Jurnal Kejuruteraan 37(5) 2025: 2191-2203
https://doi.org/10.17576/jkukm-2025-37(5)-13

# The Impact of Absorption and Scattering on Underwater Optical Wireless Communication (UOWC) Channel in The South China Sea: A Simulation Study

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*Received 25 October 2024, Received in revised form 9 May 2025*
*Accepted 10 June 2025, Available online 30 August 2025*

ABSTRACT

*Underwater Optical Wireless Communication (UOWC) is a promising technology for short-range communication in marine environments, offering significant advantages in terms of high data transfer rates and low latency. However, its performance is highly dependent on environmental factors such as absorption, scattering, and turbulence of light in seawater. This study investigates the effects of absorption and scattering on UOWC systems in the South China Sea (SCS), a region with unique marine conditions and limited research on UOWC, by estimating the attenuation coefficient, simulating the UOWC channel models, and analysing system performance in terms of path loss, impulse response, and frequency response. A key contribution of this work is the estimation of the attenuation coefficient for SCS, which is essential for accurately modelling UOWC channels in this region. Based on theoretical calculations and empirical data, the attenuation coefficient is estimated to be 0.8748 $m^{-1}$, indicating moderate optical signal loss compared to other water types. Then, using Monte Carlo numerical simulations, this estimated coefficient is incorporated to analyse path loss, impulse response, and frequency response by varying the water depth. The obtained results show that both absorption and scattering considerably increase path loss and delay spread compared to the coastal water type, with laser and LED beams experiencing delays of up to 2.92 × $10^{-11}$ and 1.13 × $10^{-9}$ seconds, respectively. Additionally, frequency-dependent attenuation leads to signal distortion. These findings offer practical implications for optimising UOWC systems in the South China Sea. The study highlights the need for further research to address regional variations in optical properties and improve system design for more reliable communication.*

*Keywords: Underwater optical wireless communication; South China Sea; Monte Carlo method; absorption, scattering*

## INTRODUCTION

More than 70 per cent of the earth's surface is covered by oceans, making them a critical domain for scientific research, environmental monitoring, resource exploration, and military operations (Mohammad Furqan Ali et al. 2019; Fang et al. 2023). Effective communication is essential for these activities. However, underwater exploration is high risk and poses significant challenges for wireless data transmission.

The recent incident in 2023, the Titan submersible losing connection and imploding while diving into the Titanic wreck, killing all five people on board (The Independent 2024), shows the importance of the advancement of underwater wireless communication (UWC) technologies. The advancement of underwater technology also gives crucial improvements in safety and optimizes various underwater applications. The advancement of UWC is also one of the components that is driven by the development of the Internet of Things (IoT), which serves as the backbone of Industrial Revolution 4.0 (IR 4.0) (Khamil et al. 2020). These applications include underwater wireless sensor networks and autonomous underwater vehicles (AUVs), which are essential for environmental monitoring, resource extraction, and scientific research (Ali et al. 2020).

Traditional UWC technologies are categorised into three types: acoustic, radio frequency (RF), and optical wireless communication. Each type has unique advantages and limitations depending on the specific underwater environment and intended application. The primary advantage of UWC is real-time, high-speed, long-distance communication in underwater environments (Islam et al. 2022). Table 1 compares the differences between these three UWC technologies.

The most widely used method is underwater acoustic communication (UAC) technology, which can transmit data over long distances of up to several tens of kilometres (Stojanovic 1996). This capability is due to the low attenuation properties of sound waves propagating in water. However, UAC suffers from low data rates due to its low modulation bandwidth. Additionally, the propagation speed of acoustic waves in underwater channels is relatively slow (Ali et al. 2020). On the other hand, underwater radio frequency (RF) communication is limited by high attenuation due to the low conductivity of electromagnetic waves in water, causing a limited transmission distance of only a few tens of meters (Ali et al. 2020; Ibrahim et al. 2021).

TABLE 1. A comparison of Underwater Wireless Communication (UWC) technologies

| Parameter | Underwater Acoustic Communication (UAC) | Underwater Radio Frequency (RF) Communication | Underwater Optical Wireless Communication (UOWC) |
|---|---|---|---|
| Transmission Distance | Up to several tens of kilometres | A few tens of meters | Moderate distances (up to 100 meters) |
| Data Rate | Low | Moderate | High (reaching Gbps) |
| Attenuation | Low | High | Moderate |
| Latency | High | Low | Very Low |
| Cost | High | Moderate | Low |
| Power Consumption | High | Moderate | Low |
| Latency | High | Low | Very Low |

In contrast, underwater optical wireless communication (UOWC) has been the promising alternative with its potential to achieve high data rates, reaching gigabits per second (Gbps), low latency, and energy efficiency (Fang et al. 2023; Alghamdi et al. 2019). These high-speed and low-latency advantages facilitate real-time underwater applications. Furthermore, it is also more effective compared to UAC and RF communication, benefiting from low-cost and low-power transceivers such as light-emitting diodes (LEDs) and photodiodes (PDs) (Zhu et al. 2020).

However, UOWC faces challenges with the scattering and absorption of light in the underwater environment, as stated by Elamassie, Sait, and Murat Uysal (2018) and M Mohamed (2021). Water molecules, suspended particles, and marine life can scatter and absorb optical signals, leading to signal attenuation and distortion, which cause condition limits to the propagation distance of UOWC systems. Light propagation in the water medium involves absorption and scattering phenomena influenced by the composition and condition of the medium. This interaction is quantified by the attenuation coefficient, $c(\lambda)$.

Another significant limitation in UOWC systems is the impact of underwater turbulence on the communication channel. Turbulence, arising from factors such as temperature gradients, water currents, and the formation of bubbles, induces random fluctuations in the water's refractive index. This condition results in optical effects like scintillation and beam wander, which disrupt the stability of the light beam (Nima Enghiyad and Abbasali Ghorban Sabbagh 2022). These disturbances can severely degrade signal quality, making reliable data transmission a challenging task in turbulent underwater environments.

Most existing research on UOWC has focused on theoretical models and controlled experimental environments. Table 2 summarises recent studies on UOWC technology. These studies commonly address challenges in UOWC by investigating factors such as optical turbulence, channel conditions, and performance under different environmental influences, ranging from theoretical models and simulations to practical experiments and reviews. However, real-world optical propagation is heavily influenced by geographical variations in sweater composition, temperature, salinity, and biological activity (Waduge, Seet and Vopel 2024). The South China Sea (SCS), a vast and complex marine region, exhibits distinct optical properties that can significantly impact UOWC performance (Jin et al. 2023).

Despite the increasing interest in UOWC technology, few studies have investigated how the unique optical general characteristics of the SCS affect UOWC channels. Understanding how absorption and scattering vary in this region is crucial for accurately modelling UOWC performance and optimizing system design for real-world applications.

Therefore, this study aims to fill this research gap by investigating the impact of absorption and scattering on the UOWC channel in the SCS. Firstly, the attenuation coefficient of the SCS, $C_{SCS}$, is estimated. This estimated $C_{SCS}$ is then incorporated into our developed UOWC simulation model. Then, an analysis is performed to determine the channel path loss, time impulse response, and frequency impulse response, providing critical insights into the feasibility and limitations of UOWC in this specific geographical region.

The following section outlines the methodology for this study. It is followed by a presentation of the simulation results and a discussion of key findings. The final section provides the conclusion of the paper.

