Red light in underwater measurement applications: a short review

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ABSTRACT
In recent years, optical systems operating in the visible spectrum have emerged as the most efficient, low-cost, and environmentally friendly technologies for underwater applications across military, scientific, and economic sectors. While blue and green wavelengths are commonly used due to their lower attenuation in clear water, red light offers distinct advantages in turbid environments. Specifically, red radiation exhibits lower attenuation than blue and green light in such conditions and is non-harmful to marine fauna. This article explores current and potential future optical technologies that utilize red light. Particular attention is given to underwater wireless optical communication systems employing red wavelengths for data transmission in turbid waters. These systems are applicable in underwater wireless sensor networks, communication buoys, and navigation of autonomous underwater vehicles and remotely operated vehicles. Additionally, the use of red light in underwater photography is discussed, along with two systems designed for fish counting in aquaculture and for monitoring marine fauna behavior in laboratory settings.

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1. INTRODUCTION

Recently, optical systems operating in the visible range have found numerous applications in underwater environments for both scientific and industrial research, due to their efficiency, low cost, and environmentally friendly nature. Notably, light does not alter the chemical or physical properties of water. However, the inherent physical characteristics of water impede the propagation of light.

Furthermore, sunlight influences biogeochemical processes, as well as the activity and behaviour of marine organisms. Therefore, understanding light penetration in water is essential for the development of artificial lighting systems in the marine environment. When sunlight reaches the water surface, a portion is reflected in accordance with Snell's law and the Fresnel equations, while the remaining part is transmitted into the water, where it undergoes scattering and absorption processes [1].

Water constituents, known as optically active constituents (OACs), which absorb and scatter light, include phytoplankton, coloured dissolved organic matter (CDOM), suspended particulate matter, and chlorophyll [2]. Their abundance or concentration directly affects the amount of light available underwater.

In clear ocean waters, red light is attenuated more rapidly than other wavelengths; at greater depths, only blue light persists (Figure 1a). In more turbid environments, such as coastal waters, the presence of organic material leads to increased absorption in the blue region of the light spectrum. The combined absorption of blue light by organic material and red light by water creates an environment in which green light predominates (Figure 1b). In highly turbid waters, such as peat lakes, the absorption of blue light by organic matter exceeds the absorption of red light by water. As a result, red light becomes the dominant wavelength that penetrates these waters (Figure 1c). In general, as turbidity increases, the portion of the
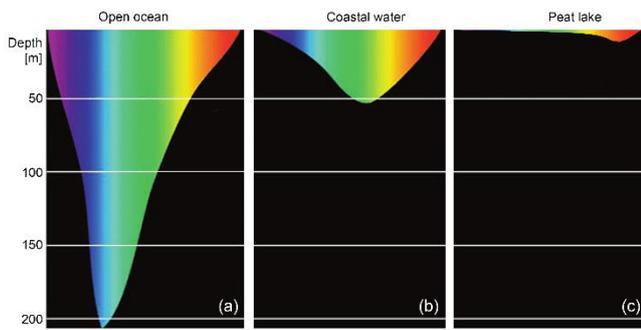
Figure 1. The figure illustrates, qualitatively, the penetration of light in water. Water absorbs the longer wavelengths (red and orange) and scatters the shorter wavelengths (UV, blue) more [3].

Figure 2. Main questions analysed in this review.

light spectrum that penetrates the water shifts progressively toward the red region [4].

The physiology and behaviour of marine organisms have evolved through long-term adaptations to variations in light and temperature, optimizing species survival. As a result, different species exhibit distinct responses to sunlight [5].

This aspect is particularly important when implementing artificial lighting systems in marine environments or aquaculture.

Although blue and green light have lower attenuation coefficients in clear water, red light offers specific advantages in marine settings. In turbid waters, red light exhibits relatively low attenuation and is non-harmful to marine fauna. These properties enable its application in various fields, including underwater wireless optical communication and biological monitoring.

2. PAPER STRUCTURE

Given the political, economic, and industrial significance of the marine environment, we have focused on analysing various underwater optical technologies due to their efficiency, low environmental impact, and cost-effectiveness. This review aims to explore the different applications of underwater light radiation, with particular emphasis on red light. Red radiation not only poses no harm to marine fauna but also exhibits a lower attenuation coefficient in turbid waters compared to blue and green light.

The main questions that emerged during this study are: How can red light be utilized in the marine environment? Which systems employ red light radiation? What are the purposes of these systems?

Figure 2 outlines the key questions that this review seeks to address.

