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Effect of Water Quality and Modulation Complexity on UOWC Performance: A Comparative Study

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Abstract – Underwater Optical Wireless Communication (UOWC) is gaining prominence as a promising solution for high-speed data transmission in marine environments, offering a viable alternative to conventional acoustic and RF systems. This study investigates the performance of six widely used modulation schemes—On-Off Keying (OOK), Pulse Position Modulation (PPM), Pulse Amplitude Modulation (PAM), Differential Quadrature Phase Shift Keying (DQPSK), 16-Phase Shift Keying (16-PSK), and 32-Quadrature Amplitude Modulation (32-QAM)—under varying underwater conditions. The evaluation is conducted across four representative water types: pure sea, clear ocean, coastal ocean, and turbid harbor, each characterized by different absorption, scattering, turbulence, and noise levels. A green Light Emitting Diode Photo-Source (LED-PS) operating at 520 nm, optimal for coastal and turbid waters, is employed alongside a Silicon Photomultiplier Photodetector (SiPM-PD) with a high sensitivity of –53.4 dBm. Performance is assessed through key metrics including received optical power, Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), Shannon spectral efficiency (upper bound), and communication distance. Results at a target BER of 10^{-6} show that the required transmitted power increases markedly with both turbidity and modulation complexity, ranging from –2.10 dBm (OOK, pure sea) to 80.63 dBm (32-QAM, turbid harbor), while SNR demands rise from 17.59 dB to 43.58 dB. Maximum channel capacity reaches 47.6 bps/Hz with 32-QAM in pure sea water but drops to nearly zero in turbid harbor conditions. Similarly, the maximum achievable distance drops from 81.1 m (OOK, pure sea) to just 3.99 m (32-QAM, turbid harbor). At fixed SNR = 30 dB and receiver sensitivity of –53.4 dBm, communication distances follow consistent trends, confirming the crucial influence of both environmental conditions and modulation technique. These findings offer valuable insights into optimal modulation selection for robust and energy-efficient UOWC system design in diverse underwater environments.

Keywords: Underwater Optical Wireless Communication (UOWC), Modulation Schemes, Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), Channel Capacity, Water Turbidity, Optical Communication Systems.

I. Introduction

The increasing demand for high-speed, energy-efficient, and reliable data communication in underwater environments has driven the evolution of advanced communication technologies tailored for marine applications [1]. Among the prominent options, UOWC has emerged as a powerful alternative to traditional acoustic and radio frequency (RF) systems, particularly for short-to-medium range applications [2]. UOWC offers several inherent advantages, including higher bandwidth, lower latency, better spatial reuse, and enhanced data security [3],[4]. These benefits make it highly suitable for a wide range of Internet of Underwater Things (IoUT) applications such as oceanographic data collection, subsea surveillance, oil and gas pipeline inspection, underwater robotics, and real-time environmental monitoring [5]-[7].

Unlike acoustic systems, which suffer from limited bandwidth, long propagation delays, and high susceptibility to multipath fading, or RF systems, which are severely attenuated in conductive seawater, optical links leverage the relatively transparent windows in the visible spectrum—most notably in the blue-green range (450–550 nm)—to enable gigabit-class data rates over distances of several meters to tens of meters [3],[4],[7]. However, the practical deployment of UOWC systems is hindered by severe channel impairments caused by water quality variations, including absorption, scattering, turbulence, and ambient noise, all of which differ markedly across underwater environments [8],[9].

Simultaneously, the selection of modulation schemes in UOWC systems plays a critical role in defining their performance boundaries. While simple modulation formats such as OOK and PPM are favored for their low complexity and robustness in noisy and highly scattering environments, advanced schemes like 16-PSK**,** DQPSK, and 32-QAM promise higher spectral efficiency and improved throughput, albeit at the cost of greater power and SNR requirements [10],[11]. This complex trade-off between modulation complexity and environmental channel degradation must be meticulously understood to design optimized UOWC systems for real-world scenarios.

I.1. Motivation

Despite significant progress in UOWC research, a comprehensive, comparative performance analysis of commonly used modulation schemes under varying water qualities remains underexplored. Most existing studies focus either on specific modulation techniques or single water types, often overlooking the synergistic impact of environmental degradation and modulation complexity on key performance indicators. Given that underwater environments differ drastically—from the relatively clean and transparent waters of the open ocean to the highly turbid and noisy conditions in harbor regions—understanding how different modulations perform under each of these conditions is crucial. Such insights are essential not only for selecting appropriate communication techniques but also for ensuring energy efficiency, reliable connectivity, and extended operational range in practical deployments.

I.2. Objective and Scope

This study aims to fill this critical gap by presenting a detailed performance evaluation of six widely-used modulation schemes—OOK, PPM, PAM, DQPSK, 16-PSK, and 32-QAM—across four distinct underwater water types: pure sea, clear ocean, coastal ocean, and turbid harbor. These environments are characterized by different levels of attenuation and noise, representing the full spectrum of underwater optical conditions. A green LED-PS at 520 nm, which offers an optimal trade-off between absorption and scattering, is used alongside a highly sensitive SiPM photodetector. Performance metrics include received optical power, BER, SNR, channel capacity, and communication range.

I.3. Key Contributions

The main contributions of this paper can be summarized as follows:

1. **Comprehensive Modulation Benchmarking**: A detailed comparative analysis of six modulation schemes (OOK, PPM, PAM, DQPSK, 16-PSK, and 32-QAM) in UOWC systems, providing quantitative insights into the performance trade-offs under varying channel conditions.
2. **Environmental Impact Evaluation**: An in-depth investigation of how different water types (pure sea, clear ocean, coastal ocean, turbid harbor) affect system performance, particularly focusing on absorption, scattering, turbulence, and ambient noise characteristics.
3. **Performance Metric Correlation**: Extensive simulation results highlighting how BER, SNR, required transmitted power, channel capacity, and communication distance vary as a function of both water quality and modulation complexity.
4. **Power and SNR Requirement Mapping**: Identification of the growing demand for higher transmitted power and SNR as modulation complexity and environmental turbidity increase, with specific values quantified for a target BER of 10^{-6}.
5. **Design Guidelines for Practical Deployment**: Clear recommendations for selecting modulation schemes based on environmental context, system requirements, and performance constraints—supporting robust and energy-efficient UOWC system design.
6. **Validation Through Fixed SNR Analysis**: Additional assessment of communication range trends at a fixed SNR level (30 dB), reinforcing the reliability of observed performance patterns and the sensitivity of system behavior to environmental factors.

The structure of the paper is as follows: **Section II** presents a comprehensive review of existing literature on UWOC, emphasizing the impact of turbulence and the performance of different modulation techniques. **Section III** outlines the proposed system's block diagram. **Section IV** introduces the detailed system model employed for UWOC. **Section V** delves into an in-depth analysis of the aquatic channel model. **Section VI** discusses and analyzes the obtained simulation results. **Section VII** concludes the study by summarizing key findings. **Finally, Section VIII** proposes future research directions, such as the development of adaptive modulation strategies and hybrid communication frameworks to enhance performance in dynamic underwater environments.

II. Literature Review

UOWC has emerged as a promising solution for high-speed data transmission in marine environments, offering advantages over traditional acoustic and RF systems. The performance of UOWC systems is influenced by various factors, including modulation schemes, water quality, and environmental conditions. Researchers have investigated different modulation techniques, such as OOK, PPM, and QAM, under various underwater environments. These studies highlight the importance of optimizing modulation choices based on specific water conditions, such as water clarity, turbulence, and absorption, to achieve efficient and reliable communication in underwater networks.

Previous studies in focused on evaluating modulation schemes for underwater optical wireless communication, especially for applications involving underwater vehicles and sensors. It was found that traditional acoustic links are bandwidth-limited, whereas optical methods offer higher bandwidth potential. The study in [12] demonstrated that PPM is ideal for low-power systems, while PSK excels in bandwidth and error performance but suffers from poor power efficiency. Simulations revealed that red light performed better in waters with higher chlorophyll concentration. The study also highlighted the disadvantages of OOK in power efficiency and error rate control, while DPSK, though offering good error control, has high power consumption and implementation complexity. For undersea optical systems, PPM was identified as the best option, with improved versions like DPPM offering higher bandwidth for specific applications.

As noted in [13], the study compared the performance of various intensity modulation techniques for underwater optical communication systems, including OOK, PPM, Pulse Width Modulation (PWM), and Digital Pulse Interval Modulation (DPIM), using realistic system parameters and different photodiodes (PIN and avalanche). The results highlighted that while PPM was the most energy-efficient, DPIM offered better bandwidth efficiency and lower Peak-to-Average Power Ratio (PAPR) compared to PPM, making it a more suitable choice than OOK. However, DPIM required more complex demodulation, which could be a trade-off in terms of implementation in power-constrained underwater environments.

The authors of [14] analyzed the performance of underwater optical wireless communication systems using different modulation techniques and avalanche photodiodes (APD) for the receiver, focusing on transmission distance, power, and Jerlov water types. The results indicated that H-QAM modulation was most suitable for underwater optical communication. Si APD outperformed Ge APD in terms of efficiency, especially in terms of BER performance across various water types. The study also found that water properties, such as chlorophyll concentration and the chosen wavelength, significantly affected received optical power and SNR. For Jerlov type I water, QAM showed superior performance, while Si APD provided better results than Ge APD. The study further revealed that Si APD had a clear advantage over Ge APD at shorter distances, with the difference in performance becoming less significant as the distance increased.

In [15], the study investigated the effect of water attenuation on UOWC based on a LOS model, considering parameters like chlorophyll concentration, receiver aperture area, and wavelength choice. The results showed that OOK and 2DPSK performed best for UOWC, particularly with a 450nm wavelength, compared to 600nm. Water attenuation, particularly in Jerlov water types, significantly impacted signal power and SNR. Higher chlorophyll concentrations reduced received optical power, while a larger receiver aperture area ($0.1m^2$) allowed for longer transmission distances. The study confirmed that 450nm is more suitable for long-distance UOWC due to its superior performance over 600nm.

