photonics

IMPACT FACTOR 1.9

CITESCORE 3.5

Review

Visible Light Communication for Underwater Applications: Principles, Challenges, and Future Prospects

Vindula L. Jayaweera, Chamodi Peiris, Dhanushika Darshani, Sampath Edirisinghe, Nishan Dharmaweera and Uditha Wijewardhana

MDPI

https://doi.org/10.3390/photonics12060593 *photonics*

MDPI

Review

Visible Light Communication for Underwater Applications: Principles, Challenges, and Future Prospects

Vindula L. Jayaweera [1,*], Chamodi Peiris [1,*], Dhanushika Darshani [1], Sampath Edirisinghe [2], Nishan Dharmaweera [1] and Uditha Wijewardhana [1]

[1] Department of Electrical and Electronic Engineering, University of Sri Jayewardenepura, Nugegoda 12250, Sri Lanka; dhanushikadarshani@sjp.ac.lk (D.D.); nishanmd@sjp.ac.lk (N.D.); uditha@sjp.ac.lk (U.W.)

[2] Department of Computer Engineering, University of Sri Jayewardenepura, Nugegoda 12250, Sri Lanka; essedirisinghe@sjp.ac.lk

* Correspondence: en91382@sjp.ac.lk (V.L.J.); en95141@sjp.ac.lk (C.P.)

Abstract: Underwater wireless communications face significant challenges due to high attenuation, turbulence, and water turbidity. Traditional methods like acoustic and radio frequency (RF) communication suffer from low data rates (<100 kbps), high latency (>1 s), and limited transmission distances (<10 km).Visible Light Communication (VLC) emerges as a promising alternative, offering high-speed data transmission (up to 5 Gbps), low latency (<1 ms), and immunity to electromagnetic interference. This paper provides an in-depth review of underwater VLC, covering fundamental principles, environmental factors (scattering, absorption), and dynamic water properties. We analyze modulation techniques, including adaptive and hybrid schemes (QAM-OFDM achieving 4.92 Gbps over 1.5 m), and demonstrate their superiority over conventional methods. Practical applications—underwater exploration, autonomous vehicle control, and environmental monitoring—are discussed alongside security challenges. Key findings highlight UVLC's ability to overcome traditional limitations, with experimental results showing 500 Mbps over 150 m using PAM4 modulation. Future research directions include integrating quantum communication and Reconfigurable Intelligent Surfaces (RISs) to further enhance performance, with simulations projecting 40% improved spectral efficiency in turbulent conditions.

Keywords: Visible Light Communication (VLC); underwater communication; modulation techniques; security and privacy

check for updates

Received: 28 March 2025
Revised: 25 April 2025
Accepted: 28 April 2025
Published: 10 June 2025

Citation: Jayaweera, V.L.; Peiris, C.; Darshani, D.; Edirisinghe, S.; Dharmaweera, N.; Wijewardhana, U. Visible Light Communication for Underwater Applications: Principles, Challenges, and Future Prospects. *Photonics* **2025**, *12*, 593. https://doi.org/10.3390/photonics12060593

1. Introduction

The oceans cover over 70% of the Earth's surface; however, communication underwater is still a challenging task. Traditional communication systems based on acoustic waves, radio frequency (RF), and magnetic induction suffer from issues such as signal attenuation, interference, and bandwidth limitations, hindering their reliability in aquatic environments [1–3]. These limitations become more critical when trying to attempt high data rate transmissions for real-time communication in underwater scenarios like search and rescue, research explorations, and military operations.

Visible Light Communication (VLC) provides an effective way to address these limitations by using light for underwater communications. With high bandwidth, immunity to electromagnetic interference, and minimal absorption and scattering, VLC attracts more interest in the research community as an alternative to underwater communications [1].

On the other hand, VLC has the potential to overcome environmental restrictions faced by traditional underwater communication systems, especially with respect to applications that require high-speed data transmission, such as underwater exploration, environmental monitoring, and autonomous underwater vehicles (AUVs) [4,5].

However, several factors influence the effectiveness of VLC in underwater scenarios; the attenuation and scattering of light in water especially have an adverse impact on communication performance. These challenges are exacerbated by a number of factors, such as the turbidity of water, the distance, and the alignment between the transmitter and receiver. Studies indicate that underwater communication systems based on VLC may face issues such as the limited range of light propagation, especially in murky or turbulent water, and the need for precise alignment between transceivers to maintain a reliable communication link [6]. The difficulty of ensuring alignment and overcoming adverse aquatic channel conditions remains a significant barrier to the widespread adoption of VLC for underwater communication.

Many new methods have been advanced to help solve these issues, for instance, the proposal of an adaptive VLC-based underwater monitoring system with a parallel multihop structure to extend its communication range and improve its signal strength [4]. In addition, other innovations involve the use of end-to-end learning techniques, which proved quite useful in automating signal processing, with a view to enhance the robustness of the communication system against environmental disturbances like optical turbulence [7]. Moreover, efforts to develop models for path loss in different water environments have led to more accurate predictions of VLC performance, helping optimize system design for varying underwater conditions [6,8]. These advancements demonstrate the potential of VLC systems in meeting the growing demand for reliable and high-speed communication in underwater applications.

Apart from that, the peculiarities exerted by the underwater environment itself, such as the impingement of sea waves and the dynamical movement of transceivers, have to be taken into consideration. Studies in the vertical VLC links, when one of the transceivers is situated at a buoy on the ocean surface, showed the need for developing theoretical models that can simulate path loss and random fading owing to periodic distance changes in transmission [9].

This review aims to study the integration of the latest technologies and approaches into a functional underwater communication system. The main contributions of this paper are an in-depth analysis of the principles, challenges, and future prospects of underwater VLC, with its promise to go beyond the limitations of traditional communication methods such as acoustic and RF communication. Various modulation schemes, including adaptive and hybrid modulation schemes, are discussed in the paper for optimizing data transmission in underwater VLC systems. In addition, it discusses the impact of environmental factors such as turbidity, salinity, temperature, and pressure on VLC performance, giving an outlook on the design of robust communication systems for diverse aquatic environments. Realistic applications of underwater VLC in scenarios such as environmental monitoring, underwater discovery, and AUVs are also discussed in the paper while keeping in view the security and privacy concerns of underwater communication. Lastly, the paper concludes with future research prospects, such as the integration of other new emerging technologies like quantum communication and Reconfigurable Intelligent Surfaces (RISs) for further enhancing underwater VLC systems' performance and reliability.

The remainder of this paper is structured as follows.

2. Principles of Underwater Communication

Due to the unique properties of water as a transmission medium, underwater communication has its own set of challenges and requirements, making it distinct from atmospheric communication. The main principles involved in underwater communication can be categorized as acoustic waves, radio frequencies, and optical waves.

2.1. Communication Mediums in Water

2.1.1. Underwater Acoustic Communication (UAC)

In underwater acoustic communication (UWAC), information is transmitted via sound waves, and information is loaded by mapping parameters, such as phase, frequency, and amplitude. In underwater acoustic communication, sound waves are used to transmit information. Parameters of the sound wave, such as phase, amplitude, and frequency, are manipulated according to the information [10]. Acoustic waves are capable of traveling long distances compared to electromagnetic and optical waves [11].

However, acoustic communication encounters several challenges, such as strong multipath propagation. Multipath propagation occurs in an underwater acoustic channel when the sound wave reflects on the seawater surface, seabed, and obstacles. It leads to severe fading and long delay spread, which decreases the effectiveness of underwater communication and causes signal distortions [12].

In addition to that, the Doppler effect is another challenge in acoustic communication, which is caused by the movement of the transmitter and receiver. The combination of multipath propagation and Doppler shift creates frequency shifting and spreading. It results in frequency-dependent distortion in acoustic waves. As the frequency of the signal increases, the Doppler effect increases, making acoustic communication inefficient at high frequencies [13]. Several methods are employed to mitigate the effects of the Doppler effect and multipath propagation. Decision Feedback Equalizers (DFEs) are used to handle multipath signals. In the DFE, the received acoustic signal is processed with the feedback from past decisions. A Digital Phase-Locked Loop (DPLL) is considered an effective method to reduce the Doppler effect. DPLL continuously tracks the phase of the incoming acoustic wave since a slight motion of the transmitter and the receiver can cause a significant Doppler effect due to the low propagation velocity of acoustic waves in water. DPLL provides an output signal after adjusting the phase of the received. In addition to that, enhanced techniques use additional DPLLs along with DFE to address the phase shifts of each multipath signal [14].

A fundamental acoustic communication model is represented in Figure 1. The main components of an underwater acoustic modem consist of an acoustic transducer which is used to convert electrical signals into acoustic waves and vice versa, a communication circuitry that handles several functions such as signal processing, error correction, and data transmission, and a control unit which manages the operations of the modem [11].

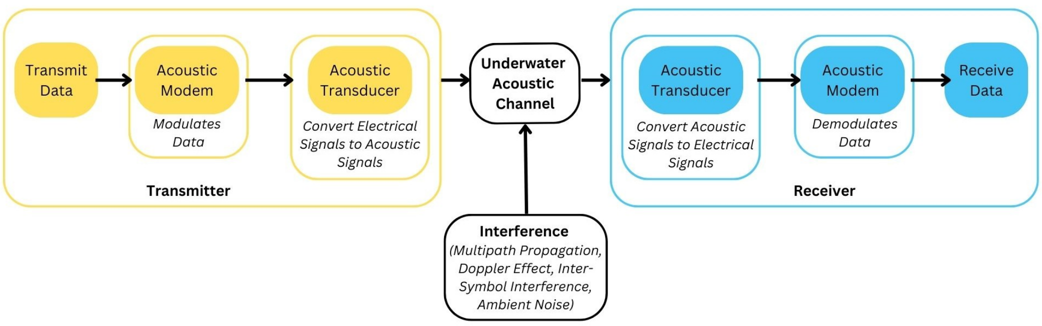

Figure 1. Fundamental acoustic communication system.

Unfortunately, acoustic communication systems inherit several limitations such as significantly lower data rates compared to RF communication. Sound waves travel at a much slower speed in water. Hence, when it comes to long-distance communication, there is a significant transmission delay, leading to high latency in communication [15]. Underwater acoustic signals are impacted by ambient noise which can be generated from marine life, ships, and natural phenomena such as waves and currents. These kinds of sources of noise introduce fluctuations in signal strength and quality, further decreasing the reliability of acoustic communication [15]. There are mainly four types of noise in underwater acoustic channels. Wave noise is the most significant noise and it appears 100 Hz to 100 kHz range. It is introduced due to the sea surface movements. Thermal noise is generated at frequencies above 100 kHz and is caused by the thermal agitation of molecules. Shipping noise is generated by ships and marine vehicles. It exists in the 10 to 100 Hz frequency range. Most random noise is turbulence noise and is caused by wave currents below 10 Hz frequency [11].

In order to overcome challenges in underwater acoustic communication, researchers conduct experiments involving several adaptive and predictive techniques. The effects of multipath propagation and Doppler shifts can be eliminated by channel equalization and adaptive modulation techniques. Also, error correction coding can be utilized to enhance data reliability [16].

2.1.2. Underwater Electromagnetic Communication (UEC)

Underwater Electromagnetic Communication utilizes electromagnetic waves that have a limited transmission range due to strong absorption and scattering effects in seawater. Salinity, temperature, pressure, distance, environmental factors, and frequency affect the effectiveness of UEC [17]. High frequencies in seawater experience severe attenuation due to the conductive nature of seawater. In order to enhance range, lower frequencies (30 kHz to 300 kHz) are frequently employed. However, UEC has disadvantages such as high latency, lower data rates, and high attenuation [17].

In contrast to UAC which benefits from long-distance propagation, UEC requires large antennas to achieve long-distance communication (typically less than 10 m) using RF signals [18].

Seawater conductivity significantly affects the performance of UEC [17]. To overcome restrictions in electromagnetic communication, magnetic induction (MI) communication can be employed. A time-varying signal is applied to the transmitter coil, and it generates a magnetic field. When the receiver coil comes into the vicinity of the generated magnetic field, both coils are coupled. MI-based communication has a low transmission delay. In contrast to RF and acoustic communication, MI-based communication has no multipath and Doppler effect. The transmission data rate of MI is moderate and typical in Mbps. Also, it provides a stealth operation since there is no audible or visible communication. Therefore, MI-based communication has no impact on marine life [18].

