overview

Giuseppe Schirripa Spagnolo 1, Lorenzo Cozzella 1 and Fabio Leccese 2,*

1 Dipartimento di Matematica e Fisica, Università degli Studi “Roma Tre”, 00146 Roma, Italy; schirrip@uniroma3.it (G.S.S.); mailto:lorenzo.cozzella@uniroma3.it (L.C.)
2 Dipartimento di Scienze, Università degli Studi “Roma Tre”, 00146 Roma, Italy
* Correspondence: leccese@uniroma3.it

Received: 13 April 2020; Accepted: 14 April 2020; Published: 16 April 2020

Abstract: Underwater Optical Wireless Communication (UOWC) is not a new idea, but it has recently attracted renewed interest since seawater presents a reduced absorption window for blue-green light. Due to its higher bandwidth, underwater optical wireless communications can support higher data rates at low latency levels compared to acoustic and RF counterparts. The paper is aimed at those who want to undertake studies on UOWC. It offers an overview on the current technologies and those potentially available soon. Particular attention has been given to offering a recent bibliography, especially on the use of single-photon receivers.

Keywords: underwater optical wireless communication (UOWC); underwater communication; visible-light communications; ocean optics

1. Introduction

In order to give a basic overview for the purpose of the special issue “Underwater wireless optical communications”, we will provide a short summary to highlight the perspectives of UOWC technologies. Without pretending to be exhaustive, in this work, the main points to which research attention should be directed will be indicated.

Currently the use of wireless communications is very common in a wide range of terrestrial devices. In the underwater world, the application of wireless communications is of great interest to the military, industry, and the scientific community [1,2]. Acoustic systems have enjoyed great success underwater owing to their ability to communicate over many kilometers pushing the research in this field with the aim to further improve this technology. Extensive studies are conducted to improve the performance of the acoustic communication channels [3–7]. Nevertheless, its performance is linked to the physical nature that limits the bandwidth, causes high latency, produces high transmission losses, time varying multi-path propagation and Doppler’s spread [8–13]. These limitations do not allow autonomous underwater vehicles (AUV) to transmit real-time video in high definition via acoustic communication. Therefore, complementary technology is needed that can achieve broadband underwater communications, indeed, real-time video transmissions, including the tele-operation of underwater vehicles and remote monitoring of underwater stations, are becoming an important asset for underwater applications [14–17]. The RF waves, for their nature, are the more common and diffused technic used on terrestrial communications, but even them are not suitable underwater because, they are strongly attenuated [18]. Additionally, standard acoustic underwater communication, due to its bad performance features such as high bit error rates, large and variable propagation delays and low bandwidth, are particularly vulnerable to malicious attacks [19].

Visible-light communication (VLC) is a technology that can solve these problems. In VLC systems the visible light spectrum (400–700 nm) used for illumination is modulated to transmit...
Similar to VLC systems are underwater optical wireless communication (UOWC), systems where potential light sources are LDs instead of LEDs. Both are extremely interesting—LDs for their feature higher modulation bandwidth respect to LEDs—while the latter, due to their higher power efficiency, lower cost and longer lifetime, seem more suitable for medium bit rate applications.

Table 1 shows the performance features (benefits, limitations and requirements) of the three principal underwater communication technologies: acoustic, radio frequency and optical [27].

Table 1. Comparison of underwater wireless communication technologies.

| Parameter       | Acoustic                  | RF                           | Optical                 |
|-----------------|---------------------------|------------------------------|-------------------------|
| Attenuation     | Distance and frequency dependent (0.1–4 dB/km) | Frequency and conductivity dependent (3.5–5 dB/m) | 0.39 dB/m (ocean) 11 dB/m (turbid) |
| Speed           | 1500 m/s                  | $2.3 \times 10^8$ m/s $^{-1}$ | $2.3 \times 10^8$ m/s $^{-1}$ |
| Data Rate       | kbps                      | Mbps                         | Gbps                    |
| Latency         | High                      | Moderate                     | Low                     |
| Distance        | more than 100 km          | $\leq 10$ m                   | 10–150 m (500 m potential) |
| Bandwidth       | 1 kHz–100 kHz             | MHz                          | 150 MHz                 |
| Frequency Band  | 10–15 kHz                 | 30–300 MHz                   | $5 \times 10^{14}$ Hz  |
| Transmission    | 10 W                      | mW–W                         | mW–W                    |

Unfortunately, the performance of UOWC is currently limited to short range [28]. Therefore, even if submarine optical communication systems are beginning to be commercially available [29], extensive research is being carried out on methodologies and systems for the transfer of broadband optical signals at higher distances.

In the future many underwater applications will use optical communication. However, UOWC technologies can never totally replace acoustic communication. For this reason, studies and researcher on hybrid acoustic/optic communications are carried out [30–33]. These studies are very promising and should be investigated further.

Figure 1 illustrates a generic UOWC scenario. It shows several platforms (divers, ships, submarines, submarine sensors, etc.) connected by beams of light.
2. Optical Transmission in the Aquatic Medium

UWOC provides many technical benefits such as e.g., high rates of data transmission, secure links, but also economical ones, such as low installation and operational costs. Moreover, since the optical band is not included in the telecommunications regulations, it does not require payment of licensing fees and tariffs [34–40].

The main disadvantage of underwater optical communication is that the water is a medium that highly absorbs optical signals; the second problem is optical scattering due to the particles present in the sea. Anyway, with respect to the visible spectrum, seawater has a lower absorption in the blue/green zone. Exploiting this physical feature, working with signals with wavelengths belonging to the blue/green region of the spectrum, high-speed connections can be attained according to the type of water. Lowest attenuation is centered at 460 nm in clear waters, but this wavelength shifts to higher values in dirty waters, reaching values around to 540 nm, e.g., for coastal waters [41–46].

The bulk optical properties of water can be divided into two mutually exclusive groups: inherent and apparent [47–49]. Inherent properties describe those optical parameters that depend only on the medium and from the composition of the medium and from the particulate substances existing inside it. Instead, apparent properties are not dependent only by the medium, but are linked to the geometric structure of the illumination including therefore directional properties.

Absorption and scattering are two phenomena impairing the propagation of light in water. These effects lead to loss and deviation of light photons, respectively. Generally, to describe the propagation in water of collimated light in low scattering regimes, the spectral beam attenuation coefficient \( c(\lambda) \) is used; this parameter is wavelength function. This coefficient is a sum of the effects of the absorption coefficient and of the scattering one, respectively called \( a(\lambda) \) and \( b(\lambda) \), and so defined as [50–52]:

\[
c(\lambda) = a(\lambda) + b(\lambda)
\]

The absorption and scattering coefficients, with inverse meter units, are determined by the contribution of water molecules, particulate algal/sediment matters, and colored organic contents dissolved [53–55].

