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A Review on Feasible and Reliable Underwater Wireless Optical Communication System for achieving High Data Rate and Longer Transmission Distance

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***Abstract*—Underwater Wireless Optical Communication (UWOC) offers significant research prospective with major challenges in the design and implementation. UWOC is capable of providing high rate of data transmission across large distances. This paper attempts to focus on the intricacies of practical implementations and open research issues of UWOC systems. Critical advances and progresses made in the field, modelling techniques and link design challenges are summarised. The purpose of this review is to give suggestions towards feasible and reliable UWOC design with improved performance. Finally the major points are summarized so that it will assist the future research in UWOC.**

***Keywords*—UWOC; underwater channel; oceanic medium; optical signals; absorption; scattering; attenuation; turbulence**

I. INTRODUCTION

OCEANOGRAPHIC investigations have inspired the scholars' intense attention and curiosity. The fact that water covers 71% of our planet's surface, with oceans holding 96.5% of it, is important in this. For academics studying underwater communications, the growing popularity of ocean exploration systems presents a huge opportunity since it may lead to the development of a communication technology that is more effective than those that rely on air communication linkages.

In the design and implementation of any underwater communication systems, the choice of the primary carrier wave is a significant problem. In [1], Kaushal et al. have outlined all the existing choices of the primary carrier for communicating underwater. The radio frequency (RF), optical, and acoustic carrier waves have been reviewed by the authors. The listed parameters include the data rate and bandwidth realized for different ranges. The conclusions from their work are presented in Table 1. Comprehensive reviews on underwater communication technologies have been outlined in [2], [3]. Evidentially, the optical wave has been proposed as the best possible option towards implementing reliable, highly efficient, ultra-high data rate underwater communication systems and networks. Over the last decade, UWOC, or underwater wireless optical communication, has gained increasing consideration by the researchers[1]–[4]. UWOC systems have potential applications specifically in realizing underwater sensor networks[5]. These systems have turned out to be a promising replacement to the existing optical fiber channel in underwater medium[6]. In its principle, a UWOC system uses transmission of wireless optical carriers, through an unguided water environment. UWOC has a significant variability which mostly finds a useful spectral range of 450nm to 550 nm, termed as the blue spectrum. Researches have proven that in this spectral region, relatively less attenuations are faced by the wireless optical carrier[7]. UWOC has its wide applications including offshore explorations, tactical surveillance, pollution monitoring, climate change monitoring, oceanographic research, operations of defense establishments and further can be extended in many other areas of industrial and scientific research. However, the major deterrents of UWOC like high attenuation, inability of precise localization, link misalignments, severe absorption and scattering creates potential design challenges among the researchers. In addition, reviewing the characteristics of the wireless optical carrier wave, there has been identified several limiting factors in the propagation which could eventually affect the link performance. The complexity of an aquatic environment has also considered as a reason to limit the development of early UWOC systems[8].Our review thus focuses on these significance factors and further to the design issues of UWOC systems towards investigating reliable UWOC link design possibilities. In order to have an effective analysis, one must outline fundamentals of physics and underwater optics in the presence of background noise thereby comment on the system performance and the commercial viability[9][10] of UWOC.

TABLE I
A COMPARISON OF UNDERWATER WIRELESS COMMUNICATION SYSTEMS

Carrier	Data rate	Distance	Latency	Power	Cost
Optical signal	high	low	low	low	low
RF signal	moderate	moderate	moderate	high	high
Acoustic Signal	low	high	high	moderate	high

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II. THE UNDERWATER FUNDAMENTALS

The fundamental understanding of light transmission in an underwater medium is required to form the foundation of UWOC system design [2]. It has to be noted that the light beam will get attenuated more in sea water than in the atmosphere[11]. Notable impacts from the ocean water's optical properties have been explored well in [1]–[3], [12], [13]. In their work, Vali et al. (2019), has concluded that the environmental factors affect the UWOC system performance[14].

To further understand the previous, it is necessary to look at the optical characteristics of water. There are two categories for water's optical characteristics[1] as shown in Figure 1 (b). Firstly, the inherent optical properties (IOPs) are defined, and they are medium dependent and are independent of the optical source[12]. The major IOPs are listed as follows. Absorption coefficient, scattering coefficient, attenuation coefficient and volume scattering function[15],[16]. In later sections of this article, the details of these coefficients will be examined. Secondly, the apparent optical properties (AOPs) can be defined which is dependent on the transmission medium and on the geometrical structure of the field[1], [2], [12]. Using these properties, the directional nature of the optical beam can be easily defined [1]. Examples of AOPs are radiance, irradiance and reflectance.