# METHODOLOGY

## ESTIMATION OF ATTENUATION COEFFICIENT FOR THE SOUTH CHINA SEA REGION

The attenuation coefficient for the SCS region, $C_{SCS}$ is estimated based on the theoretical $c$ defined by Johnson (2014):

$$c(\lambda) = a(\lambda) + b(\lambda) \tag{1}$$

where $a(\lambda)$ and $b(\lambda)$ are the absorption and scattering coefficients, respectively. Note that the attenuation coefficient is a single value at the wavelength, $\lambda$ as stated by Safiy Sabril et al. (2021). The absorption and scattering coefficients vary in composition across the different water regions. Absorption coefficient $a(\lambda)$ is given by:

TABLE 2. Summary of recent studies in Underwater Optical Wireless Communication (UOWC)
*Overview of key research areas in UOWC, noting the lack of studies in the South China Sea*

| Authors | Method Used | Focus Study |
|---|---|---|
| Zayed et al. (2025) | Simulation | Focus on developing comprehensive models that accurately represent the behaviour of optical signals in underwater settings by analyzing factors such as absorption, scattering, and turbulence. |
| Geldard, Thompson, and Popoola (2024) | Simulation | Investigates the effect of underwater optical turbulence under varying channel conditions. |
| Ji et al. (2024) | Simulation | Focus on improving the channel modelling for UWOC systems by incorporating various factors that affect the optical signal, especially in slanted paths. |
| Dong et al. (2023) | Experiment | To improve the efficiency and stability of UWLC. |
| Fang, Li, and Wang (2022) | Simulation | Develops a UOWC model, including both LOS and NLOS channels, for more accurate real-world representation. |
| Zhou et al. (2021) | Field Measurements | Examines the effects of marine particles on scattering and backscattering to understand the optical properties of water in the South China Sea. |
| Wan Hassan et al. (2022) | Experiment | Empirical study on how different light sources and water conditions affect UOWC performance. |
| Fang et al. (2023) | Literature Survey | Reviews advanced signal processing methods for high-speed UOWC and identifies promising techniques. |
| Nima Enghiyad and Abbasali Ghorban Sabbagh (2022) | Simulation | It uses the Monte Carlo simulation to analyze the impulse responses of UOWC channels considering turbulence, absorption, and scattering. |

$$a(\lambda) = a_w(\lambda) + a_{CDOM}(\lambda) + a_{chl}(\lambda) + a_{NAP}(\lambda) \tag{2}$$

Here, $a_w(\lambda)$ represents the pure water absorption coefficient, $a_{CDOM}(\lambda)$ denotes colour-dissolved organic matter absorption, $a_{chl}(\lambda)$ signifies phytoplankton absorption and $a_{NAP}(\lambda)$ represents non-algal particle absorption.

The scattering coefficient $b(\lambda)$ is defined as:

$$b(\lambda) = b_w(\lambda) + C_S b_S(\lambda) + C_L b_L(\lambda) \tag{3}$$

Here, $b_w$ denotes the pure water Rayleigh scattering coefficient. $C_S$ and $C_L$ represent concentrations of small and large humic acids, respectively, influencing $b_S$ and $b_L$:

$$C_s = 0.01739*C_{chl}\, exp[0.11631\, C_{chl}] \quad (4)$$

$$C_L = 0.76284*C_{chl}\, exp[0.03092\, C_{chl}] \quad (5)$$

where $C_{chl}$ represents the chlorophyll concentration. The scattering coefficients $b_S$ and $b_L$ are calculated as:

$$b_s = 0.341074\left(\frac{400}{\lambda}\right)^{0.3} \quad (6)$$

$$b_L = 1.151302\left(\frac{400}{\lambda}\right)^{1.17} \quad (7)$$

These parameters characterize scattering caused by both small and large particles and are also influenced by wavelength.

TABLE 3. Absorption and scattering coefficients used for estimating $C_{SCS}$

| Component | Value |
|---|---|
| $a_w$ (Johnson 2014) | 0.00638 $m^{-1}$ |
| $a_{CDOM}$ (Idris, Jafar Sidik, and Hing 2021) | 0.47600 $m^{-1}$ |
| $a_{Chl}$ (Idris, Jafar Sidik, and Hing 2021) | 0.0060 $m^{-1}$ |
| $b_w$ (Johnson 2014) | 19.3x10$^{-4}$ $m^{-1}$ |
| $C_{Chl}$ (Idris, Jafar Sidik, and Hing 2021) | 0.53 mg/m$^3$ |

From equation (1) – (7), the attenuation coefficient for SCS, $C_{SCS}(\lambda)$, is defined as

$$C_{SCS}(\lambda) = a_{SCS}(\lambda) + b_{SCS}(\lambda) \quad (8)$$

The value of $a_{SCS}(\lambda)$ is estimated from (2), with each component in (2) listed in Table 3. It should be noted that the value of $a_{NAP}(\lambda)$ for $a_{SCS}(\lambda)$ is assumed to be negligible due to the difficulty in accurately quantifying its contribution. According to Shen, Zhou, and Hong (2012), the $a_{NAP}$ in open sea conditions typically ranges from 0.001 to 0.015 $m^{-1}$ at a wavelength of 440 nm. Since absorption by non-algal particles generally decreases with increasing wavelength, it is reasonable to assume that at 550 nm, $a_{NAP}$ is significantly lower than at 440 nm and approaches zero. Additionally, the lower absorption and scattering properties of 550 nm light contribute to greater optical penetration in seawater. Additionally, previous studies (Zhang et al. 2022) suggest that the 550 nm wavelength falls within the optimal transmission window for UOWC, particularly in coastal waters with moderate turbidity.

Similarly, the value of $b_{SCS}(\lambda)$ is estimated from (2), and the value of components in (3) is listed in Table 3. With the selected wavelength of $\lambda$ = 550 nm and derived from (8), the estimate of $C_{SCS}(\lambda) = 0.8748\, m^{-1}$. The value lies within the range of coastal and harbour environments, further supporting the suitability of 550 nm for modelling underwater light propagation in the SCS. The alignment of this value with Jerlov's water-type classification theory reinforces the characterization of the study area as a coastal region (Johnson 2014).

## SIMULATION PARAMETERS

This simulation employs a line-of-sight communication link for both laser and LED beams. The simulation parameters are provided in Table 4. Apart from the estimated value of $C_{SCS}$, other values of $C(\lambda)$ are obtained from Johnson (2014), while the $C_{SCS}$ is determined empirically or through a formula outlined in the earlier discussion on methodology. Table 5 presents the attenuation coefficients $C(\lambda)$ for various water types, including Clear, Coastal, Harbour, and SCS conditions.

The wavelength of 550 nm is selected for both the laser and LED sources because it falls within the blue-green spectrum and exhibits a smaller attenuation coefficient compared to other wavelengths (Bigham and Sabbagh 2025).