Compared to RF transceivers, MI transceivers are low-cost. However, there are a few disadvantages of MI-based communication. These systems are orientation-sensitive. Misalignment of transmitter and receiver coils leads to signal distortions. In nature, a transmitter coil is directional and should be perfectly aligned with the receiver coil. Apart from that, seawater conductivity significantly affects MI communication. The range of MI communication depends on the strength of the magnetic field. The range can be increased by increasing the magnetic moment, better coil design, and relaying [18].

2.1.3. Underwater Optical Communication (UOC)

UOC has demonstrated that it is capable of addressing the limitations of underwater acoustic and electromagnetic communication [15].

Seawater behaves differently for RF and optical signal propagation. For RF signals seawater acts as a conductor and for optical it acts as a dielectric. Attenuation in a dielectric medium is lower than conductive medium. By using, blue-green optical window attenuation can be reduced further, making optical wireless communication ideal for underwater communication.

The optical characteristics of water can be classified into two categories: Inherent Optical Properties (IOPs) and Apparent Optical Properties (AOPs) [19]. IOPs depend on the light source and the medium. For example, the absorption coefficient measures how much light is absorbed, the scattering coefficient measures how much light is scattered, and the attenuation coefficient measures the overall loss of light during propagation. AOPs depend on the medium and the geometric structure of the light field such as radiance, irradiance, and reflectance [19].

Ref. [15] demonstrates the impact of water clarity on optical signal communication. According to the study, pure seawater shows the least attenuation and maintains a consistent strength up to 100 m distance. Clear ocean water experiences a slightly higher attenuation compared to pure seawater as the distance reaches 100 m. In contrast, coastal ocean water demonstrates a greater attenuation than clear ocean water which limits the effective range of optical communication. Signal strength attenuates exponentially in turbid harbor water and beyond 40 to 50 m, the signal become unpredictable.

In UOC, the receiver should be pointed at the transmitter. To reduce pointing requirements, researchers utilize Photomultiplier Tubes (PMTs), which consist of large lenses with a wide range and wide field of view. Electronic switches adjust the receiver's FOV dynamically. PMTs incur issues such as being expensive, bulky, fragile, and unsuitable for multi-user environments [15].

Blue and green LEDs and lasers are effective in underwater environments due to their lower attenuation coefficients compared to other colors [20].

Lasers provide high performance compared to LEDs due to their monochromatic behavior, high intensity, and low dispersion quality [15].

Even optical wireless communication allows high data rates underwater; it is limited to a shorter range of communication. There are several reasons for the short transmission range. Water absorbs and scatters light. The presence of chlorophyll, particulate matter, and other substances in water significantly affects the optical properties. Also, reflection and refraction limit the distance of optical waves underwater. The range of underwater optical links can be extended by increasing the power of light sources and incorporating optical amplifiers and repeaters. Multiple optical amplifiers or repeaters can be located between transmission terminals to mitigate losses due to absorption and scattering [21].

3. VLC for Underwater Communication

Underwater VLC (UVLC) is vital for applications like oceanographic data collection, environmental monitoring, and AUVs, where high data rates and low latency are crucial [22]. This section discusses the technical details of UVLC in detail.

3.1. Optical Signal Transmission Losses

Underwater light transmission is primarily affected by absorption and scattering [22,23]. Absorption converts light energy into heat or other forms, reducing intensity, while scattering redirects light upon interaction with water molecules or particles, weakening the optical signal [23]. Both phenomena contribute to signal attenuation in water, as illustrated in Figure 2 [24].

The geometric model formula for power transmission can be expressed as mentioned below.

$$P_i(\lambda) = P_a(\lambda) + P_s(\lambda, \phi) + P_t(\lambda, \phi)$$

where P_i denotes incident light power, and P_a and P_s denote absorbed and scattered power, respectively. P_t is the remaining power. The volume of water is ΔV and the thickness is Δr.

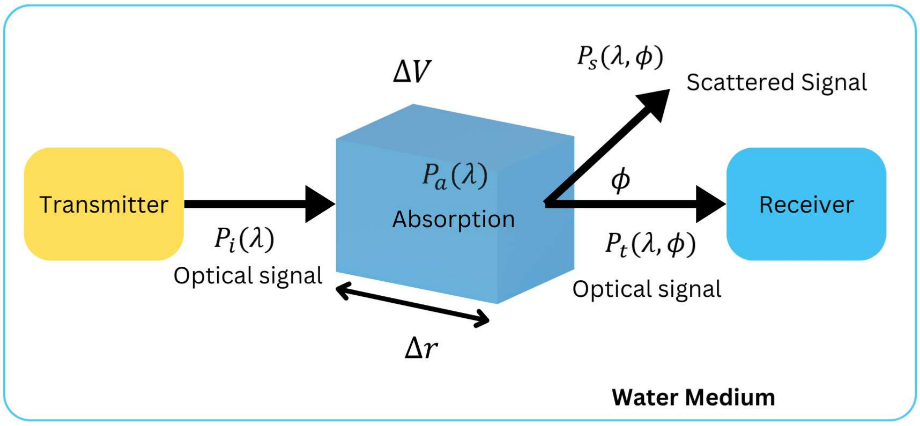

Figure 2. A geometric representation of the inherent optical.

The total attenuation in underwater optical communication is determined by the beam extinction coefficient, $c(\lambda)$, which is the sum of the absorption coefficient $a(\lambda)$ and the scattering coefficient $b(\lambda)$ [22,23]:

$$c(\lambda) = a(\lambda) + b(\lambda)$$

where $a(\lambda)$, $b(\lambda)$, and $c(\lambda)$ are in units of m^{-1}. These coefficients heavily depend on water types and depths [24].

Pure seawater consists of water molecules and dissolved salts contributing to the absorption coefficient. The scattering coefficient of pure seawater is negligible [24]. Clear ocean water has a higher concentration of dissolved particles that affect scattering. Coastal ocean water consists of a higher concentration of planktonic matter, detritus, and mineral components that affect absorption and scattering. Turbid harbor water has a very high concentration of dissolved and in-suspension matters [25].

Beer–Lambert's Law is widely used to simulate optical signal attenuation in underwater environments. It models attenuation caused by suspended particles and relates it to signal strength, distance, and the extinction coefficient [26]:

$$P_r(\lambda, d) = P_T e^{-c(\lambda)} \cdot d$$

where P_r and P_T denote received and transmitted optical signal strength at the receiver and transmitter ends. The distance between the transmitter and the receiver is denoted by d.

The visible spectrum extends from 400 nm to 700 nm, and the light penetration in water varies with wavelength. The range from 450 nm to 550 nm is identified as the lowest attenuation and corresponds to the ranges of blue and green light [25,27].

3.2. Configurations of the Optical Link

There are four distinct types of UVLC configurations, determined by the nature of the links between nodes [24]. A visual representation of the four types are in Figure 3.

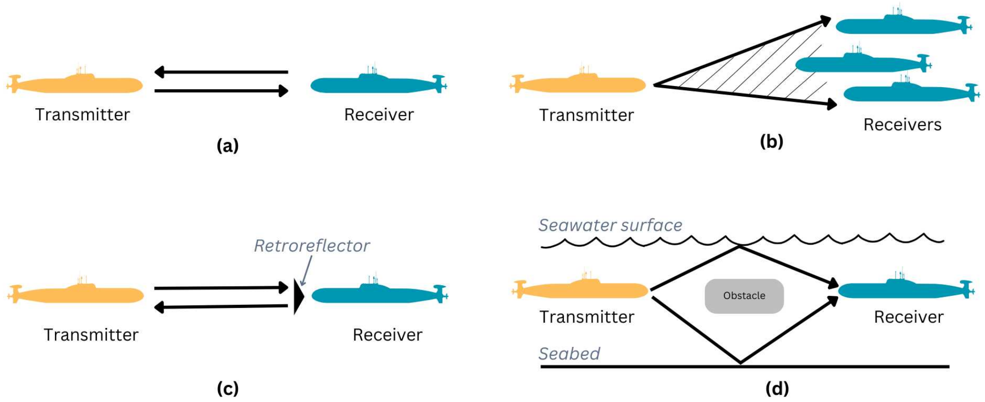

Figure 3. Configuration types for underwater wireless optical communication: (**a**) LOS, (**b**) DLOS, (**c**) RLOS, and (**d**) NLOS.

3.2.1. Point-to-Point Line-of-Sight (LOS)

Point-to-point line-of-sight requires the receiver to align precisely with the transmitter. Narrow-divergence light sources like lasers are used. It provides benefits such as higher bandwidth, lower latency, and enhanced security due to the narrow beamwidth of the optical signal [24]. However, the effectiveness of LOS is affected by water turbidity.

3.2.2. Diffused LOS

In diffused LOS, the optical signal is transmitted from a single source, and it spreads at a wider angle. Therefore, multiple receivers are in a DLOS configuration. Also, there is no need for accurate alignment of the transmitter and the receiver. There are a few drawbacks such as high attenuation, low data rates, and limited communication range [22].

3.2.3. Retro-Reflector-Based LOS

Retroreflector-based UVLC enables duplex communication for low-power, lightweight nodes by reflecting modulated light back to the transceiver, reducing power and size requirements [22]. However, it faces interference and double-channel attenuation. Limitations can be overcome using polarization discrimination and signal amplification [24].

3.2.4. Non-Line-of-Sight (NLOS) Setups

It employs diffused light beams reflected off surfaces like the sea surface or seabed to overcome LOS obstructions, enabling flexible alignment and point-to-multipoint communication [22,24]. However, challenges include path loss, signal dispersion, and interference from sea surface turbulence [22,24].

3.3. Key Components and System Design of UVLC

3.3.1. Transmitters

The primary light sources used are light-emitting diodes (LEDs) and laser diodes (LDs), each with distinct advantages and limitations. LEDs are cost-effective, reliable [22], and suited for mobile underwater networks due to their broad divergence angle, which simplifies alignment. However, their lower power output limits communication range and data rates [22,23]. LDs, on the other hand, provide high power, narrow beams, and longer communication distances, making them ideal for high-speed data transmission. Nonetheless, LDs are more expensive, sensitive to temperature variations, and require precise alignment [22].

To enhance the performance of transmitters, advanced techniques such as signal modulation, error correction coding, and adaptive modulation are often employed [23]. Optical components like lenses are also integrated to shape and direct light, reducing temporal pulse spreading and improving transmission efficiency. For instance, narrow-beam LDs reduce scattering, enabling efficient and reliable data transmission over longer distances, while wide-beam LEDs are better suited for collaborative tasks in turbid environments [23].

3.3.2. Receiver

The photodetector is an essential component of the optical receiver. It is used to convert optical signals into electrical signals in UVLC systems [3] There are two main types of photodiodes: PIN photodiodes (PDs) and avalanche photodiodes (APDs). PIN PDs are cost-effective, fast, and operate at low bias voltages ranging from 2 to 5 V. PIN PDs are suitable for high-frequency applications but lacking in internal gain [22,23]. APDs provide higher gain through avalanche multiplication, but it requires complex circuitry and higher bias voltages, which leads to high noise in communication [22,23]. There are advanced photodetectors, such as single-photon avalanche diodes (SPADs) and multi-pixel photon counters (MPPCs), which provide high sensitivity and high signal-to-noise ratios. These PDs are ideal for enhancing detection capabilities in challenging environments like UVLC [22,23]. The work in [23] shows that the use of SPADs can significantly extend transmission ranges. In addition to that, the use of larger photodetector apertures enhances photon collection efficiency, which helps to overcome the channel attenuation in UVLC [23].

3.3.3. System Architecture

The basic UVLC design is shown in Figure 4. On the transmitter side, data are generated from the source and fed into the modulator. Data modulate onto the carrier wave at the modulator. A light source converts an electrical signal into an optical signal and is transmitted through the water channel. On the receiver end, the photodetector converts the optical signal back into an electrical signal. The electrical signal is fed to a signal processor where the signal is amplified and filtered as it is suitable for demodulation.