A comprehensive knowledge of different water types and the constituents is also helpful to understand the challenges offered by the medium to the wireless optical beam. It is visible that the varying physical properties of water, are dependent on several factors including geographical locations, depth variations, and specific zones.

The characteristics of water bodies keep varying with different locations. Specific water zones have been classified based on the incident sunlight. A classification of vertical water layers is given in Fig. 1 (c). The Euphotic zone receives sufficient sunlight and is caused to have a large photosynthetic life. A few kilometers below this, there exists a Dysphotic zone. The sunlight is not sufficiently reaching in this zone and thereby not allowing a photosynthetic life in there. Further below, the Aphotic zone exists, where there is no available sunlight. On account of these differences, it must require careful and unique link designing strategies towards implementing reliable UWOC systems[1].

The concentration of dissolved particles contributes significantly towards the physiochemical complexity of a typical water environment. Following water types were considered in the work of Zeng et al. The authors marked the categories as pure water, clear ocean water, coastal ocean water and turbid harbor water[2]. Besides, in their work, Saeed et al.[3], has related the classification of the above three water types to the concentration of dissolved particles. Figure. 1 (a) displays the water types based on the concentration of dissolved particles.

Dissolved salts in pure seawater can be Chlorides of Sodium (NaCl), Potassium (KCL) and Magnesium (MgCl2), inorganic compounds like Sodium Sulphates (Na2SO4) etc. Optical beam follows straight line propagation through pure sea water. Thus, we could observe the dispersion of light waves in pure sea water as very limited. Pure sea water has many dissolved salts in it. When light travels in an underwater environment, the dependence of optical properties will be on the size and concentration of these dissolved constituents as well as on other suspensions in the sea water[17]. In a range, varying from 50m to 200m, clear ocean water has phytoplankton in it. These microscopic organisms, resides upto 15m in coastal water and upto 40 m in continental shelves. From literature, the existence of carotenoids, chlorophyll, chlorophillides, phaeophorbides and phaeophytins are evident, which critically absorb large amount of light. Among these, chlorophyll exists in high concentration along the equator and it is proven to be a significant source of absorption. Besides this, higher organic matter is concentrated in areas near the coastal region[12]. Decaying organic matter and dead plant tissues are present in seawater and is called Colored Dissolved Organic Material (CDOM) or Gelbstoff. This eventually produces humic and fulvic acids, a concentration of which is high in coastal waters and low in open waters. Besides this, possibility of non-algal materials and suspended inorganic matter is recorded in different regions[1].

III. CHARACTERISTICS OF THE UWOC CHANNEL

Understanding the UWOC channel necessarily requires in depth understanding of its major characteristics. Guerra et al. has explained these characteristics and categorized them. In their work, the following eight major UWOC characteristics are summarized. Absorption, scattering, turbulence, refractive index, surface reflections, seabed diffusion, optical fouling and attenuation index[18].

A. Absorption and scattering

The optical signal will undergo absorption in an underwater environment while interacting with molecules of water, all suspended particles and dissolved matters[2]. The process of absorption is wavelength-dependent. In the process of absorption, electromagnetic energy is transformed into different types of energy, primarily chemical or thermal forms. Absorption refers to the energy's degradation as it travels through seawater; as a result, it directly affects how many photons hit the receiver. In Scattering, the spatial dispersion of the energy is resulted because of the light-matter interaction. Together with absorption, scattering is a fundamental factor deciding the light propagation underwater, which indicates the changes in the distribution of light in underwater. To accommodate the scattering phenomenon in the UWOC design, suitable scattering models must be needed. However, these modeling strategies should consider the relative size of the particle. Considering this size as small, medium and large, Rayleigh scattering, Mie's approximation of Maxwell's equations and geometric optics modeling are used respectively [18].

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.