To address these questions, approximately 50 research papers were selected, providing a basis to summarize the use of red light in marine communication, biological monitoring, and aquaculture. The relatively small number of studies reviewed is due to the limited amount of research available in literature regarding the applications of red light in aquatic environments. This review begins with an examination of sunlight penetration into the marine environment, which is essential for understanding the technologies discussed later.

The discussion then progresses with an analysis of the environmental limitations of the optical channel, with particular focus on the water's attenuation coefficient and the factors that most significantly affect the performance of wireless optical
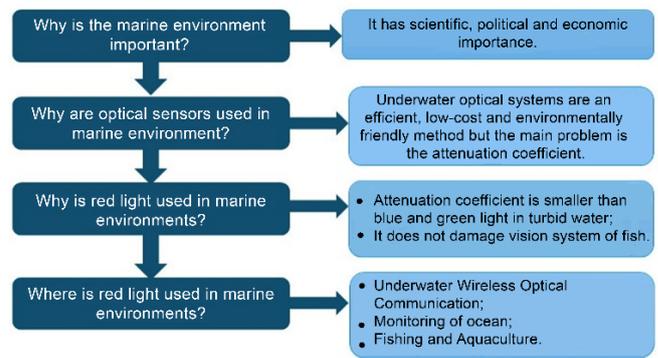
systems in marine environments, namely ambient noise and marine turbulence.

Finally, the paper concentrates on three main areas of application for underwater red-light systems. First, underwater wireless optical communication is discussed, emphasizing the system and the rationale for using red light in turbid water. Next, the potential application of red light for monitoring and counting marine species in aquaculture environments is explored. Lastly, the use of red light to analyse fish behaviour is reviewed.

3. ENVIRONMENTAL CONSTRAINTS

Electro-optical technologies have several difficulties in marine environments such as background noise, atmospheric conditions, light reflection and refraction, and the limitation of materials that can be used [6].

This section presents the fundamental characteristics of the optical channel and examines the various factors influencing underwater wireless optical communication systems, with particular emphasis on optical turbulence and ambient noise.

3.1. Water's attenuation coefficient

The underwater environment consists of water molecules, impurities such as suspended and dissolved particles, and both organic and inorganic elements, making it a complex and dynamic system. The interaction between these particles and light leads to significant attenuation of the light signal.

The attenuation of the light signal of wavelength λ is attenuated according to the Lambert-Beer law [7]:

$$I = I_0 \, e^{-c(\lambda)\,\Delta r} , \tag{1}$$

where I_0 and I are the intensity of the incident and outgoing radiation respectively; $c(\lambda)$ is the attenuation coefficient and Δr is the optical path.

It is experimentally impossible to separately quantify the contribution of absorption from that of scattering, a total attenuation coefficient $c(\lambda)$ is defined as the sum of the absorption coefficient $a(\lambda)$ and the scattering coefficient $b(\lambda)$:

$$c(\lambda) = a(\lambda) + b(\lambda) . \tag{2}$$

The value of the attenuation coefficient varies depending on water type and depth. As a result, underwater optical wireless communication systems are also influenced by the type of water [8]. The density and structure of the particles in the water affect the absorption and scattering processes. The primary contributors to the absorption and scattering coefficients are phytoplankton (respectively a_{phy}, and b_{phy}), which are

photosynthesizing autotrophic microorganisms, as well as the concentration of chlorophyll in the water. These factors influence the coefficients, which become [9]-[11]:

$$a_{\text{phy}}(\lambda) = \left[a_{\text{w}} + 0.06 \cdot a_{\text{c}}(\lambda) \cdot C_{\text{chlor}}^{0.65}\right] \tag{3}$$
$$\cdot \left[1 + 0.2 \cdot e^{-0.014\,(\lambda-440)}\right],$$

$$b_{\text{phy}}(\lambda) = 0.30 \cdot \frac{550}{\lambda} C_{\text{chlor}}^{0.62}, \tag{4}$$

where a_{w} is the absorption coefficient of pure water; a_{c} is a dimensionless number that specifies the absorption coefficient of chlorophyll and C_{chlor} is the concentration of chlorophyll expressed in $\text{mg} \cdot \text{m}^{-3}$ and λ is in nm, the resulting $a_{\text{phy}}(\lambda)$ and $b_{\text{phy}}(\lambda)$ are in m^{-1}. The concentration of chlorophyll is determined by the amount of phytoplankton present, which varies depending on the geographical position, the type of water and the depth and the sunlight that penetrates to the depth [7].