TABLE 4. Simulation parameters of the UOWC

| Parameter | Value | |
|---|---|---|
| Number of photons | 1000000 | |
| Link Range | 5 to 25m | |
| Wavelength | 550 nm | |
| Beam Waist | 1 mm | |
| Beam Divergence | Collimated (Laser) | 1.5 mrad |
| | Diffused (LED) | 15° |
| Receiver FOV | 180° | |
| Roulette Constant | 10 | |

TABLE 5. Attenuation coefficients of three different water types (Johnson 2014) and the $C_{SCS}$

| Water Type | Attenuation Coefficient, c ($m^{-1}$) |
|---|---|
| Clear Water | 0.1510 |
| Coastal Water | 0.3999 |
| Harbour Water | 2.1950 |
| South China Sea | 0.8748 |

## MONTE CARLO SIMULATION METHOD

The Monte Carlo (MC) simulation method was employed in this study to track the movement of photons within the defined homogeneous model (Safiy Sabril et al. 2021; Cox Jr. 2012). The simulation process is divided into three main parts: photon transmission, propagation through the medium channel, and photon reception at the receiver. During transmission, photons are emitted from the source with predefined properties. As they propagate through the underwater channel, they undergo multiple scattering and absorption interactions based on the optical properties of the medium. Finally, the surviving photons are detected at the receiver, where their intensity and distribution are analyzed. Figure 1 presents a flowchart summarising the Monte Carlo simulation process. The diagram outlines the key steps, including photon initialisation, propagation, interaction events, and termination.

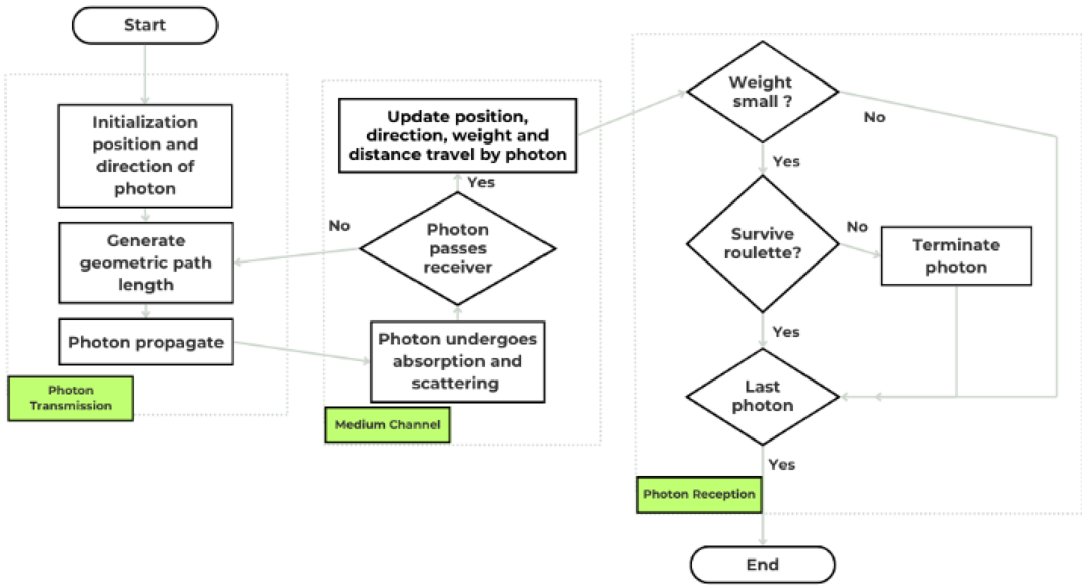


FIGURE 1. Flowchart summarising the Monte Carlo simulation process

## PHOTON TRANSMISSION

Photon movement is governed by a generic path length $S$, defined as:

$$s = -ln(q)/c \tag{9}$$

Here, $q$ is a uniformly distributed random number between 0 and 1. Algorithms evaluate the weight and scattering direction of the photon after every motion. The photon's weight is updated by multiplying it with the single scattering albedo $\omega$:

$$W_{n+1} = W_n^{\omega} = W_n\,(b/c) \tag{10}$$

where $b$ and $c$ represent parameters adjusted for brevity from equations 1 and 3. If the updated photon weight $W_{n+1}$ drops below a predefined threshold, the photon is either terminated or boosted using a roulette technique according to (Cox Jr. 2012). Surviving photons have their scattered directions updated based on angles derived from the scattering phase function (Safiy Sabril et al. 2021; Cox Jr. 2012; Petzold 1972; Kokhanovsky 2018).

## MEDIUM CHANNEL

The channel is modelled as a homogeneous medium between the transmitter and receiver, consisting of a single layer where the attenuation coefficient remains consistent and homogeneous throughout. Photons experience this attenuation coefficient as they propagate through the channel.

## PHOTON RECEPTION

The propagation of the photons continues until they are either received by the receiver, lose power in the channel, or are backscattered (not counted). Photons captured within the receiver's aperture and field-of-view (FOV) contribute to the count of received photons. This process is repeated for the predetermined number of photons involved in the simulation, from transmission to reception.

# RESULTS AND DISCUSSION

## PATH LOSS ANALYSIS

This study's path loss analysis refers to the loss of received power as the transmission link increases. Figures 2 and 3 clearly show that the normalized received power using both LED and laser light sources decreases as the link range increases, indicating that path loss is directly proportional to the distance between the transmitter and receiver. This behaviour aligns with findings from (Safiy Sabril et al. 2021; Cox Jr. 2012), which also observed significant attenuation effects in UOWC due to absorption and scattering in turbid waters.

Both LED and laser light sources have shown a similar path loss trend across all different water types. The results indicate that clear water experiences the least path loss, followed by coastal water, SCS water, and finally, harbour water, which has the highest path loss. These findings support previous research (Abla Kammoun et al. 2019; Saeed et al. 2019), where increasing turbidity levels were shown to worsen path loss due to higher absorption and scattering coefficients.

Laser-based communication demonstrates superior performance over LED, with nearly 10 dB higher received power across all water types. This observation is consistent with the work of Fei et al. (2018) and Fang et al. (2023), where laser sources were found to provide higher data rates and better transmission efficiency in underwater environments due to their narrow beam divergence and lower scattering losses.

From the path loss analysis shown in Figure 2 and Figure 3, it is evident that the path loss in SCS water is better than in harbour water but worse than in coastal water. When using a laser light source (Figure 2), the normalized received power in SCS water dropped significantly compared to coastal water as the link range increased. The most severe drop occurs at the maximum link range of 25 meters, where the normalized received power in SCS water fell 45 dB below that of coastal water. However, despite the increasing link range, the normalized received power in SCS water remained approximately 10 dB higher than in harbour water, demonstrating comparatively better performance.

In contrast, when using the LED light source (Figure 2), the path loss in SCS water was more severe. The normalized received power dropped below -90 dB as the link range reached 25 meters. Figure 3 also shows that the normalized received power in SCS water was only slightly better than in harbour water, with both conditions becoming nearly identical as the link range approaches 25 meters.

In summary, the observed path loss for each type of water is consistent with the corresponding attenuation constants listed in Table 5 and aligns with similar studies (Safiy Sabril et al. 2021). Additionally, the laser light source is known to outperform the LED in generating stronger and more focused light waves (Fang et al. 2023), supporting the above discussion. The limitation of this analysis is the assumption of a homogeneous water medium not fully representing real-world conditions, especially in dynamic conditions like SCS. The factors such as internal waves, temperature gradients, and turbulence affect signal propagation (Johnson 2014). Future work should incorporate these additional environmental factors to further refine the accuracy of path loss predictions in UOWC.