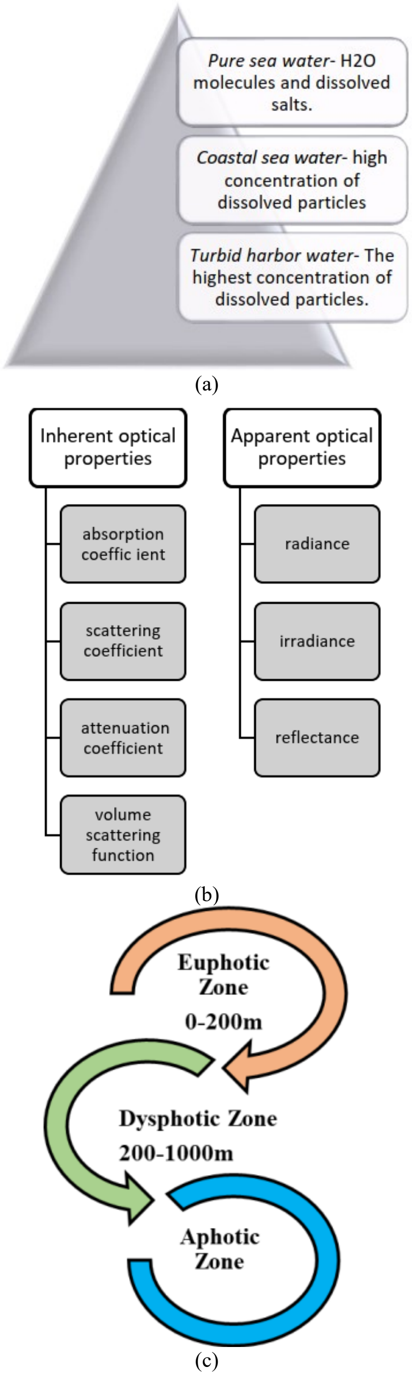

Fig.1. (a) Water types based on the particle concentration (b) Optical properties of water (c) The vertical water layers

C. *Refractive index, surface reflections, seabed diffusion and optical fouling*

Guerra et al. further elaborated the refractive index, surface reflections, seabed diffusion, optical fouling in detail. For a material, refractive index is calculated as the relation between the speeds of light in that material, with respect to that in vacuum. Refractive index has a significant role in reflections and turbulences. The refractive index of seawater is found to be dependent on salinity, temperature, and wavelength[19]. The dependence on wavelength results in chromatic dispersions. But this effect will be negligible while considering the monochromatic sources and small link ranges. But studies have been presented to indicate that in seawater, the sensitivity of the refractive index is more towards salinity than to the temperature fluctuations. The above author's work describes using a sea wave spectrum to represent the ocean surface as a superposition of moving sea waves while illustrating the concept of surface reflection. According to the authors, a noise factor also must be added to this spectrum, which is dependent on the wind stress. In particular, this stress is capable of producing random variations on the surface of water. Additionally, for a horizontal link, surface reflections may result in delayed additional power contributions. Seabed diffusion will be created due to scattering of light. There can be several models based on different scattering functions for describing this phenomenon. By considering seabed as compounded by rock, sand or coral extensions, an approximation model is proposed. The concept "optical fouling" refers to the deposition of material over the transparent shielding of optical emitters used in UWOC applications, typically algae and phytoplankton [18]. Evidently, this influences the amount of power that is effectively radiated into the surroundings. Furthermore, by analysing the spectral response of this substance, relevant causes to this phenomenon can be modelled.

D. *Attenuation index*

The attenuation index, represented as k (λ), is derived by adding the absorption and scattering indices or coefficients, respectively, a(λ) and b(λ), to account for the exponential power loss that occurs to the optical beam in the undersea medium[12].

Therefore, it is given by,

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

Effective estimation of the attenuation coefficient is performed as the total loss occur for a given pathlength[20].Thus, effects caused by absorption, turbulences and scattering become critical for deciding the variability of the UWOC channel. Conclusively, the combined effect of all these factors on the signal propagation will vary based on the amount of each sort of addition added to the medium. A numerical analysis on this signal propagation is included in [21].

Apart from the above, In [1], The authors have discussed multipath interference, beam spreading, turbulence, alignment, physical obstruction, and background noise. In [5], Cossu et al. has also mentioned that the main challenges underwater wireless optical communication faces are attenuation and background light. Eventually, ocean turbulence will create fading in the channel which in turn affects the performance of the system. Zeng et al.[2] presented two major challenges in their work. Firstly, the underwater optical links will have misalignment issues. Secondly, the complexity of the water environment, affecting the battery life and efficiency of the used devices. The values of the absorption, scattering, and attenuation coefficients for various types of water are shown in Fig 2.