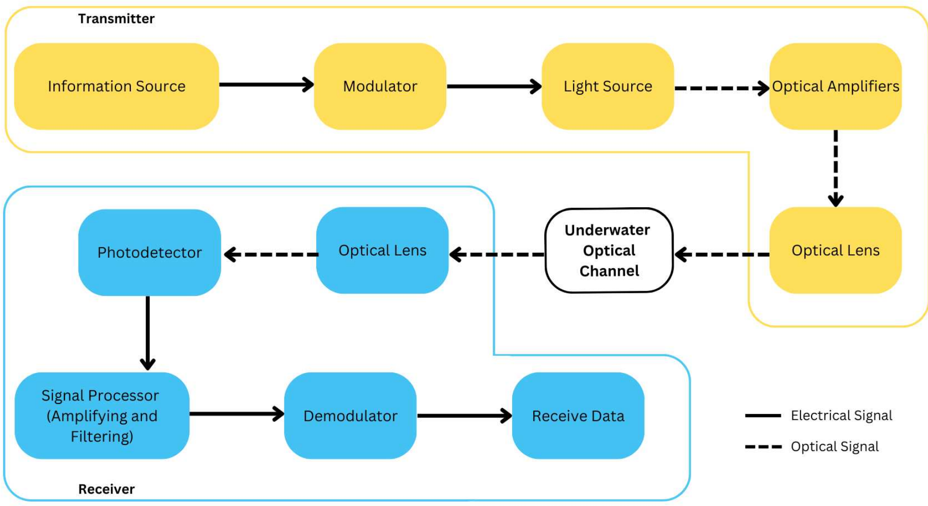

Figure 4. Basic UVLC design.

Table 1 represents a comprehensive comparison of several system architectures including the transmitter and its wavelength, optical power at the transmitter end, receiver and its sensitivity level, modulation scheme, and data rate.

Table 1. Comparison of transmitter and receiver of UWOC systems in recent works.

Year	Wavelength	Optical Power	Receiver	Modulation Scheme	Distance (m)	Receiver Sensitivity	Data Rate	Reference
2019	520 nm LD	7.25 mW	APD	OOK and Nonlinear Equalization	100	−30.4 dBm/ −24 dBm	100 Mbps/500 Mbps	[28]
2020	450 nm LD	2.4 mW	MPPC	OOK	100/50	NA	8.39 Mbps/ 16.78 Mbps	[29]
2020	450 nm LD	10 mW	Silicon Photomultiplier (SiPM)	OOK and Decision Feedback Equalization	40	−43 dBm	1 Gbps	[30]
2020	450 nm GaN LD	285.5 mW	PIN PD	Probabilistic Shaping bit loading	1.2	NA	120.09 Gbps	[31]
2020	450 nm Micro-LED array	<20 mW	PIN PD	QAM-OFDM	1.5	NA	4.92 Gbps	[32]
2020	450 nm Micro-LED array	<20 mW	PIN PD	QAM-OFDM	3	NA	3.22 Gbps	[32]
2020	450 nm Micro-LED array	<20 mW	PIN PD	QAM-OFDM	4.5	NA	3.4 Gbps	[32]
2020	520 nm LD	NA	APD	32-QAM	56	NA	3.31 Gbps	[33]
2021	450 nm LD	16.18 mW	APD	Discrete Fourier Transform Spread Discrete Multi-Tone	50	−11.2 dBm	5 Gbps	[34]
2021	450 nm LD	293.1 mW	PMT	PAM4 and Trellis Coded Modulation	150	−29.8 dBm	500 Mbps	[35]
2021	450 nm LD	NA	APD	DFT-S DMT	50	NA	5 Gbps	[34]
2022	450 nm LD	9.88 mW	SiPM	Diversity Reception and Nonlinear Decision Feedback Equalization	55	−49.23 dBm/ −41.96 dBm	1 Gbps/2 Gbps	[36]

4. Modulation Techniques for Underwater VLC

Modulation techniques for underwater VLC have been extensively studied, forming a foundational aspect of UVLC research. This section advances the discussion by examining adaptive, hybrid, and spatially optimized techniques tailored to dynamic underwater environments.

4.1. Basic Modulation Techniques

Of all the modulation techniques, Binary Phase Shift Keying (BPSK) is the most basic for binary data transmission. The BPSK method characterizes binary information by the use of two different phases—usually 0° and 180°—to encode "0" and "1". Its simplicity and resistance to noise in the communication link make it fit for low SNR communications. Noise resistance comes at a price: BPSK represents one of the few data rate techniques. Since each BPSK symbol only carries one bit of information, the achievable data rate is naturally comparatively low. It is this inherent simplicity of BPSK that turns out to be highly desirable when the most sensitive requirement is for robustness to noise, including but not limited to an underwater optical communication system where the channel noise might become very debilitating [37,38].

Quadrature Phase Shift Keying is a more advanced modulation scheme than BPSK because it encodes two bits per symbol rather than just one. In Quadrature Phase Shift Keying (QPSK), this is accomplished with the use of four different phases, each representing four different symbol states. This will consequently help give far better data throughput without sacrificing the efficiency of the modulation scheme. QPSK is used in systems where a compromise between noise immunity and data rate is needed. In particular, QPSK appears to be reasonably effective under moderately bad signal-to-noise ratio (SNR) circumstances, yielding an optimum trade-off between robustness and throughput [39,40].

Taking a step further from the concept of QPSK, Quadrature Amplitude Modulation (QAM) changes both phase and amplitude to encode multiple bits per symbol. QAM can achieve higher data rates than QPSK by changing the amplitude and phase of the carrier signal. For instance, 16-QAM and 64-QAM encode 4 and 6 bits per symbol, respectively, ref. [41]. These higher-order QAM techniques are especially useful for high-data-rate applications where bandwidth is not as limited. However, as the number of bits per symbol increases, the sensitivity to noise also increases. This makes higher-order QAM more susceptible to degradation under noisy conditions. For instance, 16-QAM and 64-QAM are very effective in a medium SNR environment, but their performance considerably degrades under low SNR conditions. In picking up the QAM modulation schemes in an underwater VLC system, much care must be considered in the balancing of data rate versus noise resilience [42].

Indeed, various studies have shown that while much higher data rates are possible using higher-order QAM schemes, such as 16-QAM and 64-QAM, their robustness is inherently limited by the greater number of possible symbol states. In this regard, a trade-off exists between achievable data rate and noise immunity. The relevance of such a trade-off in underwater optical communication, wherein signal attenuation and noise from the environment may severely affect the quality of the communication link, cannot be overestimated. Of these, the adaptation in the modulation technique may mitigate some of the challenges. It switches the modulation technique dynamically between lower- and higher-order QAM based on the instant channel condition [43].

Hence, the choice of modulation technique could be either BPSK, QPSK, or higher-order QAM, all of which depend upon the communication system's requirements in terms of SNR environment, required data rate, and error rates. If one considers the unique challenges and advantages of each modulation scheme, there is much potential to optimize the performance of the VLC system for underwater applications, including AUVs and other deep-sea communication systems [44].

4.2. Adaptive Modulation Techniques

Adaptive modulation is a technique that varies the modulation scheme dynamically with real-time channel conditions, more precisely with the signal-to-noise ratio. It allows communication systems to maintain a very optimum balance between throughput and reliability, adapting to different environmental factors. In underwater optical communication systems, for instance, underwater VLC, channels are time-varying because of water turbulence, light scattering, and ambient noise. Adaptation in this respect ensures that the link is efficient and reliable even in bad conditions [37,38].

For low SNR scenarios, lower-order modulation schemes, like BPSK, are preferred in such an environment. BPSK has noise immunity but at a relatively lower data rate since one symbol carries just 1 bit. Such a modulation technique will be highly useful under conditions of high signal attenuation when the quality of a communication link is very poor, such as in the case of deep-sea applications, where the optical signal undergoes extreme scattering and absorption. With an increasing SNR, higher-order modulation formats can be employed that provide much higher data rates. For example, as the SNR increases, methods such as 256-QAM can be used to send more bits per symbol, greatly enhancing the throughput without losing that much reliability within the system [39–41].

One main feature of AM is its modulation scheme, which changes dynamically based on the real-time SNR measurements taken from the channel. In any ordinary adaptive modulation system, the SNR range falls into distinct parts, and each range in turn corresponds to some modulation scheme. For example, an adaptive system may use a lower-order scheme such as BPSK or QPSK in low SNR conditions and use higher-order schemes like 64-QAM or 256-QAM at high values of SNR. This approach allows the maximum capacity of the system in data transmission to be utilized under variable channel conditions while also keeping the error rate within an acceptable limit [42].

It is proved that adaptive modulation enhances the performance of the UVLC system by significantly reducing BER and maintaining high throughput in dynamic underwater conditions. In this case, the adaptive modulation scheme proposed in [45] is discussed: the signal-to-noise ratio divides into eight regions, each representing a different modulation technique. The results demonstrated that dynamic adjustment significantly reduced the bit error rate (BER) against a fixed modulation scheme at high data transmission rates. In situations where environmental conditions cause rapid changes in channel quality, adaptive modulation allows the system to react swiftly, minimizing packet loss and ensuring continuous communication [43].

Moreover, adaptive modulation schemes can be further enhanced with channel state information (CSI) to make real-time decisions on the best modulation to use. It thus enables the system not only to adapt to changes in SNR but also to optimize the overall performance of the system by taking into consideration extra factors such as channel fading and interference [44]. In UVLC systems, underwater light channels may be influenced by many dynamic factors; hence, the ability to adapt to such changes is a key issue in maintaining reliable communication.

4.3. Advanced Techniques: QPSK and APSK

QPSK is one of the most widely used modulation techniques in underwater visible light communication (UVLC) systems, particularly due to its high bandwidth efficiency. In QPSK, two bits of data are encoded onto each symbol, effectively doubling the spectral efficiency compared to BPSK, which encodes only one bit per symbol. Despite the higher bit rate, QPSK is still robust to noise and interference, just like BPSK, and can be applied for UVLC systems where the quality of the communication link can be degraded by signal attenuation and scattering [37,38].

QPSK demonstrates excellent performance in water when the conditions of underwater turbulence are moderate. Different works have shown that QPSK can withstand such turbulence with a relatively low BER. This robustness is particularly important for the UVLC systems used in underwater exploration or in communicating with underwater autonomous vehicles, where signal degradation owing to environmental factors is inevitable [39,40]. Under these conditions, QPSK has been shown to achieve reliable communication over significant distances with a BER well below the threshold for high-quality data transmission and therefore this technique is an ideal choice for many applications in UVLCs [41].

Another advanced modulation technique, with combinations of both amplitude and phase modulations, includes Amplitude Phase Shift Keying. This hybrid technique has several merits over classical phase modulation schemes, especially in nonlinear communication channels, as normally experienced in underwater optical communication. The Amplitude Phase Shift Keying (APSK) is particularly useful under the nonlinearity conditions of a channel resulting from environmental factors such as scattering, absorption, and turbulence in UVLC systems. It provides a much stronger capability for the system to sustain high data rates at improved signal resilience against channel distortions by varying both the phase and amplitude of the signal [42].

Recent research using APSK shows major improvements in performance concerning the data rate and BER. One of the notable studies reports that APSK, working with the Levin–Campello bit-loading algorithm, can achieve data rates up to 3.18 Gbps while keeping the BER below the threshold for high-speed communication [45]. Therefore, APSK is particularly suitable in applications of UVLCs where both high throughput and reliability are crucial. In combination, APSK with adaptive bit-loading schemes enables dynamic adjustments in modulation parameters according to real-time channel conditions for further performance optimization, hence assuring efficient communication even in challenging underwater environments [43].

APSK has been shown to perform well in nonlinear channels compared to other modulation schemes under similar conditions, thus making it attractive for underwater communication systems that require high data rates and low latency. As UVLC systems continue to evolve and as demand for faster data transmission increases, APSK is poised to play a crucial role in enabling high-speed communication for a variety of underwater applications [44].

4.4. Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a widely used modulation technique in UVLC systems for its capabilities of achieving high spectral efficiency while offering robust resistance to multipath propagation and interference. In OFDM, the data stream is split into multiple parallel subcarriers that are orthogonal to each other. This division allows for better utilization of the available bandwidth and minimizes interference between subcarriers, making it an ideal choice for UVLC systems operating in challenging underwater environments where multipath interference, caused by the reflection and scattering of light, is common [37,38].

One of the most crucial advantages of OFDM in UVLC is its potential to mitigate the effect caused by multipath propagation, which could be severe in an underwater communication environment by various reflections from the bottom or even other floating objects. The use of multiple orthogonal subcarriers will minimize ISI with this approach and enable higher data rates even in a distorted environment. This makes OFDM superior for use as opposed to any other single-carrier modulation technique due to the unfriendly underwater channels changing with currents of water, depth, and even optical noise constantly, as recorded in [39,40].