## IMPULSE RESPONSE ANALYSIS

The impulse response was computed for four different water conditions, clear, coastal, harbour, and SCS, over a 25-meter link range. The simulation results for these conditions are presented in Figure 4. The vertical axis represents the normalized power, while the horizontal axis denotes the receiving time relative to the photon's arrival time at the receiver plane. The time-resolved profile patterns differ across the four water conditions. The findings closely resemble those reported by Johnson (2014), Schirripa Spagnolo, Cozzella, and Leccese (2020), and Adnan et al. (2021), where the scattering and multipath effects in turbid waters caused prolonged impulse responses and increased signal spreading.

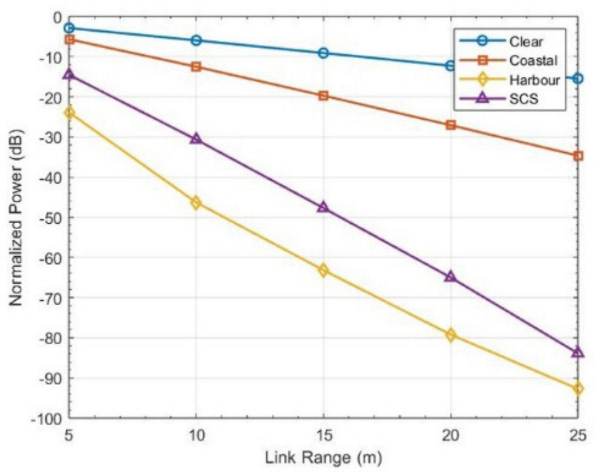


FIGURE 2. Normalized power of laser vs link range across four water conditions

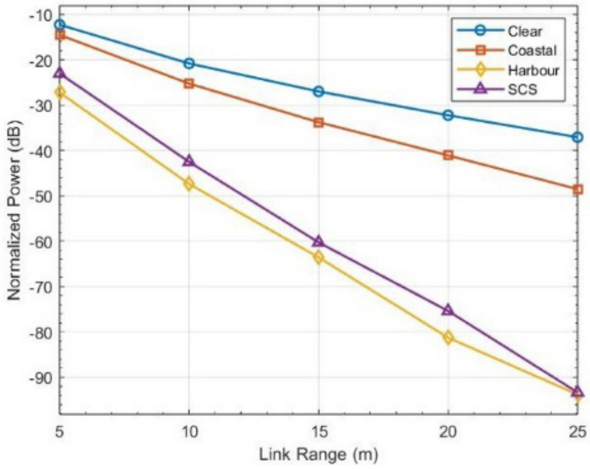


FIGURE 3. Normalized power of LED vs link range across four water conditions

The arrival time range for each water condition shows significant differences, indicating varying degrees of scattering and signal delay in the underwater environment. Clearwater, with a limit of 6 ns, has the shortest arrival time range, reflecting minimal scattering and quick signal decay. This finding means that the light signal experiences little to no delay, resulting in a sharp initial peak and rapid attenuation. Coastal water extends the arrival time range to 12 ns, demonstrating that more organic and inorganic particles cause greater scattering, increasing signal spread and temporal dispersion (Behnaz Majlesein, Gholami, and Zabih Ghassemlooy 2021).

In contrast, harbour water shows the most severe scattering and multipath effects, with an arrival time range extending to 35 ns. The higher level of suspended particles and pollutants in harbour water causes significant signal dispersion and prolonged delays, leading to a complex impulse response with multiple peaks and an extended tail. The SCS water condition has an even longer arrival time range, reaching 15 ns, indicating that scattering effects are stronger here compared to coastal water. This intermediate level of scattering and absorption results in notable multipath effects, which extend the signal's arrival time.

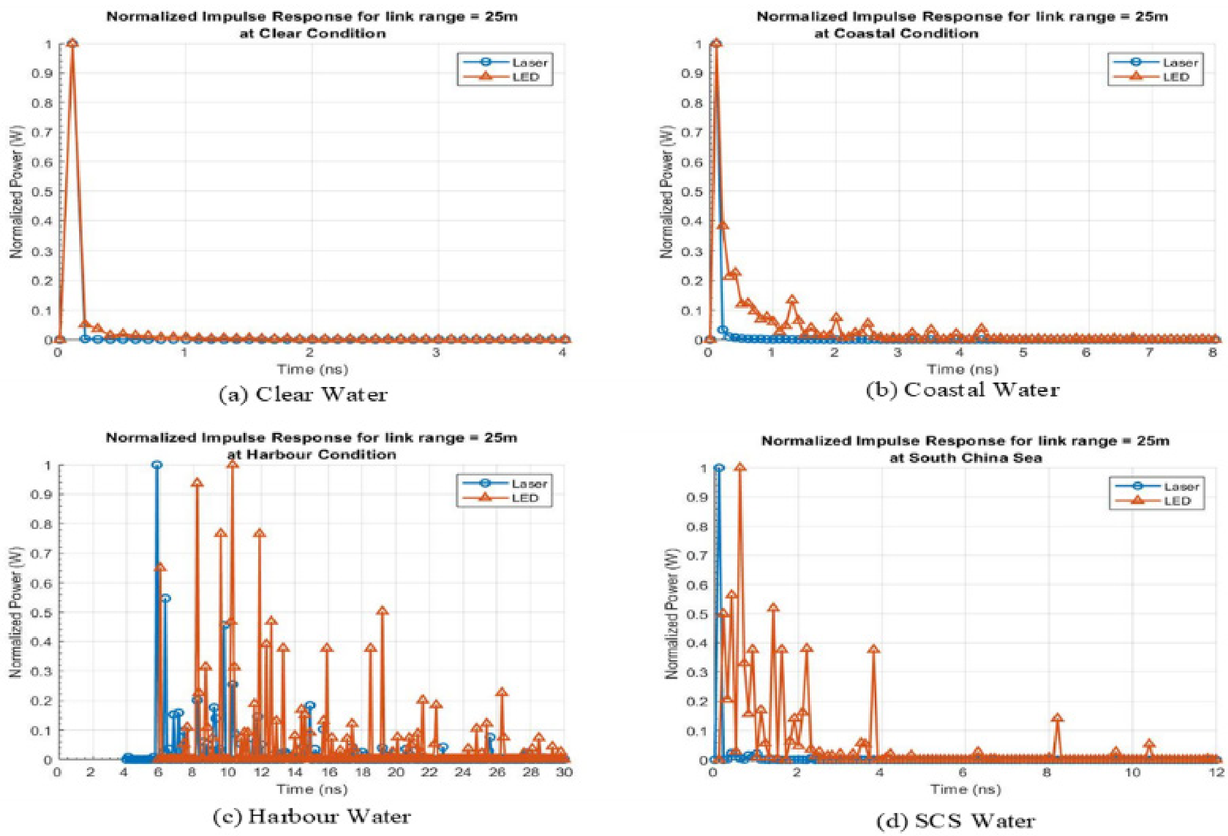


FIGURE 4. The impulse response of laser and LED systems at 25 m for (a) clear, (b) coastal, (c) harbour, and (d) SCS

The peak values further highlight the differences in water conditions. The laser peaks occur at approximately 0.1 ns in clear, coastal, and SCS water conditions but at 5.8 ns in harbour conditions. The peaks for the LED light source are around 0.1 ns for clear and coastal conditions, 0.6 ns for SCS water, and 10.3 ns for harbour conditions. In the context of UOWC, the peak in the impulse response represents the moment when the maximum amount of light energy is received after being transmitted through water. This peak occurs when most transmitted photons arrive at the receiver with minimal scattering and absorption. The higher and sharper the peak, the less the signal is affected by the water's properties, indicating better communication performance. As seen in the harbour condition, a lower or delayed peak suggests more scattering, absorption, and multipath effects, where the light is reflected and scattered before reaching the receiver.