The primary optically active elements found in natural waters are phytoplankton (microalgae), detritus (plankton or sediment debris), and coloured dissolved organic matter (also known as yellow compounds). As shown in Figure 3, absorption by pure water increases with wavelength, whereas absorption by dissolved or dispersed elements in water decreases [12].

Three zones can be distinguished:

- the first zone, for $\lambda < 350$ nm, in which an attenuation is recorded which is due to Rayleigh scattering (λ^{-4});
- the second zone, for 350 nm $< \lambda < 550$ nm, the minimum attenuation is recorded;
- Finally, for $\lambda > 550$ nm, he wavelengths an increase in the absorption coefficient is recorded.

Therefore, based on experimental data, to optimize optical communication and minimize the attenuation coefficient, it is advisable to choose radiation in the blue/green frequencies, i.e., with wavelengths between 450 nm and 550 nm.

However, red light can be studied for turbid water because it suffers less from scattering by suspended particles. Turbidity, which measures the clarity of a liquid, is influenced by suspended particles, inorganic and organic chemical materials, and temperature [13].
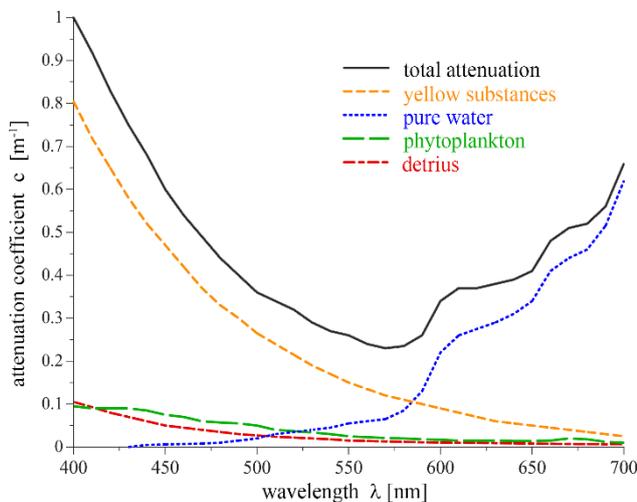

Figure 3. The total attenuation coefficient of pure water $c(\lambda)$ as a function of the wavelength of the incident radiation [12].

3.2. Ambiental noise

The majority of the noise originates [8] from the marine environment, and it is predominantly composed of ambient light, primarily sourced from solar radiation, and bioluminescence of aquatic species.

Bioluminescence is a chemiluminescent reaction in which the chemical energy produced is converted into light. The primary contributors are dinoflagellates and plankton, which emit luminous radiation around 440–500 nm. The background light from these organisms is measured using a bathyphotometer in terms of bioluminescence potential (BP). BP, along with the organism's spectral signature, is utilized to calculate irradiance and depth distribution of the organisms, both of which are correlated with the total concentration of constituents in the water column.

Recent research has extensively examined the effects of ambient noise on underwater optical communication channels. In particular, the bit error rate (BER) has been estimated through Monte Carlo simulation techniques [14], [15], as well as data-driven methods based on neural networks [16].

To mitigate noise, an optical bandpass filter can be incorporated into the system to select the appropriate wavelength used for signal transmission. Additionally, algorithms can be developed for noise filtering and data recovery.

3.3. Optical turbulences

Optical turbulence refers to random fluctuations in the refractive index of water, primarily induced by variations in salinity, turbidity, temperature gradients, and the presence of air bubbles [17]. These turbulent effects distort the optical beam, leading to phenomena such as beam wander and spreading. Consequently, they adversely affect the performance and reliability of underwater optical wireless systems by increasing the bit error rate (BER). Notably, optical turbulence can cause misalignment between the transmitter and receiver, rendering the system incapable of establishing a stable communication link.

To prevent communication interruptions, the transmission beam can be expanded by exploiting water reflections or deploying a network of sensors. Additionally, automatic alignment and tracking systems can be developed to enable a focused and directed transmission path, thereby maximizing the signal received from the transmitter.

4. METHODS

4.1. Underwater Wireless Optical Communication

Underwater wireless optical communication (UOWC) is an efficient, environmentally friendly, and cost-effective method for transmitting data using light radiation [18]. This communication method is crucial for the development of distributed measurement systems. Figure 4 illustrates a typical UOWC system scenario.

Typical applications of underwater optical wireless communication (UOWC) include underwater wireless sensor networks (UWSNs) for optical communication with aerospace and terrestrial systems, facilitated by autonomous underwater vehicles (AUVs), remotely operated underwater vehicles (ROVs), communication buoys, and satellites [19].