According to [16], the study evaluated the performance of UWOC using different modulation techniques, including OOK, QPSK, and OFDM, with a red laser. The results showed that OFDM outperformed OOK and QPSK in terms of BER, data transmission rate, and signal-to-noise ratio, especially under the same atmospheric turbulence conditions. OFDM demonstrated superior performance with lower energy consumption, offering high bandwidth and acceptable BER. The study concluded that laser-based UWOC systems, particularly using OFDM modulation, are suitable for high-speed, long-distance data transmission applications due to their efficiency and reduced interference.

Ref. [17] evaluated the performance of different modulation techniques—PSK, DPSK, PAM, and QAM—on underwater optical communication in various water media (pure sea, clean ocean, coastal ocean, and turbid harbor). The results showed that QAM was the most suitable modulation technique for all types of seawater, offering the best performance in terms of BER. The study also found that optical waves traveled longer distances in pure seawater due to lower attenuation, while the worst communication performance occurred in turbid harbor water.

The authors of [18] evaluated the BER performance of various modulation techniques for a single-channel underwater wireless optical communication system, using a 532 nm wavelength and a Si APD receiver. The analysis showed that 4-QAM provided the best BER performance in all water types, with pure sea water yielding the best results. For a 25 m link, 4-QAM maintained a BER of 10^{-9} at −9.2 dBm in pure sea water, while clear ocean and coastal ocean water required higher transmitted powers for similar performance.

The study in [19] compared various modulation schemes (PPM and SIM) under still and turbulent water conditions. It showed that both PPM and SIM were resilient to turbulence-induced fading, with SIM achieving higher data rates. The study introduced pairwise coding (PWC) with SIM, achieving a maximum data rate of 5.2 Gbps in still water. While PPM was spectrally inefficient, SIM's data rate was enhanced using PWC. Bit and power loading improved performance in turbulent waters, offering a significant gain over basic QAM-SIM by adjusting modulation based on channel conditions.

As noted in [20], the study proposed a hybrid DPSK-mPPM modulation scheme to improve UOWC performance over turbulent channels. Closed-form average BER expressions were derived for both mPPM and DPSK-mPPM under Gamma-Gamma turbulence. Simulation results showed that the hybrid DPSK-mPPM outperformed single modulation techniques, with a decrease in BER as mPPM order increased. The study also analyzed the impact of oceanic turbulence parameters, including temperature and salinity fluctuations, on system performance. The proposed scheme offers high transmission performance for applications in oceanography, offshore oil exploration, and autonomous underwater vehicles.

In [21], the study focused on designing an underwater optical communication link with a 130-meter horizontal reach at a depth of 40 meters, evaluating it under clear ocean conditions. The system employed DQPSK and OFDM-QAM modulation techniques at a 15 Gbps bit rate. The results showed that DQPSK outperformed other schemes in terms of eye-opening, Q-factor, and link reach, making it suitable for long-range communication, though it is more complex to implement. OFDM-QAM demonstrated good performance for underwater ranges up to 123 meters, effectively mitigating power penalties caused by polarization mode dispersion.

The authors of [22] presented a simulation framework for modeling optical underwater turbulence, absorption, and scattering. The results showed that turbulence's impact on the received signal is lower in highly scattering channels, with the Log-Normal fading model accurately describing received intensity fluctuations. The study revealed that turbulence causes increased spatial and temporal spreading at the receiver plane and decreases the channel capacity. It was also found that the turbulence effect is more significant in channels with fewer scattering interactions and that the maximum achievable data rate decreases as turbulence increases. The study emphasized that turbulence should not be modeled in isolation from absorption and scattering for accurate UOWC system performance.

III. The Proposed System Block Diagram

The block diagram of the UWOC system consists of several key components that work together to transmit and recover data efficiently. First, the system receives input data, which is then modulated using various modulation schemes such as OOK, PPM, PAM, DQPSK, 16-PSK, and 32-QAM. Next, the modulated signal is transmitted through photo-sources, which can be LEDs or lasers, depending on the application requirements. The signal is then projected using optics, which may consist of a Galilean or Keplerian beam expander [23],[24], to focus or direct the light through the aquatic channel. The aquatic channel itself is characterized by various impairments, including absorption, scattering, and noise, with turbulence models such as Log-Normal, Gamma-Gamma, and Weibull helping to model the underwater environment's impact on the optical signal. The signal is then received by collection optics, which include either a hemispherical emerging lens operating at a 90-degree Field of View (FOV) angle or a Compound Parabolic Concentrator (CPC) with a 30-degree FOV angle [3],[4],[23]. Afterward, the optical signal is captured by a Silicon Photomultiplier (SiPM), a highly sensitive photodetector suitable for low-power signals, with a receiver sensitivity of -53.4 dBm [25]. The demodulation process is then carried out to extract the transmitted data, resulting in the recovery of the original input data. The block diagram depicting the key components of an UWOC system is shown in Figure 1.

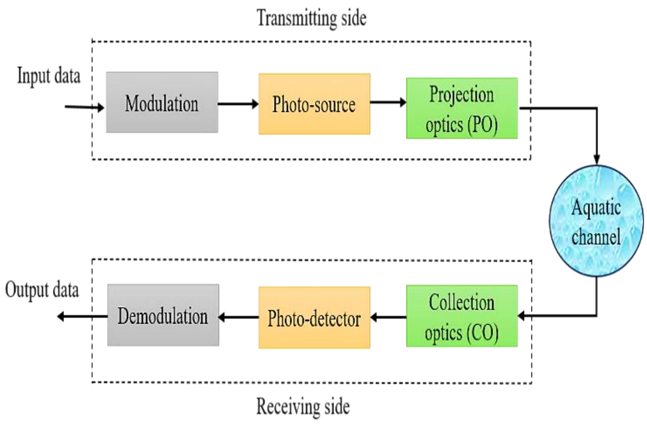

Fig.1. The block diagram of the UWOC system [3],[4]

IV. The Proposed System Model

This study explores the application of underwater visible light communication (VLC) for uplink data transmission. As illustrated in Figure 2, the system architecture consists of a source node located on the seabed, functioning as the transmitter. This node projects an optical beam upward, characterized by a beam divergence angle (θ) and a semi-angle at half power ($\theta_{1/2}$). At the surface of the water, the sink node operates as the receiver, capturing the transmitted signal at an incident angle (ϕ). The receiver is equipped with a defined field of view (FOV) angle (ϕ_{FOV}), which, in conjunction with the spatial orientation between the transmitter and receiver, determines the effective communication range ($d/cos(\Theta)$) within the underwater optical channel where (d) is the vertical distance between the transmitter and the receiver.

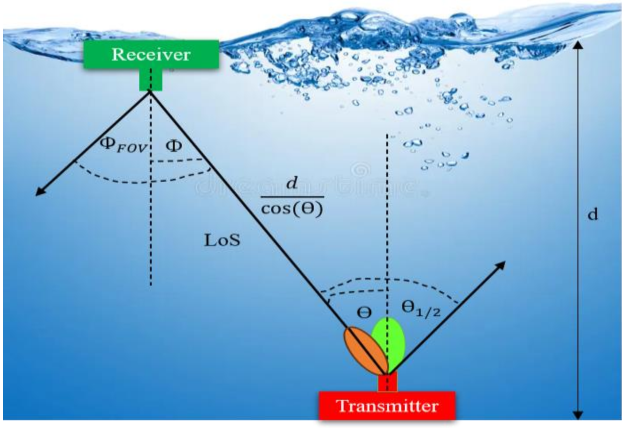

Fig.2. The proposed system Model

V. Aquatic Channel Modeling

The underwater channel is primarily affected by attenuation due to absorption and scattering, and by turbulence due to random refractive index fluctuations.

V.1 Attenuation (Absorption + Scattering)

The total attenuation coefficient c(λ) is given by [23],[24],[30]:

$$c(\lambda) = a(\lambda) + b(\lambda) \quad (1)$$

where $a(\lambda)$ is the absorption coefficient (m^{-1}), $b(\lambda)$ is the scattering coefficient (m^{-1}), and λ is the operating wavelength (e.g., 450–550 nm).

The signal intensity *I(d)* at a distance *d* underwater can be modeled with an exponential attenuation law:

$$I(d) = I_o . e^{-c(\lambda)d} \quad (2)$$

where I_o is the initial signal intensity at the source and *d* is the distance from the source (in meters). This equation shows how the intensity of the signal decays as it travels through the water.

In UWOC, blue-green wavelengths (450–550 nm) are used due to their minimal absorption and scattering in water, allowing for greater transmission distances compared to other wavelengths. These wavelengths penetrate deeper into the aquatic environment, making them ideal for high-data-rate communication in underwater scenarios [26],[27]. As shown in Figure 3, the absorption of light in pure seawater varies according to its wavelength.

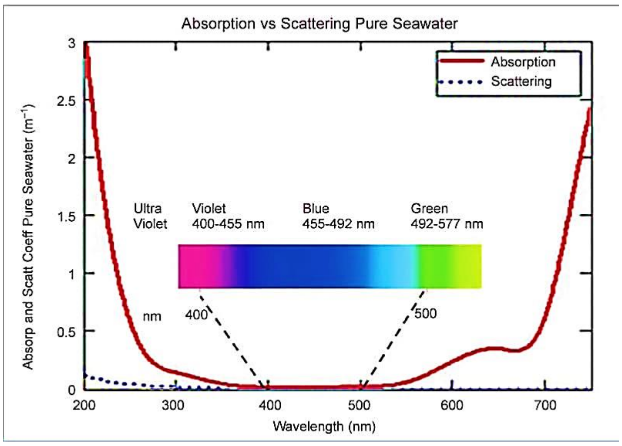

Fig.3. The absorption coefficient of the light as a function of wavelength in pure seawater [27].