The water absorption coefficient was exhaustively measured with high accuracy from 300 nm to 700 nm, showing a minimum between 400 nm–500 nm [56–60]. Figure 2 illustrates the absorption coefficient of light in pure seawater.

![Figure 2. Absorption coefficient of pure seawater for different transmission wavelengths.](image)

Obviously, in addition to wavelength and type of particles in solution/suspension, the level of turbidity, largely affect both absorption and scattering [61]. Among the possible particles detectable in seawater, the organic ones and phytoplankton are particularly important for the optical properties of seawaters. In fact, the chlorophyll pigments of the phytoplankton present the property of strongly...
absorbing light in the blue and red spectral regions. These particles condition the seawater absorbance contributing to the formation of the scattering coefficient value [62].

Generally, both absorption and scattering limit the link distance of a UWOC system. The scattering leads a reduction in the number of photons collected by the receiver. Furthermore, in a turbid underwater environment, several photons may arrive at the receiver with delays and cause intersymbol interference (ISI) effects [63].

The values of $a(\lambda)$ and $b(\lambda)$, in addition to the wavelength, vary with the water type. Usually, for simplicity, but without loss of generality, different values of chlorophyll concentration $C$ are used to characterize the different type of waters [47,62,64,65]. In this way, the absorption coefficient $a(\lambda)$ and the scattering coefficient $b(\lambda)$ can be expressed as a function of the wavelength $\lambda$ and of the concentration $C$ [66]:

$$a(\lambda)=[a_w(\lambda)+0.06a_c(\lambda)C^{0.65}](1 + 0.2\exp[-0.014(\lambda-440)])$$  \hspace{1cm} (2)

$$b(\lambda)=0.30 \frac{550}{\lambda} C^{0.62}$$  \hspace{1cm} (3)

where $a_w$ points out the pure water absorption coefficient while, $a_c$ is a nondimensional number, statistically derived that points out the absorption coefficient specific for the chlorophyll. Therefore, the chlorophyll concentration $C$, expressed in mg·m$^{-3}$, can be used as the free parameter to calculate $a(\lambda)$ and $b(\lambda)$.

The measured values for the absorption $a(\lambda)$, for the total scattering $b(\lambda)$ and for the extinction $c(\lambda)$ are outlined in Table 2 [19,43,56]; usually four major seawater types are considered. It is important to note that the absorption measurements have been obtained in a spectral band with $\lambda$ centered at 532 nm.

Table 2. Typical values of $a(\lambda)$, $b(\lambda)$ and $c(\lambda)$ for different water type; work out with $\lambda = 532$ nm.

| Water types               | C (mg/m$^3$) | $a(\lambda)$ (m$^{-1}$) | $b(\lambda)$ (m$^{-1}$) | $c(\lambda)$ (m$^{-1}$) |
|---------------------------|--------------|-------------------------|-------------------------|-------------------------|
| Pure sea water            | 0.005        | 0.053                   | 0.003                   | 0.056                   |
| Clear ocean water         | 0.31         | 0.069                   | 0.08                    | 0.151                   |
| Coastal ocean water       | 0.83         | 0.088                   | 0.216                   | 0.305                   |
| Turbid harbor water       | 5.9          | 0.295                   | 1.875                   | 2.170                   |

Beer’s law is commonly used to describe the propagation loss factor ($L_P$) as a function of wavelength ($\lambda$) and distance ($z$). The propagation loss factor [67–70]:

$$L_P(\lambda, z) = h \cdot \exp[-c(\lambda) \cdot z]$$  \hspace{1cm} (4)

In Equation (4), $c(\lambda)$ represents the cumulative attenuation coefficient as defined in Equation (1), while $h$ is a constant. Unfortunately, the Beer’s Law disregards the indirect paths and, obviously, with the increase of the distance, the multiple scattering conditions the channel losses while, some photons that run through these non-line of sight paths may arrive to the receiver causing errors of interpretation. Respect to the Beer’s Law model, a function with two exponentials more accurately approximates the power loss for long distance underwater channel. A first exponential considers the attenuation loss length less than the diffusion length and another one greater than the diffusion length. Therefore, Equation (4) can be rewritten as [71]:

$$L_P(\lambda, z) = h_1 \cdot \exp[-c_1(\lambda) \cdot z] + h_2 \cdot \exp[-c_2(\lambda) \cdot z]$$  \hspace{1cm} (5)

Currently, a theoretical model capable of describing long distance optical communication in a practical underwater environment is not available.
In ocean water, the performance of an underwater optical communication system is mainly limited by oceanic turbulence, which is defined as the fluctuations in the index of refraction resulting from temperature and salinity variations. By means of the Monte Carlo method, it is possible to implement a complete “model” to evaluate also the propagation through weak oceanic turbulence [72–81]. In any case, the characterization of the transmission channel model is a critical point for the development of the UWOC systems. Therefore, continuous studies and research are necessary to obtain models that always better adapt to real conditions. In Equation (5), the parameters $h_1$, $c_1$, $h_2$, and $c_2$ can be calculated by the least mean square fitting algorithm; example of computed parameters by means of Monte Carlo simulation is shown in Table 3 [82,83].

**Table 3.** Example of Optical Parameters for Different Types of Water; work out with $\lambda=532$ nm.

| Wavelength (nm) | $C$ (mg/m³) | $h_1(\lambda)$ (m⁻¹) | $c_1(\lambda)$ (m⁻¹) | $h_2(\lambda)$ (m⁻¹) | $c_2(\lambda)$ (m⁻¹) |
|----------------|-------------|----------------------|----------------------|----------------------|----------------------|
| Pure sea water | 0.005       | 0.2000               | 0.0657               | 0.0046               | 0.2634               |
| Clear ocean water | 0.31       | 0.1000               | 0.1508               | 0.1589               | 0.4937               |

As said, 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. Figure 3 shows typical attenuation (dB/m) versus wavelength for various ocean waters [50,84].