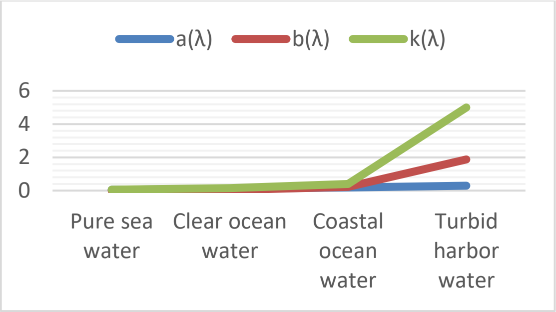

Fig.2. Absorption, Scattering and Attenuation coefficient values of different water types

In clear ocean water and pure sea water, the operational wavelength range is 450 nm to 500 nm. As a result, the blue-green portion of the spectrum is present. The spectrum for coastal ocean water and turbid harbour water is known as the yellow green spectrum and is located in the wavelength range of 520 nm to 570 nm.

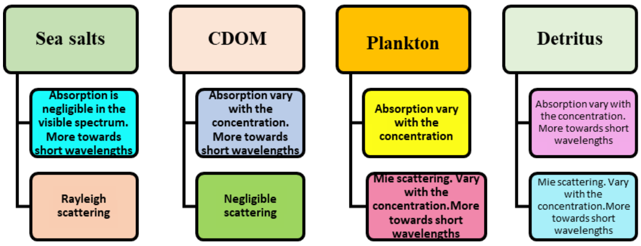

Fig.3. Absorption and Scattering Characteristics with different Seawater Compositions

Fig. 3. shows absorption and scattering characteristics with different seawater compositions. Furthermore, humic, fulvic, and chlorophyll concentrations are high in coastal ocean water, whereas they are low in pure seawater and clean ocean water. A relatively high quantity of the same can be seen in turbid harbor water.

IV. UWOC CHANNEL MODELLING

A. *Focus on channel modelling*

It is vital to have a general understanding of the channel models that have been put out by researchers in order to comprehend how light behaves as it propagates in an undersea medium. Johnson et al. has published a survey on the various channel models used for underwater optical communication [22]. An underwater channel model thus aims at describing the exact state of light originated from a source after completing a specific propagation distance through an underwater medium. The models are useful for calculating the losses, formulating the link budget, and performance evaluations. The composition of the channel is a deciding factor as there is a large impact of absorption and scattering mechanisms on the interaction of the photons with the water medium[23].

The link distances will be constrained by absorption because of the ongoing reduction in propagation energy it causes, whilst scattering will disperse the light beam and result in fewer photons being captured by the receiver. Thus, each photon can arrive at the destination in a different time window, leading to timing jitter, inter-symbol interference, and multipath dispersions [24].

B. *Channel modeling techniques*

Different channel modelling techniques are included in the literature. In [25] and [26] the authors have discussed the absorption and scattering models based on seawater properties and chlorophyll concentration.

Zeng et al. in his paper has clearly outlined the literatures on existing UWOC channel models[2]. Table.2 shows a general summary of the channel modelling techniques.

There were primarily two configurations employed in the modelling based on aquatic optical attenuation. Firstly, the line of sight (LOS) configuration, which has been the main application of Beer Lambert's law. The effects of light attenuation in an underwater environment are described by Beer Lambert's law. It is written as follows.

$$I= I_0\, e^{=C(\lambda)z} \qquad (2)$$

Where I_0 denotes the source's irradiance at a given distance z, and λ is the vacuum wavelength of transmission[22]. The equation (2) shows an exponential decrease in power where the rate of decay is dictated by the attenuation coefficient. Two assumptions were mostly used in the modelling based on the foregoing. One is that the transmitter and receiver are exactly aligned, and the other is that all of the scattered photons are lost, even though some of them can still reach the receiver after many scattering events.