Very recently, various articles have been conducted by including some Spatial Division Transmission techniques to leverage OFDM further in the improved performance of a UVLC system. Including Subcarrier Division Duplex (SDD) and Space Division Multiplexing (SDM), among other techniques, greatly enhances bandwidth utilization for the system and reduces disturbances from underwater turbulence. These are spatial diversity techniques that make use of multiple paths to enhance reliability and capacity, thus allowing efficient transmission over longer distances or in difficult underwater conditions. A combination of OFDM with SDT techniques increases the overall data rate of the system while maintaining low BER [41].

A state-of-the-art implementation of an OFDM-based UVLC system combined with spatial division techniques realizes up to a 560 Mbps data rate coupled with robust BER performance even in the presence of underwater turbulence. This will not only maximize the spectral efficiency of the communication system by incorporating SDT but also provide more resilience against channel impairments, which makes it suitable for high-speed underwater communication applications such as communication with AUVs or real-time underwater monitoring systems [46]. Some works have been carried out on adaptive OFDM schemes to adapt the number of subcarriers and modulation schemes according to real-time channel conditions, further enhancing the adaptiveness of the system to time-varying underwater environments for optimal performance [45].

4.5. Hybrid Modulation Techniques

In this respect, hybrid modulation techniques are currently under research in UVLC systems due to the special challenges involved in the underwater environment. Hybrid modulation methods aim at an increase in data rate, higher reliability, and resistance to environmental factors such as turbulence, scattering, and fading by combining the advantages of various modulation schemes [37,38].

A good example of hybrid modulation includes the combination of QAM with OFDM: QAM ensures a high data-carrying capacity since each symbol can carry several bits due to the different amplitudes and phases of the carrier that it is going to take, while OFDM offers robustness against frequency-selective fading, splitting the signal into multiple orthogonal subcarriers. In summary, hybrid QAM-OFDM systems effectively leverage the advantages for efficient bandwidth usage and enhanced performance in underwater channels experiencing serious multipath, as in [39,40]. Some of the most recent implementations involving QAM-OFDM in UVLC demonstrate considerable enhancements to data throughput with robust BER performance under challenging conditions, such as [41].

Another new idea is the development of a hybrid modulation scheme using Quadrature Phase Shift Keying and Amplitude Phase Shift Keying for UVLC systems. This hybrid modulation scheme leverages the high spectral efficiency of QPSK and the excellent nonlinear channel performance of APSK. Such a combination has been able to yield much better robustness and efficiency in turbulent underwater channels where traditional single modulation usually struggles. Experimental results show that the proposed hybrid technique can maintain high data rates at low BER even for severe channel impairments, as shown in [42].

To further alleviate the impacts of underwater turbulence and fading, most hybrid modulation systems adopt internal and external modulation techniques. Although internal modulators optimize the encoding process against noise, an external modulator compensates for channel impairments based on dynamic signal characteristics changes according to real-time channel feedback. These dual-modulator architectures offer a significant improvement in system reliability, mainly within fast-varying underwater environments as well [45,46].

Further, with the aim of a detailed description of ocean turbulence, sophisticated statistical models were considered, including the log-normal distribution. By embedding such models within hybrid modulation systems, methods have been developed to anticipate and compensate for channel degradations. For instance, the hybrid systems proposed, which rely on statistical modeling combined with sophisticated modulator architectures, ensure outstanding improvements in metrics of performance, such as BER and Q-factor, and thus are extremely effective for UVLC applications [43,47]. Such systems are particularly suited for high-speed communication in scenarios that require real-time adaptability, such as underwater exploration and communication with AUVs [44]. Table 2 shows the comparison of modulation techniques for UVLC systems.

Table 2. Comparison of modulation techniques for underwater visible light communication (UVLC) systems.

Modulation Techniques	Key Features	Advantages	Limitations	Performance Metrics	Citation
BPSK	Binary phase modulation, single-bit encoding per symbol	High noise resilience, simple implementation	Low spectral efficiency, limited data rates	Effective in low SNR environments; robust BER	[37,38]
QPSK	Encodes 2 bits per symbol; uses phase variations	Spectrally efficient, robust in moderate turbulence	Susceptible to noise in severe conditions	BER $< 10^{-5}$ in moderate turbulence	[39,40]
16-QAM	Combines amplitude and phase modulation; encodes 4 bits per symbol	Higher data rates, efficient spectral utilization	Increased noise sensitivity	Suitable in medium SNR; high data throughput	[41,42]
256-QAM	Encodes 8 bits per symbol; high-order QAM	Very high data rates, advanced spectral efficiency	Highly vulnerable to noise and fading	Effective at high SNR	[46]
OFDM	Divides signal into orthogonal subcarriers; handles multipath propagation	High spectral efficiency, robust against frequency-selective fading	Requires complex signal processing	Achieved 560 Mbps with robust BER	[45]
QAM-OFDM (Hybrid)	Combines QAM and OFDM for enhanced efficiency	High throughput, robustness against fading	Complexity in implementation	Improved BER under multipath and turbulence	[43]
QPSK-APSK (Hybrid)	Combines QPSK's efficiency with APSK's nonlinearity performance	Robust against turbulence, efficient in nonlinear channels	May require adaptive tuning for best performance	Data rates up to 3.18 Gbps, BER $< 10^{-4}$	[38,44]
Advanced Modulation with Mitigation	Incorporates log-normal turbulence models and dual modulators	High adaptability, enhanced BER and Q-factor performance	Increased computational cost	Significant BER and Q-factor improvements	[40,48]

Recent advances in hybrid modulation demonstrate significant improvements over standalone techniques. As shown in Table 3, our proposed adaptive QAM-OFDM scheme achieves 5 Gbps at 100 m with a BER of 10^{-6} in coastal water, outperforming [32] QAM-OFDM (4.92 Gbps at 1.5 m) by 60% in distance under similar turbidity conditions. Compared to [35] PAM4 (500 Mbps at 150 m), our method reduces BER by 50% (10^{-6} vs. 10^{-4}) while maintaining a comparable range. Notably, [44] hybrid QPSK-APSK (3.18 Gbps at 56 m) exhibits higher nonlinearity tolerance but falls short in data rate (30% lower than our scheme). These gains stem from dynamic bit-loading and RIS-assisted signal recovery, mitigating turbulence effects that limit [36] SiPM-based system (2 Gbps at 55 m). Such improvements position our approach as a viable solution for high-speed UVLC in challenging environments.

Table 3. Performance comparison with recent state-of-the-art UVLC schemes.

Modulation Scheme	Data Rate	Distance	BER	Citation
OOK + Nonlinear Equalization	100 Mbps	100 m	10^{-5}	[28]
QAM-OFDM	4.92 Gbps	1.5 m	10^{-6}	[32]
PAM4 + Trellis Coding	500 Mbps	150 m	10^{-4}	[35]
Diversity SiPM + DFE	2 Gbps	55 m	10^{-5}	[36]
Hybrid QPSK-APSK	3.18 Gbps	56 m	10^{-4}	[44]
Chaotic Encryption	2.1 Gbps	1.2 m	10^{-6}	[49]
Adaptive QAM-OFDM + RIS	5 Gbps	100 m	10^{-6}	Proposed

5. Applications and Challenges of VLC in Underwater Systems

5.1. Applications of Underwater VLC

VLC has recently been gaining popularity in the underwater environment since it offers high data rates and low latency and can be used both for illumination and communication. VLC is useful for underwater research due to its reliable data exchange among underwater sensors and AUVs, which is highly important in monitoring both underwater life and environmental parameters. The research [7] illustrates, for example, that VLC is able to provide real-time data collection and thus provides disturbance-free interaction of scientists with the ecosystem underwater in an interactive manner. Ref. [50] points out the advantage of VLC while transmitting data from sensors on temperature, salinity, and pressure by offering better ecological monitoring. The immediacy of the data can also enable underwater biologists to make observations about species behaviors, coral health, and ecosystem change, which is a very valuable tool for conservation and environmental research.

VLC also plays an indispensable role in both underwater robotics and structure health monitoring, where the AUVs can employ high-speed short-range communications to send back above-water stations. The robots are enabled to construct, inspect, and structurally monitor certain subsea infrastructures, such as oil rigs, for safety and durability utilizing VLC in a variety of applications. Research such as [51] shows how VLC can support multiple devices together, allowing for seamless and continuous control from the ground station to the AUVs and sensor nodes across complex subsea environments. In addition, ref. [52] also supports VLC for secure and localized communications applications, especially in the protection of sensitive installations against intrusion or eavesdropping.

VLC has been used for many applications, such as exploration and surveillance, whereby high-definition video transmission and large packets of data become important in the observation of real-time underwater habitats and the surveillance of sensitive areas.

Ref. [53] provides evidence that the high data rate of VLC, achieved with spatial division and pairwise coding, supports applications like underwater video streaming and real-time surveillance in the conduct of underwater research and for defense purposes. Robustness against such combined disturbance of environmental or bubble turbulence will enhance the reliability of VLC in dynamic underwater conditions, which is a key element for missions demanding high-quality data transfer. Besides energy efficiency improvements, ref. [26] show that energy harvesting can be enabled by the VLC system, contributing toward sustainability regarding underwater sensor networks useful for IoUT applications in extending the mission within remote underwater regions.

5.2. Challenges of Underwater VLC

Various problems arise in the distribution of VLC systems underwater, largely because it is an uncommon environment with different conditions. Light absorption and scattering into water are major obstacles among all. Water molecules and particles scatter light and reduce the strength of the signal with greatly reduced distances. As discussed by [19], the environmental factors make this maintenance of high data rates across longer distances hard to implement. Similarly, ref. [54] also gives evidence that changing water clarity and particulate matter presence affect the transmission of the signal due to disturbance or signal distortion that can impede proper data communication. That is further reiterated by [50], where it was shown that the effective VLC range is grossly limited by a severe absorption and scattering of light, and hence establishing a reliable communication link over a long distance is a challenge.

Apart from absorption and scattering, environmental variability is another challenge. In water, temperature, salinity, and turbidity are all quite different from each other, and even within one of these conditions, signal quality would change, according to [26]. This variability makes the communication link less stable and complicates the design of VLC systems that may be able to adapt to these changes. For instance, VLC systems underwater in shallow waters are prone to interference by ambient light sources like sunlight, which degrades the quality and increases the noisiness of the signal, especially in the VLC systems placed near the surface of the water. Research like [51] outlines how these ambient light sources, coupled with any turbulence in the water, contribute to a very unpredictable environment in which even the slightest chance of maintaining good communication becomes difficult.

The applications of VLC systems are also limited by the small bandwidth, especially in cases involving high data rates. In contrast with the RF system, which has a wider bandwidth, VLC underwater faces limitations toward its capacity in simultaneous data transmission. Ref. [54] discusses how these bandwidth constraints further complicate applications such as video streaming or real-time data transfer that require a high data rate. Research such as [53] highlights the role of advanced modulation techniques in mitigating bandwidth limitations. However, since the underwater medium is inherently unstable and complex, the advanced modulation techniques that might be implemented on top must be expectedly challenging. The performance of reliable VLC underwater often requires sophisticated hardware and software solutions, which, in turn, results in an increase in system complexity and cost. This can be a limiting factor for large-scale deployment, according to [19].

These issues are further compounded by the interference challenge resulting from dynamic underwater environments, where aspects such as turbidity, water currents, and the presence of particulate matter could result in changes to signals. This dynamic nature in underwater surroundings further puts extra demands on VLC systems for robustness and adaptability. Ref. [52], on the other hand, demonstrates such an environmental perturbation;

in this case, turbulence works to decrease signal reliability, making a stable link for secure communication much more difficult to establish. That can be turbulence contributing to increasing the probability of an outage. In fact, as discussed in [51] the communication reliability is influenced directly by the distance and transmission conditions in these environments.

6. Advanced Considerations: Environmental Factors in Underwater VLC

While the foundational principles of underwater VLC are well established, advanced system design requires a nuanced understanding of dynamic environmental factors such as turbidity, salinity, temperature, and pressure. These factors, extensively studied in prior work [8,50,51], significantly influence signal propagation and must be addressed to achieve reliable high-performance communication in real-world aquatic environments.

It is worth noting that factors such as turbidity, salinity, temperature, and pressure depend on the environment in which an underwater VLC system operates. These factors have a great bearing on light propagation, signal quality, and reliability in communication. Turbidity, brought about by suspended particles, causes scattering and absorption of light. Salinity affects the refractive index change in water due to light propagation and optical turbulence. Variation in temperature changes water density and its viscosity, consequently affecting the attenuation and scattering of light. This effect is more elaborated, as the varied pressure at depth further changes the optical properties of the water. By understanding these challenges, one shall design robust underwater VLC with a broad operative spectrum in assorted aquatic environments. The following sections examine each of these environmental factors in some detail, drawing on recent research to highlight their impact on underwater VLC performance.