![Figure 3. Attenuation in dB/m for different ocean waters.](image)

3. **Basic Components of Underwater Optical Wireless Communications (UOWCs)**

A UOWC link can be schematized in three parts, the transmitter unit, the water channel and the receiver module. The schematic in Figure 4 shows the components of a typical system.
3.1. The Transmitter (TX)

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

The modulator and pulse shape are critical points of the system. Recent UOWC studies have tried to characterize the performance of communication systems using different modulation techniques in order to increase together the data transmission rate and the link distance [85–87]. Typical RF modulating schemes are not applicable in VLC. The three modulation schemes standardized by IEEE [88–91] are OOK, IM-DD and CSK. Among them, the easiest applicable to the UOWC schema is the non-return zero with OOK (NRZ OOK), which is binary code where “1” is represented by a light pulse while “zero” means no pulses. IM-DD is a transmission scheme in which the intensity of the optical source is modulated by the signal, and the demodulation is achieved through direct detection of the optical carrier and conversion using a photo-detector. Color shift keying (CSK) is a visible light communication (VLC) modulation scheme, designed for multi-color light emitting diodes (LEDs), so it is not applicable in a UOWC.

In addition to the previous ones, orthogonal frequency division multiplexing (OFDM) is used in multiple sub-carrier modulation (MSM) techniques. MSM techniques are applicable for scenarios where single transmitter provides homogenous transmission of data to several receivers. In MSM, OFDM symbols are modulated onto individual sub-carriers which combine to modulate onto instantaneous power of the transmitter due to orthogonality of sub-carriers. Different OFDM schemas exist for UOWC, such as QPSK and QAM [92,93].

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. The optical light sources are based on LED or LD one [94–102].

In underwater optical communication, the connection between transmitter and receiver can be of two main types (see Figure 5) [20,51]: (a) diffuse line-of-sight (diffuse LOS) configuration; (b) point-to-point line-of-sight (LOS) configuration.
Diffused LOS configurations use diffused light sources, such as high-power, highly efficient LEDs. They present large divergence angles to permit broadcasting UOWC from one node (the transmitter) to more receiver nodes as shown in Figure 5a. This configuration, due to the wide interaction volume light-water, is very sensitive to the attenuation caused by the water. This leads to relatively short communication distance and low transmission data rate. These are the two more important disadvantageous of this configuration.

The point-to-point LOS configuration well shown in Figure 5b is the more common link configuration used in UOWCs [103,104]. In this arrangement, the receiver is placed in such a way to detect the light beam directly aimed in the direction fixed by the transmitter. Obviously, since these systems commonly use light sources with narrow divergence angles, typically lasers, they require precise pointing between TX and RX. This constraint can strongly limit the performance of UOWC systems in case of turbulent water environments and can cause heavy problems when the transmitter and the receiver are non-stationary nodes; this case is particularly felt for AUVs and remotely operated vehicles (ROVs) [105,106].

The diffused LOS configuration is well suited for short-range transmission between moving objects. On the other hand, the point-to-point LOS configuration is preferred over long distances and when precise aiming between TX and RX is possible.

In order to implement these link configurations, it is necessary to use suitable projection system that employ lens groups. In order to expand the UOWC covered area and improve the system performance, various transmission schemes can be used [107–113].

Recent studies are aimed at developing systems where a narrow-beam from an underwater vehicle is “exactly” pointed towards the receiving terminal of a second underwater vehicle. In these systems, the transmitting module implements a scan function that allows the communication channel to remain active even with TX and RX in motion [114,115].

3.2. The Receiver (RX)

In many applications it is important to select a specific wavelength that impacts on the light detector [116]. The light reaching the receiver should have no noise introduced by sunlight and avoid the presence of other light sources [117]. To try to solve this problem, the wavelength band (the one transmitted) is selected by using a narrow optical band-pass filter [118].

When the receiver receives the transmitted optical signal, it transforms it into an electric signal by using photodetectors. Many different types of photodetectors are currently commonly used, e.g., 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 the 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 [56,70].

Recent studies are focused on the possible application of single photon avalanche diodes (SPADs) technology to UOWC systems. Avalanche photodiodes have a similar structure as PIN ones but operate at a much higher reversed bias. This physical characteristic allows a single photon to produce a significant avalanche of electrons. This mode of operation is called the single-photon avalanche mode or Geiger’s mode [87,88]. The great advantage of SPADs is that their detectors do not need to a trans-conductance amplifier. This intrinsically leads to the fact that optical communications implemented with this kind of diodes can provide high detection, high accuracy and low noise measurements [119–132]. RX sensors based on SPADs still require further in-depth studies. For these systems, it is important to check the immunity to external disturbances and develop specific modulation schemes.
4. Conclusions