The use of green light at 520 nm in UWOC offers significant advantages, particularly in coastal and turbid waters. Due to its lower absorption and scattering compared to other visible wavelengths in such environments, green light achieves better propagation performance, enabling longer transmission distances and improved signal quality. This makes it a more reliable and efficient choice for UWOC systems operating in challenging, particle-rich water conditions often found near coastlines. Table I illustrates the values of absorption, scattering, and total attenuation coefficients of the green color wavelength (520 nm) for various types of water.

TABLE I
ABSORPTION, SCATTERING, AND EXTINCTION COEFFICIENTS FOR DIFFERENT TYPES OF WATER AT WAVELENGTH = 520 NM [26], [27].

Types of Water	Absorption Coefficient $a(\lambda)$ (m^{-1})	Scattering Coefficient b (λ) (m^{-1})	Extinction Coefficient c (λ) (m^{-1})
Pure Sea	0.04418	0.0009092	0.0450892
Clear Ocean	0.08642	0.01226	0.09868
Costal Ocean	0.2179	0.09966	0.31756
Turbid Harbor	1.112	0.5266	1.6386

V.2 Noise Model

Noise includes thermal noise, dark current noise, background light (ambient noise), and signal shot noise [28]:

$$Total\ noise, \sigma_{total}^2 = \sigma_{thermal}^2 + \sigma_{dark}^2 + \sigma_{shot}^2 + \sigma_{ambient}^2 \quad (3)$$

(a) Thermal Noise

$$\sigma_{thermal}^2 = \frac{4K\ T\ B}{R_L} \tag{4}$$

where: k is the Boltzmann constant (1.38×10^{-23} J/K), T is the absolute temperature (K), B is the bandwidth (Hz), and R_L is the load resistance (Ω).

(b) Dark Current Noise

$$\sigma_{dark}^2 = 2qI_d\ B \tag{5}$$

where: q is the electron charge (1.6×10^{-19} C) and I_d is the dark current (A).

(c) Shot Noise

$$\sigma_{shot}^2 = 2q(I_s + I_b)B \tag{6}$$

where: I_s is the signal current (A) and I_b is the background current (A).

(d) Ambient Light-Induced Noise

$$\sigma_{ambient}^2 = k\ B\ P_{ambient} \tag{7}$$

where: k is the efficiency factor and $P_{ambient}$ is the ambient light power.

V.3 Turbulence Model

Turbulence introduces random fluctuations in received signal intensity. The following models apply depending on turbulence strength [28]:

(a) Log-Normal Distribution (Weak Turbulence)

$$P(I) = \frac{1}{2I\sqrt{2\pi\sigma_X^2}} \exp\left(-\frac{(\ln I - \mu_X)^2}{2\ \sigma_X^2}\right) \tag{8}$$

where I is the received irradiance, μ_X= - $\sigma_X^2/2$, and σ_X^2 is the Log-amplitude variance.

(b) Gamma-Gamma Distribution (Moderate Turbulence)

$$P(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}} I^{\frac{\alpha+\beta}{2}-1}}{\Gamma(\alpha)\Gamma(\beta)} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \tag{9}$$

where α, β Related to small- and large-scale eddies, and $K_V(\cdot)$ Modified Bessel function of second kind.

(c) Weibull Distribution (Strong Turbulence)

$$P(I) = \frac{\beta}{\eta}\left(\frac{I}{\eta}\right)^{\beta-1} \exp\left(-\left(\frac{I}{\eta}\right)^{\beta}\right) \tag{10}$$

where β is the Shape parameter (turbulence level) and η is the Scale parameter (average intensity).

V.4 Signal-to-Noise Ratio (SNR)

The SNR at the receiver is:

$$SNR = \frac{(RP_r)^2}{\sigma_{total}^2} \tag{11}$$

where R is the photodetector responsivity (A/W) and P_r is the received optical power (W).

V.5 Bit Error Rate (BER) Models for Modulation Schemes

(a) On-Off Keying (OOK)

$$BER_{OOK} = Q\left(\sqrt{\frac{SNR}{2}}\right) \tag{12}$$

(b) Pulse Position Modulation (2-PPM)

$$BER_{2-PPM} = \mathrm{Q}\left(\sqrt{SNR}\right) \tag{13}$$

(c) Pulse Amplitude Modulation (2-PAM)

$$BER_{2-PAM} = \mathrm{Q}\left(\sqrt{2.SNR}\right) \tag{14}$$

(d) DQPSK (Differential QPSK)

$$BER_{DQPSK} \approx Q\left(\sqrt{2.SNR}\right)\left(1 - \frac{1}{2}\ Q\left(\sqrt{2.SNR}\right)\right) \tag{15}$$

(e) M-PSK

$$BER_{M-PSK} \approx \frac{1}{log_2 M}\mathrm{Q}\left(\sqrt{2.SNR.log_2 M.sin^2\left(\frac{\pi}{M}\right)}\right) \tag{16}$$

For **16-PSK** (M=16):

$$BER_{16-PSK} \approx \frac{1}{4}\mathrm{Q}\left(\sqrt{8.SNR.sin^2\left(\frac{\pi}{16}\right)}\right) \tag{17}$$

(f) M-QAM

$$BER_{M-QAM} \approx \frac{4}{log_2 M}\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3.SNR.log_2 M}{M-1}}\right) \tag{18}$$

For **32-QAM** (M=32):

$$BER_{M-QAM} \approx \frac{4}{5}\left(1 - \frac{1}{\sqrt{32}}\right) Q\left(\sqrt{\frac{15.SNR}{31}}\right) \tag{19}$$

V.6 Final Received Power Considering All Effects

Considering attenuation and turbulence fading (modeled as a random multiplicative variable *h*):

$$P_r = P_t.\eta_t.\eta_r.e^{-c(\lambda)d}.\frac{A_r\cos(\Phi)}{2\pi d^2(1-\cos(\theta))}.h \qquad (20)$$

where P_t is the transmitted power, η_t and η_r are the transmitter and receiver efficiencies respectively, *Ɵ* is the transmitter light beam divergence angle, *Φ* is the receiver light beam incident angle, and *h* is the Fading coefficient (random variable from turbulence distribution)

V.7 Link Reliability

Link reliability (R_{link}) is modeled as the probability of maintaining sufficient SNR over the channel:

$$R_{link} = p(SNR > SNR_{threshold}) \qquad (21)$$

Using the PDF of turbulence and noise distributions, this can be computed numerically.

Also, Link reliability is a probabilistic metric that takes into account factors like link outages due to attenuation, noise, and interference. It can be expressed as the probability that the received signal power is above a certain threshold:

$$R_{link} = p(P_{received} \geq P_{threshold}) \qquad (22)$$

where $P_{threshold}$ is the power threshold required for successful reception, which depends on the minimum SNR required for the modulation scheme to function reliably.

V.8 Channel Capacity

The capacity *C* of an optical wireless channel can be estimated using the Shannon-Hartley theorem:

$$C = B.log_2(1 + SNR) \qquad (23)$$

where: *C* is the channel capacity in bits per second, *B* is the bandwidth of the channel (Hz), and *SNR* is the signal-to-noise ratio.

In underwater optical communication systems, where the bandwidth can be limited by attenuation and other environmental conditions, the capacity might be reduced, and the link design should consider various trade-offs.

VI. Simulation Results Analysis and Discussions

The simulation parameters employed in this study are presented in Table II.

TABLE II
SIMULATION PARAMETERS

Parameter	Symbol	Value and Unit
Type of photo-source	-	LED-PS
Wavelength	⅄ (green color)	520 nm
BER	-	10^{-6}
Transmitter efficiency	η_t	0.9
Transmitted power	P_t	1 W
Transmitter light beam divergence angle	Ɵ	30°
Transmitter semi-angle at half power	$\theta_{1/2}$	60°
Modulation Scheme	-	OOK, PPM, PAM, DQPSK, 16-PSK and 32-QAM
Transmission Distance	*d*	1-100 m
Channel bandwidth	*B*	1 MHz
Water Types	-	Pure, clear, coastal, and turbid harbor waters
Total attenuation coefficient [26], [27]	*C (⅄)*	0.0450892, 0.09868, 0.31756, 1.6386 m^{-1}
Noise sources	-	Thermal, shot, dark, ambient
Noise model	-	AWGN
Turbulence Model	-	Log-Normal, Gamma-Gamma, and Weibull
Receiver efficiency	η_r	0.9
Receiver light beam incident angle	*Φ*	15°
Type of photo-detector	-	SiPM
Receiver FOV angle	Φ_{FOV}	30° (CPC)
Refractive index of lens at PD	*n*	1.5
Receiver PD aperture area	A_r	1 mm^2
Photodetector Sensitivity [29]	P_s	-53.4 dBm
Photodetector Responsivity	*R*	0.4-0.6 A/W
Load resistance	R_L	1000 Ω
Simulation Tool	-	Python

Figures 4, 5, 6, and 7 compare the BER performance of various modulation schemes (OOK, PPM, PAM, DQPSK, 16-PSK, 32-QAM) across different underwater environments (pure sea, clear ocean, coastal ocean, turbid harbor) as a function of transmitted power (dBm). The results show that higher-order modulations like 32-QAM generally require more power to achieve a target BER (e.g., 1e-06), especially in challenging conditions like turbid harbor, while simpler schemes like OOK or PPM perform better at lower power levels but with limited spectral efficiency. The environment significantly impacts performance, with turbid harbor requiring the highest power for reliable communication.

