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A Literature Review on How Salinity and Turbidity Affect the Data Rate of Underwater Visible Light Communication

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Abstract - UVLC gives us low latency and a lot of bandwidth but there are lots of factors that can affect the quality of the data stream and communication pathways. A couple of the biggest. factors affecting communication quality are season and salinity of the water. Particles suspended in water will block and absorb the light, making the water turbid and UVLC weak. This is a phenomenon that is seen in many FTU. Experiments including coastal and estuarine FTU studies. Salinity changes the water density and the refractive index by air and fuels negative optical turbulence. This can lead to wandering of the beam and unstable output signals making the UVLC stream extremely random. The lattice fragmentation of data UVLC streams is caused by the combination of turbulence and salinity driven data streams. This loss of data is worsen without the use of advanced optical algorithms and exemplary UVLC streams. This decreased data stream speed is of utmost importance to underwater communication. Many recent studies for predictive channel modeling have focused on the rapid alteration of the parameters for the UVLC systems response to the surrounding changes. The reliable combination of turbulence and stream fragmentation can lead to the construction of a optical lattice system to Wifi systems such as AUV communication, reliable system monitoring, and short range sensor networks. This allows for more secure and confident use in the real world.

Keywords: Salinity, Turbidity, Future prospect, Data rate, UVLC, Modulation

1 INTRODUCTION

The requirement for sharing information/data in water brought attention to the underwater communication technologies. Underwater exploration, monitoring marine/aquatic ecosystems, AUV, and underwater industrial operations do need reliable and fast communication. Traditional methods such as radio-based and acoustic systems have some well-known drawbacks. Long distance acoustic communication is practical but it has high latency and low data rates. Radio frequency communication will be strongly absorbed in water especially at higher frequencies, which will limit its efficiency and range. Due to these major challenges, alternative communication techniques capable of handling higher data were developed.

One of the most promising approaches for underwater wireless communication is UVLC. Compared to acoustic or radio systems, in UVLC much higher data rates could be achieved by transmitting information through water using visible light wavelengths. Some of the advantages of using are high bandwidth, low latency, enhanced security, and the potential for a small and energy-efficient tranceiver. Given these features, UVLC is a very good solution for future underwater networks that require high data transfer rates.

The fundamental reason UVLC "simply works" lies in the optical window of seawater. While water is highly absorbent of most electromagnetic frequencies, it is remarkably transparent to the visible light spectrum, specifically in the **blue-green wavelengths (400nm to 550nm)**. In these "windows," the absorption coefficient is at its minimum, allowing light to propagate through the medium with significantly less energy loss compared to other frequencies.

Nevertheless, despite their huge promise, the performance of UVLC systems is highly susceptible to the optical properties of the water medium. Water as a transmission medium may be considered to contain simultaneous effects of absorption, scattering, refraction, and turbulence on the moving light beam. Several studies have pointed out that water type, environmental turbulence, particulate concentrations, temperature variations, and transmitter c

haracteristics significantly affect system performance (Zayed and Shokair 2025b). These variations in different parameters contribute towards optical attenuation, thereby decreasing the intensity of the received signal and restricting the achievable data rate and communication range.

Different water types present distinct environmental challenges. Pure and clear waters allow light to travel relatively farther, while coastal and turbid waters significantly restrict optical transmission due to their high absorption and scattering. (Zayed and Shokair 2025a) Turbidity, caused by suspended particles such as sediments, organic matter, and biological organisms, increases scattering and disrupts the directionality of the light beam. Thereafter, the received signal becomes much weaker and more dispersed, leading to reduced signal-to-noise ratio and lower data throughput. (Sun et al. 2020) Turbidity has been commonly cited as one of the dominant limiting factors in the performance of UVLC, especially in natural aquatic environments where water clarity generally fluctuates within a wide range.