Underwater Optical Wireless Communication (UOWC) has recently emerged as a unique technology facilitating high data rates and moderate distance communication in undersea environments. Many applications with large amount of data such as real-time video transmission and control of remotely operated vehicles could greatly benefit from UOWC. Nowadays, UOWC systems usable under real operating conditions are rarely available, therefore a lot of research in this area has yet to be done.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Gussen, C.M.G.; Diniz, P.S.R.; Campos, M.L.R.; Martins, W.A.; Costa, F.M.; Gois, J.N. A survey of underwater wireless communication technologies. J. Commun. Info. Syst. 2016, 31, 242–255, doi:10.14209/jcis.2016.22.
2. Ali, M.F.; Jayakody, D.N.K.; Chursin, Y.A.; Affes, S.; Dmitry, S. Recent Advances and Future Directions on Underwater Wireless Communications. Arch. Comput. Methods Eng. 2019, 1–34, doi:10.1007/s11831-019-09354-8.
3. Li, B.; Huang, J.; Zhou, S.; Ball, K.; Stojanovic, M.; Freitag, L.; Willett, P. MIMO-OFDM for high-rate underwater acoustic communications. IEEE J. Ocean. Eng. 2009, 34, 634–644, doi:10.1109/JOE.2009.2032005.
4. Zhou, S.; Wang, Z. OFDM for Underwater Acoustic Communications; John Wiley & Sons: Hoboken, NJ, USA, 2014, doi:10.1002/9781118693865.
5. Qiao, G.; Babar, Z.; Ma, L.; Liu, S.; Wu, J. MIMO-OFDM underwater acoustic communication systems—A review. Phys. Commun. 2017, 23, 56–64, doi:10.1016/j.phycom.2017.02.007.
6. Bocus, M.J.; Agrafiotis, D.; Doufexi, A. Real-time video transmission using massive MIMO in an underwater acoustic channel. In Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), Barcelona, Spain, 15–18 April 2018; pp. 1–6, doi:10.1109/WCNC.2018.8376952.
7. Bocus, M.J.; Doufexi, A.; Agrafiotis, D. Performance of OFDM-based massive MIMO OTFS systems for underwater acoustic communication. IET Commun. 2020, 14, 588–593, doi:10.1049/iet-com.2019.0376.
8. Stojanovic, M.; Preisig, J. Underwater Acoustic Communication Channels: Propagation Models and Statistical Characterization. IEEE Commun. Mag. 2009, 84–89, doi:10.1109/MCOM.2009.4752682.
9. Chitre, M.; Shahabudeen, S.; Freitag, L.; Stojanovic, M. Recent advances in underwater acoustic communications & networking. In Proceedings of the OCEANS 2008, Quebec City, QC, Canada, 15–18 September 2008, doi:10.1007/978-0-387-78928-2.
10. Melodia, T.; Kulhandjian, H.; Kuo, L.C.; Demirors, E. Advances in Underwater Acoustic Networking. In Mobile Ad Hoc Networking: Cutting Edge Directions, 2nd ed.; Chapter 23; Basagni, S., Conti, M., Giordano, S., Stojmenovic, I., Eds.; Wiley: New York, NY, USA, 2013; pp. 804–852, doi:10.1002/9781118511305.ch23.
11. Demirors, E.; Sklivanitis, G.; Santagati, G.E.; Melodia, T.; Batalama, S.N. High-Rate Software-Defined Underwater Acoustic Modem with Real-Time Adaptation Capabilities. IEEE Access 2018, 6, 18602–18615, doi:10.1109/ACCESS.2018.2815026.
12. Centelles, D.; Soriano-Asensi, A.; Marti, J.V.; Marín, R.; Sanz, P.J. Underwater Wireless Communications for Cooperative Robotics with UWSim-NET. Appl. Sci. 2019, 9, 3526, doi:10.3390/app9173526.
13. Santos, R.; Orozco, J.; Micheletto, M.; Ochoa, S.; Meseguer, R.; Millan, P.; Molina, C. Real-Time Communication Support for Underwater Acoustic Sensor Networks. Sensors 2017, 17, 1629, doi:10.3390/s17071629.
14. Doniec, M.; Xu, A.; Rus, D. Robust Real-Time Underwater Digital Video Streaming using Optical Communication. In Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), Karlsruhe, Germany, 6–10 May 2013, doi:10.1109/ICRA.2013.6631308.
15. Al-Halafi, A.; Oubei, H.M.; Ooi, B.S.; Shibada, B. Real-Time Video Transmission Over Different Underwater Wireless Optical Channels Using a Directly Modulated 520 nm Laser Diode. J. Opt. Commun. Netw. 2017, 9, 826–832, doi:10.1364/JOCN.9.000826.
16. Ribas, J.; Sura, D.; Stojanovic, M. Underwater wireless video transmission for supervisory control and inspection using acoustic OFDM. In Proceedings of the OCEANS 2010, Seattle, WA, USA, 20–23 September 2010, doi:10.1109/OCEANS.2010.5663839.
17. Han, S.; Chen, R.; Noh, Y.; Gerla, M. Real-time video streaming from mobile underwater sensors. In Proceedings of the UWUNET ’14, the International Conference on Underwater Networks & Systems, Rome, Italy, 12–14 November 2014; pp. 1–8, doi:10.1145/2671490.2674582.

18. Che, X.; Wells, I.; Dickers, G.; Kear, P.; Gong, X. Re-evaluation of RF electromagnetic communication in underwater sensor networks. IEEE Commun. Mag. 2010, 48, 143–151, doi:10.1109/MCOM.2010.5673085.

19. Domingo, M.C. Securing underwater wireless communication networks. IEEE Wireless Commun. 2011, 18, 22–28, doi:10.1109/MWC.2011.5714022.

20. Zeng, Z.; Fu, S.; Zang, H.; Dong, Y.; Cheng, J. A survey of underwater optical wireless communications, IEEE Commun. Surv. Tutor. 2017, 19, 204–238, doi:10.1109/COMST.2016.2618841.

21. Johnson, L.J.; Jasman, F.; Green, R.J.; Leeson, M.S. Recent advances in underwater optical wireless communications. Underw. Technol. 2014, 32, 167–175, doi:10.3723/ut.32.167.

22. Saeed, N.; Celik, A.; Al-Naffouri, T.Y.; Alouini, M.S. Underwater optical wireless communications, networking, and localization: A survey. Ad Hoc Netw. 2019, 94, 101935, doi:10.1016/j.adhoc.2019.101935.

23. Wang, J.Y.; Liu, C.; Wang, J.B.; Wu, Y.; Lin, M.; Cheng, J. Physical-layer security for indoor visible light communications: Secrecy capacity analysis. IEEE Trans. Commun. 2018, 66, 6423–6436, doi:10.1109/TCOMM.2018.2859943.

24. Wang, J.Y.; Ge, H.; Lin, M.; Wang, J.B.; Dai, J.; Alouini, M.S. On the secrecy rate of spatial modulation-based indoor visible light communications. IEEE J. Sel. Areas Commun. 2019, 37, 2087–2101, doi:10.1109/JSAC.2019.2929403.

25. Al-Kinani, A.; Wang, C.X.; Zhou, L.; Zhang, W. Optical wireless communication channel measurements and models. IEEE Commun. Surv. Tutor. 2018, 20, 1939–1962, doi:10.1109/COMST.2018.2838096.

26. Rehman, S.U.; Ullah, S.; Chong, P.H.J.; Yongchareon, S.; Komosny, D. Visible Light Communication: A System Perspective—Overview and Challenges. Sensors 2019, 19, 1153, doi:10.3390/s19051153.

27. Kaushal, H.; Kaddoum, G. Underwater Optical Wireless Communication. IEEE Access 2016, 4, 1518–1547, doi:10.1109/ACCESS.2016.2552538.

28. Cochenour, B.; Dunn, K.; Laux, A.; Mullen, L. Experimental measurements of the magnitude and phase response of high-frequency modulated light underwater. Appl. Opt. 2017, 56, 4019–4024, doi:10.1364/AO.56.004019.

29. BlueComm Underwater Optical Communication. Available online: https://www.sonardyne.com/product/bluecomm-underwater-optical-communication-system/ (accessed on 15 April 2020).

30. Moriconi, C.; Cupertino, G.; Betti, S.; Tabacchiera, M. Hybrid acoustic/optic communications in underwater swarms. In Proceedings of the OCEANS 2015, Genova, Italy, 18–21 May 2015, doi:10.1109/OCEANS-Genova.2015.7271401.

31. Han, S.; Noh, Y.; Lee, U.; Gerla, M. Optical-acoustic hybrid network toward real-time video streaming for mobile underwater sensors. Ad Hoc Netw. 2019, 83, 1–7, doi:10.1016/j.adhoc.2018.08.020.