In coastal water, the impulse response shows more peaks compared to clear water, indicating increased scattering from particles. This scattering causes greater temporal dispersion and signal spreading than clear water. The impulse response in the SCS water condition, classified as coastal water according to Jerlov's water type classification (Johnson 2014), has more pronounced peaks than in typical coastal water, suggesting stronger scattering effects. Despite this, SCS water performs better than harbour water, as seen in the shorter arrival time range of 15 ns compared to 35 ns. According to Nima Enghiyad and Abbasali Ghorban Sabbagh (2022), this response reflects intermediate scattering and absorption levels in the SCS, which could be due to the regional variation in water quality and particulate matter concentration.

The harbour condition presents the most complex impulse response, with a prolonged arrival time range and multiple peaks. Due to suspended particles and pollutants, the high turbidity in harbour water causes severe scattering, extending the signal's arrival time and introducing significant multipath effects. Both the laser (5.8 ns) and LED (10.3 ns) responses in harbour water reflect the highly challenging environment for underwater optical communication. This complex environment aligns with findings from Gussen et al. (2016), which suggests that high turbid waters introduce significant delays and multipath effects that degrade communication performance.

In summary, the arrival time range differences across the water types clearly illustrate the impact of scattering on signal transmission. Clear water provides the best conditions with minimal delay, while harbour water poses the greatest challenge due to severe scattering and prolonged signal dispersion. Coastal and SCS waters lie in between, with moderate scattering effects but still showing considerable signal degradation over longer distances. These findings underscore the importance of adapting UOWC systems to specific water conditions to optimize performance.

The delayed spread of optical signals from laser and LED sources under various underwater conditions, specifically clear, coastal, harbour, and SCS, is tabulated in Table 6. These results indicate a progressive increase in delay spread from clear to coastal, harbour, and SCS conditions. This observed trend suggests that clearer waters, characterized by lower attenuation coefficients, result in minimal optical scattering and, consequently, smaller delay spreads. In contrast, coastal regions exhibit progressively higher delay spreads, with the SCS showing the most substantial increase. This finding indicates that optical scattering is more severe in the SCS, consistent with the environmental factors affecting light propagation in this region. The variations in delay spread are directly related to the frequency response of the optical signals. Increased delay spreads, especially in environments similar to harbours and the SCS, lead to greater multipath effects and enhanced scattering. This degradation in signal clarity underscores the impact of environmental conditions on the performance of optical communication systems, affecting both laser and LED sources.

The challenge in impulse response analysis is the need for accurate modelling of real-world scattering and absorption effects. The Monte Carlo approach provides good approximations and real-world water condition dynamic variation that may not be fully captured in the simulation. Additionally, the assumption of uniform scattering properties may not be accurate, especially in SCS. Future studies should consider real-time oceanography data to enhance model accuracy and validate simulation results with experimental measurements.

## FREQUENCY RESPONSE ANALYSIS

Figures 5 and 6 illustrate the frequency response of laser and LED light sources across different water types. The frequency response plot is generated by applying the Fast Fourier Transform (FFT) to the previously obtained impulse time response.

In clear water conditions, the laser light source (Figure 5) maintains a near-perfect signal up to around $10^9$ Hz, after which it experiences a sharp drop in power. In contrast, the LED light source (Figure 6) shows a gradual decline in power starting at lower frequencies, indicating that LED light is more susceptible to attenuation even in ideal underwater conditions. The laser retains much higher power levels across a broader frequency range, suggesting it is more robust for high-frequency applications in clear water than the LED (Saeed et al. 2019).

In the coastal water condition, the laser source experiences a steady reduction in power as the frequency increases, with a noticeable drop-off occurring after $10^9$ Hz. The LED source exhibits similar behaviour but starts losing power rapidly and at lower frequencies, with power levels significantly lower than the laser. This finding indicates that while both sources are affected by coastal water conditions, the laser remains more resilient, maintaining higher power levels over a broader range of frequencies. The LED, more prone to environmental interference and scattering, experiences a more rapid decline in power.

In the harbour water condition, both sources experience significant degradation. The laser's power drops sharply and shows noisy fluctuations at higher frequencies, likely due to heavy scattering from suspended particles and pollution in the water. The LED source is even more affected, with its signal almost entirely lost at lower frequencies and displaying more erratic fluctuations at higher frequencies. This comparison reveals that while the laser is better suited to maintaining a stable signal in harsh, turbid environments like harbours, the LED struggles to perform consistently under such conditions (Saeed et al. 2019; Safiy Sabril et al. 2021).

TABLE 6. Delay Spread for laser and LED at 25 m across four water conditions

| | Delay Spread (s) | | | |
|---|---|---|---|---|
| Water Condition | Clear | Coastal | Harbour | SCS |
| Laser | $2.52 \times 10^{-13}$ | $6.45 \times 10^{-12}$ | $2.91 \times 10^{-9}$ | $2.91 \times 10^{-9}$ |
| LED | $2.85 \times 10^{-11}$ | $3.5251 \times 10^{-10}$ | $4.55 \times 10^{-9}$ | $1.13 \times 10^{-9}$ |