Salinity is the second key environmental parameter influencing UVLC systems. Varying salt concentrations change the refractive index and absorption characteristics of the water. Increased salinity levels can increase absorption and affect the propagation path, further limiting the effective range of transmission of the optical signal (Hayle et al. 2024; Ali, Perera, et al. 2022). Indeed, in seawater or hypersaline, such conditions become more obvious and can call into question the stability and dependability of UVLC links. While salinity is recognized as a contributor, its precise influence is irregularly reported in different studies. (Ali, Jayakody, et al. 2022; Ata and Kiasaleh 2023)

A main problem with the existing literature is the inconsistency of experimental approaches. The measurement setups, water samples used, environmental control, choices of wavelength, modulation technique, and transmitter configuration have all varied greatly from one study to another. These methodological differences lead to conflicting results about how much salinity and turbidity affect UVLC attenuation and data rate. In some studies, strong correlations have been found to exist between environmental conditions and performance degradation, while in others, the impact has been observed to be more limited. These inconsistencies mean that developing generalized models that are capable of describing UVLC behavior under real conditions remains elusive.

Given such variations, there exists a clear need for a systematic and comprehensive review of the literature to identify consistent patterns and explain conflicting results. The SLR offers a formal synthesis methodology for reviewing existing research, comparing methodological differences, and highlighting which environmental factors have been cited most frequently as constraints to performance. It can therefore be determined what conditions are typically the most challenging for UVLC reliability and which parameters of variation consistently emerge across numerous studies.

These issues are addressed in the present study by systematically reviewing research findings related to salinity, turbidity, and wavelength selection in UVLC systems. The main goal of the work presented here is to analyze and summarize the effect of salinity changes on optical attenuation and achievable data rate in UVLC channels. Additionally, this work aims to determine those environmental conditions that most frequently appear as limiting factors in the performance of underwater optical communications.

Based on this objective, the general research question would be: Which environmental conditions (salinity level, turbidity range) consistently appear as the major limiting factors for UVLC data rate across the literature?. This will hopefully ensure a more profound understanding of UVLC channel behaviour and facilitate the development of robust and effective underwater optical communication systems.

2 METHODOLOGY

This study employs a Systematic Literature Review (SLR) approach to identify, evaluate, and synthesize existing experimental research on how salinity and turbidity influence the data rate of Underwater Visible Light Communication (UVLC) systems. The SLR method is used to ensure that the review process is structured, transparent, and reproducible, enabling a comprehensive understanding of the environmental factors that degrade optical performance underwater.

2.1 Review Design

The review follows a structured SLR process consisting of defining the search strategy, identifying relevant studies, screening based on predefined criteria, extracting data, assessing study quality, and synthesizing the findings. The entire process is designed to answer the research question: Which environmental conditions (salinity level, turbidity range) consistently appear as the major limiting factors for UVLC data rate across the literature?

2.2 Information Source and Search Strategy

All literature was sourced from **Lens.org**, selected for its broad coverage of scientific journal articles. Searches were conducted using the following keywords:

“Salinity and turbidity affect on the data rate of Underwater Visible Light Communication”
“experimental”

To improve retrieval quality, Boolean operators and alternative UVLC terminology (e.g., “underwater optical wireless communication”) were incorporated where necessary. Search filters were applied to refine the results to:

1. Journal articles only
2. English-language publications
3. Full-text accessible manuscripts
4. Publication year 2020 or later

These parameters ensured that only recent and relevant experimental works were included in the review.

2.3 Eligibility Criteria

To maintain focus and filter irrelevant studies, clear inclusion and exclusion criteria were established before screening.

Inclusion criteria:

1. Studies that experimentally examine the effect of salinity and/or turbidity on UVLC system performance.
2. Research reporting measurable outcomes on data rate, signal attenuation, or related optical communication metrics.
3. Full-text accessible journal articles.
4. Publications written in English.
5. Studies published from 2020 onward.

Exclusion criteria:

1. Opinion articles, blogs, books, theses, or non-peer-reviewed materials.
2. Papers lacking full text or containing incomplete data.
3. Studies not mentioning experimental work or relying solely on simulation without validation.
4. Publications before 2020.
5. Research unrelated to UVLC (e.g., acoustic or RF communication).
6. Studies not addressing salinity, turbidity, or data rate.

These criteria ensured that the final dataset consisted only of experimentally grounded and relevant studies.

2.4 Study Selection Procedure

The study-selection process comprised three stages:

1. **Identification:**
   All records from Lens.org were collected, and duplicates were removed.
2. **Screening:**
   Titles and abstracts were screened to exclude obviously irrelevant works.
   Studies that did not mention UVLC, salinity, turbidity, or experimental data were removed at this stage.
3. **Eligibility Assessment:**
   Full texts were reviewed in detail.
   Each article was evaluated against the inclusion/exclusion criteria.
   Papers excluded at this stage were documented with specific reasons (e.g., lacks experimental data, no data rate measurements, irrelevant methodology).