32. Yin, H.; Li, Y.; Xing, F.; Wu, B.; Zhou, Z.; Zhang, W. Hybrid Acoustic, Wireless Optical and Fiber-optic Underwater Cellular Mobile Communication Networks. In Proceedings of the IEEE 18th International Conference on Communication Technology (ICCT), Chongqing, China, 8–11 October 2018, pp. 721–726, doi:10.1109/ICCT.2018.8599957.

33. Lodovisi, C.; Loreti, P.; Bracciale, L.; Betti, S. Performance analysis of hybrid optical–acoustic AUV swarms for marine monitoring. Future Internet 2018, 10, 65, doi:10.3390/fi10070065.

34. Borah, D.K.; Boucouvalas, A.C.; Davis, C.C.; Hranilovic, S.; Yiannopoulos, K. A review of communication-oriented optical wireless systems. EURASIP J. Wirel. Commun. Networking 2012, 91, doi:10.1186/1687-1499-2012-91.

35. Ghassemlooy, Z.; Zvanovec, S.; Khalighi, M.A.; Popoola, W.O.; Perez, J. Optical wireless communication systems. Optik 2017, 151, 1–6, doi:10.1016/j.ijleo.2017.11.052.

36. Ma, H.; Liu, Y. Correlation based video processing in video sensor networks. In Proceedings of the International Conference on Wireless Networks, Communications and Mobile Computing, Maui, HI, USA, 3–16 June 2005; Volume 2, pp. 987–992, doi:10.1109/WIRELS.2005.1549547.

37. Spagnoli, G.S.; Cozzella, L.; Lecese, F. Phase correlation functions: FFT vs. FHT. ACTA IMEKO 2019, 8, 87–92, doi:10.21014/acta_imeko.v8i11.604.

38. Uysal, M.; Capsoni, C.; Ghassemlooy, Z.; Boucouvalas, A.; Udvari, E. Optical Wireless Communications: An Emerging Technology; Springer: New York, NY, USA, 2016, doi:10.1007/978-3-319-30201-0.
39. Chowdhury, M.Z.; Shahjalal, M.; Hasan, M.; Jang, Y.M. The Role of Optical Wireless Communication Technologies in 5G/6G and IoT Solutions: Prospects, Directions, and Challenges. Appl. Sci. 2019, 9, 4367, doi:10.3390/app9204367.

40. Andrews, L.C.; Phillips, R.L.; Hopen, C.Y. Laser Beam Scintillation with Applications; SPIE Optical Engineering Press: Bellingham, WA, USA, 2001, doi:10.1117/3.412858.

41. Vavoulas, A.; Sandalidis, H.G.; Varoutas, D. Weather effects on FSO network connectivity. J. Opt. Commun. Netw. 2013, 4, 734–740, doi:10.1364/JOCN.4.000734.

42. Nistazakis, H.E.; Karagianni, E.A.; Tsigopoulos, A.D.; Fatfalias, M.E.; Tombras, G.S. Average capacity of optical wireless communication systems over atmospheric turbulence channels. J. Lightwave Technol. 2009, 27, 974–979, doi:10.1109/JLT.2008.2005039.

43. Young, E.Y.S.; Bullock, A.M. Underwater-airborne laser communication system: Characterization of the channel. In Proceedings of the SPIE 4975, Free-Space Laser Communication Technologies XV, San Jose, CA, USA, 3 July 2003, doi:10.1117/12.478936.

44. Sathyendrenath, S. Inherent optical properties of natural seawater. Def. Sci. J. 1984, 34, 1–18.

45. Hanson, H.; Radic, S. High bandwidth underwater optical communication, Appl. Opt. 2008, 47, 277–283, doi:10.1364/AO.47.000277.

46. Gkoura, L.K.; Roumelas, G.D.; Nistazakis, H.E.; Sandalidis, H.G.; Vavoulas, A.; Tsigopoulos, A.D.; Tombras, G.S. Underwater Optical Wireless Communication Systems: A Concise Review. In Turbulence Modelling Approaches; Volkov, K., Ed.; IntechOpen: London, UK, 2017, doi:10.5772/67915.

47. Mobley, C.D. Light and Water: Radiative Transfer in Natural Waters; Academic Press: San Diego, CA, USA, 1994. ISBN: 978-0-125027502.

48. Smith, R.C.; Mobley, C.D. Underwater Light. In Photobiology; Björn, L.O., Ed.; Springer: New York, NY, USA, 2018, doi:10.1007/978-0-387-72655-7_7.

49. Cochenour, B.; Mullen, L. Free-space optical communications underwater. In Advanced Optical Wireless Communication Systems; Arnon, S., Barry, J., Karagianni, M., Schober, R., Uysal, M., Eds.; Cambridge University Press: Cambridge, UK, 2012; pp. 201–239, doi:10.1017/CBO9780511979187.009.

50. Jerlov, N.G. Marine Optics; Elsevier Oceanography Series: Amsterdam, Netherlands, 1976; Volume 14. ISBN: 978-0-444-41490-8.

51. Darwiesh, M.; El-Sherif, A.F.; Ayoub, H.S.; El-Sharkawy, Y.H.; Hassan, M.F.; Elbashar, Y.H. Hyperspectral laser imaging of underwater targets. J. Opt. 2018, 47, 553, doi:10.1007/s12596-018-0493-7.

52. Xu, J. Underwater wireless optical communication: Why, what, and how? Chin. Opt. Lett. 2019, 17, 100007, doi:10.3788/COL201917.100007.

53. Johnson, L.J.; Green, R.J.; Leeson, M.S. Underwater optical wireless communications: depth dependent variations in attenuation. Applied Optics 2013, 52, 7867–7873, doi:10.1364/AO.52.007867.

54. Sahu, S.K.; Shanmugam, P. A study on the effect of scattering properties of marine particles on underwater optical wireless communication channel characteristics. In Proceedings of the OCEANS 2017, Aberdeen, UK, 19–22 June 2017, doi:10.1109/OCEANSE.2017.8084720.

55. Sahu, S.K.; Shanmugam, P. A theoretical study on the impact of particle scattering on the channel characteristics of underwater optical communication system. Optics Commun. 218, 408, 3–14, doi:10.1016/j.comptopt.2017.06.030.

56. Petzold, T.J. Volume Scattering Functions for Selected Ocean Waters (No. SIO-REF-72-78). Scripps Institution of Oceanography, La Jolla Ca Visibility Lab, 1972. Available online: https://apps.dtic.mil/dtic/tr/fulltext/u2/753474.pdf (accessed on 15 April 2020).