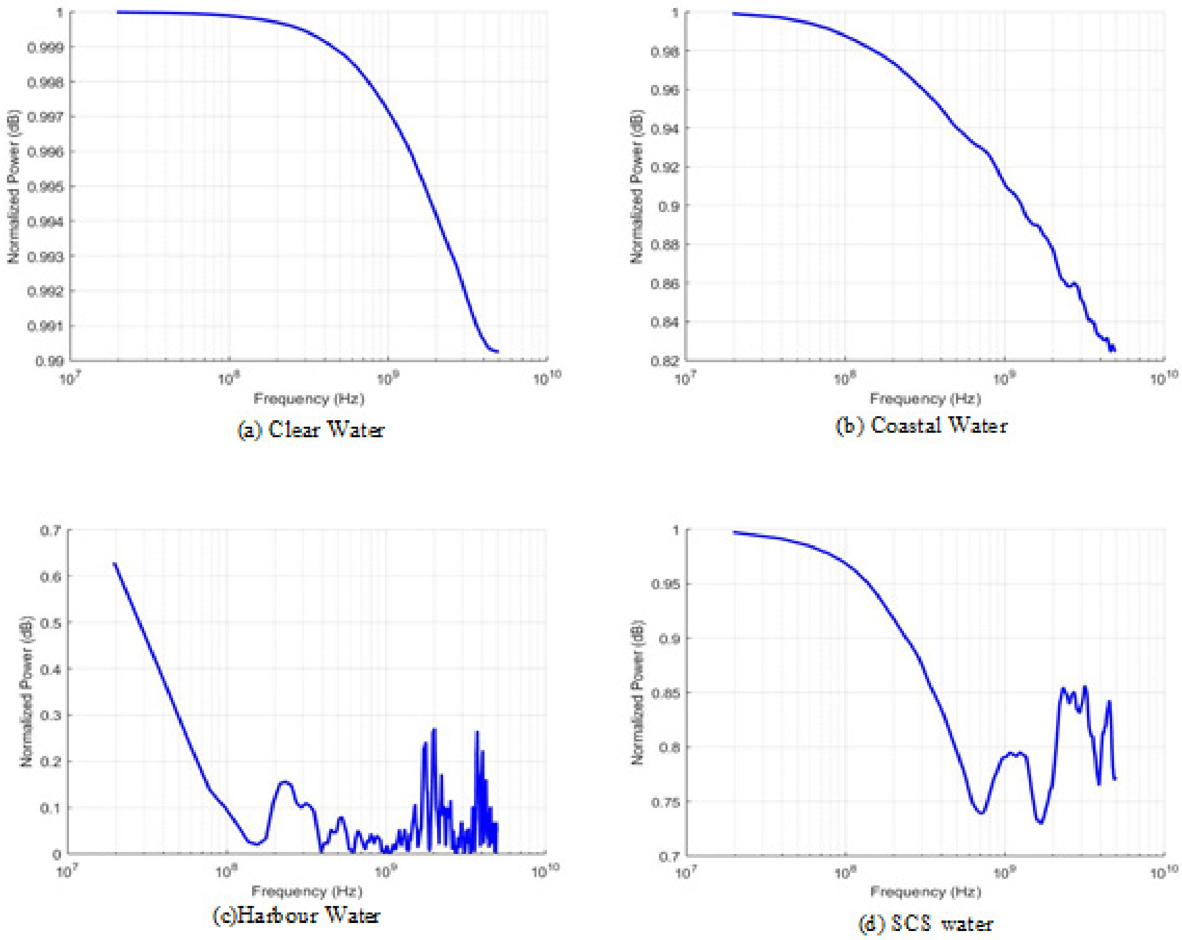


FIGURE 5. Frequency response of laser system at 25 m for (a) clear, (b) coastal, (c) harbour, and (d) SCS

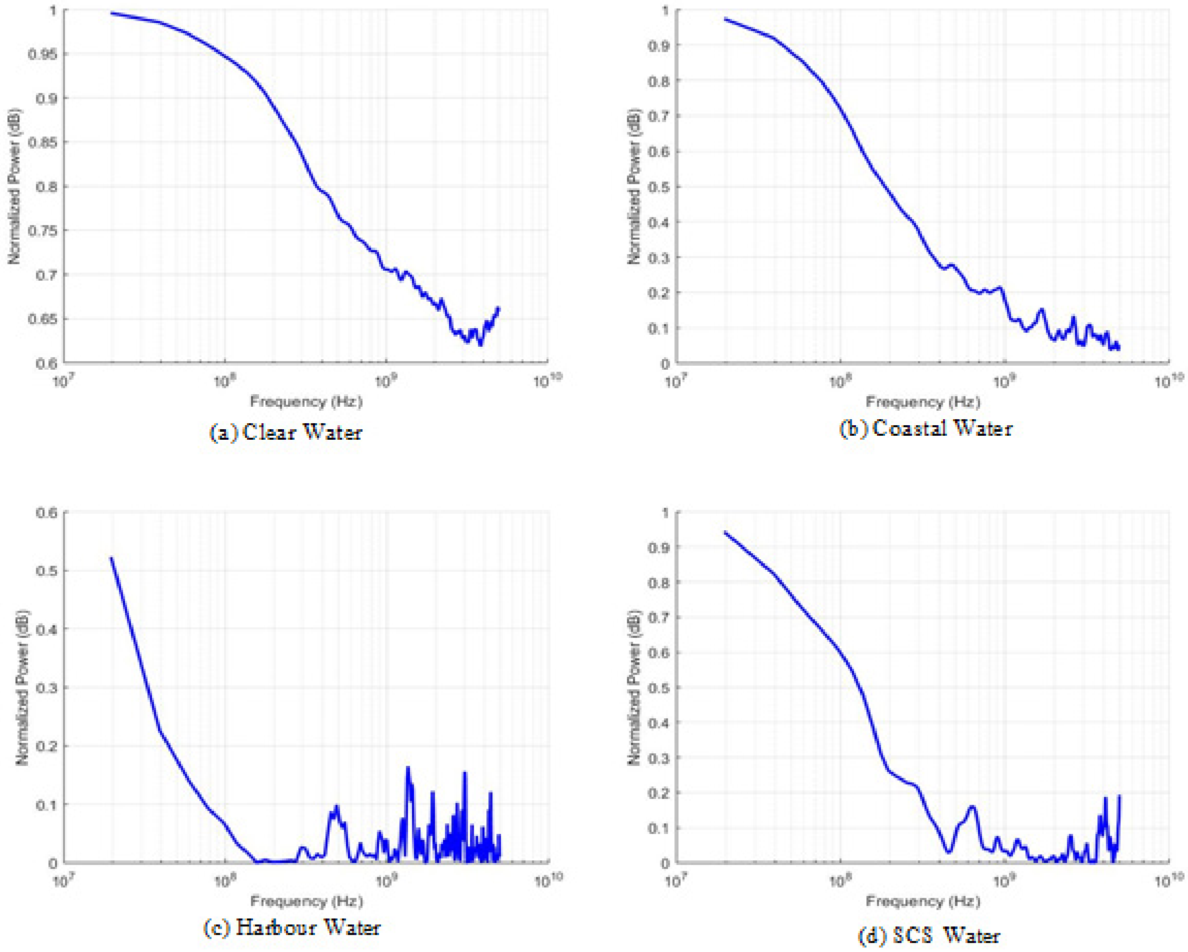


FIGURE 6. Frequency response of LED system at 25 m for (a) clear, (b) coastal, (c) harbour, and (d) SCS

In the SCS water condition, the laser again shows a gradual decline in power, with dips and fluctuations appearing around $10^9$ Hz, likely due to scattering caused by suspended particles in the sea. The LED source, however, experiences a more severe power drop at lower frequencies and shows larger fluctuations, indicating greater sensitivity to underwater scattering effects. The laser retains a stronger signal overall, highlighting its superior performance in maritime environments where the underwater medium introduces significant scattering and absorption.

For a 25 m link range, the 3 dB bandwidth for laser links reaches over 4.96 GHz in clear, coastal, and SCS conditions. In contrast, the 3 dB bandwidth significantly drops drastically to only 29.8 MHz in harbour conditions. Similarly, LEDs achieve a bandwidth greater than 4.96 GHz solely in clear water conditions, while in coastal, SCS, and harbour environments, the bandwidth drops to 186 MHz, 131 MHz, and 21 MHz, respectively. All the results are simplified in Table 7 and in line with the findings in (Johnson 2014), where harbour waters exhibited significant bandwidth reduction due to strong multipath effects and increased delay spreads. This reduction is also primarily due to the high scattering present in these environments, especially at the harbour. Both laser and LED sources exhibit a decreasing trend in channel bandwidth as environmental conditions worsen. The increased delay spread observed in Table 6 also negatively impacts the 3 dB bandwidth, as higher delay spreads lead to greater multipath effects that further degrade signal clarity and overall frequency response (Wang et al. 2021). This relationship illustrates how environmental factors influence the frequency response of optical signals in UOWC systems. The bandwidth degradation in turbid waters underscores the importance of understanding these dynamics for optimizing communication performance.