The Volume Scattering Function (VSF), which is defined as the scattered intensity per unit incident irradiance per unit volume of water, is not well suited for situations where there are a large number of photons, so a Radiative Transfer Equation (RTE) was proposed to explain how the passing light beam is converted into energy. The assumptions required to solve RTE are challenging, and the answers that can be gained from this analysis are constrained in several ways. The numerical solutions of RTE are so well chosen for UWOC study. One of the widely used methods for solving RTE numerically is the Monte Carlo method[2]. By simulating the underwater propagation of many photons, the probabilistic numerical solution approach known as Monte Carlo simulation can be used. However, it still has time complexity issues, is susceptible to statistical inaccuracies, and needs extremely effective algorithms to correct for stochastic imperfections[28],[32]. Novel approach towards impulse response modelling techniques based on Monte Carlo simulation is presented in Li.Y et al. and the authors concludes better accuracy of predicting the channel behavior[33]. An integration approach accounting scattering, absorption and turbulence effects, by using a Monte Carlo simulation network is published in the work of Zhang et al. in 2020[34], which is helpful in better characterization of the channel. Recent UWOC channel modelling considers the effect of air bubbles, medium salinity, and temperature-related turbulence. Further exploration into channel modelling is required to take the aforementioned impacts into account[13].

TABLE II
UWOC CHANNEL MODELLING TECHNIQUES

Category	Examples	References
Based on aquatic optical attenuation line of sight configuration	Beer Lambert's law, Radiative Transfer Equation (RTE)	[9][27],[28]
Based on aquatic optical attenuation non-line of sight configuration	Non-line of sight models	[29]
Based on geometric misalignment	Poynting error models	[30]
Based on link turbulence	Turbulence models	[31]

V. SYSTEM MODEL, LINK CONFIGURATIONS AND DESIGN CHALLENGES

A. General system design

The system design for UWOC is shown in Fig 4. transmitter, channel, and receiver are the key components. The optical carrier is modified at the source, transforming the electrical signal into a light signal. The beam is then collimated and sent through the underwater medium. A photoelectric detector eventually receives the transmitted signal and converts the feeble light signal into an electrical signal. Precise estimation of the medium or channel characteristics is an important step in the overall system design[35].

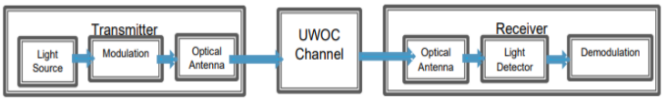

Fig.4. UWOC System design

B. Major link configurations

While reviewing the analysis models of optical wireless communication links, three models are generally proposed. The most typical channel utilised in UWOC can be regarded of as the line-of-sight (LOS) communication link. In a LOS scenario, the transmitter points the optical beam in the proper direction of the receiver. Secondly, a Modulating Retroreflector (MRR) link which allows optical communication by using the combination of an optical modulator with an optical retro reflector is used. A third type is named as Reflective communication link. When there are issues with LOS, mainly because of blockage, link misalignment issues, or misallocations, then a possible option is to use the reflective link[2]. The line of sight (LOS) model has limitations due to multiple scattering. This eventually causes that a photon might lose its LOS path. NLOS link suits to this scenario. It is useful in turbulent environments due to ease of alignment requirements and its ability to increase the robustness of UWOC links.

C. Design challenges

It is obvious that the choice of the desired wavelength is dependent on the water characteristics. The need for modeling vertical links is a remarkable challenge, since the horizontal link-based channel modeling has been addressed and resolved to an extent. The Turbulence effect is a major issue. Turbulence creates fading, an intensity fluctuation, and further phase fluctuations of the light beam. The turbulence is caused by refractive index variations in water, which are random in nature[14].Johnson et al. investigated the effect of dynamically varying ocean composition, on the attenuation factors of the vertical communication links. As the ocean composition changes rapidly with depth variations, assuming the attenuation coefficient as a constant, would result in inaccurate approximations. Indeed, it is important to know about how attenuation varies with a vertical profile. The authors have stated a scenario of establishing a link vertically. A link between a receiver operating above the ocean surface and a diver is the best example for the above scenario. Furthermore, changing attenuations per depth, would be applied to the secure low noise underwater communications[22].

A performance evaluation and analysis has been illustrated in[37], where in order to examine the effects of turbulence and further-induced fading in UWOC channels, the fading effect has been treated as a multiplicative coefficient together with the coefficients of scattering and absorption. In their work of Cai, R. et al. [38], the authors have developed a detailed multiparameter model for the UWOC channel. The findings showed that by boosting the transmitting light power, bit error rate (BER) performance may be significantly improved under weak or medium turbulence. The mean light intensity and scintillation index were assessed using various channel parameters.