The final number of included studies and all screening steps will be documented using a PRISMA-style flow diagram in the results section.

2.5 Data Extraction

A structured data-extraction table was developed to ensure consistency. The following information was collected from each study:

1. Author(s), year, and publication details
2. Experimental setup and environment (e.g., laboratory tank, seawater samples, controlled turbidity levels)
3. Water type and measured salinity values (PSU or g/L)
4. Turbidity levels (e.g., NTU, mg/L suspended particles, attenuation coefficients)
5. Wavelengths and optical transmitters used
6. Receiver specifications, modulation schemes, and distance
7. Reported data rate or throughput
8. Measured attenuation, BER, or SNR
9. Key findings on how salinity or turbidity affected performance

The extraction process ensured that all variables influencing data rate were fully captured.

2.6 Quality Assessment

All included studies were evaluated using a quality-assessment checklist adapted for experimental underwater communication research. Criteria included:

1. Clarity of experimental design and reproducibility
2. Proper reporting of salinity and turbidity measurement methods
3. Adequacy of optical system description (transmitter, receiver, wavelength)
4. Appropriateness of performance metrics
5. Transparency in data reporting

6. Discussion of study limitations

Each study was assigned a quality score based on these criteria, allowing the synthesis to give more weight to methodologically strong work.

2.7 Data Synthesis

1. Because the included studies are expected to vary in methodology, water conditions, and reported metrics, a **narrative synthesis** is used as the primary method of integration. Findings are grouped and compared based on:
2. Salinity ranges tested
3. Turbidity levels
4. Wavelength bands used
5. Resulting data rate performance
6. Optical attenuation and scattering behavior

Where possible, studies with comparable methodologies and units will be analyzed collectively to highlight consistent trends. If a subset of studies provides compatible quantitative data, a simple effect comparison or trend analysis may be added.

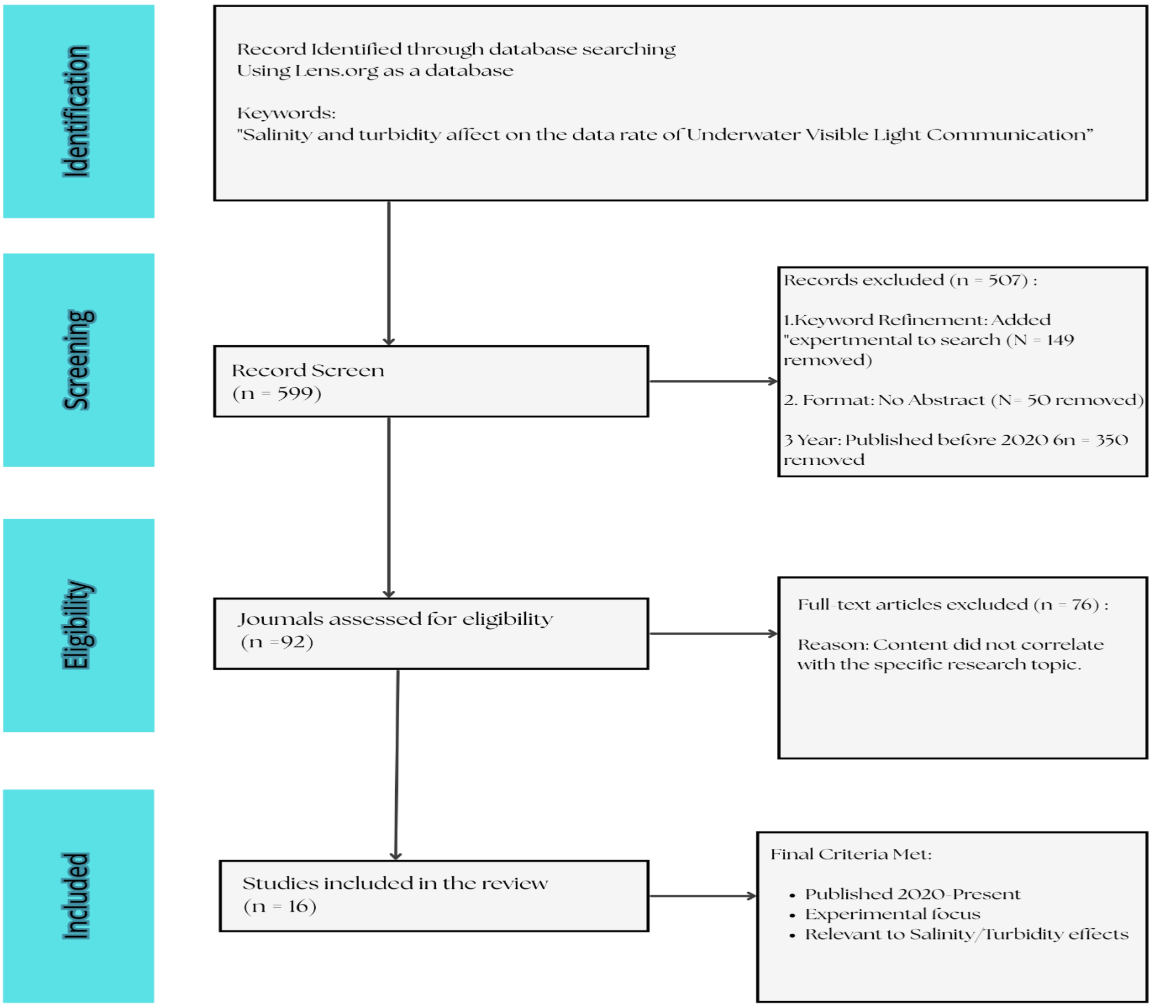
The synthesis focuses on identifying environmental thresholds (e.g., turbidity limits, salinity levels) at which UVLC performance experiences significant degradation.