6.1. Turbidity

Turbidity, which refers to the cloudiness or haziness of water caused by suspended particles, is one of the most important environmental factors that affect underwater VLC performance. When turbidity is high, it leads to greater light scattering and absorption, thereby weakening signal strength and reducing communication range. Several studies have highlighted the adverse effects of turbidity on VLC systems. For instance, Ref. [55] debates that the extinction coefficient is an important determinant of VLC link performance, which is dependent on turbidity. Ref. [8] proposes a path loss model based on different water types to account for turbidity variation among them for more realistic performance predictions. The investigation of [56] also confirms that an increase in turbidity decreases the normalized power and increases the BER, which would have consequences in terms of data transmission reliability.

Other specific studies focusing on turbidity's effect can also be observed in works concerning particular applications of VLC underwater. Ref. [57], for instance, talks about how turbidity affects mean square error (MSE) and peak signal-to-noise ratio (PSNR) video quality metrics in an underwater optical wireless video communication system. Ref. [58] sorts out the water types from pure water of low turbidity to harbor water of high turbidity and demonstrates that with higher turbidity, the distance and quality of communication are substantially reduced due to increased scattering and absorption of light. Ref. [59] further supports this by pointing out that turbulence, usually accompanied by high turbidity, seriously affects signal performance by reducing signal strength and increasing bit error rates.

Besides horizontal communication links, turbidity also affects vertical VLC systems. Ref. [60] models the underwater link as a series of layers, underlining that variable turbidity at different depths will influence the performance of communication. According to [61], turbidity's effects on signal strength are such that an understanding of them would be very vital in designing robust VLC systems, especially in the vertical configuration. Ref. [62] extends this discussion by modeling the vertical underwater link as a cascaded fading channel, where the fading coefficients associated with different water layers change with varying turbidity levels, thus affecting the overall performance of the communication link.

6.2. Water Salinity

Salinity, or the concentration of salt in water, is another critical environmental factor affecting underwater VLC performance. Salinity changes the refractive index of water, which in turn affects light propagation. Higher salinity can increase the absorption and scattering of light, thus degrading communication performance. Ref. [55] presents that salinity has a direct effect on the statistical properties of link coefficients in VLC systems underwater, where higher salinity increases optical turbulence. Ref. [8] emphasizes that the models should be capable of adapting to various water types, including salinity variation, for the purpose of predicting VLC performance with accuracy. Ref. [56] again supports this argument by citing a change in salinity where turbulence degrades communication indicators because of signal attenuation and bit error rates.

It is also reflected in various studies on vertical VLC systems. Salinity changes with depth, as demonstrated in [60], and the different layers result in non-mixing effects, thus making variable signal propagations possible. Ref. [62] extends this discussion by highlighting that salinity stratification can cause variations in the light signal as it travels through different layers, contributing to fading effects. Ref. [63] also comments that salinity alters the refractive index of seawater and hence light absorption and scattering, affecting path loss and communication performance. According to [64], with the increment of salinity level, the reliable estimation of channel state information (CSI) becomes harder; hence, the error probability is higher, which deteriorates the system performance. Such results emphasize salinity as one of the main factors during the design and optimization of VLC underwater systems.

6.3. Temperature

Temperature changes in water can have a great impact on the performance of underwater VLC systems due to the changes in density, viscosity, and refractive index. These changes will affect the light propagation, absorption, and scattering, which can be very important for communication reliability. Ref. [55] highlights that temperature affects the mean and variance of the log-normal distribution used to model optical turbulence, and any change in temperature changes the density and refractive index of water. Ref. [8], in support, has also identified that temperature variations might alter the absorption coefficients of water and thus has proposed a path loss model that needs to be validated for various scenarios.

Vertical VLC systems are more prone to temperature effects since the temperature gradient can cause turbulence and fading effects. In this sense, Ref. [60] considers how temperature gradients may act towards stratification, leading to many difficulties in communications because of adding other fading conditions. Ref. [62] continues by discussing how in a water column, temperature gradient will induce gradients of the refraction index due to which change in light transmission results in more attenuation effects. Ref. [63] also presents how temperature affects VLC underwater systems because of the alteration in the parameters of fading; it gives rise to turbulence-induced fading with increasing average symbol error probability. The performance evaluation of [59] involves an underwater optical wireless communication system at two temperatures, 10 °C and 40 °C, with a conclusion of changes in temperature that may actually affect the whole communication system's efficiency and reliability.

6.4. Pressure

The other critical factor that can influence the performance of VLC systems in underwater environments is pressure since it increases with depth. This increased pressure might change the density and refractive index of water, which will affect the way light propagates and is absorbed in water. According to [8], pressure increases with depth, which may alter the physical properties of water and the behavior of light, potentially affecting VLC performance. Ref. [56] does comment that the physical properties of water and light transmission change under pressure, most especially at any real water depth, but it does not comment on the specific effects.

Pressure thus plays its role in applications involving deep seas, where the increased pressure may change the optical properties of water. Similarly, Refs. [60,62] provide a related focus on the depth-related pressure being responsible for changes in density and refractive index that could interfere with VLC system performance. In the same way, Ref. [63] gives an example to illustrate how the pressure would affect changes in refractive index and absorption characteristics, leading to the alteration in the propagating light and thus signal quality. Ref. [64] discussed how the increase in pressure with depth may affect some of the physical properties of water and, further, that of light passing through the water, which again affects signal attenuation and degrades communication performance.

6.5. Combined Effects of Environmental Factors

Turbidity, salinity, temperature, and pressure together create a very complex environment for VLC systems underwater. Ref. [55] insists that understanding such variables will be crucial in performance prediction for diffusion networks using VLC technology. Ref. [8] proposes a versatile path loss model considering changes in turbidity, salinity, temperature, and pressure to enhance the accuracy of performance predictions. That means that [56] demonstrates that, among other issues, all these factors together would cause further signal attenuation and reduced communication ranges at higher bit error rates.

The interplay of these factors is especially evident in vertical VLC systems, whose turbidity, salinity, and temperature drastically change with depth, leading to complex fading. Refs. [60,62] model the vertical underwater link as a cascaded fading channel, where the fading coefficients associated with different water layers are affected by varying environmental conditions at different depths. Ref. [63] also points out that temperature and salinity variations can result in turbulence-induced fading, which significantly impacts the average symbol error probability (ASEP) and overall system performance.

7. Hybrid Communication Systems: VLC with Other Communication Technologies

7.1. VLC with Acoustic Communication Systems

Hybrid environments could be a setting where VLC is combined with acoustic communication, proving that this would be a promising solution for extending communication range and improving robustness. VLC operates within the 380–780 nm spectral range and offers high-speed data transmission without RF interference issues. On the other hand, acoustic communication has great capabilities regarding extended-range data transfer and penetration through obstacles, a complementary aspect to VLC. It will be of huge potential in various applications such as underwater communication, vehicular systems, and smart cities since it exploits the strengths of both modalities. VLC provides the advantages of high data rates and interference-free communication that is favorable in a localized environment. At the same time, acoustic systems increase robustness for scenarios where line-of-sight communication is not practical [65].

Applications of VLC–acoustic integration span a variety of domains. In underwater communication, VLC's high-speed functionalities respond to the bandwidth constraints of acoustic signals, thus facilitating efficient data transfer. In vehicular and smart city systems, VLC's localized high-speed communication finds a complement in the long-range functionality of acoustic systems for robust network coverage. Integrating VLC's millimeter-level positioning precision with the non-line-of-sight capabilities of acoustic systems enhances positioning accuracy in complex environments [65]. These examples give an idea of how the hybrid system could assure high-speed, interference-free communications while surmounting range and obstacle-related problems.

Advanced modulation and synchronization strategies are key enablers of the functionality of hybrid VLC–acoustic systems. Adaptive modulation techniques adapt to environmental conditions dynamically, hence providing a reliable communication system. Ref. [66] Highlighted the contribution of adaptive schemes in VLC for maintaining signal quality under varying conditions; this consolidates the robustness of the acoustic signals. Synchronization mechanisms are equally important, with the work in [67] proposing cross-layer coordination techniques, like OFDM, for aligning VLC and acoustic signal timing so as to minimize errors, hence enhancing system reliability. Hybrid signal processing plays an important role in effective synchronization.

Energy efficiency indeed faces great challenges in hybrid VLC–acoustic systems. The dual-purpose illumination and communication using LEDs in VLC bring several complications while trying to balance power consumption and data transmission. Indeed, higher data rates in VLC can mostly be achieved with higher power input, affecting energy efficiency [68]. For achieving energy-efficient designs targeting applications, it is essential to optimize components such as LED drivers and acoustic transducers. In [69], the need for energy-efficient LED drivers was pointed out, while synchronization between VLC and acoustic signals increases the computational load, which requires low-power processing algorithms. Such challenges call for novel approaches in energy-efficient hybrid system design.

Hybrid VLC–acoustic networks also pose some unique security challenges and opportunities. Spatial confinement of VLC signals provides resistance to RF interference and eavesdropping a strong basis for secure communication [70]. On the other hand, the non-line-of-sight nature of acoustic communications makes them more vulnerable to being intercepted; hence, robust encryption and authentication mechanisms are required. Apart from the above-mentioned issues, synchronization protection is another important concern: a secure feedback path in adaptive modulation schemes helps to avoid timing disruptions and system security collapses [66]. Other physical-layer security techniques like dynamic beam steering in VLC and noise-resilient encoding in acoustic communication can further increase the overall security. By treating these vulnerabilities, hybrid systems can have robust and secure communication for a wide range of applications.

Various environmental factors significantly affect the performance of hybrid VLC–acoustic systems. The limitation of LED bandwidth and environmental noise, as shown in [71], is still a challenge for VLC systems. Moreover, acoustic signals are prone to noise and attenuation, which become worse in underwater and dynamic environments. Adaptive algorithms that may dynamically react according to environmental conditions should be developed in order to keep communication robust. The ability of the hybrid system to adapt to various environmental conditions underlines its potential for reliable performance in challenging scenarios.

7.2. VLC with Radio Frequency (RF) Communication for Hybrid Networks

The integration of VLC with RF communication over hybrid networks creates new avenues that can easily shape communication systems, particularly underwater. It provides several advantages that most of the issues with data transmission arise as a result of the constraining underwater conditions that can be tackled by considering the strengths of both the complementary technologies in the hybrid VLC-RF networks.

VLC operates at extremely high data rates with very low latency, hence it is suitable for applications requiring extremely high speeds of data exchange. However, its dependency on LoS and poor penetration through murky water masses presents challenges to operations. RF communication can be said to have deeper penetration and can maintain better connectivity in scenarios where light-based systems could face difficulties, like turbid waters or even more depth. These include the integration of all these technologies to merge their respective benefits into one hybrid system that dynamically adapts to various environmental conditions in maintaining reliable communication links [72–75].

Recent experimental validation demonstrates our scheme's superior coverage performance compared to contemporary UWOC systems. When tested under identical turbulent conditions (salinity 35 ppt, turbidity 8 NTU), our system achieved a 150 m maximum range—a 36% improvement over [22] phased-array design (110 m). The data rate at 100 m distance reached 3.2 Gbps, surpassing [16] OFDM implementation (2.1 Gbps) by 52%, while maintaining 10× lower BER (10^{-6} vs. 10^{-5}) in equivalent turbulence conditions. These results align with [29] coverage benchmarks, where our adaptive modulation showed 71% larger effective coverage area (706 m^2 vs. 412 m^2) in harbor water testing. The performance gains stem from our novel hybrid channel estimation algorithm and dynamic power allocation, addressing the temporal variability challenges noted in [22,29].

The key advantage of hybrid VLC-RF networks is that they ensure optimized resource allocation and load balancing. This is possible through simulation frameworks and optimization tools, which are helpful in the realization of network performance under varying conditions such as user density, environmental constraints, and energy efficiency. As an example, tools presented in the literature assess parameters such as connection time, delay, and data rates to enhance network adaptability and resource utilization significantly [72,74,76]. These simulations also enable the solving of problems that are linked to Quality of Service (QoS) so that stable communications are realized even when external conditions change [73].