The use of a particular model for the probability density function of the intensity of the propagating plane wave does not give rise to appreciable variations in the values of the BER, according to an analysis of the impact of turbulence parameters such as temperature and energy dissipation rates, and the temperature-salinity gradient ratio in [39].

VI. OPTICAL TRANSMITTERS, RECEIVERS, MODULATION AND CODING

A. Optical transmitters and variables

The optical transmitters, which function as the light sources, have a significant impact on the UWOC link's performance. Mostly there are two types of UWOC transmitting devices used. They are the Laser Diodes and Light Emitting Diodes (LDs) (LEDs). The advantages of LEDs are affordability and energy efficiency. The broad angle beam profile of LEDs can also assist with the alignment challenges. In natural waters, LED is considered to be more susceptible due to its broad angle beam profile. Its emitter power is supportive to a relatively shorter distance[36]. Table III shows the major laser types and wavelengths used.

TABLE III
LASER TYPES AND WAVELENGTHS.

Laser Type	Wavelength
Semiconductor laser	375-473 nm (GaN),405 nm, 450-470 nm (InGaN)
Metal vapour laser	441.6 nm, 570 nm, 578 nm
Liquid dye laser	450-530 nm
Doubled Ti-Sapphire	455 nm
Argon-ion laser	455-529 nm
Diode pumped solid state	473 nm (Blue), 532 nm (Green)
Fiber laser	518 nm
Flash lamp pumped frequeny doubled Nd:YAG	532 nm

B. Optical receivers and variables

Avalanche Photodiodes (APD), Multipixel Photon Counters (MPPC) and PIN photodiodes are the common detectors used. There are many receiver parameters that are significant towards the link performance in the receiver side. A notable design guide line is given by Cox et al.[20], wherein they have proposed areas useful in finding the design tradeoffs. It is hypothesised that optical losses increase with distance, with receiver aperture and field of view, and eventually with transmitter and receiver offsets.

Table IV displays a comparison of UWOC detectors. One may see that the accuracy is high in all cases. The PIN photodiodes has a short range while the other two has long ranges. Besides, the uniformity of MPCC and PIN photodiodes are marked good whereas for APDs, it is dependent on size. From theory, the response time of MPCC is fast while the others have a medium response time. PIN photodiodes have the highest ambient light immunity and APDs have the highest temperature sensitivity.

TABLE IV
A COMPARISON OF DETECTORS

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

C. Modulation and coding

UWOC system performance is highly dependent on the use of suitable modulation techniques. Generally, the wireless optical modulation schemes are categorized into two main classes. They are intensity modulation (IM) or Non coherent Modulation and Coherent Modulation (CM). To implement these techniques, either a direct or an external modulator is used. The former one is easy to implement but at the cost of limitations in link distances and data rates. The latter one is useful in utilizing full power of the source at the cost of high drive current. IM is mostly used, in which the data is modulated on the intensity of the optical receiver. When the IM data is detected by a direct detection receiver, then the scheme is referred to as Intensity Modulated Direct Detection (IM/DD). The other name for this is non-coherent detection and is widely used in UWOC systems. There is another approach knows as coherent detection, in which, homodyne or heterodyne detection is put to use. However, the method is costly and has complexities in it. The goal of selecting, experimenting with, and evaluating the performance of various available modulation schemes and multiplexing techniques is to increase the transmission distance and improve the data rate. Optically pumped solid state lasers have nonlinearities which will affect the direct modulation. While semiconductor lasers are more useful in blue regions, extending the use of the same into green regions is a notable research issue of direct modulation. IM/DD is a simple and widespread technique. ON/OFF Keying (OOK) is also used with this. In simple sense, the 1s and 0s are represented by the presence and absence of light in OOK. It is generally divided into RZ OOK and NRZ OOK. The disadvantage of OOK is its dynamic thresholding requirement and the performance is greatly reduced with channel variations. Pulse position modulation (PPM) is another alternative. This is a lower energy-consuming scheme. At the same time, spectrum efficiency is low for PPM. Modified PPMs are also used. Differential PPM (DPPM) is one such technique. Pulse Width Modulation (PWM) is useful in some schemes as it has a spectral efficiency and immunity towards ISI effects. Pulse Interval Modulation (PIM) like Dual PIM (DPIM) and Dual Header PIM (DH-PIM) are two other important schemes used. Coherent modulation schemes are listed with merits in terms of higher spectral efficiency, rejection of background noise and good receiver sensitivity but at the expenses of cost and complexity. Phase Shift Keying (PSK) has better Bit Error Rate (BER) performance. Polarization Shift Keying (PolSK) systems are good in turbid environments. The Binary PolSK(BPolSK) technique uses polarised light states. Quadrature Amplitude Modulation (QAM) technique is spectral efficient and capable of rejecting background noise and cost effective. Subcarrier Intensity Modulation (SIM) schemes are having increased system capacity [1][2].