However, despite the significant advantages, the main challenge lies in the high attenuation coefficient of water, which limits communication to a range of just a few dozen meters.
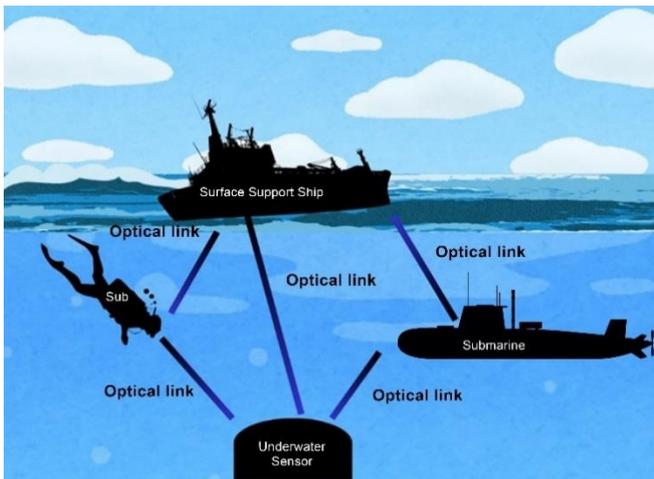
Figure 4. Typical scenario of UOWC.

Furthermore, current systems face alignment issues: the receiver and transmitter must be perfectly aligned, as any misalignment prevents communication.

An optical system consists of a transmitter, an optical channel, and a receiver (Figure 5).

The main components of the transmitter include a modulator, an optical driver, a light source, and a lens. The light sources can be lasers or laser diodes (LDs). LDs offer higher power and can cover greater distances; however, they require precise alignment between the transmitter and receiver. In contrast, light-emitting diodes (LEDs) have lower power and shorter range but, due to their broader emission angle, do not require such precise alignment between the transmitter (TX) and receiver (RX) [20], [21].

The main component of the receiver is the photodetector, such as photodiodes, which come in various types, each with distinct characteristics in terms of sensitivity, voltage, cost, and size. Among the most commonly used are PIN photodiodes and avalanche photodiodes (APDs) [20].

Over the years, several systems have been developed that demonstrate the feasibility of communication using red light.

Xu et al. [11] studied the attenuation coefficient for different wavelengths of light using Monte Carlo simulations in harbour water. They observed that the attenuation coefficient for red light is smaller than that for green light. Furthermore, red light

exhibited a larger bandwidth due to its smaller temporal dispersion. Following this, they implemented an underwater optical wireless communication (UWOC) system based on an OFDM-modulated red-light laser diode (LD). For the experimental tests, two photodetectors were used: a 150-MHz PIN photodiode for high spectral efficiency and a 1-GHz APD for higher transmission speed, allowing for a comparison between the two. The OFDM parameters were optimized separately for each detector, and the final channel estimate was obtained by averaging to mitigate random noise. A red LD operating at 685 nm was driven by the baseband signals through a bias-tee.

To simulate the optical channel, a 2-meter-long water tank filled with fresh tap water was used. Mirrors were employed to extend the optical path, and two lenses were utilized for focusing. The tests were conducted under direct illumination from indoor lights, which induced low-frequency noise that was negligible. Initially, the PIN photodiode was used as the detector, and the frequency response was flat within the 150-MHz bandwidth of the PIN, ensuring a high signal-to-noise ratio due to the use of high-order quadrature amplitude modulation (QAM). Subsequently, they implemented power loading (PL), and the data rate achieved was 1.34 GB/s using OFDM 128-QAM with a bit error rate (BER) of 2.2×10^{-3}, and 1.135 GB/s using OFDM 64-QAM with a BER of 3.34×10^{-4}, over a 6-meter underwater channel. Finally, they used the 1-GHz avalanche photodiode (APD) to achieve a higher bit rate. By extending the signal bandwidth to 986.3 MHz, they achieved a record gross bit rate of 4.883 Gb/s using 32-QAM at a BER of 3.20×10^{-3}, over the same 6-meter underwater channel.

However, higher transmission rates can be achieved with broadband vertical external cavity surface-emitting lasers (VECSELs). VCSELs are widely used in optical communication systems, optical sensing, and applications that require high power, high efficiency, and low-cost lasers, as they offer low threshold current, low power consumption, and high efficiency [22]. Using a setup similar to the one described above, the high-speed multimode 680-nm VCSEL is capable of supporting the transmission of 16-QAM-OFDM signals [23].

Modulation techniques are typically selected based on the specific applications of the system and the communication requirements [7].