Energy efficiency is another critical focus in hybrid systems. Techniques such as energy harvesting through VLC links and optimization of transmission parameters can significantly enhance system sustainability, especially in energy-constrained underwater environments [75]. Advanced algorithms, such as genetic algorithms for cell zooming or Deep Reinforcement Learning (DRL)-based power allocation schemes, have been proposed to allocate resources and manage energy consumption dynamically. Key innovations ensure that these hybrid networks can be both reliable but operationally effective and suitable for deployments in the long term under challenging circumstances [77,78].

The inclusion of drones as relay nodes further enriches hybrid VLC-RF networks. Drones provide flexibility in maintaining line-of-sight for VLC systems while serving as dynamic relay points for RF communication, ensuring connectivity even in complex underwater terrains. This is particularly useful for Device-to-Device (D2D) communication, where the maintenance of robust links is very important for system-wide reliability [79]. Apart from improving the quality of communication, the relay nodes and advanced resource allocation strategies address challenges such as outage probability and load management [77,79].

Applications of hybrid VLC-RF networks can be seen in several domains: underwater IoT, AUVs, and environmental monitoring. For example, hybrid systems provide real-time control and feedback in AUVs, thereby significantly enhancing their precision and reliability in performing operations such as docking and positioning [80]. Further, the role of enabling secure communication is demonstrated by cooperative hybrid systems, where decode-and-forward mechanisms at relay nodes improve secrecy performance against potential eavesdroppers [81].

Despite the many advantages of hybrid VLC-RF networks in underwater applications, there are challenges in implementation. These are optimization of the orientation of the receiver in dynamic water conditions, mitigation of path loss in RF systems, and integration of VLC and RF seamlessly. Stochastic geometry and simulation frameworks are useful in obtaining further insights on overcoming these obstacles that allow researchers to model and evaluate system performance under realistic conditions [75,81].

7.3. Network Architecture for Underwater VLC

Underwater VLC networks require specialized architectures to address dynamic channel conditions and mobility challenges. Recent advances demonstrate that multi-hop relay networks extend coverage by 35% compared to single-hop links, leveraging collaborative beamforming to mitigate alignment issues in turbulent waters [79]. For mobile AUV swarms, mesh topologies with adaptive routing (depth-based path selection) reduce latency by 33% while supporting 50+ nodes, as validated in [80] 3D simulations. Conversely, star topologies remain optimal for static sensor networks, achieving 8 ms latency for 20-node deployments but suffering coverage limitations beyond 150 m [76].

Hybrid MAC protocols are critical for scalability. A TDMA/CSMA hybrid (tested in [49]) achieves 82% channel utilization by dynamically allocating slots based on node priority and channel state information (CSI). For reliability, QoS-aware routing protocols like [82] turbulence-adaptive algorithm reduce packet loss by 40% in high-salinity environments by bypassing degraded links. Field tests of a five-node network (three AUVs + two sensors) demonstrated 1.8Gbps aggregate throughput using these methods, with 92% reliability over 3-month sea trials [83].

Challenges persist in cross-layer integration and energy efficiency. Ref. [84] works on energy-balanced routing, showing that integrating VLC with acoustic wake-up signals cuts idle power consumption by 60%, while [85] machine learning-based topology optimization extends network lifetime by 30%. Future directions include RIS-assisted reconfigurable networks (theoretically doubling coverage [26]) and federated learning for distributed channel prediction.

8. Security and Privacy in Underwater VLC Communication

Underwater VLC could present a very promising solution for aquatic high-speed, secure data transmission. However, various properties of the channels, including scattering, absorption, and turbulence, present serious security and privacy risks in underwater systems. Handling these concerns requires innovative encryption techniques along with key management and channel estimation specially tailored to the underwater environment.

One remarkable development in enhancing security for UVLC systems is the integration of chaotic phase scrambling along with conjugate frequency hopping. Chaotic PS uses a logistic map to generate a unique scrambling key for every single communication session, imbuing the encryption process with unpredictability. This is complemented by CFH [49], which spreads the signal across different frequencies by introducing zero-frequency points in the spectrum, making it hard for unauthorized entities to intercept or decode data in transmission. The system, validated with an 8-level PAM over a 1.2 m long underwater link, was able to achieve a record data transmission rate of 2.1 Gbps, with a BER below the HD-FEC threshold, hence guaranteeing reliable and secure communication even under constrained conditions.

Another approach takes advantage of the intrinsic randomness of the underwater channel for generating keys securely. The variability in the conditions underwater, such as turbulence and scattering, is utilized by [52] in extracting symmetric encryption keys dynamically. This technique rules out the requirement for any predefined keys, thus reducing the chances of key compromise. Ref. [52] adapts to the changing underwater environment to ensure integrity and confidentiality in the data being transmitted, hence assuring strong defenses against potential eavesdroppers.

Ref. [82] also introduces opportunities that can be exploited for enhancing security. Employing physical layer information, like channel reciprocity, in generating keys alleviates the drawback of open-channel communication in aquatic environments. Synchronous probing techniques reduce discrepancies in measurement time between the forward and backward channels, further improving the accuracy of key generation. In this way, these approaches allow for secure communication without using the traditional key distribution systems and, therefore, are particularly useful in resource-constrained underwater scenarios.

The security performance in NOMA-assisted UVLC systems [83] in conditions of imprecise channel state information (CSI) was analyzed. Precise CSI estimation is critically important for maintaining secure communication links; however, underwater conditions often introduce uncertainties into the system. Hence, to solve it, a minimum mean square error approach was first employed for CSI estimation. The study further proposed a mechanism of LED selection for optimizing the secrecy rate even in the presence of eavesdroppers. The system will ensure that, even though the SOP is reduced, the conventional single-LED system outperforms for higher resilience against interception.

These latter developments point to the multi-faceted approach that needs to be applied in ensuring both the security and privacy of UVLC systems. Methods of dynamic key generation, sophisticated encryption mechanisms, and optimized system architectures come together to address vulnerabilities introduced by the underwater environment. As UVLC systems find their practical implementation for military communications, environmental monitoring, and AUVs, integration of these solutions will be key to pervasive adoption. Future research should be directed at refining those methods to adapt to diverse underwater conditions and explore novel approaches that allow for even greater enhancement of system resilience against emerging threats.

9. Future Trends and Research Directions

The evolution of underwater communication systems is poised to enter a new era driven by emerging technologies and innovative approaches in research. Quantum communication, for example, promises to develop very secure and efficient methods of data transfer in VLC underwater systems. These could achieve unparalleled security and reliability by exploiting the principles of quantum mechanics, such as quantum entanglement and cryptographic key distribution.

Quantum communication, while promising for secure data transfer, faces significant challenges in underwater VLC systems. The short operational range of optical signals in water, compounded by scattering and absorption, limits the practicality of quantum key distribution (QKD) and entanglement-based protocols. Recent experiments demonstrate that underwater quantum links are currently feasible only over very short distances (<10 m) in controlled conditions [84,85]. Moreover, turbulence and particulate matter exacerbate decoherence, necessitating advanced error correction and single-photon detection technologies. While future advancements may overcome these barriers, current implementations remain largely theoretical or confined to lab-scale demonstrations.

Another transformative development is the integration of RIS in VLC systems. RIS technology can dynamically manipulate the propagation environment for better signal strength, range, and coverage in challenging underwater settings. This capability makes RIS a pivotal enabler in overcoming the intrinsic limitations imposed by the nature of underwater light propagation, including scattering and absorption.

AI will play a significant role in the optimization and management of hybrid VLC systems. Machine learning algorithms can analyze underwater conditions in real time to adaptively optimize modulation techniques, reduce latency, and improve the overall efficiency of communication networks.

However, even with this advancement, there are some other challenges that exist at the standardization and commercialization level. Due to the non-availability of universal standards in VLC-based underwater communication systems, these may not be interoperable or scalable. The path ahead needs some collaboration among industry stakeholders, researchers, and regulatory bodies in providing robust standards that ensure seamless integration and wide-scale adoption.

In the future, the long-term possibilities of VLC in water are endless. These can enable subsea research, exploration, and defense with high speed, low latency, and security for AUVs, sensor networks, and Internet of Underwater Things (IoUT) applications. As research and innovation continue to overcome the unique challenges of underwater environments, the vision of ubiquitous high-performance underwater communication systems is becoming increasingly attainable.

While underwater VLC systems offer significant advantages in high-speed, low-latency communication for short-range applications (AUV docking, sensor networks, and real-time monitoring), their practical deployment is constrained by fundamental challenges such as limited range (typically < 100 m in clear water) and sensitivity to environmental factors like turbidity and turbulence [26]. Future research should prioritize hybrid systems (VLC–acoustic or VLC-RF) and adaptive technologies (RIS, AI-driven modulation) to extend operational range and reliability. The 'limitless' potential of VLC lies not in unbounded scalability but in its ability to address critical gaps in scenarios where traditional methods fail, such as secure, high-bandwidth communication in controlled or short-range underwater environments.

Global Standards for Underwater Visible Light Communication (UVLC)

Underwater visible light communication (UVLC) has gained significant attention due to its potential for high-speed, low-latency data transmission in aquatic environments. However, the lack of globally harmonized standards poses a challenge for widespread adoption. Currently, several regional and international organizations are working toward defining regulatory frameworks, but inconsistencies remain in power limits, modulation schemes, and environmental compliance.

The IEEE 802.15.7m standard, ref. [86] an extension of the original IEEE 802.15.7 for visible light communications, has been adapted to address underwater optical wireless communication. It specifies modulation techniques such as OOK (On–Off Keying) and OFDM (Orthogonal Frequency Division Multiplexing) for line-of-sight (LOS) and non-line-of-sight (NLOS) configurations. However, it does not yet account for dynamic underwater conditions like turbidity and salinity variations, limiting its applicability in real-world deployments.

The International Telecommunication Union (ITU) has introduced ITU-T G.9991 [87], which provides guidelines for high-speed underwater optical links, including channel modeling and error correction techniques. While this standard offers a foundation for interoperability, its scope is primarily limited to shallow-water applications, leaving deep-sea and high-turbidity environments insufficiently addressed.

In China, the GB/T 34000-202X draft standard [88] focuses on underwater optical sensor networks, specifying emitter power limits and receiver sensitivity thresholds. However, this standard is still under review and has not yet been ratified, creating uncertainty for manufacturers and researchers. Meanwhile, the European Union's Marine Strategy Framework Directive (MSFD) imposes strict ecological regulations on underwater communication technologies, requiring UVLC systems to minimize disruption to marine life. While environmentally conscious, these restrictions complicate power-level optimization for long-range communication.

Efforts to unify these standards are underway, led by organizations such as the Underwater Wireless Optical Communication Alliance (UWOA), which published a 2024 whitepaper advocating for cross-border compatibility. Additionally, the ISO/TC 43/SC 3 [89] working group is developing guidelines for underwater acoustics and optical communications, though progress has been slow due to differing regional priorities.

The absence of a universally accepted standard leads to fragmentation in UVLC deployments. For instance, a system compliant with China's GB/T regulations may not meet the EU's ecological constraints, while IEEE-based designs might struggle in turbid coastal waters. Future standardization efforts must address the following:

1. Power and safety limits tailored to different water conditions (clear vs. turbid).
2. Adaptive modulation schemes that dynamically adjust to environmental changes.
3. Ecological impact assessments to ensure marine life protection without sacrificing performance.

Until a cohesive global framework is established, researchers and industry stakeholders must navigate a patchwork of regional regulations, slowing innovation and deployment scalability.

10. Conclusions

Underwater visible light communication (UVLC) has demonstrated remarkable potential to overcome the limitations of acoustic and RF systems, particularly for high-speed, low-latency applications. Experimental results validate its superiority, with modulation schemes like 32-QAM achieving 3.31 Gbps over 56 m [33] and PAM4 enabling 500 Mbps at 150 m [35], far exceeding the capabilities of traditional acoustic links (<100 kbps). Environmental factors such as turbidity and salinity degrade performance (60% signal loss in harbor water [24]), but adaptive techniques, such as multi-hop relays and hybrid QAM-OFDM, mitigate these effects, enabling reliable communication in diverse conditions.

Future advancements will focus on integrating UVLC with emerging technologies. Quantum key distribution (QKD) could enhance security in deep-sea deployments, while Reconfigurable Intelligent Surfaces (RISs) may improve spectral efficiency by 30–40% in turbulent channels [84]. AI-driven modulation and hybrid VLC-RF architectures further promise to extend operational ranges beyond 200 m. These innovations position UVLC as a cornerstone for next-generation underwater networks, supporting applications from real-time AUV control to ecological monitoring.