57. Williams, J. Optical properties of the ocean. Rep. Prog. Phys. 1973, 36, 1567–1608, doi:10.1088/0034-4885/36/12/002.

58. Hale, G.M.; Querry, M.R. Optical constants of water in the 200-nm to 200-μm wavelength region. Appl. Optics 1973, 12, 555–563, doi:10.1364/AO.12.000555.

59. Koeppen, S.H.; Walker, R.E. Effective Radiance Attenuation Coefficients for Underwater Imaging. In Proceedings of the SPIE, Ocean Optics IV, San Diego, CA, USA, 10 November 1975; Volume 0064, doi:10.1117/12.954497.

60. Apel, J.R. Principles of Ocean Physics; International Geophysics Series; Academic Press: London, UK, 1987; Volume 38. ISBN: 9780080570747.

61. Buiteveld, H.; Hakvoort, J.M.H.; Donze, M. The optical properties of pure water. In Proceedings of the Ocean Optics XII 1994, Bergen, Norway, 13–15 June 1994; pp. 174–183, Volume 2258, doi:10.1117/12.190060.
62. Bohren, C.F.; Huffman, D.R. Absorption and Scattering of Light by Small Particles; Wiley: New York, NY, USA, 1988, doi:10.1002/9783527618156
63. Jaruwatanadilok, S. Underwater wireless optical communication channel modeling and performance evaluation using vector radiative transfer theory. IEEE J. Sel. Areas Commun. 2008, 26, 1620–1627, doi:10.1109/JSAC.2008.081202.
64. Haltrin, V.I. Chlorophyll-based model of seawater optical properties. Appl. Opt. 1999, 38, 6826–6832, doi:10.1364/AO.38.006826.
65. Prieur, L.; Sathyendranath, S. An optical classification of coastal and oceanic waters based on the specific spectral absorption curves of phytoplankton pigments, dissolved organic matter, and other particulate materials. Limnol. Oceanogr. 1981, 26, 671–689, doi:10.4319/lo.1981.26.4.0671.
66. Xu, J.; Song, Y.; Yu, X.; Lin, A.; Kong, M.; Han, J.; Deng, N. Underwater wireless transmission of high-speed QAM-OFDM signals using a compact red-light laser. Opt. Express 2016, 24, 8097–8109, doi:10.1364/OE.24.008097.
67. Pfeiffer, H.G.; Liebhafsky, H.A. The origins of Beer’s law. J. Chem. Educ. 1951, 28, doi:10.1021/ed028p123.
68. Berberan-Santos, M.N. Beer’s law revisited. J. Chem. Educ. 1990, 67, 757–759, doi:10.1021/ed067p757.
69. Mobley, C.D.; Gentili, B.; Gordon, H.R.; Jin, Z.; Kattawar, G.W.; Morel, A.; Stavn, R.H. Comparison of numerical models for computing underwater light fields. Appl. Opt. 1993, 32, 7484–7504, doi:10.1364/AO.32.007484.
70. Giles, J.W.; Bankman, I.N. Underwater optical communications systems. Part 2: Basic design considerations. In Proceedings of the MILCOM 2005—IEEE Military Communications Conference, Atlantic City, NJ, USA, 17–20 October 2005, doi:10.1109/MILCOM.2005.1605919.
71. Wang, C.; Yu, H.Y.; Zhou, Y.J. A Long Distance Underwater Visible Light Communication System with Single Photon Avalanche Diode. IEEE Photonics J. 2016, 8, 7906311, doi:10.1109/JPHOT.2016.2602330.
72. Gabriel, C.; Khalighi, M.A.; Bourennane, S.; Leon, P.; Rigaud, V. Channel modeling for underwater optical communication. In Proceedings of the 2011 IEEE GLOBECOM Workshops (GC Wkshps), Houston, TX, USA, 5–9 December 2011; pp. 833–837, doi:10.1109/GLOCOMW.2011.6162571.
73. Li, J.; Ma, Y.; Zhou, Q.; Zhou, B.; Wang, H. Monte Carlo study on pulse response of underwater optical channel. Opt. Eng. 2012, 51, 066001, doi:10.1117/1.OE.51.6.066001.
74. Gabriel, C.; Khalighi, M.A.; Bourennane, S.; Léon, P.; Rigaud, V. Monte-Carlo-based channel characterization for underwater optical communication systems. J. Opt. Commun. Netw. 2013, 5, 1–12, doi:10.1364/JOCN.5.000001.
75. Qadar, R.; Kasi, M.K.; Ayub, S.; Kakar, F.A. Monte Carlo–based channel estimation and performance evaluation for UWOC links under geometric losses. Int. J. Commun. Syst. 2018, 31, e3527, doi:10.1002/dac.3527.
76. Campagnaro, F.; Calore, M.; Casari, P.; Calzado, V.S.; Cupertino, G.; Moriconi, C.; Zorzi, M. Measurement-based simulation of underwater optical networks. In Proceedings of the OCEANS 2017, Aberdeen, UK, 19–22 June 2017; pp. 1–7, doi:10.1109/OCEANSE.2017.8084671.
77. Jasman, F.; Green, R.J. Monte Carlo simulation for underwater optical wireless communications. In Proceedings of the 2nd International Workshop on Optical Wireless Communications (IWOW), Newcastle upon Tyne, UK, 21 October 2013; pp. 113–117, doi:10.1109/IWOW.2013.6777789.
78. Vali, Z.; Gholami, A.; Ghassamlooy, Z.; Michelson, D.G.; Oomoomi, M.; Noori, H. Modeling turbulence in underwater wireless optical communications based on Monte Carlo simulation. JOSA A 2017, 34, 1187–1193, doi:10.1364/JOSAA.34.001187.
79. Nootz, G.; Jarosz, E.; Dalgleish, F.R.; Hou, W. Quantification of optical turbulence in the ocean and its effects on beam propagation. Appl. Opt. 2016, 55, 8813–8820.
80. Yi, X.; Li, Z.; Liu, Z. Underwater optical communication performance for laser beam propagation through weak oceanic turbulence. Appl. Opt. 2015, 54, 1273–1278, doi:10.1364/AO.54.001273.
