

A Comprehensive Review on Underwater Wireless Optical Communication

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Abstract—Underwater Wireless Optical Communication (UWOC) offers high-speed data transmission in aquatic environments. This paper reviews challenges and advancements in transmitting images over UWOC systems, considering factors like water turbidity and attenuation. It discusses modulation techniques, encoding schemes, and signal processing methods for efficient image transmission. Recent developments, including adaptive optics and deep learning algorithms, aim to improve reliability and speed. Practical applications and future research directions for underwater image transmission highlight its potential in exploration, surveillance, and scientific endeavours.

Index Terms— Underwater Channel, Wireless optical communication, turbulence, absorption, scattering.

I. INTRODUCTION

Oceanographic studies intrigue scholars due to the vast coverage of water on Earth, especially in oceans. The burgeoning interest in ocean exploration systems offers opportunities for surpassing air-based communication networks. Choosing the primary carrier wave for underwater communication poses a challenge. Kaushal et al. [1] extensively reviewed radio frequency (RF), optical, and acoustic waves, presenting conclusions in Table 1. Optical waves emerge as promising for highly efficient underwater communication [2][3]. UWOC (Underwater Wireless Optical Communication) gains traction [1]–[4], operating in the blue spectrum (450nm to 550 nm) with potential applications in various domains [5][6]. Despite benefits, challenges like high attenuation and link misalignments hinder UWOC development [7][8]. Factors affecting link performance and aquatic environments complexity require deeper exploration [9][10]. Efforts focus on overcoming design complexities for reliable UWOC systems.

II. THE UNDERWATER FUNDAMENTALS

Understanding how light propagates underwater is crucial for designing UWOC systems [2]. Light undergoes significant attenuation in seawater compared to the atmosphere [11]. Various studies have examined the effects of ocean water's optical properties [1]–[3], [12], [13]. Environmental factors impact UWOC system performance [14]. Water's optical traits include inherent optical properties (IOPs) and apparent optical properties (AOPs) [1]. IOPs include absorption, scattering, attenuation coefficients, and volume scattering function [15], [16]. Different water types present challenges for UWOC systems [1]. Dissolved particles' concentration affects water complexity [2]. For instance, pure seawater exhibits limited light dispersion, while clear ocean water contains

phytoplankton and light-absorbing elements like chlorophyll [17]. Coastal waters contain elevated concentrations of organic matter, affecting light absorption [1].

III. CHARACTERISTICS OF THE UWOC CHANNEL

Understanding the UWOC channel requires comprehension of its primary features, classified by Guerra et al. into eight characteristics: Absorption, scattering, turbulence, refractive index, surface reflections, seabed diffusion, optical fouling, and attenuation index [18].

A. Absorption and Scattering

When light travels underwater, it undergoes absorption and scattering, impacting energy distribution [2]. Absorption transforms light energy into chemical or thermal forms, while scattering disperses energy spatially. These processes influence photon reach and light distribution, crucial in UWOC design. Various scattering models, like Rayleigh and Mie's approximation, are employed based on particle size [18]. The attenuation index ($k(\lambda)$) combines absorption ($a(\lambda)$) and scattering ($b(\lambda)$) indices, representing the decay of optical beam in water [12].

B. Optical Turbulence

Optical turbulence is an indication that the refractive index of the seawater is changing quickly. At any depth, these changes could take effect. The temperature, salinity, turbidity and presence of air bubbles can cause turbulence [1]. Vali et al. [14] have presented the variations in refractive index and the link span as two important decision factors towards the turbulence strength.

C. Refractive Index, Surface Reflection, Seabed Diffusion and Optical Fouling

Guerra et al. provided insights into refractive index, surface reflections, seabed diffusion, and optical fouling [18]. Refractive index, dependent on salinity, temperature, and wavelength, affects light speed and reflections, with salinity having a greater impact. Surface reflections result from sea wave movements, influenced by wind stress noise, causing random variations. Seabed diffusion arises from light scattering, described using various models. Optical fouling, accumulation of substances like algae, affects emitted power in UWOC systems, with spectral analysis aiding in modelling [18].

Figure 1 illustrates the values of absorption, scattering, and attenuation coefficients for various water types.

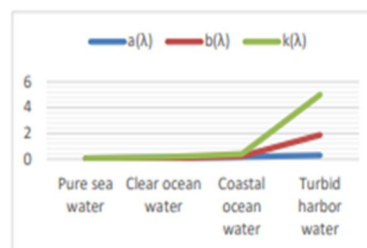


Figure 1. Absorption, Scattering and Attenuation co efficient values of different types of water

In clear ocean water and pure sea water, the working wavelength range is 450 nm to 500 nm, covering the blue-green spectrum. Coastal ocean water and turbid harbor water, in the yellow-green spectrum, operate within 520 nm to 570 nm.

Figure 2 depicts absorption and scattering characteristics across different seawater compositions. Coastal ocean water has high concentrations of humic, fulvic, and chlorophyll compared to pure seawater and clear ocean water, while turbid harbour water shows a relatively higher abundance of these elements.