TABLE 7. 3dB bandwidth of laser and LED across four water conditions

| 3dB Bandwidth (Hz) | | | | |
|---|---|---|---|---|
| Water Condition | Clear | Coastal | Harbour | SCS |
| Laser | >4.96x10$^9$ | >4.96x10$^9$ | 2.98x10$^7$ | >4.96x10$^9$ |
| LED | >4.96x10$^9$ | >1.86x10$^8$ | 2.10x10$^7$ | 1.31x10$^8$ |

The limitation in frequency response analysis is the assumption of constant optical properties across all depths and locations. In reality, the water column variation can influence light propagation and affect the system. The SCS water exhibits the intermediate scattering behaviour, which differs slightly from traditional coastal waters. This finding suggests that regional water properties in the SCS may require adaptive modulation and error correction techniques to optimize UOWC system performance.

## CONCLUSION

The significant impact of absorption and scattering on the performance of UOWC systems in the SCS has been demonstrated in this study. A key contribution of this work is the estimation of the attenuation coefficient for SCS, which has been determined to be 0.8748 m$^{-1}$; the value lies within the range of coastal and harbour environments. Thus supporting the suitability of 550 nm for modelling underwater light propagation in the South China Sea. This coefficient serves as an essential parameter for accurately modelling UOWC channels in the region. Monte Carlo simulations have been used to analyze key performance metrics, including path loss, impulse response, and frequency response. It has been found that absorption and scattering significantly contribute to signal degradation, with laser and LED sources experiencing delay spreads of $2.92 \times 10^{-11}$ s and $1.13 \times 10^{-9}$ s, respectively. Furthermore, frequency-dependent attenuation has been observed to cause signal distortion, affecting communication reliability.

Bandwidth and delay spread area are important parameters to determine the effect of the UOWC signal system. Higher bandwidth gives the transmission of more data, but the absorption and scattering properties constrain it. It gives the limited system frequency responses. Delay spread increases with the link distance due to the multipath effect, which causes signal distortion and intersymbol interference (ISI). Delay spread negatively impacts communication reliability, especially at high data rates. Thus, optimizing bandwidth and mitigating delay spread is essential to achieving robust and high-speed UOWC systems.

The findings of this study can be applied to improve the design and deployment of UOWC systems in real-world applications. More accurate predictive models for underwater communication performance can be developed using the estimated attenuation coefficient, allowing system parameters such as transmission power, wavelength selection, and receiver sensitivity to be optimized. Additionally, improvements in underwater sensor networks can be achieved, leading to more efficient data transmission for marine exploration, environmental monitoring, and offshore infrastructure inspection. Autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) can also benefit from the findings by incorporating adaptive modulation techniques and power control strategies to maintain stable communication in varying water conditions.

In order to enhance the reliability of UOWC systems, further research should be conducted to validate these findings through real-world experiments. The incorporation of dynamic oceanic factors such as turbulence, temperature variations, and biological activity is recommended. Moreover, the exploration of alternative wavelengths and advanced signal processing techniques should be pursued to improve the robustness and efficiency of UOWC systems under diverse underwater conditions.

## ACKNOWLEDGEMENT

This research was supported by the Ministry of Higher Education (MOHE) Malaysia through the Fundamental Research Grant Scheme FRGS/1/2022/TK07/UMT/02/2.

## DECLARATION OF COMPETING INTEREST

None.

## REFERENCES

Abla Kammoun, Zhou Jiusi, Boon S Ooi, and Mohamed-Slim Alouini. 2019. "Impact of wavelength on the path-loss of turbid underwater communication systems." *2022 IEEE Wireless Communications and Networking Conference (WCNC)* 29: 1–7. https://doi.org/10.1109/wcnc.2019.8886098.

Adnan, Salah A, Hassan Ahmed Hassan, Ahmed Alchalaby, and Ahmed C Kadhim. 2021. "Experimental study of underwater wireless optical communication from clean water to turbid harbor under various conditions." *International Journal of Design & Nature and Ecodynamics* 16 (2): 219–26. https://doi.org/10.18280/ijdne.160212.

Alghamdi, Rawan, Nasir Saeed, Hayssam Dahrouj, Mohamed-Slim Alouini, and Tareq Y Al-Naffouri. 2019. "Towards ultra-reliable low-latency underwater optical wireless communications." *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall):* September. https://doi.org/10.1109/vtcfall.2019.8891506.

Ali, Mohammad Furqan, Dushantha Nalin K. Jayakody, Yury Alexandrovich Chursin, Soféine Affes, and Sonkin Dmitry. 2020. "Recent advances and future directions on underwater wireless communications." *Archives of Computational Methods in Engineering* 27 (5). https://doi.org/10.1007/s11831-019-09354-8.

Behnaz Majlesein, Asghar Gholami, and Zabih Ghassemlooy. 2021. "Investigation of the scattering noise in underwater optical wireless communications." *Sci* 3 (2): 27. https://doi.org/10.3390/sci3020027.

Bigham, Ahmad, and Abbasali Ghorban Sabbagh. 2025. *8-Ary Underwater Optical Wireless Communication Systems Using Blue-Green Color Shift Keying and Multi-Level Intensity Modulation*. Quchan University of Technology.

Cox Jr., William Charles. 2012. *Simulation, Modeling, and Design of Underwater Optical Communication Systems*. North Carolina State University. http://www.lib.ncsu.edu/resolver/1840.16/7588.

Dong, Bing, Shoufeng Tong, Peng Zhang, and Yangfan Du. 2023. "Research on duplex underwater wireless laser communication system." *Frontiers in Physics* 11 (July). https://doi.org/10.3389/fphy.2023.1225869.

Elamassie, Mohammed, Sadiq M Sait, and Murat Uysal. 2018. "Underwater visible light communications in cascaded gamma-gamma turbulence." *IEEE Globecom Workshops, GC Wkshps 2018 - Proceedings*, December, 1–6. https://doi.org/10.1109/glocomw.2018.8644170.

Fang, Chengwei, Shuo Li, and Ke Wang. 2022. "Accurate underwater optical wireless communication model with both line-of-sight and non-line-of-sight channels." *IEEE Photonics Journal* 14 (6): 1–12. https://doi.org/10.1109/jphot.2022.3216599.

Fang, Chengwei, Shuo Li, Yinong Wang, and Ke Wang. 2023. "High-speed underwater optical wireless communication with advanced signal processing methods survey." *Photonics* 10 (7): 811. https://doi.org/10.3390/photonics10070811.

Fei, Chao, Xiaojian Hong, Guowu Zhang, Ji Du, Yu Gong, Julian Evans, and Sailing He. 2018. "166 Gbps data rate for underwater wireless optical transmission with single laser diode achieved with discrete multi-tone and post nonlinear equalization." *Optics Express* 26 (26): 34060. https://doi.org/10.1364/oe.26.034060.

Geldard, Callum T, John S Thompson, and Wasiu O Popoola. 2024. "On the relative effect of underwater optical turbulence in different channel conditions." *IEEE Access* 12: 11104–13. https://doi.org/10.1109/access.2024.3352914.

Gussen, Camila M. G., Paulo S. R. Diniz, Marcello L. R. Campos, Wallace A. Martins, Felipe M. Costa, and Jonathan N. Gois. 2016. "A survey of underwater wireless communication technologies." *Journal of Communication and Information Systems* 31 (1): 242–55. https://doi.org/10.14209/jcis.2016.22.

Ibrahim, Md, A. S. M. Badrudduza, Shakhawat Hossen, M K Kundu, and Imran Shafique Ansari. 2021. "Enhancing security of TAS/MRC-based mixed RF-UOWC System with induced underwater turbulence effect." *IEEE Systems Journal* 16 (4): 5584–95. https://doi.org/10.1109/jsyst.2021.3123515.