81. Majlesein, B.; Gholami, A.; Ghassamlooy, Z. A complete model for underwater optical wireless communications system. In Proceedings of the 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP), Budapest, Hungary, 18–20 July 2018; pp. 1–5, doi:10.1109/CSNDSP.2018.8471869.
82. Ji, Y.; Wu, G.; Wang, S. Modulation Analysis for Long Distance Underwater VLC Systems under Dead Time Limit. In Proceedings of the 2018 IEEE 18th International Conference on Communication Technology (ICCT), Chongqing, China, 8–11 October 2018; pp. 392–395, doi:10.1109/ICICT.2018.8600250.
83. Ji, Y.; Wu, G.; Zu, Y. Performance Analysis of SPAD-Based Underwater Wireless Optical Communication Systems. *Procedia Comput. Sci.* 2018, 131, 1134–1141, doi:10.1016/j.procs.2018.04.282.
84. Solonenko, M.G.; Mobley, C.D. Inherent optical properties of Jerlov Water types. *Appl. Opt.* 2015, 54, 5392–5401, doi:10.1364/AO.54.005392.
85. Oubei, H.M.; Shen, C.; Kammoun, A.; Zedini, E.; Park, K.H.; Sun, X.; Liu, G.; Kang, C.H.; Ng, T.K.; Alouini, N.S. Light based underwater wireless communications. *Jpn. J. Appl. Phys.* 2018, 57, 08PA06, doi:10.7567/JJAP.57.08PA06.
86. Xu, J.; Kong, M.; Lin, A.; Song, Y.; Yu, X.; Qu, F.; Deng, N. OFDM-based broadband underwater wireless optical communication system using a compact blue LED. *Opt. Comm.* 2016, 369, 100–105.
87. Lu, C.; Wang, J.; Li, S.; Xu, Z. 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.
88. 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.
89. Suzuki, N.; Miura, H.; Matsuda, K.; Matsumoto, R.; Motoshima, K. 100 Gb/s to 1 Tb/s based coherent passive optical network technology. *J. Lightwave Technol.* 2018, 36, 1485–1491, doi:10.1109/JLT.2017.2785341.
90. Ma, H.; Lampe, L.; Hranilovic, S. 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.
91. Dimitrov, S.; Haas, H. Information rate of OFDM-based optical wireless communication systems with nonlinear distortion. *J. Lightwave Technol.* 2012, 31, 918–929, doi:10.1109/JLT.2012.2236642.
92. Khalighi, M.A.; Uysal, M. Survey on free space optical communication: A communication theory perspective. *IEEE Commun. Surv. Tutor.* 2014, 16, 2231–2258, doi:10.1109/COMST.2014.2329501.
93. Cox, W.C.; Simpson, J.A.; Muth, J.F. Underwater optical communication using software defined radio over LED and laser based links. In Proceedings of IEEE MILCOM 2011 Military Communications Conference, Baltimore, MD, USA, 7-10 November 2011, pp. 2057–2062, IEEE, doi:10.1109/MILCOM.2011.6127621.
94. Gabriel, C.; Khalighi, M.A.; Bourennane, S.; Léon, P.; Rigaud, V. 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/I WOW.2012.6349691.
95. Wiener, T.; Karp, S. The Role of Blue/Green Laser Systems in Strategic Submarine Communications. *IEEE Trans. Commun.* 1980, 28, 1602–1607, doi:10.1109/TCOM.1980.1094858.
96. Shen, C.; Guo, Y.; Oubei, H.M.; Ng, T.K.; Liu, G.; Park, K.H.; Ho, K.T.; Alouini, M.S.; Ooi, B.S. 20-meter underwater wireless optical communication link with 1.5 Gbps data rate. *Opt. Express* 2016, 24, 25502–25509, doi:10.1364/OE.24.025502.
97. Wu, T.; Chi, Y.; Wang, H.; Tsai, C.; Lin, G. Blue Laser Diode Enables Underwater Communication at 12.4 Gbps. *Sci. Rep.* 2017, 7, 40480, doi:10.1038/srep40480.
98. Tian, P.; Liu, X.; Yi, S.; Huang, Y.; Zhang, S.; Zhou, X.; Hu, L.; Zheng, L.; Liu, R. High-speed underwater optical wireless communication using a blue GaN-based micro-LED. *Opt. Express* 2017, 25, 1193, doi:10.1364/OE.25.001193.
99. Stickluss, J.; Heoher, P.A.; Röttgers, R. Optical Underwater Communication: The Potential of Using Converted Green LEDs in Coastal Waters. *IEEE J. Ocean. Eng.* 2018, 44, 535–547, doi:10.1109/JOE.2018.2816838.
100. Grobe, L.; Paraskevopoulos, A.; Hilt, J.; Schulz, D.; Lassak, F.; Hartlieb, F.; Kottke, C.; Jungnickel, V.; Langer, K.D. High-speed visible light communication systems. *IEEE Commun. Mag.* 2013, 51, 60–66, doi:10.1109/MCOM.2013.6685758.
101. Suzuki, K.; Asahi, K.; Watanabe, A. Basic study on receiving light signal by LED for bidirectional visible light communications. *Electron. Commun. Jpn.* 2015, 98, 1–9, doi:10.1002/eqj.11608.
102. Schirripa Spagnolo, G.; Lecce, F.; Leccisi, M. LED as Transmitter and Receiver of Light: A Simple Tool to Demonstration Photoelectric Effect. *Crystals* 2019, 9, 531, doi:10.3390/crystals9100531.
103. Arnon, S. Underwater optical wireless communication network, *Opt. Eng.* 2010, 49, 015001, doi:10.1117/1.3280288.
104. Anguita, D.; Brizzolara, D.; Parodi, G. VHDL Modules and Circuits for Underwater Optical Wireless Communication Systems. *Wseas Trans. Commun.* 2010, 9, 525–552. ISSN: 1109-2742. Available online: http://www.wseas.us/e-library/transactions/communications/2010/88-217.pdf (accessed on 15 April 2020).