Fig.3. Absorption and Scattering Characteristics with different Seawater Compositions

Figure 2. Absorption, Scattering Characteristics with different seawater compositions

IV. UWOC CHANNEL MODELLING

Understanding established channel models is crucial for comprehending light behaviour underwater. Johnson et al. surveyed various models used in underwater optical communication, aiding in loss calculations and performance evaluation [19]. Absorption and scattering mechanisms significantly impact photon interaction in the water medium [20], affecting timing irregularities and multipath dispersions [21]. Literature covers absorption and scattering models, detailing seawater properties and chlorophyll concentration [22][23]. Zeng et al. provided an overview of UWOC channel models [2]. Two main configurations, Line of Sight (LOS) and Volume Scattering Function (VSF), are employed based on aquatic optical attenuation [19]. Monte Carlo method is widely used for numerical simulation, though facing challenges like time complexity and statistical inaccuracies [24][25]. Novel approaches like impulse response modelling and simulation networks aid in improved channel characterization [26][27]. Recent models consider additional factors like air bubbles and temperature-related turbulence effects, but further exploration is needed [13].

V. CHALLENGES IN SYSTEM MODEL

The UWOC system design comprises a transmitter, channel, and receiver. Optical carrier modulation occurs at the source, with interception by a photoelectric detector [28]. Proposed models include LOS, MRR, and Reflective links [2]. Turbulence challenges include intensity and phase fluctuations, especially in vertical links [14]. Johnson et al. studied oceanic composition's impact on attenuation in vertical links [19]. UWOC link effectiveness depends on transmitters like Laser Diodes and LEDs [29]. Receiver parameters, including PIN photodiodes, APDs, and MPCCs, significantly affect overall link performance.

TABLE I. A COMPARISON OF DETECTORS

Parameter	MPCC	APD	PIN Photodiode
Gain	100000	10 to 100	1
Range	Long	Long	Short
Accuracy	High	High	High

UWOC system performance relies on modulation techniques: Intensity Modulation (IM) or Coherent Modulation (CM) [1][2]. IM, like IM/DD, offers simplicity by modulating data on receiver intensity. Coherent detection (homodyne or heterodyne) provides higher spectral efficiency but at a higher cost [1][2]. Various schemes (OOK, PPM, PIM) aim to enhance transmission distance and data rate. Coherent schemes (PSK, QAM) offer higher efficiency and BER performance, albeit with increased complexity and cost [1][2]. Error detection methods (FEC with RS, BCH, LDPC) improve system performance under interference [2].

VII. COMPREHENSIVE REVIEW ON UWOC

Cossu et al. provided an overview of UWOC, positioning it as a promising solution [5], while Saeed et al. delineated challenges and strategic directions for Underwater Optical Wireless Networks (UOWNs) [3]. A comprehensive survey summarized crucial aspects of UWOC, including channel characterization and modulation schemes [2]. Kaushal et al. detailed UWOC system implementation [1]. Breakthroughs in UWOC include high-speed transmissions and advancements in technology [13]. Li et al. achieved a remarkable 50 Gbps transmission [30], while Singh et al. analyzed underwater communication using a statistical model [31]. Li et al. developed a full-duplex UWOC system based on FPGA architecture [32]. Oubei et al. reviewed UWOC data rates and link distances [13]. Hong et al. demonstrated a 2-Gbps UWOC system, setting a new data rate benchmark [33]. These advancements pave the way for the Internet of Underwater Things (IoUT) [8][34].

VIII. DISCUSSION AND SUMMARY

Developing new channel models tailored for Underwater Optical Communication (UWOC) is crucial due to the inadequacy of existing terrestrial Free-Space Optical (FSO) models. Turbulence effects must be accounted for, influencing signal transmission underwater. Energy-efficient modulation and coding techniques are needed, especially in murky waters. Innovation in smart localization, beam alignment, and adaptable transmitters/receivers is essential. Research into enhancing data rates within the blue-green spectrum is

warranted. Nonlinearity issues affecting receiver performance must be addressed, with proposed solutions like nonlinear equalizers. Exploiting light scattering in the ocean can mitigate link misalignment, enabling optimized receiver design with minimal adjustments to transmitter power.

IX. CONCLUSION

In conclusion, advancing underwater wireless optical communication (UWOC) requires a multidisciplinary approach to tackle its unique challenges. Specialized channel models considering underwater conditions and turbulence effects are crucial. Energy-efficient modulation, coding schemes, and adaptive technologies are essential for reliable communication in varying underwater environments. Addressing nonlinearity issues and exploring innovative light scattering techniques to mitigate link misalignment are key areas for improving UWOC systems. Continued research and innovation in these areas promise efficient, reliable, and high-speed communication in underwater settings, facilitating advancements in fields such as ocean exploration, environmental monitoring, and underwater data transmission.

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