For example, Chu-Yi Li et al. [24] used an NZR-OOK modulation because it allows real-time bit error rate (BER) and eye diagram analysis, whereas QAM and OFDM modulations require offline processing of the BER. The system was developed with a two-stage injection-locked 680 nm red-light VCSEL transmitter to improve the frequency response, along with a laser beam expander to increase the collimated beam diameter. The laser beam was then transmitted through the highly turbid harbour water, coupled into a convex lens, and focused onto a 25-GHz photodiode (PD).

The high turbidity in the underwater conditions was simulated using a commercial antacid preparation, Maalox. Maalox contains two active ingredients, $Mg(OH)_2$ and $Al(OH)_3$, which have a particle distribution similar to that observed in certain types of seawater [25], [26].

Finally, red LDs and VCSELs offer higher power, greater bandwidth, and lower cost compared to green ones. Additionally, silicon photodiodes exhibit higher responsiveness to red light, compensating for the increased light absorption in water, thus enabling communication [22].
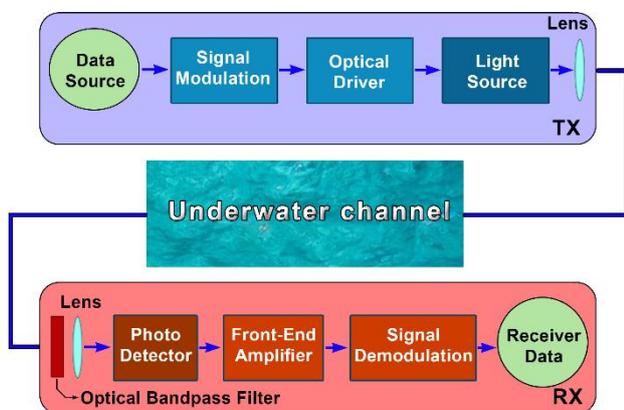

Figure 5. Schematic of a typical UOWC connection. The transmitter (TX) is composed of a modulator, an optical driver, a light source and a lens. The receiver (RX) consists of an optical band-pass filter, photodetector, amplifier and demodulator.

Figure 6. Typical scenario of full duplex underwater wireless optical communication with different wavelengths.

Figure 7. Full duplex underwater wireless optical communication system.

Based on these studies and experimental tests, a full-duplex underwater wireless optical communication system can be developed, capable of operating in harbour waters with high turbidity.

Figure 6 illustrates a typical scenario for full-duplex underwater wireless optical communication. The system to be implemented will enable simultaneous communication in both directions over the same frequency band, thereby doubling the system's capacity [27]. To achieve this, two different wavelengths in the red spectrum (590 nm and 630 nm) will be selected. One wavelength will be used for transmission in one direction, while the other will be used for transmission in the opposite direction.

Each system will consist of a transmitter made up of a cluster of LEDs and a receiver with a photodiode (Figure 7). One system will transmit light radiation at 630 nm and be capable of receiving radiation at 590 nm. The other system will transmit light radiation at 590 nm and be capable of receiving radiation at 630 nm.

However, full-duplex systems are subject to a self-interference phenomenon, which alters the propagation direction of photons and leads to a degradation in the received signal-to-noise ratio (SNR), making long-distance link transmission less favourable [19], [28].

Therefore, it is crucial to study the backscattering channel in these systems, and various optical components are employed to mitigate the self-interference effect [29].

Finally, several areas require further research, such as addressing misalignment between the transmitter and receiver, developing modulation techniques to maximize data rates while minimizing signal degradation, and improving receiver sensitivity and signal-to-noise ratio (SNR).

Current research on underwater optical communications primarily focuses on developing systems capable of medium-range communication (50-100 meters and beyond). As a result,
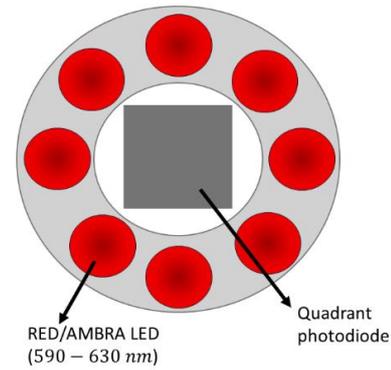
studies on communication in turbid water environments remain limited.

Table 1 presents the performance of optical communication systems using red light as reported in the literature.

4.2. Practical limitations in Underwater Wireless Optical Communication

As with all forms of underwater wireless optical communication, the use of red light for optical transmission presents several challenges that must be carefully studied and addressed when designing systems for practical, real-world applications.