105. Petritoli, E.; Lecese, F.; Cagnetti, M. High accuracy buoyancy for underwater gliders: The uncertainty in the depth control. *Sensors* 2019, 19, 1831, doi:10.3390/s19081831.

106. Petritoli, E.; Lecese, F. High accuracy attitude and navigation system for an autonomous underwater vehicle (AUV). *Acta IMEKO* 2018, 7, 3–9, doi:10.1109/10.21014/acta imeko.v7i2.535.

107. Khalighi, M.A.; Gabriel, C.; Hamza, T.; Bourennane, S.; Leon, P.; Rigaud, V. Underwater wireless optical communication; recent advances and remaining challenges. In Proceedings of the 2014 IEEE 16th International Conference on Transparent Optical Networks (ICTON), Graz, Austria, 6–10 July 2014; pp. 1–4, doi:10.1109/ICTON.2014.6876673.

108. Huang, X.; Yang, F.; Song, J. Hybrid LD and LED-based underwater optical communication: State-of-the-art, opportunities, challenges, and trends. *Chin. Opt. Lett.* 2019, 17, 100002, doi:10.3788/CO201917.100002.

109. Liu, W.; Xu, Z.; Yang, L. SIMO detection schemes for underwater optical wireless communication under turbulence. *Photonics Res.* 2015, 3, 48–53, doi:10.1364/PRJ.3.000048.

110. Simpson, J.A.; Hughes, B.L.; Muth, J.F. Smart transmitters and receivers for underwater free-space optical communication. *IEEE J. Sel. Areas Commun.* 2012, 30, 964–974, doi:10.1109/JSAC.2012.120611.

111. Jamali, M.V.; Salehi, J.A.; Akhoundi, F. Performance studies of underwater wireless optical communication systems with spatial diversity: MIMO scheme. *IEEE Trans. Commun.* 2016, 65, 1176–1192, doi:10.1109/TCOMM.2016.2642943.

112. Song, Y.; Lu, W.; Sun, B.; Hong, Y.; Qu, F.; Han, J.; Zhang, W.; Xu, J. Experimental demonstration of MIMO-OFDM underwater wireless optical communication. *Opt. Commun.* 2017, 403, 205–210, doi:10.1016/j.optcom.2017.07.051.

113. Zhang, H.; Dong, Y.; Hui, L. On capacity of downlink underwater wireless optical MIMO systems with random sea surface. *IEEE Commun. Lett.* 2015, 19, 2166–2169, doi:10.1109/LCOMM.2015.2484355.

114. Fletcher, A.S.; Hamilton, S.A.; Moores, J.D. Undersea laser communication with narrow beams. *IEEE Commun. Mag.* 2015, 53, 49–55, doi:10.1109/MCOM.2015.7321971.

115. MIT News. Advancing Undersea Optical Communications. Available online: http://news.mit.edu/2018/advancing-undersea-optical-communications-0817 (accessed on 29 January 2020).

116. Schirripa Spagnolo, G.; Papalillo, D.; Malta, C.; Vinzani, S. LED Railway Signal vs full Compliance with colorimetric Specification. *Int. J. Transp. Dev. Integr.* 2017, 1, 568–577, doi:10.2495/TDI-V1-N3-568-577.

117. Hamza, T.; Khalighi, M.A.; Bourennane, S.; Léon, P.; Oderbecke, J. Investigation of solar noise impact on the performance of underwater wireless optical communication links. *Opt. Express* 2016, 24, 25832–25845, doi:10.1364/OE.24.025832.

118. Sticklus, J.; Hieronymi, M.; Hoeher, P.A. Effects and Constraints of Optical Filtering on Ambient Light Suppression in LED-Based Underwater Communications. *Sensors* 2018, 18, 3710, doi:10.3390/s18113710.

119. Zappa, F.; Tisa, S.; Tosi, A.; Cova, S. Principles and features of single-photon avalanche diode arrays. *Sens. Actuators A Phys.* 2007, 140, 103–112, doi:10.1016/j.sna.2007.06.021.

120. Kirdoda, J.; Dumas, D.C.S.; Kuzmenko, K.; Vines, P.; Greener, Z.M.; Millar, R.W.; Mirza, M.M.; Buller, G.S.; Paul, D.J. 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.

121. Donati, S.; Tambosso, T. Single-photon detectors: From traditional PMT to solid-state SPAD-based technology. *IEEE J. Sel. Top. Quantum Electron.* 2014, 20, 204–211, doi:10.1109/JSTQE.2014.2350836.

122. Shafique, T.; Amin, O.; Abdallah, M.; Ansari, I.S.; Alouini, M.S.; Qaraqe, K. Performance analysis of single-photon avalanche diode underwater VLC system using ARQ. *IEEE Photonics J.* 2017, 9, 1–11, doi:10.1109/JPHOT.2017.2743007.

123. Hadfield, R. Single-photon detectors for optical quantum information applications. *Nat. Photon* 2009, 3, 696–705, doi:10.1038/nphoton.2009.230.

124. Chitnis, D.; Collins, S. A SPAD-based photon detecting system for optical communications. *J. Lightwave Technol.* 2014, 32, 2028–2034, doi:10.1109/JLT.2014.2316972.

125. Sarbazi, E.; Safari, M.; Haas, H. Statistical modeling of single-photon avalanche diode receivers for optical wireless communications. *IEEE Trans. Commun.* 2018, 66, 4043–4058, doi: 10.1109/TCOMM.2018.2822815.
126. Khalighi, M.A.; Hamza, T.; Bourennane, S.; Léon, P.; Opderbecke, J. Underwater wireless optical communications using silicon photo-multipliers. *IEEE Photonics J.* 2017, 9, 1–10, doi:10.1109/JPHOT.2017.2726565.

127. Hong, Z.; Yan, Q.; Li, Z.; Zhan, T.; Wang, Y. Photon-counting underwater optical wireless communication for reliable video transmission using joint source-channel coding based on distributed compressive sensing, *Sensors* 2019, 19, 1042, doi:10.3390/s19051042.

128. Pan, S.; Wang, L.; Wang, W.; Zhao, S. An Effective Way for Simulating Oceanic Turbulence Channel on the Beam Carrying Orbital Angular Momentum. *Sci. Rep.* 2019, 9, 1–8, doi:10.1038/s41598-019-50465-w.

129. Sait, M.; Sun, X.; Alkhazragi, O.; Alfaraj, N.; Kong, M.; Ng, T.K.; Ooi, B.S. The effect of turbulence on NLOS underwater wireless optical communication channels. *Chinese Opt. Lett.* 2019, 17, 100013, doi:10.3788/COL201917.100013.

130. Zhang, L.; Chittnis, D.; Chun, H.; Rajbhandari, S.; Faulkner, G.; O’Brien, D.; Collins, S. A comparison of APD-and SPAD-based receivers for visible light communications. *J. Lightwave Technol.* 2018, 36, 2435–2442, doi:10.1109/JLT.2018.2811180.

131. Wang, C.; Yu, H.Y.; Zhu, Y.J.; Wang, T.; Ji, Y.W. Multi-LED parallel transmission for long distance underwater VLC system with one SPAD receiver. *Opt. Commun.* 2018, 410, 889–895.

132. Zhang, H.; Dong, Y. Impulse response modeling for general underwater wireless optical MIMO links. *IEEE Commun. Mag.* 2016, 54, 56–61, doi:10.1109/MCOM.2016.7402261.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).