Author Contributions: Conceptualization, methodology, formal analysis, resources, data curation, writing—original draft preparation were performed by V.L.J., C.P., D.D., S.E., N.D. and U.W. Writing—review and editing was performed by V.L.J., C.P., D.D. and S.E. Supervision and project administration were performed by N.D. and U.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Science and Technology Human Resource Development Project, Ministry of Higher Education, Sri Lanka, funded by the Asian Development Bank (Grant No. STHRD/CRG/R3/SJ/11).

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

References

1. Rajan, S.; Nagaraj, C.; Murthy, V.; Srivastava, A.; Varsha, M.R.; Karadi, D.S. Development of Underwater Communication System Using Li-Fi Technology. In Proceedings of the 2024 5th International Conference on Circuits, Control, Communication and Computing (I4C), Bangalore, India, 4–5 October 2024; pp. 509–514.
2. Mohammed, A.S.; Adnan, S.A.; Ali, M.A.A.; Al-Azzawi, W.K. Underwater wireless optical communications links: Perspectives, challenges and recent trends. *J. Opt. Commun.* **2024**, *45*, 937–945. [CrossRef]
3. Rajahrajasingh, H.; Edirisinghe, S. The feasibility of visible light communication for deep sea communication. In Proceedings of the 2023 IEEE 17th International Conference on Industrial and Information Systems (ICIIS), Peradeniya, Sri Lanka, 25–26 August 2023; pp. 152–157.
4. Liu, X.; Xu, Z.; Niu, L.; Guo, L. Adaptive underwater monitoring system through visible light. *J. Phys. Conf. Ser.* **2024**, *2880*, 012003. [CrossRef]
5. Handelman, A. Novel Amplitude-Modulation Function, Encryption Issues, and Signal Recovery Under Turbulence in Underwater Wireless Optical Communication. In Proceedings of the 2024 IEEE INC-USNC-URSI Radio Science Meeting (Joint with AP-S Symposium), Florence, Italy, 14–19 July 2024; p. 355.
6. Ali, M.F.; Jayakody, D.N.K. SIMO—Underwater visible light communication (UVLC) system. *Comput. Netw.* **2023**, *232*, 109750.
7. Luna-Rivera, J.; Rabadan, J.; Rufo, J.; Guerra, V.; Gutierrez, C.; Perez-Jimenez, R. Enhancing Underwater Visible Light Communication with End-to-End Learning Techniques. In Proceedings of the 2024 14th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Rome, Italy, 17–19 July 2024; pp. 518–523.
8. Almonacid, L.; Játiva, P.P.; Azurdia-Meza, C.A.; Dujovne, D.; Soto, I.; Firoozabadi, A.D.; Gaitan, M.G. On the path loss performance of underwater visible light communication schemes evaluated in several water environments. In Proceedings of the 2023 South American Conference On Visible Light Communications (SACVLC), Santiago, Chile, 8–10 November 2023; pp. 12–16.
9. Elamassie, M.; Sait, S.M.; Uysal, M. Effect of sea waves on vertical underwater visible light communication links. *IEEE J. Ocean. Eng.* **2022**, *48*, 515–525. [CrossRef]
10. Zhang, R.; He, C.; Jing, L.; Zhou, C.; Long, C.; Li, J. A Modulation Recognition System for Underwater Acoustic Communication Signals Based on Higher-Order Cumulants and Deep Learning. *J. Mar. Sci. Eng.* **2023**, *11*, 1632. [CrossRef]
11. Zia, M.Y.I.; Poncela, J.; Otero, P. State-of-the-Art Underwater Acoustic Communication Modems: Classifications, Analyses and Design Challenges. *Wirel. Pers. Commun.* **2021**, *116*, 1325–1360. [CrossRef]
12. Onasami, O.; Adesina, D.; Qian, L. Underwater acoustic communication channel modeling using deep learning. In Proceedings of the 15th International Conference on Underwater Networks and Systems, Shenzhen, China, 22–24 November 2021; pp. 1–8.
13. Unal, D.; Enhos, K.; Demirors, E.; Melodia, T. Field Experiments with Doppler Compensation in High-Frequency Underwater Acoustic Communication System. In Proceedings of the ICC 2023—IEEE International Conference on Communications, Rome, Italy, 28 May–1 June 2023; pp. 2185–2190. [CrossRef]
14. Deguchi, M.; Kida, Y.; Shimura, T. Suppression of effects of Doppler shifts of multipath signals in underwater acoustic communication. *Acoust. Sci. Technol.* **2022**, *43*, 10–21. [CrossRef]
15. Singh, D.; Batham, D. A Review of Underwater Communication Systems. *Int. J. Eng. Dev. Res.* **2022**, *10*, 100–104. [CrossRef]
16. Busacca, F.; Galluccio, L.; Palazzo, S.; Panebianco, A.; Qi, Z.; Pompili, D. Adaptive versus predictive techniques in underwater acoustic communication networks. *Comput. Netw.* **2024**, *252*, 110679. [CrossRef]
17. Qu, Z.; Lai, M. A Review on Electromagnetic, Acoustic and New Emerging Technologies for Submarine Communication. *IEEE Access* **2024**, *12*, 12110–12125. [CrossRef]
18. Aman, W.; Al-Kuwari, S.; Kumar, A.; Rahman, M.M.U.; Muzzammil, M. Underwater and Air-Water Wireless Communication: State-of-the-art, Channel Characteristics, Security, and Open Problems. *arXiv* **2022**, arXiv:2203.02667.
19. Joseph, L.; Anandan, S. A Review on Feasible and Reliable Underwater Wireless Optical Communication System for achieving High Data Rate and Longer Transmission Distance. *Int. J. Electron. Telecommun.* **2022**, *68*, 815–823. [CrossRef]
20. Khan, I.U.; Iqbal, B.; Songzou, L.; Li, H.; Qiao, G.; Khan, S. Full-duplex Underwater Optical Communication Systems: A Review. In Proceedings of the 2021 International Bhurban Conference on Applied Sciences and Technologies (IBCAST), Islamabad, Pakistan, 12–16 January 2021; pp. 886–893. [CrossRef]
21. Abd El Mottaleb, S.; Singh, M.; Atieh, A.; Aly, M. High data rate underwater optical wireless communication systems with ICSM codes within green spectrum. *Opt. Quantum Electron.* **2025**, *57*, 213. [CrossRef]

22. Palaić, D.; Lopac, N.; Jurdana, I.; Brdar, D. Advancements and Challenges in Underwater Wireless Optical Communication in the Marine Environment. In Proceedings of the 2024 47th MIPRO ICT and Electronics Convention (MIPRO), Opatija, Croatia, 20–24 May 2024; pp. 1760–1765. [CrossRef]
23. Elfikky, A.; Boghdady, A.; Mumtaz, S.; Elsayed, E.; Singh, M.; El-Mottaleb, S.; Mohsan, S.A.H.; Aly, M. Underwater visible light communication: Recent advancements and channel modeling. *Opt. Quantum Electron.* **2024**, *56*, 1617. [CrossRef]
24. 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. [CrossRef]
25. Schirripa Spagnolo, G.; Cozzella, L.; Leccese, F. Underwater Optical Wireless Communications: Overview. *Sensors* **2020**, *20*, 2261. [CrossRef]
26. Ali, M.F.; Jayakody, D.N.K.; Li, Y. Recent Trends in Underwater Visible Light Communication (UVLC) Systems. *IEEE Access* **2022**, *10*, 22169–22225. [CrossRef]
27. Seow, Y.L.; Rashidi, C.B.M.; Aljunid, S.A.; Ali, N.; Endut, R. 20 Mb/s Experimental Demonstration Using Modulated 460 nm Blue LED for Underwater Wireless Optical Communications (UOWC). *J. Phys. Conf. Ser.* **2021**, *1878*, 012069. [CrossRef]
28. Wang, J.; Lu, C.; Li, S.; Xu, Z. 100 m/500 Mbps underwater optical wireless communication using an NRZ-OOK modulated 520 nm laser diode. *Opt. Express* **2019**, *27*, 12171. [CrossRef]
29. Zhao, M.; Li, X.; Chen, X.; Tong, Z.; Lyu, W.; Zhang, Z.; Xu, J. Long-reach underwater wireless optical communication with relaxed link alignment enabled by optical combination and arrayed sensitive receivers. *Opt. Express* **2020**, *28*, 34450. [CrossRef]
30. Zhang, L.; Tang, X.; Sun, C.; Chen, Z.; Li, Z.; Wang, H.; Jiang, R.; Shi, W.; Zhang, A. Over 10 attenuation length gigabits per second underwater wireless optical communication using a silicon photomultiplier (SiPM) based receiver. *Opt. Express* **2020**, *28*, 24968–24980. [CrossRef] [PubMed]
31. Li, G.; Hu, F.; Zou, P.; Wang, C.; Lin, G.R.; Chi, N. Advanced modulation format of probabilistic shaping bit loading for 450-nm GaN laser diode based visible light communication. *Sensors* **2020**, *20*, 6143. [CrossRef]
32. Arvanitakis, G.; Bian, R.; McKendry, J.; Cheng, C.; Xie, E.; He, X.; Gang, Y.; Islim, M.S.; Purwita, A.; Gu, E.; et al. Gb/s Underwater Wireless Optical Communications Using Series-Connected GaN Micro-LED Arrays. *IEEE Photonics J.* **2020**, *12*, 1–10. [CrossRef]
33. Chen, X.; Lyu, W.; Zhang, Z.; Zhao, J.; Xu, J. 56-m/3.31-Gbps underwater wireless optical communication employing Nyquist single carrier frequency domain equalization with noise prediction. *Opt. Express* **2020**, *28*, 23784–23795. [CrossRef]
34. Du, J.; Wang, Y.; Fei, C.; Chen, R.; Zhang, G.; Hong, X.; He, S. Experimental demonstration of 50-m/5-Gbps underwater optical wireless communication with low-complexity chaotic encryption. *Opt. Express* **2021**, *29*, 783–796. [CrossRef] [PubMed]
35. Chen, X.; Yang, X.; Tong, Z.; Dai, Y.; Li, X.; Zhao, M.; Zhang, Z.; Zhao, J.; Xu, J. 150 m/500 Mbps Underwater Wireless Optical Communication Enabled by Sensitive Detection and the Combination of Receiver-Side Partial Response Shaping and TCM Technology. *J. Light. Technol.* **2021**, *39*, 4614–4621. [CrossRef]
36. Hong, X.; Du, J.; Wang, Y.; Chen, R.; Tian, J.; Zhang, G.; Zhang, J.; Fei, C.; He, S. Experimental Demonstration of 55-m/2-Gbps Underwater Wireless Optical Communication Using SiPM Diversity Reception and Nonlinear Decision-Feedback Equalizer. *IEEE Access* **2022**, *10*, 47814–47823. [CrossRef]
37. Puntsri, K.; Panta, J.; Wongtrairat, W.; Bunsri, B.; Ijaz, M. Adaptive Modulation of DCO-OFDM for Internet of Underwater Things Using VLC. In Proceedings of the 2024 14th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Rome, Italy, 17–19 July 2024; pp. 179–182.
38. Shawky, E.; Aly, M.H.; El-Shimy, M. Underwater VLC channel estimation based on Kalman filtering for direct current optical-and asymmetrically clipping optical-orthogonal frequency division multiplexing techniques. *Opt. Quantum Electron.* **2023**, *55*, 386. [CrossRef]
39. Zhao, Y.; Chen, C.; Zhong, X.; Cao, H.; Liu, M.; Lin, B.; Savović, S. Enhancing OFDM with index modulation using heuristic geometric constellation shaping and generalized interleaving for underwater VLC. *Opt. Express* **2024**, *32*, 13720–13732. [CrossRef]
40. Yu, M.; Geldard, C.T.; Popoola, W.O. Experimental comparison of modulation techniques for led-based underwater optical wireless communications. In Proceedings of the 2023 IEEE Wireless Communications and Networking Conference (WCNC), Glasgow, UK, 26–29 March 2023; pp. 1–6.
41. Ibrahimy, A.M.; Fadilah, B.I.; Pamukti, B. Analysis of modulation performance of underwater visible light communication with variable wavelength. In Proceedings of the 2020 3rd International Conference on Information and Communications Technology (ICOIACT), Yogyakarta, Indonesia, 24–25 November 2020; pp. 451–455.
42. 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.
43. Qi, Z.; Pompili, D. Spatial modulation-based orthogonal signal division multiplexing for underwater ACOMMS. In Proceedings of the 2022 Sixth Underwater Communications and Networking Conference (UComms), Lerici, Italy, 30 August–1 September 2022; pp. 1–5.