Idris, Md Suffian, Madihah Jafar Sidik, and Lee Siang Hing. 2021. "Optical characterisation and classification of water types in the Southern South China Sea and Straits of Malacca." *Estuarine, Coastal and Shelf Science* 262 (November): 107594. https://doi.org/10.1016/j.ecss.2021.107594.

Islam, Kazi Yasin, Iftekhar Ahmad, Daryoush Habibi, and Adnan Waqar. 2022. "A survey on energy efficiency in underwater wireless communications." *Journal of Network and Computer Applications* 198 (December 2021): 103295.

Ji, Xiuyang, Hongxi Yin, Fangyuan Xing, Lianyou Jing, Zhongwei Shen, Jianying Wang, and Yanjun Liang. 2024. "A Generalized and Comprehensive Slant Channel Modeling Method for Underwater Wireless Optical Communication and Its System Performance Analysis." *Optics Communications* 557 (April): 130270. https://doi.org/10.1016/j.optcom.2024.130270.

Jin, Shanshan , Xunwei Nie, Guanlin Wang, Fei Teng, and Tengfei Xu. 2023. "Analysis of the Distribution and Seasonal Variability of the South China Sea Water Masses Based on the K-Means Cluster Method." *Journal of Marine Science and Engineering* 11 (February): 485. https://doi.org/10.3390/%20jmse11030485%20Academic.

Johnson, Laura J. 2014. *Optical Property Variability in the Underwater Optical Wireless Channel*. PhD diss. University of Warwick.

Khamil, K. N, Sabri M. F. M., A. M. Yusop, R. Mohamed, and M. S. Sharuddin. 2020. "Modelling and Simulation of the Performance Analysis for Peltier Module and Seebeck Module Using MATLAB/Simulink K.N." *Jurnal Kejuruteraan* 32 (2): 231–38.

Kokhanovsky, Alexander. 2018. *Springer Series in Light Scattering*. *Springer Series in Light Scattering*. Vol. 2. Springer International Publishing. https://doi.org/10.1007/978-3-319-70796-9.

M Mohamed, Ibrahim M. 2021. "Accurate Path-Loss Estimation for Wireless Cellular Networks." *Jurnal Kejuruteraan* 33 (2): 317–28. https://doi.org/10.17576/jkukm-2021-33(2)-16.

Mohammad Furqan Ali, Dushantha Nalin K. Jayakody, Ponnimbaduge Perera, Kathiravan Srinivasan, Abhishek Sharma, and Ioannis Krikidis. 2019. "Underwater Communications: Recent Advances." *ETIC Conference*.

Nima Enghiyad, and Abbasali Ghorban Sabbagh. 2022. "Impulse Response of Underwater Optical Wireless Channel in the Presence of Turbulence, Absorption, and Scattering Employing Monte Carlo Simulation." *Journal of the Optical Society of America* 39 (December): 115–26. https://doi.org/10.1364/josaa.435288.

Petzold, Tj. 1972. *Volume Scattering Functions for Selected Ocean Waters*. *Scripps Inst. Oceanogr.* UC San Diego : Scripps Institution of Oceanography.

Saeed, Nasir, Abdulkadir Celik, Tareq Y. Al-Naffouri, and Mohamed-Slim Alouini. 2019. "Underwater Optical Wireless Communications, Networking, and Localization: A Survey." *Ad Hoc Networks* 94 (November 2019): 101935. https://doi.org/10.1016/j.adhoc.2019.101935.

Safiy Sabril, Faezah Jasman, Wan Hafiza, Zaiton A Mutalip, Rosmiwati Mohd-Mokhtar, and Zainuriah Hassan. 2021. "The Effect of Medium Inhomogeneity in Modeling Underwater Optical Wireless Communication." *Journal of Communications* 16 (9): 386–93. https://doi.org/10.12720/jcm.16.9.386-393.

Schirripa Spagnolo, Giuseppe, Lorenzo Cozzella, and Fabio Leccese. 2020. "Underwater Optical Wireless Communications: Overview." *Sensors* 20 (8): 2261. https://doi.org/10.3390/s20082261.

Shen, Fang, Yun-xuan Zhou, and Guan-lin Hong. 2012. "Absorption Property of Non-Algal Particles and Contribution to Total Light Absorption in Optically Complex Waters, a Case Study in Yangtze Estuary and Adjacent Coast." In *Advances in Intelligent and Soft Computing*, 61–66.

Stojanovic, M. 1996. "Recent Advances in High-Speed Underwater Acoustic Communications." *IEEE Journal of Oceanic Engineering* 21 (2): 125–36. https://doi.org/10.1109/48.486787.

The Independent. 2024. "One Year on and the Titan Tragedy Still Haunts Deep-Sea Explorers," June 17, 2024. https://www.independent.co.uk/news/world/americas/titan-sinking-titanic-deaths-deep-b2563776.html.

Waduge, Tharuka Govinda , Boon-Chong Seet, and Kay Vopel. 2024. "Optimal Signal Wavelengths for Underwater Optical Wireless Communication under Sunlight in Stratified Waters." *Journal of Sensor and Actuator Networks* 13 (5): 54.

Wan Hassan, Wan Hafiza , Muhammad Safiy Sabril, Faezah Jasman, and Sevia Mahdaliza Idrus. 2022. "Experimental Study of Light Wave Propagation for Underwater Optical Wireless Communication (UOWC)." *Journal of Communications* 17 (1): 23–29. https://doi.org/10.12720/jcm.17.1.23-29.

Wang, Xiaozheng, Minglun Zhang, Hongyu Zhou, and Xiaomin Ren. 2021. "Performance Analysis and Design Considerations of the Shallow Underwater Optical Wireless Communication System with Solar Noises Utilizing a Photon Tracing-Based Simulation Platform." *Electronics* 10 (5): 632. https://doi.org/10.3390/electronics10050632.

Zayed, M Mokhtar, Mona Shokair, ahmed rosas, and Rna Ghallab. 2025. "Modeling and Analysis of Underwater Optical Wireless Communication Channels." *International Journal of Engineering and Applied Sciences - October 6 University* . 2 (1): 32–45. https://doi.org/10.21608/ijeasou.2025.349270.1040.

Zhang, Chao, Wei Zixian, Xueyang Li, Yibin Li, Lei Wang, Lai Wang, H. Y. Fu, and Yanfu Yang. 2022. "3.8 Gb/S PAM-4 UOWC System over a 2-m Underwater Channel Enabled by a Single-Pixel 175-Mm GaN-Based Mini-LED." *IEEE Photonics Journal* 14 (3): 1–7.

Zhou, Wen, Wenxi Cao, Jun Zhao, Guifen Wang, Wendi Zheng, Lin Deng, and Cai Li. 2021. "Variability of Scattering and Backscattering of Marine Particles in Relation to Particle Concentration, Size Distribution, and Composition off the Eastern Hainan Coast in the South China Sea." *Continental Shelf Research* 232 (2022): 104615. https://doi.org/10.1016/j.csr.2021.104615.

Zhu, Shijie, Xinwei Chen, Xiaoyan Liu, Guoqi Zhang, and Pengfei Tian. 2020. "Recent Progress in and Perspectives of Underwater Wireless Optical Communication." *Progress in Quantum Electronics* 73 (2020): 100274. https://doi.org/10.1016/j.pquantelec.2020.100274.