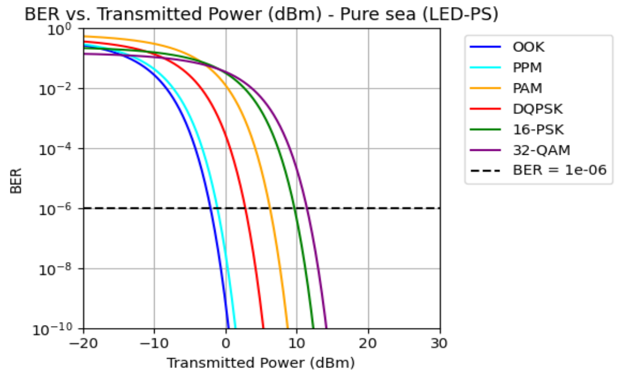

Fig.4. BER versus transmitted power for LED-PS across different modulation schemes in pure seawater

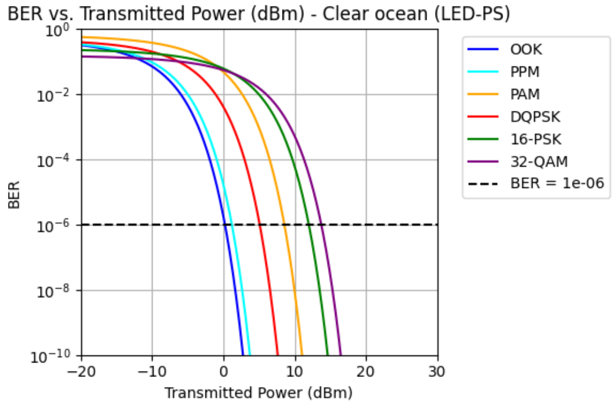

Fig.5. BER versus transmitted power for LED-PS across different modulation schemes in clear ocean water

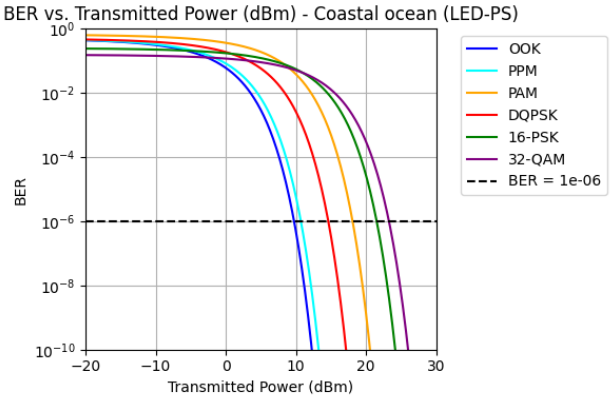

Fig.6. BER versus transmitted power for LED-PS across different modulation schemes in coastal ocean water

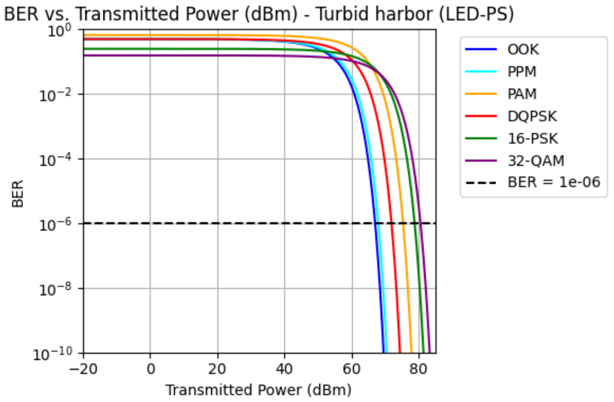

Fig.7. BER versus transmitted power for LED-PS across different modulation schemes in turbid harbor water

Table III presents the transmitted power values (in dBm) required for achieving a BER of approximately 10^{-6} for various modulation schemes (OOK, PPM, PAM, DQPSK, 16-PSK, and 32-QAM) across four distinct underwater environments: Pure Sea, Clear Ocean, Coastal Ocean, and Turbid Harbor. The table highlights how the transmitted power required to maintain a specified BER increases with the complexity of the modulation scheme and is significantly influenced by the water type and its associated attenuation characteristics.

TABLE III
THE TRANSMITTED POWER VALUES IN (dBm) FOR LED-PS ACROSS VARIOUS WATER TYPES AND MODULATION SCHEMES AT (BER=10^{-6})

Water Type	Modulation Type	Transmitted Power (dBm) for BER ≈ 10^{-6}
Pure sea	OOK	-2.10
	PPM	-1.05
	PAM	6.31
	DQPSK	2.85
	16-PSK	9.76
	32-QAM	11.56
Clear ocean	OOK	0.30
	PPM	1.20
	PAM	8.71
	DQPSK	5.11
	16-PSK	12.01
	32-QAM	13.81
Coastal ocean	OOK	9.76
	PPM	10.81
	PAM	18.17
	DQPSK	14.71
	16-PSK	21.62
	32-QAM	23.27
Turbid harbor	OOK	67.12
	PPM	68.17
	PAM	75.53
	DQPSK	72.07
	16-PSK	78.98
	32-QAM	80.63

- In the **Pure Sea** environment, the transmitted power requirements for maintaining a BER of 10^{-6} are relatively low, with the lowest value for OOK modulation at -2.10 dBm, followed by PPM at -1.05 dBm. As expected, more complex modulation schemes such as 32-QAM require the highest transmitted power of 11.56 dBm. The increase in transmitted power from OOK to 32-QAM illustrates the trade-off between higher modulation schemes and the sensitivity to noise and distortion in underwater optical channels.
- For the **Clear Ocean** environment, the transmitted power values are higher across all modulation schemes compared to Pure Sea. OOK requires a transmitted power of 0.30 dBm, while 32-QAM requires 13.81 dBm. The increase in transmitted power across all modulation schemes reflects the slightly higher attenuation in Clear Ocean waters compared to Pure Sea, which results in a greater power requirement to maintain the same BER.
- In the **Coastal Ocean** environment, the transmitted power values continue to increase, with OOK requiring 9.76 dBm and 32-QAM reaching 23.27 dBm. The Coastal Ocean environment, characterized by more pronounced attenuation due to factors like suspended particles and turbidity, necessitates higher transmitted power levels to compensate for the increased path loss. The trend in transmitted power increases is consistent across all modulation schemes, with the most complex modulations again requiring the highest transmitted power.

- Finally, in the **Turbid Harbor** environment, the highest transmitted power values are observed. OOK modulation requires 67.12 dBm, while 32-QAM requires a substantial 80.63 dBm. This dramatic increase in required transmitted power is a direct result of the significantly higher attenuation in Turbid Harbor waters, where the presence of suspended particles and other environmental factors severely impact the optical signal. The large increase in required transmitted power underscores the challenging nature of operating in highly turbid environments where signal degradation is more pronounced.

Overall, Table III underscores the critical role of water type in determining the power requirements for underwater optical communication systems. The results demonstrate that as the water becomes more turbid and the attenuation increases, the transmitted power required to maintain a low BER grows significantly. Additionally, more advanced modulation schemes, which offer higher data rates, necessitate even higher transmitted power levels. This trade-off between modulation complexity, water type, and power requirements is a crucial consideration when designing optical communication systems for varying underwater environments.

Figures 8, 9, 10, and 11 compare the BER performance versus SNR for various modulation schemes (OOK, PPM, PAM, DQPSK, 16-PSK, 32-QAM) in different underwater environments (pure sea, clear ocean, coastal ocean, turbid harbor). The results show that higher-order modulations (e.g., 32-QAM) require significantly higher SNR to achieve a target BER (10^{-6}) compared to simpler schemes like OOK or PPM. Performance degrades notably in turbid harbor conditions, demanding the highest SNR for reliable communication. This highlights the trade-off between spectral efficiency and robustness across varying water conditions.

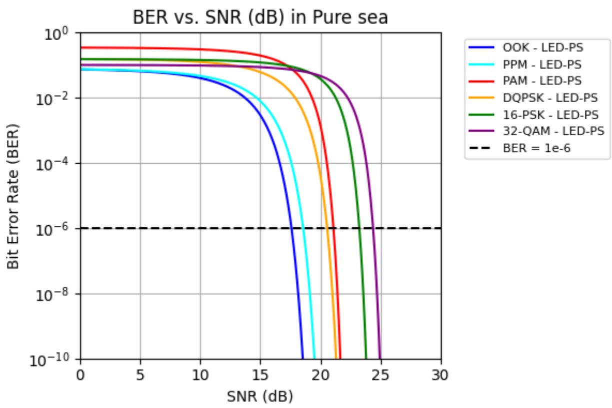

Fig.8. BER versus SNR for LED-PS across different modulation schemes in pure seawater

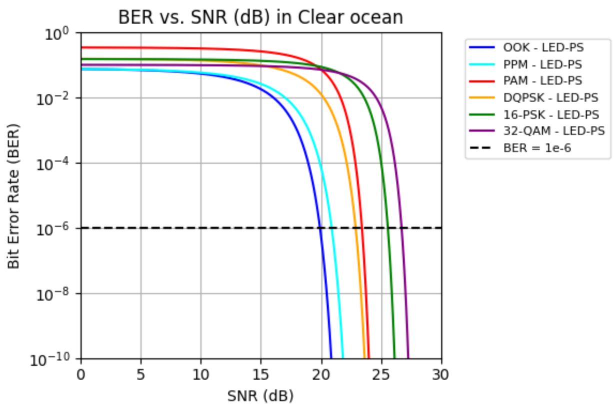

Fig.9. BER versus SNR for LED-PS across different modulation schemes in clear ocean water