3 RESULT

3.1 Result of Identification and Screening

The systematic search on Lens.org returned 599 records using the keyword phrase “Salinity and turbidity affect on the data rate of underwater visible light communication.” During initial screening, 507 records were excluded through three filters: a keyword refinement to “experimental” (149 removed), removal of entries without abstracts (50 removed), and exclusion of studies published before 2020 (350 removed).

This left 92 records for full-text assessment. Of these, 76 were excluded for lacking direct relevance to salinity or turbidity effects on UVLC data rate. Ultimately, 16 studies met all criteria, experimental design, publication from 2020 onward, and thematic relevance and were included in the final review.



3.2. Eligibility Assessment

Full-text inspection implemented definite input-output exclusion lists for each intervention group;

Table 1.1 Screening Inclusion and Exclusion Criteria Applied to PRISM

Criteria	Inclusion	Exclusion
Timeline	2020–2025	Articles published before 2020
Type of Source	Peer-reviewed journal articles	Conference abstracts, cosmetic marketing texts, grey literature, unindexed commentary
Fomat	Records with available abstracts	Records with no abstract available

Methodology	Studies with an experimental focus	Non-experimental studies or theoretical papers without experimental validation
Research Focus	Impact of salinity and turbidity on Underwater Visible Light Communication (UVLC)	Content that did not correlate with the specific research topic (e.g., unrelated environmental factors)
Outcomes	Data rate performance, signal quality under varying water conditions	Studies lacking specific data on salinity or turbidity effects

These rules guaranteed that only articles published from 2020 to the present were taken into consideration and that all the studies utilized an experimental focus to report measurable outcomes on salinity and turbidity. Works published before 2020, those lacking abstracts, or studies where the content did not strictly correlate with the specific research topic were disqualified at this point. The decision to eliminate 75 full-text articles was made here, ensuring that the remaining 16 studies possessed direct relevance to the effects of environmental factors on UVLC

Based on the provided sources, here is the results section formatted to match your example, addressing your research question regarding environmental limiting factors (salinity and turbidity) for UVLC data rates.

3.3. Final Study Selection

There were 16 studies that fulfilled all the criteria both methodologically and conceptually:

- 9 studies investigated **turbidity and water type** as the primary attenuation factor limiting data rate and link range.
- 7 studies examined **salinity-induced turbulence** and refractive index fluctuations as the major cause of signal fading and bit error rate (BER) degradation.

A.1 Turbidity: The Attenuation and Scattering Factor

In the literature provided, turbidity is consistently framed as the measure of water clarity and is the primary cause of signal power loss (attenuation) and geometric distortion.