In other words, Underwater Wireless Optical Communication (UWOC) offers high data rates and low latency, but it also faces several practical limitations that impact its real-world application. These limitations can be broadly grouped into environmental, technological, and operational challenges.

1) Absorption and Scattering
- Water absorption significantly attenuates optical signals, especially for wavelengths outside the blue-green region (≈ 450–550 nm), which have the least loss.
- Scattering caused by suspended particles (sediment, plankton, etc.) leads to signal distortion and reduces the effective communication range.
- Turbid waters (e.g., coastal or harbour environments) worsen both effects, drastically shortening communication distances.

2) Limited Range
- UWOC systems typically achieve ranges of only a few meters to 100 meters, depending on water clarity and power constraints.
- In clear ocean water, communication can reach up to ~100 meters, but in turbid water, the range may shrink to just a few meters.

Table 1. A summary of research progress in the UWOC system based on Red Light source.

BitRate	Distance	Optical Sorce	Photodetector	Modulation	(BER)	Reference
4.9 Gbps	Clear water 6 m	Laser Diode λ= 658 nm - 35 mW	Avalanche PhotoDiode (APD)	32-quadrature amplitude modulation– orthogonal frequency-division multiplexing (32QAM-OFDM)	$2.2 \, 10^{-3}$	[11]
10-Gbps	Tap water 6 m	multimode vertical cavity surface emitting laser (VCSEL) λ= 680 nm - < 5.76 mW	Avalanche PhotoDiode (APD)	16-quadrature amplitude modulation– orthogonal frequency-division multiplexing (16QAM-OFDM)	$2.9 \, 10^{-4}$	[23]
25 Gbps	Harbour water 5 m	multimode vertical cavity surface emitting laser (VCSEL) λ= 680 nm - 3 mW	Diode PIN	Injection-locking ON-OFF keying (OOK)	$3 \, 10^{-4}$	[24]

3) Line-of-Sight (LOS) Requirement
- Optical signals propagate in a straight line and are highly directional, so precise alignment between transmitter and receiver is essential.
- Any misalignment due to water currents, platform movement, or misorientation can result in communication loss.

4) Beam Divergence and Pointing Accuracy
- Narrow optical beams can reduce scattering losses but require high-precision pointing and tracking systems, which add complexity and cost.
- Wider beams are easier to align but suffer from increased attenuation.

5) Power Consumption
- High-power light sources are often needed to compensate for absorption and scattering, leading to increased energy consumption.
- This can be a critical issue for battery-powered underwater vehicles or sensor nodes.

6) Environmental Variability
- Changes in water properties (salinity, temperature, turbidity, biological content) over time or location affect optical channel characteristics.
- These fluctuations make channel modelling and system design more complex and less predictable.

7) Background Light and Noise
- Ambient light from the surface or bioluminescence can introduce noise in the optical receiver.
- This limits UWOC usability in shallow waters during daylight or near bioluminescent organisms.

8) Modulation and Synchronization Challenges
- Optical links suffer from inter-symbol interference (ISI) due to multipath scattering.
- Reliable data transmission over UWOC links requires advanced modulation schemes and error correction, which add processing overhead.

9) Hardware Durability and Cost
- Optical components (LEDs, lasers, detectors) must be encapsulated in pressure-resistant, corrosion-proof materials.
- This increases system cost and maintenance requirements.

4.3. Underwater optical barrier

Manipulating the light spectrum can become an effective, low-cost, and easy-to-implement method in fish production, as controlling light in intensive indoor fish farming is relatively straightforward [30]. In particular, LEDs are gaining popularity due to their energy efficiency, environmental friendliness, and durability compared to incandescent and fluorescent lamps in fish farming [31].

Additionally, optical sensors can be developed to monitor and count fish in both rivers and aquaculture environments.

Ferrero et al. [32] implemented an optical barrier based on an array of emitters and infrared receivers, which detect the presence of a fish when the light beam is interrupted by the silhouette of the fish.

Although the infrared region corresponds to the wavelength band of maximum sensitivity for silicon photodiodes [33], the main limitation of infrared (IR) light is its attenuation in water. As a result, this system is only suitable for specific locations, as the IR barrier system is constrained by the beam's distance and water turbidity.
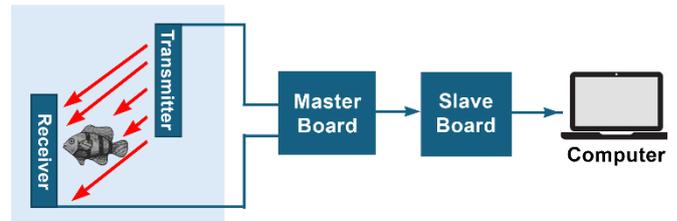

Figure 8. Optical barrier to counting fish.