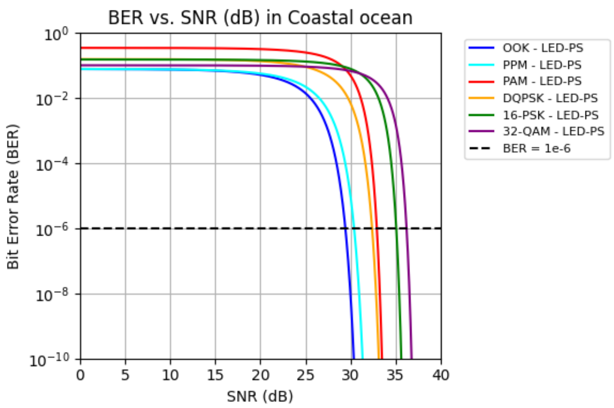

Fig.10. BER versus SNR for LED-PS across different modulation schemes in coastal ocean water

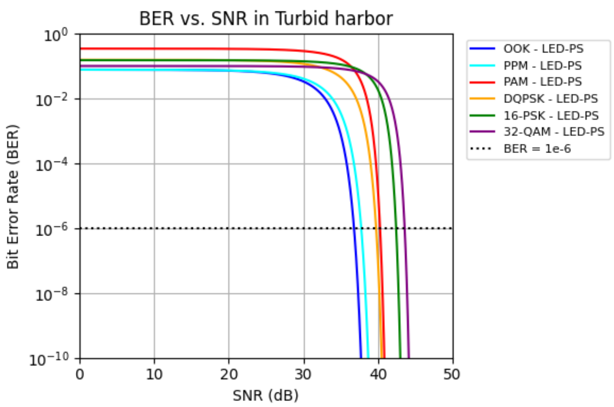

Fig.11. BER versus SNR for LED-PS across different modulation schemes in turbid harbor water

Table IV presents the SNR values in dB required to achieve a BER of approximately 10^{-6} for various modulation schemes and water types when utilizing LED-PS. The results demonstrate a clear trend of increasing SNR values across different water environments and modulation techniques, highlighting the influence of water clarity and modulation complexity on the required SNR for reliable communication.

TABLE IV
THE SNR VALUES IN (dB) FOR LED-PS ACROSS VARIOUS WATER TYPES AND MODULATION SCHEMES AT (BER=10^{-6})

Water Type	Modulation Type	SNR (dB) for BER ≈ 10^{-6}
Pure sea	OOK	17.59
	PPM	18.56
	PAM	21.07
	DQPSK	20.55
	16-PSK	23.23
	32-QAM	24.37
Clear ocean	OOK	19.92
	PPM	20.88
	PAM	23.40
	DQPSK	22.88
	16-PSK	25.56
	32-QAM	26.70
Coastal ocean	OOK	29.42
	PPM	30.39
	PAM	32.91
	DQPSK	32.38
	16-PSK	35.06
	32-QAM	36.21
Turbid harbor	OOK	36.79
	PPM	37.76
	PAM	40.28
	DQPSK	39.76
	16-PSK	42.44
	32-QAM	43.58

- In the **Pure Sea** environment, the SNR values start at 17.59 dB for OOK modulation and increase progressively as the modulation scheme becomes more complex, with the highest SNR of 24.37 dB achieved for 32-QAM. This suggests that simpler modulation schemes such as OOK require lower SNR to achieve a given BER, while more complex schemes like 32-QAM necessitate significantly higher SNR values to maintain performance.
- The **Clear Ocean** environment exhibits a noticeable increase in required SNR compared to the Pure Sea, with OOK reaching 19.92 dB and 32-QAM rising to 26.70 dB. This is consistent with the expectation that water quality, as reflected by the attenuation and scattering properties of the medium, directly impacts the communication performance. As the water type transitions from Pure Sea to Clear Ocean, the higher clarity and reduced attenuation require slightly higher SNR values to achieve the same BER.
- In the **Coastal Ocean** environment, the SNR values show a marked increase, with OOK requiring 29.42 dB and 32-QAM reaching 36.21 dB. This further emphasizes the role of water type in determining communication quality, where greater water turbidity or particulate matter can reduce the available signal power, thereby necessitating higher SNR to maintain communication reliability.
- Finally, the **Turbid Harbor** environment presents the highest SNR requirements across all modulation types, with OOK reaching 36.79 dB and 32-QAM requiring a substantial 43.58 dB. This can be attributed to the high attenuation and scattering effects prevalent in turbid waters, which significantly degrade the signal, thus demanding higher SNR levels to achieve the same BER.

Overall, the results indicate that water quality has a profound effect on the SNR required for maintaining reliable communication at a given BER, with more complex modulation schemes being more sensitive to changes in water clarity. These findings underscore the importance of selecting appropriate modulation schemes based on environmental conditions in underwater optical wireless communication systems. The clear trend observed across different water types highlights the need for adaptive communication strategies to optimize system performance in varying underwater conditions.

Figures 12, 13, 14, and 15 compare the Shannon spectral efficiency (upper bound) versus SNR for various modulation schemes (OOK, PPM, PAM, DOPSK, 16-PSK, 32-QAM) in different underwater environments: pure sea, clear ocean, coastal ocean, and turbid harbor. In pure sea and clear ocean, higher-order modulations like 32-QAM and 16-PSK achieve significantly higher capacities (up to 50 bits/sec/Hz) at SNR = 40 dB, while simpler schemes like OOK and PPM perform poorly. Coastal ocean shows reduced capacity (≤30 bits/sec/Hz) for all schemes, and turbid harbor exhibits drastically lower performance (≤0.006 bits/sec/Hz), highlighting the severe impact of water turbidity on communication efficiency.

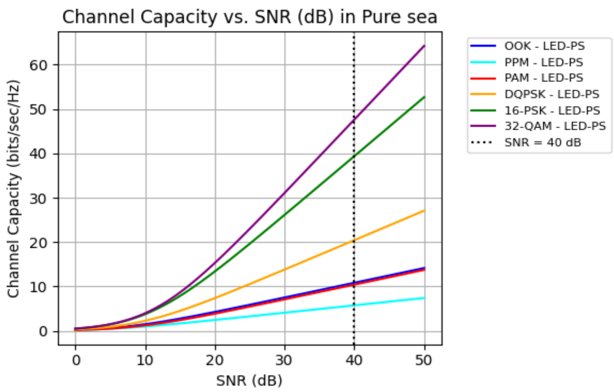

Fig.12. Channel capacity versus SNR for LED-PS across different modulation schemes in pure seawater

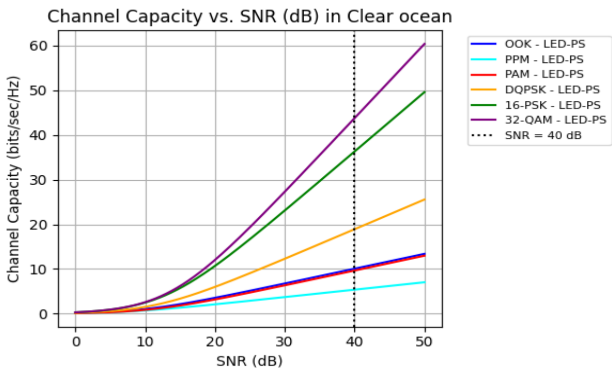

Fig.13. Channel capacity versus SNR for LED-PS across different modulation schemes in clear ocean water

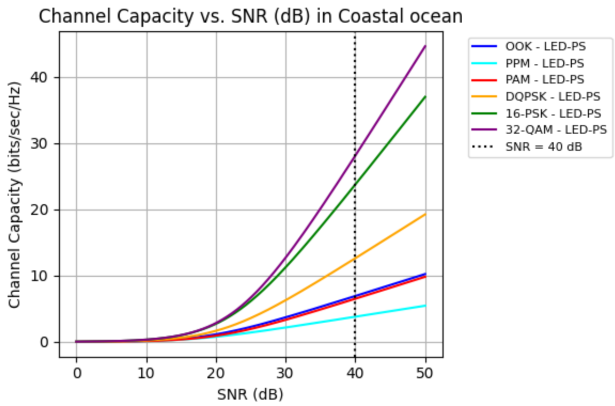

Fig.14. Channel capacity versus SNR for LED-PS across different modulation schemes in coastal ocean water

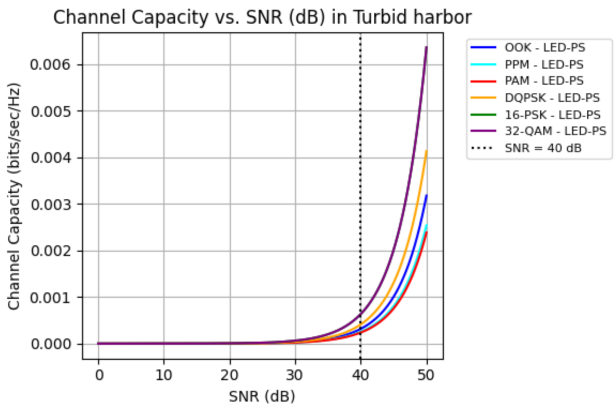

Fig.15. Channel capacity versus SNR for LED-PS across different modulation schemes in turbid harbor water

TABLE V
THE SHANNON SPECTRAL EFFICIENCY (UPPER BOUND) VALUES IN (bps/Hz) FOR LED-PS ACROSS VARIOUS WATER TYPES AND MODULATION SCHEMES AT (SNR =40 dB)

Water Type	Modulation Type	Channel capacity(bits/sec/Hz) at SNR=40 dB
Pure sea	OOK	10.8393
	PPM	5.7585
	PAM	10.4245
	DQPSK	20.4365
	16-PSK	39.3604
	32-QAM	47.5928
Clear ocean	OOK	10.0667
	PPM	5.3721
	PAM	9.6521
	DQPSK	18.8919
	16-PSK	36.2723
	32-QAM	43.7340
Coastal ocean	OOK	6.9196
	PPM	3.7966
	PAM	6.5085
	DQPSK	12.6090
	16-PSK	23.7258
	32-QAM	28.0770
Turbid harbor	OOK	0.0003
	PPM	0.0003
	PAM	0.0002
	DQPSK	0.0004
	16-PSK	0.0006
	32-QAM	0.0006

The channel capacity values presented in Table V offer significant insights into the impact of water type and modulation scheme on the performance of UOWC systems utilizing LED-based photo sources (LED-PS) at a high SNR of 40 dB. Across all water types, it is evident that higher-order modulation schemes such as 32-QAM and 16-PSK consistently yield the highest channel capacities, highlighting their superior spectral efficiency when the channel conditions permit.