Region/ Water Type	Absorption Coefficient (a)	Scattering Coefficient (b)	UVLC Performance Outcome	Additional Notes	Source
Pure Seawater	Very low (≈0.02–0.05 m^{-1})	Very low (<0.01 m^{-1})	LD range ≈ **68.39 m**	Supports high-capacity modulation (64-QAM stable)	(Zayed and Shokair 2025a)
Clear Ocean Water	Moderate	Moderate	Moderate range and stable link	Noticeable attenuation but manageable	(Hayle et al. 2024)
Coastal Ocean Water	Higher (≈0.3–0.6 m^{-1})	Higher (≈0.2–0.4 m^{-1})	Strong attenuation, reduced data rate	Suspended particles increase scattering	(Hayle et al. 2024)
Turbid Harbor Water	**1.112 m^{-1}**	**0.5266 m^{-1}**	LD range drops from **68.39 m → 5.06 m**	Capacity collapses: spectral efficiency **≈0 bps/Hz**	(Zayed and Shokair 2025a; Bariah et al. 2022)
Kaolin - Induced Turbidity (o-6 FTU)	Variable	Variable	Optical systems fail beyond **2.1 FTU**	Acoustic sensors unaffected	(Sørensen et al. 2023)
Maalox Induced Turbidity	Variable	High scattering	OOK & PPM more robust than OFDM	Used to emulate coastal/harbor water	(Guo et al. 2020)

A.2 Salinity: The Turbulence and Refractive Factor

Salinity is behaving differently rather than just stopping the light (attenuation), salinity changes the *density* and *refractive index* of the water, causing the light beam to bend, wander, or flicker (scintillation).

Salinity Condition/Phenomenon	Mechanism Observed	UVLC Performance Impact	Additional Notes	Source
Salinity Gradients at Water Mixing Zones	Mixing of two water bodies with distinct salinity creates refractive index fluctuations	Causes unstable signal intensity and deep fading	Observed at Baltic–North Sea	(Ali, Jayakody, et al. 2022)

A.3 Summary of Turbidity and Salinity

To distinct both of them in a formal form, this table will explain key point on what make their effect so different

Feature	Turbidity	Salinity
Primary Mechanism	Scattering & Absorption : Physical particles block or redirect photons	Refraction & Scintillation : Dissolved salts change water density, bending light rays
Key Metrics	Extinction Coefficient ($c(\lambda)$), FTU (Formazin Turbidity Units).	Scintillation Index (σ_I^2), Refractive Index Structure Parameter (C_n^2)
Major Effect	Reduces Range and Power (signal attenuation).	Reduces Stability and Alignment (signal fading/jitter).
Experimental Agent	Simulated using Maalox ( ) and Kaolin	Simulated using Saline solutions or comparative ocean studies in (Baltic vs. North Sea).

A.4 Innovation and Future of UVLC

According to recent studies, advancements in hardware, modulation, networking, and energy systems are propelling UVLC into a period of rapid technological growth. The field is advancing through a number of complementary innovations that each address a distinct problem in the underwater environment, such as boosting data rates, enhancing alignment, facilitating mobility, enabling dense sensor networks, or powering devices without frequent battery changes. The following table lists the key innovation areas and their contributions to UVLC's future to provide a clear picture of how these developments fit together.

Innovation Area	Technology/ Technique	Impact on Future UVLC	Source
5G Convergence	RGB 3- Wavelength WDM	Enables ultra-high speeds (27.3 Gb/s) by integrating FSO, HCF, and UWOC links for drone-to-underwater comms.	(Hayle et al. 2024)
Hardware	GaN-based Micro-LEDs	Optimizes modulation bandwidth (>1 GHz) to achieve data rates up to 420 Mbps over medium distances (e.g., 2.3m to 11.5m).	(Wang et al. 2025)
Mobility	Diffused-Line-of-Sight (DLOS)	Uses broad-beam lasers to maintain connectivity with mobile nodes (ROVs) without strict alignment; PPM is preferred over OOK/OFDM.	(Guo et al. 2020)
Beam Tracking	Spatial Light Modulator (SLM)	Mitigates beam misalignment caused by ocean currents or drone movement using electrical comparator feedback.	(Hayle et al. 2024)
Energy	SLIPT (Solar Receivers)	Allows underwater nodes to harvest energy and receive data simultaneously, enabling energy-autonomous sensor networks.	(Sun et al. 2020)
Modulation	NOMA	Enhances spectral efficiency and supports massive connectivity for dense underwater sensor networks (IoUT).	(Bariah et al. 2022)
Modulation	LACO-OFDM with SiPM	Offers a better trade-off between power efficiency and range flexibility compared to DCO-OFDM for highly sensitive SiPM receivers.	(Essalih et al. 2020)
Security/AI	Deep Learning Recognition	Uses neural networks to classify and recover speech/data signals distorted by surface water waves and encryption effects.	(Sartori et al. 2022)
Performance	Modulation Selection	Identifies trade-offs: 64-QAM for high capacity (53 bps/Hz) vs. OOK for max range (up to 123m with Laser Diode).	(Zayed and Shokair 2025b)
Receivers	Scintillating Fibers	Large-area photoreceivers that relieve alignment requirements while maintaining high modulation bandwidths (>90 MHz).	(Sun et al. 2020)