Control codes and error detection methods can be used to fix for BER performance degradations brought on by channel defects. To increase power efficiency, UWOC systems can use Forward Error Correction (FEC) coding. The bandwidth efficiency, however, will be low. Block codes and convolutional codes are the two subcategories of FEC codes. Reed-Solomon (RS) and Bose-Chaudhuri-Hocquenghem (BCH) codes are two of the more basic and robust block coding methods. Some systems use the Cyclic Redundancy Coding approach as a convenient and simple method of error detection. Block coding, however, is not adequate to produce an optimal performance in interference conditions. Better coding methods like Low Density Parity Check (LDPC) and Turbo coding are used in these cases[2].

VII. RECENT WORKS IN UWOC

Cossu et al.[5] has addressed recent achievements in the field by presenting the technology as a promising futuristic solution. The authors have listed various UWOC researches and reviewed several experimental realizations. Saeed et al.[3] has outlined the open problems and has pointed out directions in UWOC research towards development of Underwater Optical Wireless Networks (UOWNs). The authors have elaborated the physical, data link, network, transport and application layer approaches descriptively. Finally, a differential analysis has been made among the levels of UWOC networks so as to conclude that the goal is to develop architectures of accurate and practical UOWNs. In [2],a comprehensive survey on UWOCs, is given. Mainly, three aspects have been summarized. They are, characterization of the channel, schemes of modulation and necessary coding techniques. Besides, this survey has explained various configurations of UWOC links. By evaluating UWOC against Free Space Optical (FSO) technologies, it has been clearly stated that terrestrial FSO channel models are not very much suggestive to be used in underwater. Thus, it has been concluded that new reliable channel models must be proposed. Furthermore, the authors have presented significant details of UWOC system implementations. Comprehensive description of the transmitter, underwater channel, receiver, modulators and channel coders has been discussed in details by Kaushal et al.[1].

As listed in[5], from 2015 to 2019, several experiments were carried out in clean and turbid water using different combinations of sources and modulation schemes. In 2015, Oubei et al. has experimentally demonstrated a high speed UWOC in 2.3 Gbits per second over 7 m distance and published a work of it[41]. The authors have also recorded a transmission to realize 4.8 Gbps at a distance of 5.4 m [42]. In this work, the authors have used spectral efficient modulation schemes with a 450 nm fiber pigtailed using LD as the optical transmitter and an APD as the receiver. In 2017, the authors have published an experimental evaluation to find the impact of air bubbles on the UWOC links. Additionally, the effectiveness of UWOC systems in the presence of various air bubble sizes was examined to conclude that small air bubble sizes causes less fading of the optical beam and suggestively proposed beam expansion technique to improve the UWOC performance[49].A real-time transmission through an underwater channel at 4.8 m with 1.45 Gbps optical Orthogonal Frequency Division Multiplexing (OFDM) signal is published by Nakamura et al.[40].

In 2016, A transmission of 8 m with 9.6 Gbps is described in work of Lu et al. in which it is described that there has been use of a two-stage injection locked method for the first time in an effort to increase UWOC performance. The transmitter utilized low threshold current, 405 nm blue light LD and the transmission was demonstrated as an innovative approach towards achieving longer transmission distances[43]. In another published work of Shen et al. in 2016, there demonstrated a 20 m transmission covered with a rate of 1.5 Gbps, and a 12 m long transmission at 2 Gbps, which the authors have achieved this with a small, low-power UWOC system that uses a Si APD detector and a 450 nm LD transmitter [44].