- In the **pure sea** environment, characterized by minimal absorption and scattering effects, all modulation schemes achieve their peak capacities. Here, 32-QAM records the highest capacity of 47.5928 bps/Hz, followed closely by 16-PSK at 39.3604 bps/Hz and DQPSK at 20.4365 bps/Hz. Simpler schemes such as OOK, PAM, and PPM achieve lower capacities of 10.8393, 10.4245, and 5.7585 bps/Hz, respectively, reflecting their limited ability to exploit the available bandwidth compared to multilevel modulations.
- As the water clarity decreases, the channel capacity for all modulation types correspondingly degrades. In the **clear ocean**, the values decrease moderately, with 32-QAM and 16-PSK still maintaining high performance at 43.7340 and 36.2723 bps/Hz, respectively. The capacity for DQPSK drops to 18.8919 bps/Hz, while that of OOK, PAM, and PPM decreases to 10.0667, 9.6521, and 5.3721 bps/Hz, respectively.
- In **coastal ocean** waters, which exhibit greater turbidity due to increased particulate matter, the impact on channel capacity becomes more pronounced. 32-QAM and 16-PSK show a notable reduction to 28.0770 and 23.7258 bps/Hz, while DQPSK, PAM, OOK, and PPM experience further drops, reaching 12.6090, 6.5085, 6.9196, and 3.7966 bps/Hz, respectively.
- The most challenging environment, the **turbid harbor**, demonstrates a near-complete attenuation of optical signals, resulting in negligible channel capacities for all modulation schemes. Under such highly scattering and absorbing conditions, even the most spectrally efficient schemes like 32-QAM and 16-PSK yield only 0.0006 bps/Hz, underscoring the severe limitations of optical communication in highly turbid waters without enhanced power sources, advanced error correction, or adaptive modulation.

Overall, this analysis confirms that water quality is a critical determinant of channel capacity in LED-based UOWC systems, and the choice of modulation must be aligned with the environmental conditions to ensure optimal communication performance.

Figures 16, 17, 18, and 19 show BER vs. communication distance for six modulation schemes (OOK, PPM, PAM, DQPSK, 16-PSK, 32-QAM) in four underwater environments: Pure Sea, Clear Ocean, Coastal Ocean and Turbid harbor. OOK and PPM achieve the longest distances at BER = 10^{-6} due to their noise resilience, especially in turbid conditions, while higher-order modulations (16-PSK, 32-QAM) degrade quickly with distance. Performance is best in Pure Sea, followed by Clear Ocean, and worst in Coastal Ocean and Turbid harbor, where even OOK struggles beyond ~80m. This confirms that simpler modulations are preferred for long-range UWOC, particularly in challenging environments.

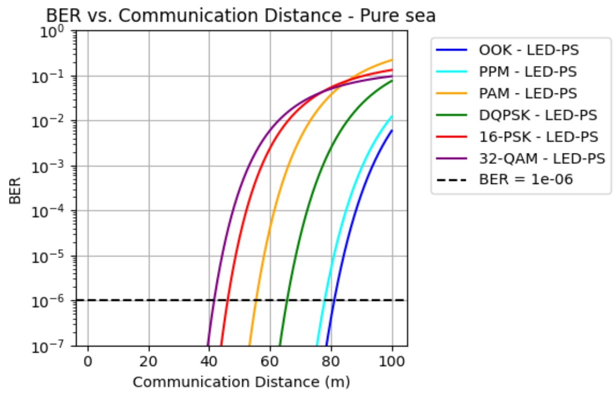

Fig.16. BER versus communication distance for LED-PS across different modulation schemes in pure seawater

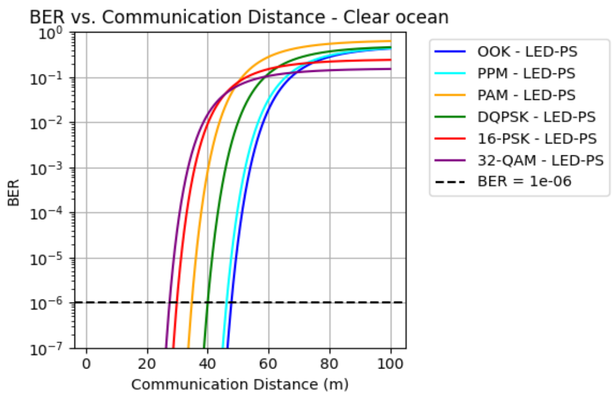

Fig.17. BER versus communication distance for LED-PS across different modulation schemes in clear ocean water

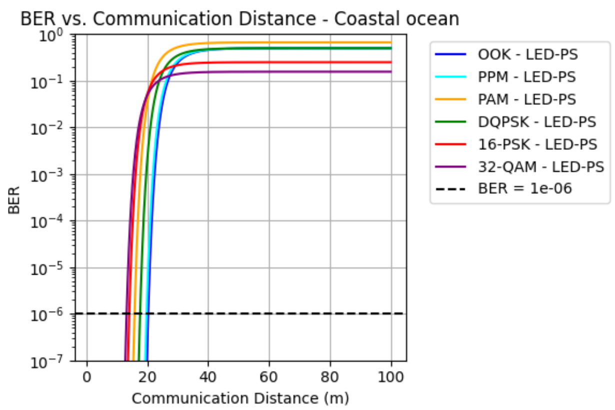

Fig.18. BER versus communication distance for LED-PS across different modulation schemes in coastal ocean water

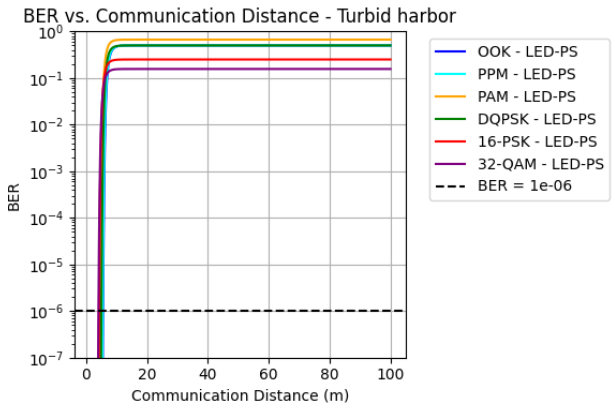

Fig.19. BER versus communication distance for LED-PS across different modulation schemes in turbid harbor water

Table VI presents the communication distances achieved for different modulation schemes using LED-PS across various water types at a fixed BER of 10^{-6}. The results demonstrate the significant impact of both water quality and modulation scheme on the achievable communication distance in UOWC systems.

TABLE VI
THE COMMUNICATION DISTANCE VALUES IN (m) FOR LED-PS ACROSS VARIOUS WATER TYPES AND MODULATION SCHEMES AT (BER=10^{-6})

Water Type	Modulation Type	Communication distance (m) at BER = 10^{-6}
Pure sea	OOK	81.11
	PPM	77.93
	PAM	55.41
	DQPSK	65.60
	16-PSK	46.06
	32-QAM	41.62
Clear ocean	OOK	47.78
	PPM	46.20
	PAM	34.76
	DQPSK	40.00
	16-PSK	29.84
	32-QAM	27.45
Coastal ocean	OOK	20.23
	PPM	19.72
	PAM	15.77
	DQPSK	17.58
	16-PSK	14.01
	32-QAM	13.16
Turbid harbor	OOK	5.43
	PPM	5.38
	PAM	4.52
	DQPSK	4.89
	16-PSK	4.19
	32-QAM	3.99

- In the **pure sea** water type, which represents the ideal conditions for optical communication, OOK achieves the longest communication distance at 81.11 meters. This is followed by PPM at 77.93 meters, which also performs well but slightly worse than OOK due to its inherent energy efficiency trade-offs. PAM reaches 55.41 meters, and DQPSK follows with a distance of 65.60 meters, indicating its robustness in maintaining signal quality. Higher-order modulations like 16-PSK and 32-QAM experience a notable decline in communication distance, with values of 46.06 meters and 41.62 meters, respectively, suggesting that these schemes, while capable of higher data rates, are more susceptible to noise and thus have a reduced range.

- In **clear ocean** conditions, the communication distances decrease across all modulation schemes compared to pure sea conditions, which is expected due to increased scattering and absorption of light. OOK still leads with a distance of 47.78 meters, although it is noticeably lower than in pure sea. PPM performs similarly with 46.20 meters, followed by DQPSK at 40.00 meters. PAM, 16-PSK, and 32-QAM experience even greater reductions, with PAM achieving 34.76 meters, 16-PSK at 29.84 meters, and 32-QAM at 27.45 meters, demonstrating that higher-order modulations are more sensitive to the environmental conditions and have a faster drop-off in communication range.
- The **coastal ocean** exhibits further attenuation due to the combination of turbidity and organic material in the water. OOK continues to exhibit the longest communication distance at 20.23 meters, but the distance for all modulation schemes decreases significantly compared to the clear ocean. PPM follows at 19.72 meters, and DQPSK at 17.58 meters shows a more substantial decline, reflecting its vulnerability to the more challenging water conditions. Higher-order modulations such as 16-PSK (14.01 meters) and 32-QAM (13.16 meters) perform notably worse, with a marked reduction in distance.
- Finally, in the **turbid harbor** water type, which represents the most challenging environment for optical communication due to high levels of suspended particles and pollutants, the communication distances are significantly shorter across all modulation schemes. OOK still performs the best, but its range drops drastically to 5.43 meters. PPM, PAM, and DQPSK exhibit similar behavior, with communication distances of 5.38 meters, 4.52 meters, and 4.89 meters, respectively. Higher-order modulations such as 16-PSK and 32-QAM suffer the most, with distances of 4.19 meters and 3.99 meters, respectively, illustrating the severe impact of water quality on high-data-rate schemes.