4 DISCUSSION

4.1 Resolving Environmental Inconsistencies: From Static to Dynamic Modelling

Early studies on Underwater Visible Light Communication (UVLC) frequently relied on simplified turbulence representations such as Nikishov's power spectrum, which assumes fixed ratios between temperature and salinity gradients. This assumption created inaccuracies, particularly when applied to heterogeneous or rapidly varying water environments, leading to inconsistent descriptions of underwater turbulent behavior (Ata and Kiasaleh 2023). More recent work addresses these inconsistencies through the Oceanic Turbulence Optical Power Spectrum (OTOPS) model, which incorporates measured temperature and salinity values rather than fixed proportions. By accommodating realistic environmental parameters, OTOPS provides a more accurate representation of natural aquatic conditions across major ocean basins (Ata and Kiasaleh 2023).

In weak turbulence regions, traditional Log-Normal statistical distributions remain sufficient to estimate fluctuations in received optical signal intensity. However, in coastal, harbor, and estuarine environments where turbulence effects become similar in magnitude to absorption and scattering losses, more comprehensive distributions such as Gamma-Gamma and Weibull are necessary to reliably predict signal degradation. (Ata and Kiasaleh 2023; Zayed and Shokair 2025a). These models better capture the heavier tails observed in the irradiance fluctuations of strongly perturbed channels.

Further inconsistencies in previous UVLC performance findings are resolved when dynamic mixing between different water masses is taken into account. For example, transitional zones such as the Baltic–North Sea interface exhibit distinct layering caused by differences in salinity, temperature, and suspended particulate concentration. Such stratified environments cannot be described using a single extinction coefficient, as each layer exhibits its own turbulence and absorption characteristics that influence data rate differently (Ali, Perera, et al. 2022) Incorporating these multi-layer conditions into optical channel modeling enables a more realistic interpretation of environmental impact on UVLC data rate.

4.2 Technological Evolution: Light Sources and Modulation Trade-offs

The synthesis of experimental findings reveals a clear trade-off between spectral efficiency and environmental robustness across modulation schemes. High-order modulations such as 64-QAM offer strong spectral efficiency advantages in clear water, yet rapidly lose reliability in turbid environments. In contrast, simpler intensity-modulation techniques such as On-Off Keying (OOK) and Pulse Position Modulation (PPM) remain the most dependable for long-range or energy-limited scenarios due to their tolerance to scattering and turbulence (Zayed and Shokair 2025b).

Developments in optical sources also show a divergence in suitability based on communication range. GaN-based micro-LEDs have demonstrated exceptional performance for high-bandwidth, short-range UVLC links, achieving data rates exceeding 400 Mbps owing to their fast modulation bandwidth. For long-range transmission, Laser Diodes (LDs) remain superior due to their high coherence, narrow beam divergence, and resistance to scattering-induced spreading (Sun et al. 2020; Wang et al. 2025).

For receiver systems utilizing silicon photomultipliers (SiPM), orthogonal frequency-division multiplexing (OFDM) variants demonstrate notable differences in power efficiency. Asymmetrically Clipped Optical OFDM (ACO-OFDM) offers improved power efficiency over DC-biased OFDM (DCO-OFDM) by eliminating the need for a high DC bias. Layered ACO-OFDM (LACO-OFDM) further enhances spectral efficiency while managing computational complexity, making it a practical compromise for sensor-scale underwater systems (Sartori et al. 2022; Essalih et al. 2020).