In 2017, An effective transmission of 2.7 Gbps is described in with 34.5 m distance in the work of Karp et al. The authors have explained the experiment using a green GaN based LD directly modulated suing OOK scheme[45]. An 80 µm Micro LED transmission using GaN reached a distance of 0.6 meters at 800 Mbps data rate as described by Tian P. et al. in [46]. An arrayed transmitter and receiver system used by Kong M. et al. with optical superimposition based PAM4 scheme has marked various transmission rates from 6.144 Mbps to 12.288 Mbps over a 2 m channel using tap water [50].

In 2019, a demonstration of 50 Gbps UWOC has been published with water-air-water interface. In this, the authors Li et al. have used PAM4 modulation scheme and employed reflective spatial light modulator (SLM)[47]. In another work, A 500 Mbps communication with 100 m range is explained in by Wang et al[48]. Tian P. et al. has tested a UWOC system realising data transmission rates varying from 790-933 Mbps at 2.3 m distance in four different transmissions with and without impurities added in the channel, and has concluded that the addition of impurities causes performance degradation[51].

In 2020, a test setup was designed to transmit an image through an underwater channel with various-sized air bubbles were present. The authors, Singh M. et al., evaluated the experimental data using a statistical Gaussian Mixture Model (GMM), and they conclude that the observed data and the analytical expression fit well[52]. In their work of Li, J. et al.[53] ,with its hardware structure based on an FPGA and an underwater channel optical link model, the authors experimentally presented a full-duplex UWOC transmission system that has been tested in an indoor water tank. A high-power LED array's electrical power requirements and transmitted optical power have indeed been directly estimated. Additionally, a technique for choosing an acceptable APD was proposed. A suitable reverse voltage for the APD can be chosen theoretically in order to enhance SNR. The system was able to transmit underwater video for 10 metres at a data rate of 1 Mbps.

In their work, Oubei et al. summarised the recently attained UWOC data rates as ranging from 0.2 Mbps to 14.8 Gbps and link distances from 1.7 m to 34.5 m[13].

In 2022, Hong, X. et al.[54] state that their experimental demonstration of a 55-m,2-Gbps UWOC system, which incorporates Silicon Photo Multiplier (SiPM) diversity reception and a nonlinear decision-feedback equalisation, is the highest data rate ever achieved utilising an off-the-shelf SiPM.

It has now been demonstrated that UWOC is effective at tens of Gbps data rate and hundreds of meters of distance through the deployment of several links and physical layer evaluation. These links would ensure the possibility of realising an internet of underwater things (IoUT) in the future. However, the practical challenges should be efficiently addressed[8][55].

VIII. DISCUSSION AND SUMMARY

By reviewing the literature, the following points could be summarized as suggestions for feasible and reliable UWOC system design.

1. New reliable channel models must be proposed for UWOC as those for terrestrial FSO are not suitable to be used in UWOC.
2. It is required to propose channel models to include the effects of turbulence.
3. Development of energy-efficient schemes of modulation and coding, especially for turbid waters, is a major research challenge.
4. Following that, energy-efficient techniques for smart localization, beam alignment, and implementing transmitters and receivers with self-adaptability to operating conditions must be developed.
5. Significant research is required to increase the data rate in the blue-green region with amplification along with frequency conversion techniques.
6. Nonlinearity issues caused by the transmitting components, which eventually induce impairments in receivers, must be accounted for. To resolve this, the use of nonlinear equalizers was proposed[36].
7. The issue on link misalignment has been addressed in[30]. A diffused field of light would be formed as a result of the ocean's ability to scatter light, which gradually minimizes the need for link alignment. This would provide a receiver design that is optimized with a marginally changed transmitter power.

CONCLUSION

The UWOC field is more interesting and distinctive due to the demanding high rate of data transmission requirements and prospective system developments related to underwater sensor networks. Major hurdles and research problems in UWOC have been put into consideration in our work since we perceive it to be a potential platform in which substantial research can be conducted. A considerable research barrier has been recognized in the development of accurate channel modelling and reliable links. Reviews of the performance indicators of a UWOC system have been combined with a summary of the important designing concerns for the transmitter, channel, and receiver. Making accurate estimates about the attenuation profile and link construction needs would require a thorough understanding of the channel parameters. It is evident from the literature that in order to build high performance networks, simulation model formulation and evaluation are crucial.

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