In conclusion, the results in Table VI emphasize that the communication distance in UOWC systems is heavily influenced by both the modulation scheme and the quality of the water. In ideal conditions (pure sea), simpler modulation schemes like OOK and PPM outperform more complex ones, achieving longer communication distances. However, as the water quality degrades (moving from pure sea to turbid harbor), the communication distances for all modulation schemes decrease significantly, with higher-order modulations (such as 32-QAM) experiencing the most substantial reductions. This indicates that while higher-order modulations can provide higher data rates, they are more susceptible to the impairments caused by poor water quality, making them less suitable for longer communication distances in challenging underwater environments.

Figures 20, 21, 22, and 23 depict SNR vs. communication distance for six modulation schemes (OOK, PPM, PAM, DQPSK, 16-FSK, 32-QAM) across four underwater environments. OOK and PPM maintain higher SNR over longer distances, especially in Clear ocean and Pure sea, while higher-order modulations (16-FSK, 32-QAM) suffer rapid SNR degradation. Turbid harbor shows the worst performance, with SNR plunging below −200 dB even at short ranges, highlighting severe signal attenuation. Coastal ocean exhibits intermediate behavior, with SNR dropping sharply beyond 20m. These results reinforce that simpler modulations (OOK, PPM) are optimal for extended-range UWOC, particularly in challenging conditions.

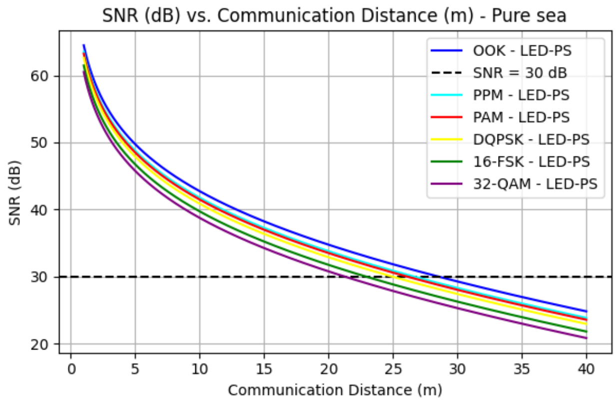

Fig.20. SNR versus communication distance for LED-PS across different modulation schemes in pure seawater

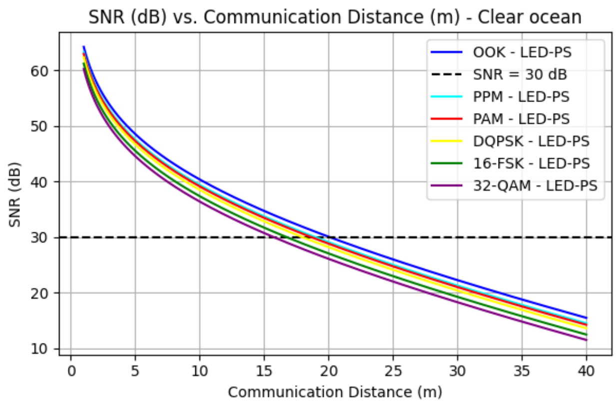

Fig.21. SNR versus communication distance for LED-PS across different modulation schemes in clear ocean water

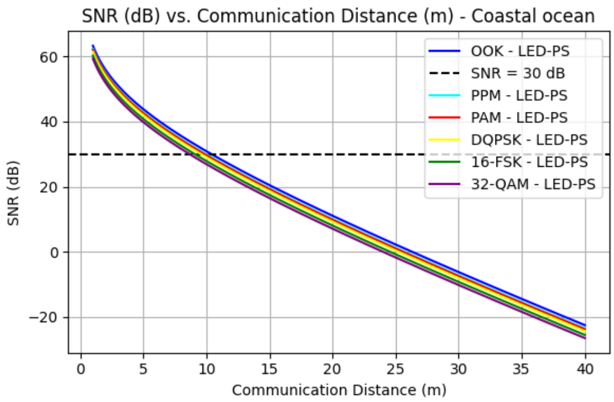

Fig.22. SNR versus communication distance for LED-PS across different modulation schemes in coastal ocean water

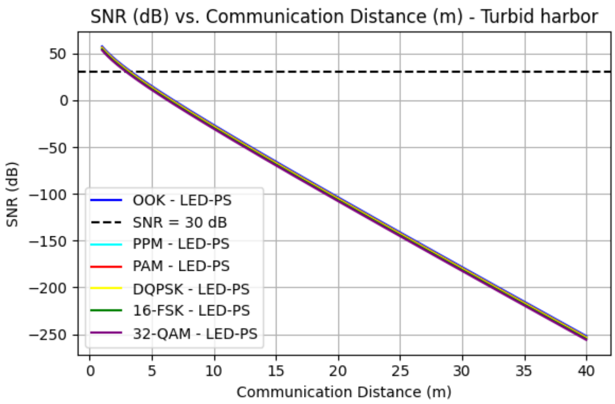

Fig.23. SNR versus communication distance for LED-PS across different modulation schemes in turbid harbor water

TABLE VII
THE COMMUNICATION DISTANCE VALUES IN (m) FOR LED-PS ACROSS VARIOUS WATER TYPES AND MODULATION SCHEMES AT (SNR=30dB)

Water Type	Modulation Type	Communication distance (m) at SNR=30 dB
Pure sea	OOK	28.51
	PPM	26.61
	PAM	26.08
	DQPSK	24.92
	16-PSK	22.88
	32-QAM	21.24
Clear ocean	OOK	20.10
	PPM	18.99
	PAM	18.68
	DQPSK	17.99
	16-PSK	16.76
	32-QAM	15.76
Coastal ocean	OOK	10.40
	PPM	9.97
	PAM	9.84
	DQPSK	9.57
	16-PSK	9.07
	32-QAM	8.66
Turbid harbor	OOK	3.39
	PPM	3.29
	PAM	3.26
	DQPSK	3.19
	16-PSK	3.08
	32-QAM	2.98

Table VII presents the communication distances for LED-PS across various water types and modulation schemes at a SNR of 30 dB. The results show a clear trend: as the modulation scheme becomes more complex, the communication distance decreases across all water types. This behavior can be attributed to the reduced efficiency of higher-order modulation schemes in maintaining a sufficient SNR for reliable communication.

- In the **pure sea** water type, the highest communication distance is observed for OOK at 28.51 meters, followed by PPM (26.61 m), PAM (26.08 m), and DQPSK (24.92 m). The more advanced modulation schemes, such as 16-PSK (22.88 m) and 32-QAM (21.24 m), show progressively shorter communication distances, which reflects their lower power efficiency due to their increased complexity and higher symbol rate.
- The communication distances decrease significantly in **clear ocean** conditions, with OOK still maintaining the longest communication distance at 20.10 meters, but all modulation types exhibit a reduction compared to the pure sea water type. The impact of the ocean water's attenuation on optical signals is evident here, as the higher absorption and scattering characteristics of the water limit the signal propagation.
- In the **coastal ocean** water type, the communication distances continue to shrink, with OOK reaching only 10.40 meters, followed by PPM (9.97 m), PAM (9.84 m), and DQPSK (9.57 m). The more complex modulation schemes again show a marked decrease in performance, with 16-PSK and 32-QAM reaching even shorter distances of 9.07 meters and 8.66 meters, respectively. This further emphasizes the challenges of maintaining high-quality communication in environments with higher turbidity and scattering.
- Finally, in the **turbid harbor** water type, which represents highly turbid and polluted water, the communication distances are significantly reduced across all modulation schemes. OOK achieves the longest distance of only 3.39 meters, and the distance further decreases for more complex modulations, with 32-QAM reaching the shortest communication distance of 2.98 meters. This substantial reduction in communication range highlights the severe impact of water quality on the performance of underwater optical communication systems, where high turbidity leads to increased scattering and absorption, drastically attenuating the optical signals.

Overall, the results underscore the critical influence of both modulation schemes and water quality on the performance of LED-PS-based underwater optical communication systems. In environments with low water transparency, simpler modulation schemes like OOK offer better performance in terms of communication distance, while more complex schemes, despite offering higher data rates, are less effective due to their increased sensitivity to signal degradation.

Figures 24, 25, 26, and 27 depict received power versus communication distance for six modulation schemes (OOK, PPM, PAM, DQPSK, 16-FSK, 32-QAM) across four water types. OOK and PPM maintain received power above the receiver sensitivity threshold (-53.4 dBm) for the longest distances, especially in Clear ocean and Pure sea, while higher-order modulations (16-FSK, 32-QAM) drop below sensitivity much sooner. Turbid harbor shows the most severe attenuation, with received power plunging below -200 dBm even at short ranges. Coastal ocean exhibits intermediate performance. The results confirm that simpler modulations (OOK, PPM) are optimal for reliable long-range UWOC, particularly in challenging environments.