However, the same system can be implemented with red light to increase the beam distance and detect fish in high-turbidity environments, such as rivers or aquaculture settings. Figure 8 illustrates a possible example of a red optical barrier.

The transmitter and receiver consist of clusters of red LEDs. In fact, LEDs can also function as photodiode light sensors/detectors, enabling bidirectional communication [34].

The transmitter and receiver are connected to the master board, which serves two functions: controlling the active red transmitters and reading the red receivers. The received signal is then sent to a slave board, which processes the data and transmits it to the computer.

By developing a program that can display the signals received by each LED receiver, it becomes possible to detect the passage of fish. Specifically, when a fish crosses the optical barrier, the signal will be interrupted and will not reach the receiver.

Figure 9 [32] illustrates the passage of fish. Specifically, a high signal indicates that the light beam is not interrupted, meaning the radiation successfully reaches the receiver. Conversely, a low signal indicates that the beam has been interrupted, as the receiver does not register the radiation, thereby indicating the passage of the fish.

A camera can be integrated into this system, which is activated when the fish crosses the barrier.

For fish counting in aquaculture, computer vision technology offers a non-invasive and preferred method.

In aquaculture, there are two main computer vision-based counting systems: image processing and video analysis [35]. These systems enable the creation of datasets, and through neural networks, it is possible to extract images and recognize fish species by comparing them with the dataset. For example, Crescitelli et al. [36] developed a system to semi-automatically create large datasets of fish species images using image processing and neural networks.

4.4. Underwater photography and aquaculture applications

Underwater photography is essential for marine biology, oceanography, underwater archaeology, and underwater surveillance [37]. However, the colours in the air differ from those underwater, as only solar radiation in the blue range can penetrate deeply into the ocean [38]. As shown in Figure 10a
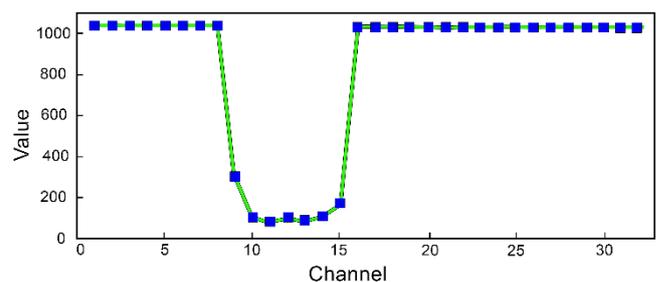

Figure 9. Optical barrier results marking the passage of fish [32].

Figure 10. Underwater photography: a) photo with natural colours in deep ocean; b) photo with red light application on the camera.

(left), the images take on a blue tone, losing colour, clarity, and sharpness. To compensate for the lack of solar radiation in the red range, red lights are added to the cameras. Figure 10b (right) shows the same scene as in Figure 10a, but with the addition of red light to the camera. Not only are all the natural colours restored, but the photo becomes sharper and clearer.

Similarly, to cameras, red light is applied to stereo cameras for the behavioural analysis of marine animals in situ [39]-[41].

Red light can also be used to study the behaviour of marine animals, as studies show that most marine species react less to red light compared to blue and green light, meaning red radiation does not significantly alter their behaviour [42].

However, such systems can also be implemented for laboratory analyses.

Pasquali et al. [43] implemented a system to detect the spontaneous locomotor activity of Antarctic invertebrates, aiming to study their circadian cycle and analyse chronobiological activity. The system consists of a box containing the animal, with infrared barriers that generate an electrical impulse when the animal crosses the barrier.

Since IR radiation penetrates only a few centimetres into water, red LEDs can be used instead, enabling the development of a larger system without affecting the behaviour of marine species.

Figure 11 illustrates a possible system for analysing the behaviour of marine species. As described in [44], the system consists of an aquarium with an optical barrier inside, using red radiation in this case, along with a conditioning circuit and a controller, such as a Raspberry-Pi or a computer. The transmitters are arrays of red LEDs, and the transmitted beam must be narrow to ensure sensitive detection of animal activity [45]. The receiver consists of an array of photodetectors.

When the animal interrupts the beam, an electrical pulse is generated.