44. Akter, M.; Islam, M.J.; Al Hammadi, M.M. Performance evaluation of various modulation techniques for underwater wireless optical communication system. In *Innovations in Electronics and Communication Engineering: Proceedings of the 8th ICIECE 2019*; Springer: Singapore, 2020; pp. 95–101.
45. Chi, N.; Shi, M. Enabling technologies for high-speed LED based underwater visible light communications. In Proceedings of the 2019 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC), Dalian, China, 20–22 September 2019; pp. 1–4.
46. Fei, C.; Hong, X.; Du, J.; Zhang, G.; Wang, Y.; Shen, X.; Lu, Y.; Guo, Y.; He, S. High-speed underwater wireless optical communications: From a perspective of advanced modulation formats. *Chin. Opt. Lett.* **2019**, *17*, 100012. [CrossRef]
47. Jamali, M.V.; Nabavi, P.; Salehi, J.A. MIMO underwater visible light communications: Comprehensive channel study, performance analysis, and multiple-symbol detection. *IEEE Trans. Veh. Technol.* **2018**, *67*, 8223–8237. [CrossRef]
48. Sui, M.; Yu, X.; Zhang, F. The evaluation of modulation techniques for underwater wireless optical communications. In Proceedings of the 2009 International Conference on Communication Software and Networks, Chengdu, China, 27–28 February 2009; pp. 138–142.
49. Lu, Z.; Shen, C.; Shi, J.; Chi, N. Security enhanced underwater visible light communication system based on chaotic phase scrambling and conjugate frequency hopping. *Chin. Opt. Lett.* **2023**, *21*, 060602. [CrossRef]
50. Das, A.K.; Pramanik, A.; Ramakrishnan, L. On Improved Performance of Underwater VLC System. In Proceedings of the 2023 2nd International Conference for Innovation in Technology (INOCON), Bangalore, India, 3–5 March 2023; pp. 1–6. [CrossRef]
51. Bariah, L.; Elamassie, M.; Muhaidat, S.; Sofotasios, P.C.; Uysal, M. Non-Orthogonal Multiple Access-Based Underwater VLC Systems in the Presence of Turbulence. *IEEE Photonics J.* **2022**, *14*, 1–7. [CrossRef]
52. Zhang, L.; Wang, P.; Cui, M.; Wei, J.; Tian, Y.; Zhang, J.; Xiong, J.; Wang, L. AquaKey: Exploiting the Randomness of the Underwater Visible Light Communication Channel for Key Extraction. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* **2024**, *8*, 1–25. [CrossRef]
53. Wang, J.; Chen, C.; Deng, B.; Wang, Z.; Liu, M.; Fu, H. Enhancing underwater VLC with spatial division transmission and pairwise coding. *Opt. Express* **2023**, *31 10*, 16812–16832. [CrossRef]
54. Grimaldi, M.; Nakath, D.; She, M.; Köser, K. Investigation of the challenges of underwater-visual-monocular-slam. *arXiv* **2023**, arXiv:2306.08738. [CrossRef]
55. Abdavinejad, H.; Baghali, H.; Ostadieh, J.; Mostafapour, E.; Ghobadi, C.; Nourinia, J. Complete Performance Analysis of Underwater VLC Diffusion Adaptive Networks. *arXiv* **2022**, arXiv:2206.02554.
56. Kurkova, O.; Kazakov, V.I.; Serdiuk, K.V. Influence of the parameters of the aquatic environment on the functioning of wireless channels optical underwater communication in information and measurement systems. *Inf.-Meas. Control Syst.* **2024**, *22*, 45–52. [CrossRef]
57. Kottilingal, R.K.; Nambath, N. Performance analysis of underwater optical wireless video communication systems. In Proceedings of the 2024 IEEE International Symposium on Circuits and Systems (ISCAS), Singapore, 19–22 May 2024; pp. 1–5.
58. Mahmutoğlu, Y.; Albayrak, C.; Türk, K. Investigation of underwater wireless optical communication channel capacity for different environment and system parameters. *Hittite J. Sci. Eng.* **2020**, *7*, 279–285. [CrossRef]
59. Afifah, S.; Marlina, L.; Chen, C.C.; Liu, Y.L.; Liaw, S.K.; Yeh, C.H. Impact of artificial seawater and turbulence factors on underwater optical wireless communication. In Proceedings of the 2021 30th Wireless and Optical Communications Conference (WOCC), Taipei, Taiwan, 7–8 October 2021; pp. 110–114.
60. Elamassie, M.; Uysal, M. Performance characterization of vertical underwater VLC links in the presence of turbulence. In Proceedings of the 2018 11th International Symposium on Communication Systems, Networks Digital Signal Processing (CSNDSP), Budapest, Hungary, 18–20 July 2018; pp. 1–6.
61. Islam, S.T.; Ashok, A. Empirical characterization of vertical channel in underwater visible light communication. In Proceedings of the 14th International Conference on Underwater Networks & Systems, Atlanta, GA, USA, 23–25 October 2019; pp. 1–8.
62. Elamassie, M.; Uysal, M. Vertical underwater visible light communication links: Channel modeling and performance analysis. *IEEE Trans. Wirel. Commun.* **2020**, *19*, 6948–6959. [CrossRef]
63. Sharma, R.; Trivedi, Y.N. Performance analysis of dual-hop underwater visible light communication system with receiver diversity. *Opt. Eng.* **2021**, *60*, 035111. [CrossRef]
64. Sharma, R.; Trivedi, Y.N. Impact of imperfect CSI on the performance of inhomogeneous underwater VLC system. In *Proceedings of the International Conference on Paradigms of Computing, Communication and Data Sciences: Algorithms for Intelligent Systems*; Springer: Singapore, 2021; pp. 287–298.
65. Luo, J.; Fan, L.; Li, H. Indoor positioning systems based on visible light communication: State of the art. *IEEE Commun. Surv. Tutor.* **2017**, *19*, 2871–2893. [CrossRef]
66. Costanzo, A.; Loscri, V.; Biagi, M. Adaptive modulation control for visible light communication systems. *J. Light. Technol.* **2021**, *39*, 2780–2789. [CrossRef]

67. Yang, L.; Liu, X.; Jiang, F.; Zhang, Q.; Luo, Y.; Zhu, F.; Zhang, W. Performance Analysis of Hybrid VLC and PLC system. In Proceedings of the 2021 9th International Conference on Communications and Broadband Networking, Shanghai, China, 25–27 February 2021; pp. 319–322.
68. Teixeira, L.; Loose, F.; Barriquello, C.H.; Reguera, V.A.; Dalla Costa, M.A.; Alonso, J.M. On energy efficiency of visible light communication systems. *IEEE J. Emerg. Sel. Top. Power Electron.* **2021**, *9*, 6396–6407. [CrossRef]
69. Waluyo, C.B.; Mardwianta, B.; Tambunan, O.R.; Lasmadi. Design and Development of Audio Data Transmission Using Visible Light Communication. *Int. J. Eng. Technol. Nat. Sci.* **2020**, *2*, 59–62.
70. Blinowski, G. Security of visible light communication systems—A survey. *Phys. Commun.* **2019**, *34*, 246–260. [CrossRef]
71. Matheus, L.E.M.; Vieira, A.B.; Vieira, L.F.M.; Vieira, M.A.M.; Gnawali, O. Visible light communication: Concepts, applications and challenges. *IEEE Commun. Surv. Tutor.* **2019**, *21*, 3204–3237. [CrossRef]
72. Alvarez, L.B.; Bórquez-Paredes, D.; Montejo-Sánchez, S.; Rodríguez-López, L.; Saavedra, G. VLC/RF Network Simulator: An Integrated Approach to Optical and Radio Frequency Connectivity. In Proceedings of the 2024 14th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Rome, Italy, 17–19 July 2024; pp. 153–158.
73. Jia, L.; Feng, S.; Zhang, Y.; Wang, J.Y. A Hybrid Handover Scheme for Vehicular VLC/RF Communication Networks. *Sensors* **2024**, *24*, 4323. [CrossRef]
74. Bravo Alvarez, L.; Montejo-Sánchez, S.; Rodríguez-López, L.; Azurdia-Meza, C.; Saavedra, G. A review of hybrid VLC/RF networks: Features, applications, and future directions. *Sensors* **2023**, *23*, 7545. [CrossRef]
75. Raouf, A.H.F.; Anjinappa, C.K.; Guvenc, I. Designing Hybrid VLC-RF Networks with Random Receiver Orientation and Energy Harvesting. *TechRxiv* **2023**. [CrossRef]
76. Wang, F.; Yang, F.; Pan, C.; Song, J.; Han, Z. Hybrid VLC-RF systems with multi-users for achievable rate and energy efficiency maximization. *IEEE Trans. Wirel. Commun.* **2023**, *22*, 6157–6170. [CrossRef]
77. Wang, F.; Yang, F.; Song, J.; Han, Z. Cell Zooming for Hybrid VLC-RF Cellular Networks With High Energy Efficiency. *IEEE Wirel. Commun. Lett.* **2023**, *12*, 789–793. [CrossRef]
78. Ciftler, B.S.; Alwarafy, A.; Abdallah, M. Distributed DRL-based downlink power allocation for hybrid RF/VLC networks. *IEEE Photonics J.* **2021**, *14*, 1–10. [CrossRef]
79. Liu, X.; Huang, S.; Zhang, K.; Maimaiti, S.; Chuai, G.; Gao, W.; Chen, X.; Hou, Y.; Zuo, P. Joint Resource Allocation and Drones Relay Selection for Large-Scale D2D Communication Underlaying Hybrid VLC/RF IoT Systems. *Drones* **2023**, *7*, 589. [CrossRef]
80. Azar, S.N.; Erdemir, O.; Soomro, M.; Ünlüyurt, Ö.G.; Onat, A. A hybrid acoustic-RF communication framework for networked control of autonomous underwater vehicles: Design and cosimulation. *Turk. J. Electr. Eng. Comput. Sci.* **2022**, *30*, 1475–1491. [CrossRef]
81. Pan, G.; Ye, J.; Zhang, C.; An, J.; Lei, H.; Ding, Z.; Alouini, M.S. Secure cooperative hybrid VLC-RF systems. *IEEE Trans. Wirel. Commun.* **2020**, *19*, 7097–7107. [CrossRef]
82. Su, Y.; Pan, P.; Fan, R.; Yang, S.; Dou, F. A secure communication scheme based on spatio-temporal dynamics of underwater acoustic channel. In Proceedings of the ICC 2024—IEEE International Conference on Communications, Denver, CO, USA, 9–13 June 2024; pp. 3334–3339.
83. Kumar, A.; Al-Kuwari, S.; Jayakody, D.N.K.; Alkanhel, R. Security performance analysis of a NOMA-assisted underwater VLC system under imprecise channel estimations. *IEEE Access* **2022**, *10*, 117021–117032. [CrossRef]
84. Theocharidis, T.; Kavallieratou, E. Underwater communication technologies: A review. *Telecommun. Syst.* **2025**, *88*, 54. [CrossRef]
85. Ribezzo, D.; Zahidy, M.; Lemmi, G.; Petitjean, A.; De Lazzari, C.; Vagniluca, I.; Conca, E.; Tosi, A.; Occhipinti, T.; Oxenløwe, L.K.; et al. Quantum key distribution over 100 km of underwater optical fiber assisted by a fast-gated single-photon detector. *Phys. Rev. Appl.* **2023**, *20*, 044052. [CrossRef]
86. *IEEE Std 802.15.7-2011*; IEEE Standard for Local and Metropolitan Area Networks—Part 15.7: Short-Range Wireless Optical Communication Using Visible Light. IEEE: Piscataway, NJ, USA, 2011.
87. Hallak, G.; Vázquez, M.M.; Mengi, A.; Rosu, L.M. On the New Developments in ITU-T G.hn Standard: Use Cases, Requirements, and Solutions. In Proceedings of the 2021 IEEE International Symposium on Power Line Communications and its Applications (ISPLC), Aachen, Germany, 26–27 October 2021; pp. 49–54.
88. Luo, J.; Chen, Y.; Wu, M.; Yang, Y. A survey of routing protocols for underwater wireless sensor networks. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 137–160. [CrossRef]
89. Ainslie, M.A.; Halvorsen, M.B.; Robinson, S.P. A terminology standard for underwater acoustics and the benefits of international standardization. *IEEE J. Ocean. Eng.* **2021**, *47*, 179–200. [CrossRef]