4.3 Addressing Mobility and Alignment: The Novelty of Adaptive Systems

The issue of maintaining Line-of-Sight (LOS) alignment in mobile underwater nodes is one of the most persistent challenges in UVLC. Recent research addresses this through the integration of adaptive tracking mechanisms that combine Spatial Light Modulators (SLMs) with 5G millimeter-wave feedback control. These systems dynamically adjust beam direction to counter disturbances caused by waves and ocean currents, ensuring stable UVLC connections even under movement (Hayle (Hayle et al. 2024).

Diffused Line-of-Sight (DLOS) configurations also provide substantial advantages in mobile environments. By employing broad-beam lasers together with PPM, DLOS systems maintain consistent connectivity with Remotely Operated Vehicles (ROVs) moving at variable speeds. These configurations demonstrate superior robustness compared to OOK and OFDM in dynamic misalignment cases, preserving data throughput despite platform motion (Guo et al. 2020).

Experiments using servo motors and Arduino-based feedback systems have further shown that mechanical beam steering guided by real-time received signal strength significantly enhances alignment stability. Such low-cost adaptive setups provide a practical pathway for small-scale or resource-constrained underwater platforms (Rehman et al. 2025). Additionally, air–water interface distortion has been mitigated by employing deep-learning neural networks capable of recognising speech commands from water-distorted analogue signals with high accuracy, even under encryption. This offers new possibilities for robust sensing and communication in fluctuating surface environments (Sartori et al. 2022).

4.4 Future Directions: 5G Integration and Massive Connectivity

There is now an increasing connection between ultrahigh capacity systems and telecommunications networks. There is now also an increasing connection between telecommunication networks and ultrahigh capacity systems (Hayle et al. 2024).

The integration of free-spaceOptics (FSO), Hollow-Core Fibers (HCF), and Underwater Optical Communications (UWOC) systems has shown successful integration and handovers between aerial, terrestrial, and underwater links, and recent use of RGB wavelength-division multiplexing (WDM) has further improved system performance (streaming capacity) with negligible delay (streaming) with stand to be greatly aligned (Compatible) with 5G systems and even beyond 5G (Hayle et al. 2024).

The deployments above the surface used within the Internet of Underwater Things (IoUT) networks are now also in use. There is also the increasing use of Non-orthogonal multiple access (NOMA) within the aforementioned networks to improve spectral efficiency and concurrent connections. There are claims to (NOMA) that will greatly improve concurrent connections in spectral efficiency and so (NOMA) usage, connections become a (Major) concern with respect to resource management (Bariah et al. 2022).

For the long underwater sense deployments, the concern is solar systems use cells that are receivers and optical energy harvesting devices. They have the devices that self-harvest ambient optical energy While dual system capable of decoding optical comm. signals. So (self-powered) energy storage is a device well designs for long deployments (Kong et al. 2020).

5 CONCLUSION

This review demonstrates how the optical properties of the water medium have a significant impact on the performance of Underwater Visible Light Communication (UVLC). The most significant limiting factor is always turbidity, since suspended particles increase scattering and drastically lower signal strength and achievable data rates. Through variations in absorption and refractive index, salinity also influences UVLC performance; however, the effect varies between studies because of different experimental conditions.

This review demonstrates how the optical properties of the water medium have a significant impact on the performance of Underwater Visible Light Communication (UVLC). The most significant limiting factor is always turbidity, since suspended particles increase scattering and drastically lower signal strength and achievable data rates. Through variations in absorption and refractive index, salinity also influences UVLC performance; however, the effect varies between studies because of different experimental conditions.

Many of the discrepancies in the literature can be attributed to variations in research techniques, water types, wavelengths, and turbulence models. Improved turbulence modeling, optimized modulation schemes, and adaptive alignment technologies are examples of recent developments that show promise for boosting system robustness in actual underwater environments.

Overall, blue-green wavelengths can accommodate strong UVLC performance in pure water, although in turbid or very salty water this performance will quickly drop off unless energy adaptive or other more efficient communication methods are employed. These findings support the need for standardized test conditions and modelling of realistic environments when developing advanced and reliable systems for underwater optical communication.

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