The signal is amplified by the conditioning circuit and sent to the controller. The controller not only drives the emitter
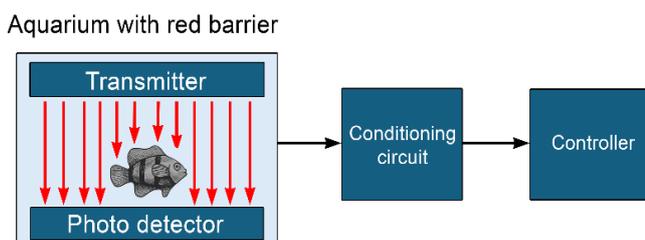
beam and stores the received data, but it can also modify the modulation.

By applying different types of modulation, such as photoperiod, intensity, and light changes, various behavioural aspects can be characterized [46].

By developing software, it becomes possible to study actograms, power spectra, and periodograms, which enable the chronobiological and circadian analysis of the species under examination [44].

Behavioural analysis of marine species is also crucial in aquaculture [47]. Animal behaviour provides valuable insights into the environment in which they are cultivated [48]. For example, poor water quality can impact behaviour, particularly influencing reproduction and growth in species [49].

4.5. Red light communication in the marine animal world

To hunt without detection, dragonfish (family *Stomiidae*) employ red bioluminescence, which remains invisible to the majority of deep-sea organisms. The ability of certain fish species to produce and emit light through internal biochemical reactions is known as bioluminescence. This adaptation is particularly common among deep-sea fish, where sunlight does not penetrate, and bioluminescence serves a variety of ecological functions such as communication, predation, and camouflage. The mechanism of bioluminescence in fish typically involves a chemical reaction that includes:

(1) Luciferin: A light-emitting molecule. In fish, it is an indole derivative composed of isoleucine, arginine, and tryptamine.

(2) Luciferase: An enzyme that catalyses the oxidation of luciferin.

(3) Oxygen: A critical reactant required for the oxidation process.

When luciferin reacts with oxygen in the presence of luciferase, energy is released in the form of visible light, typically blue or blue-green. However, some fish exhibit red bioluminescence. Notably, dragonfish utilize red bioluminescence to hunt undetected, as this wavelength remains invisible to most deep-sea organisms [50]-[52].

5. CONCLUSIONS

In recent years, numerous studies have focused on the use of light radiation in the marine environment. The adoption of LEDs has facilitated the development of energy-efficient, environmentally friendly, and long-lasting systems. Additionally, their wide beam eliminates the alignment issues between the transmitter and receiver. For the receiver, various photodiodes are employed, such as PIN, APD, and SPAD photodiodes. SPAD photodiodes, being single-photon detectors, offer high detection capability and precise measurements, thus enhancing the system's sensitivity.

This article provides insights into the use of red light, which experiences minimal attenuation in turbid marine environments. However, to date, real-world applications of wireless optical systems utilizing red radiation have not yet been developed.

Radiation in the red band enables the development of systems suitable for marine environments with high turbidity, such as rivers, coastal areas, and aquaculture facilities. This motivates the adoption of optical technologies to create systems that are efficient, cost-effective, and have a low environmental impact. Many of these systems can be employed not only for aerospace and terrestrial communication - via autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), communication buoys, and satellites - but also in

Figure 11. Optical barrier to study fish behaviour.

aquaculture, for monitoring fish behaviour and performing fish counts.

To develop an effective and reliable underwater wireless optical communication system operating in the red spectrum for turbid water environments, future research will focus on several key aspects:

- the use of LEDs as transmitters, including optimization of light intensity to ensure signal penetration in highly turbid conditions;
- modulation techniques aimed at maximizing data rates, optimizing bandwidth usage, and enhancing system robustness;
- the investigation of photodiodes capable of high detection accuracy and precision, to increase the overall sensitivity of the system;
- the development of tracking and automatic alignment systems to maintain proper alignment between transmitter and receiver in dynamic underwater environments affected by currents or waves.

Finally, it will be possible to integrate sensors into the system to enable the collection of oceanographic data and support environmental monitoring, facilitating the rapid and efficient transmission of information from underwater sensors to surface stations. In aquaculture in particular, since red light is not harmful to marine fauna, sensors can be implemented to detect key marine parameters - such as water quality, the health status of aquatic species, the presence of pathogens - and to monitor production control parameters like temperature and pH.

AUTHORS' CONTRIBUTION

Conceptualization, G.S.S.; methodology, F.P.; validation, L.R. and E.D.F.; formal analysis, G.S. and L.R.; investigation, G.S. and F.P.; resources, F.L; data curation, G.S.S.; writing - original draft preparation, G.S.; writing - review and editing, G.S.S. and F.L.; supervision, F.L and E.D.F.. All authors have read and agreed to the published version of the manuscript.

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