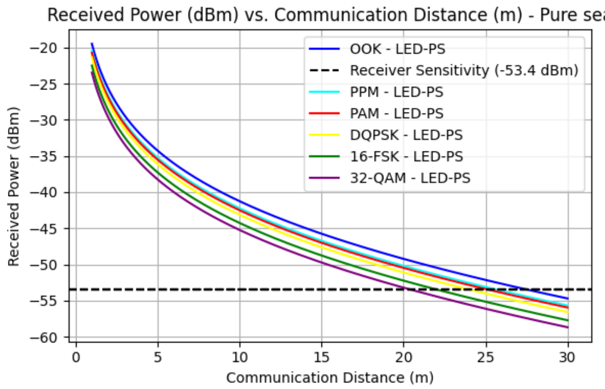

Fig.24. The received power versus communication distance for LED-PS across different modulation schemes in pure seawater

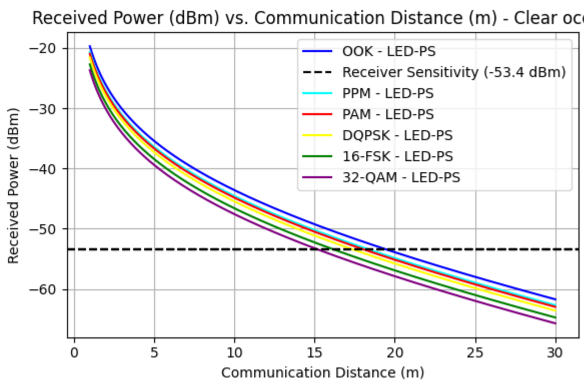

Fig.25. The received power versus communication distance for LED-PS across different modulation schemes in clear ocean water

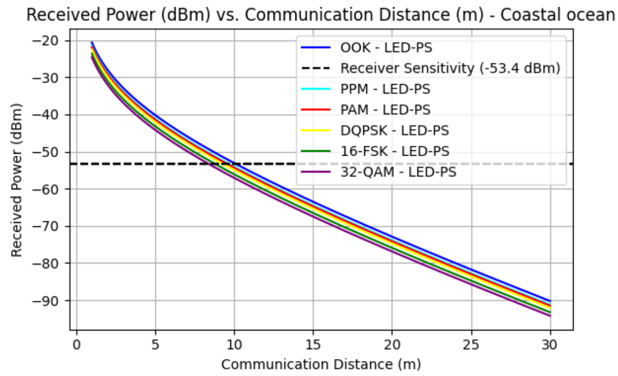

Fig.26. The received power versus communication distance for LED-PS across different modulation schemes in coastal ocean water

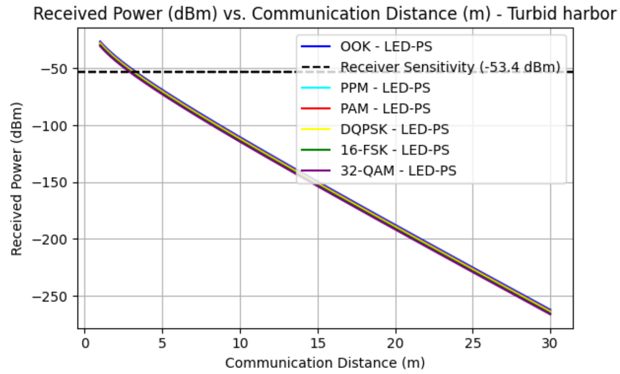

Fig.27. The received power versus communication distance for LED-PS across different modulation schemes in turbid harbor water

TABLE VIII

THE COMMUNICATION DISTANCE VALUES IN (m) FOR LED-PS ACROSS VARIOUS WATER TYPES AND MODULATION SCHEMES AT RECEIVER SENSITIVITY (P_S= -53.4 dBm)

Water Type	Modulation Type	Communication distance (m) at P_S= -53.4 dBm
Pure sea	OOK	27.37
	PPM	25.52
	PAM	25.00
	DQPSK	23.88
	16-PSK	21.90
	32-QAM	20.30
Clear ocean	OOK	19.44
	PPM	18.35
	PAM	18.04
	DQPSK	17.36
	16-PSK	16.16
	32-QAM	15.17
Coastal ocean	OOK	10.14
	PPM	9.71
	PAM	9.59
	DQPSK	9.32
	16-PSK	8.83
	32-QAM	8.42
Turbid harbor	OOK	3.33
	PPM	3.23
	PAM	3.20
	DQPSK	3.13
	16-PSK	3.02
	32-QAM	2.92

Table VIII presents the communication distance values for LED-PS across various water types and modulation schemes at the receiver sensitivity of -53.4 dBm. The results demonstrate a clear trend where simpler modulation schemes, such as OOK and PPM, consistently achieve longer communication distances compared to more complex schemes like 32-QAM and 16-PSK across all water types.

- In the **Pure Sea** environment, OOK achieves the longest communication distance of 27.37 meters, followed by PPM at 25.52 meters, and PAM at 25.00 meters. As the modulation scheme becomes more complex, the communication distance decreases, with 32-QAM reaching the shortest distance of 20.30 meters. This trend is evident across all water types, highlighting the impact of modulation complexity on communication range.
- In the **Clear Ocean**, OOK maintains the longest communication distance of 19.44 meters, while 32-QAM again achieves the shortest distance at 15.17 meters. The pattern of reduced communication distance with higher-order modulation schemes persists in the **Coastal Ocean**, with OOK reaching 10.14 meters, while 32-QAM only extends to 8.42 meters.
- The most significant attenuation occurs in the **Turbid harbor** environment, where the communication distances are drastically reduced for all modulation schemes. OOK still achieves the longest distance of 3.33 meters, but 32-QAM only reaches 2.92 meters, reflecting the severe degradation in signal strength caused by increased water turbidity and scattering.

These results underscore the critical role that both modulation scheme and water type play in determining the effective communication distance in underwater optical wireless communication systems. Simpler modulation schemes like OOK and PPM are shown to be more resilient in maintaining communication over longer distances, especially in clearer water environments. In contrast, higher-order modulations, while potentially offering higher data rates, suffer from significantly reduced communication ranges, particularly in environments with high turbidity. Therefore, for long-range and reliable underwater communication, simpler modulation schemes are preferable, particularly in challenging water conditions.

VII. Conclusions

This study provides a detailed comparison of the performance of six modulation schemes (OOK, PPM, PAM, DQPSK, 16-PSK, and 32-QAM) for UOWC systems in varying marine environments. The evaluation was carried out across four distinct water types—pure sea, clear ocean, coastal ocean, and turbid harbor—under both theoretical and practical conditions to analyze the impact of water quality and modulation complexity on key performance metrics such as transmitted power, SNR, BER, channel capacity, and communication distance. The findings from the tables presented in this study offer valuable insights into how different environmental factors affect UOWC performance and guide the optimal choice of modulation schemes for diverse underwater scenarios.

Firstly, the transmitted power required for each modulation scheme significantly increased with water turbidity, with the lowest power demand in pure sea water (ranging from -2.10 dBm for OOK to 11.56 dBm for 32-QAM) and the highest in turbid harbor waters (ranging from 67.12 dBm for OOK to 80.63 dBm for 32-QAM). This highlights the detrimental effect of water impurities on the propagation of optical signals, requiring higher transmitted power to achieve the same BER of approximately 10^{-6}. Similarly, the SNR values follow a consistent trend, with the best performance observed in pure sea water and the worst in turbid harbor water. For instance, SNR ranged from 17.59 dB (OOK, pure sea) to 43.58 dB (32-QAM, turbid harbor), further emphasizing the importance of water quality in optimizing communication system performance.

In terms of Shannon spectral efficiency (upper bound), the results revealed that the highest capacity was achieved in pure sea water with 32-QAM (47.59 bps/Hz), while the lowest capacity was observed in turbid harbor water, where the capacity approached zero across all modulation schemes. This drastic reduction in channel capacity in turbid environments underscores the limitations of optical communication systems in highly turbid water, making them less viable for long-distance communication in such conditions. The decrease in channel capacity correlates with the diminishing quality of the underwater optical signal as water turbidity increases, which impedes the effective transmission of data.

The analysis of communication distance at various water qualities showed that distances were maximized in pure sea water, with OOK achieving up to 81.11 meters, whereas in turbid harbor water, distances were drastically reduced, with OOK reaching only 5.43 meters. This trend was consistent across all modulation schemes, where higher modulation complexity, such as 32-QAM, led to shorter communication distances in all water types. For example, the communication distance for 32-QAM in pure sea was 41.62 meters, but this dropped to only 3.99 meters in turbid harbor. The results illustrate that while higher-order modulation schemes can provide greater data rates in clearer waters, they suffer significant performance degradation in turbid environments due to the reduced signal quality and increased absorption and scattering.

In addition, when considering the receiver sensitivity, a trend similar to the communication distance was observed. For instance, the communication distance at a receiver sensitivity of -53.4 dBm was again highest in pure sea (27.37 meters for OOK) and lowest in turbid harbor (3.33 meters for OOK), further demonstrating the impact of water quality on signal propagation.

Overall, the study concludes that water quality plays a critical role in the performance of UOWC systems, significantly influencing transmitted power, SNR, channel capacity, and communication distance. Moreover, modulation complexity also affects performance, with simpler modulation schemes like OOK achieving longer distances but at lower data rates, while complex schemes like 32-QAM offer higher data rates but are more susceptible to degradation in turbid water environments. Therefore, when designing UOWC systems for real-world applications, particularly in coastal or turbid waters, a careful balance between modulation type and environmental conditions must be considered to optimize system performance. These findings are crucial for selecting the appropriate modulation schemes to ensure robust and energy-efficient communication in various underwater settings.

VIII. Future Work Directions

Future work could focus on exploring adaptive modulation schemes that dynamically adjust to varying water qualities, enabling more efficient UOWC systems in real-time. Additionally, investigating the use of advanced optical sources, such as laser diodes, and alternative detection technologies could improve performance in turbid waters. Further research on hybrid modulation schemes and machine learning techniques to predict optimal modulation based on environmental conditions may enhance system reliability and data throughput.

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