Marine Information Technology Curriculum Report

Title：Recent advances in UWOC systems.

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Contents

1. Introduction

A swirling large body known as "Ocean" that covers more than 70 percent of the Earth's surface and provides nearly about half the air we breathe and yet much about the planet's oceans remains a mystery. According to the National Oceanic and Atmospheric Administration (NOAA) it is estimated that as much as only 5 percent of the world's oceans and 1 percent of the ocean floor are explored, which gives us an opportunity to look in the unexplored ocean and its basin. The traditional methods use acoustic, radio-frequency technologies, in-situ, cabled or fiber-based techniques and other available physical measurements techniques which provide high speed and reliable communication medium to collect the data measurements from the oceans. Still there are some difficulties in their use at remote locations and Deep Ocean, where the range and maneuverability will be limited. These techniques have flaws like expensive, time consuming, spatial, and temporal coverage and errors made by humans while acquiring the data. To overcome these flaws in measurements, scientist communities shifted to remote sensing (RS) techniques of oceans. Satellite RS technique gives detailed picture of ocean surface which covers large areas, less time consuming, frequent availability of data but still it is an expensive and does not allow us to see underneath the ocean surface. In such scenario, there is a broad interest in the use for wireless optical communication techniques. Optical wireless communication systems provide high data rates (in the order of Mbps to few Gb/s) for short and moderate ranges (up to few tens of meters), for the large available bandwidth. Because of the high propagation speed of optical waves, optical transmission suffers less from latency. Therefore, optical communication is a potential alternate solution to long range traditional acoustic communication.

Acoustic transmissions techniques are being used for diverse underwater operations such as real time transmission of signals from underwater sensors were made possible. However, acoustic signals transmitted in water bodies are subjected largely to be attenuated by reflection loss, multi path signals and scattering at the water surface and bottom, this result in significant data loss in the communication system. In 1995, an underwater wireless communication system (UWC) with high speed acoustic data transmission was proposed [1], with a data rate of 8 kbps was achieved over a horizontal path length of 13 km at a depth of 20 m. Later in 1996, author's eexperimentally showed the detection of digital signals transmitted at 40 kb/s over one-mile shallow water channel [2]. Further, more advanced systems were developed to achieve high speed data transmission using underwater acoustic wireless communication (UAWC) systems. Better underwater communications systems were developed for horizontal underwater microwaves-based wireless communication system which can communicate over a distance of 85m, where, in [3] authors have achieved 500 kb/s data speed over a horizontal path length of 90m. However, acoustic communication techniques have many drawbacks including high time delay, low propagation speeds, low bandwidth, scattering and high attenuation. The UAWC systems have proven over the time for their contribution in long distance communication range, but the biggest drawback of UAWC is system security, bandwidth, and propagation delays.

However, in recent years, there are growing research activities in underwater wireless optical communication (UWOC). There is an urgent need for a comprehensive survey that can provide researchers with a fundamental understanding of UOWC and knowledge of the state-of-the-art UWOCresearch.There is a recent shift in the use of UWOC in remotely-operated vehicles (ROVs), autonomous underwater vehicles (AUVs) and underwater wireless sensor networks (UWSNs). Optical wireless communication (OWC) is most prominent way to transfer data using propagation media as an ultraviolet (UV), visible and infrared (IR) spectrum of EM band. UWOC has attracted increasing interest in various underwater activities ocean environmental monitoring, ocean research and underwater exploration because of its order-of-magnitude, high bandwidth, large unlicensed spectrum compared to traditional acoustic and radiofrequency (RF) technologies. Demand for use of robotics in underwater surveillance in order to increase precision and operability. Underwater communication systems are crucial piece in the underwater surveillance and data transmission.

The UWOC system uses the visible band of the electromagnetic spectrum (450-570 nm), where water is relatively transparent to the light and scattering and beam attenuation takes its minimum value. The performance of associate underwater optical wireless communication system is highly contingent with the channel through which it propagates. Within the underwater, previous studies have shown that however very tiny variations within the composition of water results in native changes in the attenuation and scattering properties of water [4, 5], recently these concepts are accustomed confirm the attenuation and scattering as a function of depth [6]. The study explains the communication channel for links where the receiver is directly placed underneath the transmitter, the directional properties of the travelling beam must be considered for links that are neither perpendicular nor parallel to the ocean surface. As a result of this the directional changes to occur because the transmitted light beam undergoes multiple refractions. These refractions caused because of the variation within the index of refraction of water, significantly because it changes with depth.

Lately, UWOC systems with high bandwidth and greater transmission range has become a growing research interest and prerequisite for better foundation of UWOC systems, various communications systems were developed using LED's to improve data rate of UWOC systems [8]. The first experimental UWOC system demonstration was made by Snow et al. in 1992, where they achieved a data rate of 50 Mb/s over a 5.1 m water channel [7]. In [8], with the low cost commercial blue LED and PIN photodiode authors have experimentally demonstrated an UWOC system employing intensity modulation/direct detection-OFDM (IM/DD-OFDM) modulation technique. The 450nm blue LD based UWOC system proposed using 16-QAM OFDM to achieve bitrate of 7.2 Gb/s for transmission in seawater over 6.8 m path length and to 12.4 Gb/s in the course of 1.7 m path length in tap water [9].

	Technology		
Index	RF	Acoustic	Optics
Dependencies on Sea water properties	Conductivity (σ) Frequency (λ) Seawater permittivity	Frequency (λ) Temperature T Salinity S Pressure P Bubbles	Absorption Scattering/Turbidity Phytoplankton Organic Matter Bubbles
Effective Range	≈ 100m	≤20 km	10-100 m
Speed	$2.25 * 10^8$ m/s	1500 m/s	$2.25 * 10^8$ m/s
Data rate	Upto 100 Mb/s	Few Kb/s	Several Gb/s
Power Consumption	100 Watts	Few 100 Watts	Few Watts
Antenna Size	0.5 m	0.1 m	0.1 m
Latency	Moderate	High	Low
Cost	High	High	Low

Table 1: Available underwater wireless communication systems have been summarized in table above

Some hybrid systems having combinations of both acoustic and optical underwater wireless communication system can be another alternative for underwater wireless communication network [10]. However, the research on development of hybrid systems still needs some improved techniques for better communication.

2. Overview of Underwater Wireless Communication System

Basic pictorial 3D architecture of an underwater wireless sensor network (UWSN) with multiple node communication technologies are explained in. The node in UWSNs uses optical as well as acoustic links for signal communication between each other and with other underwater optical base stations (OBS) or surfaced floating OBSs, optical. UWSNs consist of many distributed nodes such as AUVs, ROVs, seabed/floor sensors, relay buoys, anchored sensors and floating sensors.The communication between the multiple OBSs at the horizontal depth uses optical links, while the communication between the OBSs at different depths in a vertical orientation or non-horizontal path may use optical as well as RF links. As shown in Figure 1 some surface buoys or underwater vehicles can operate on solar power which provides energy efficient solutions to the communication link.

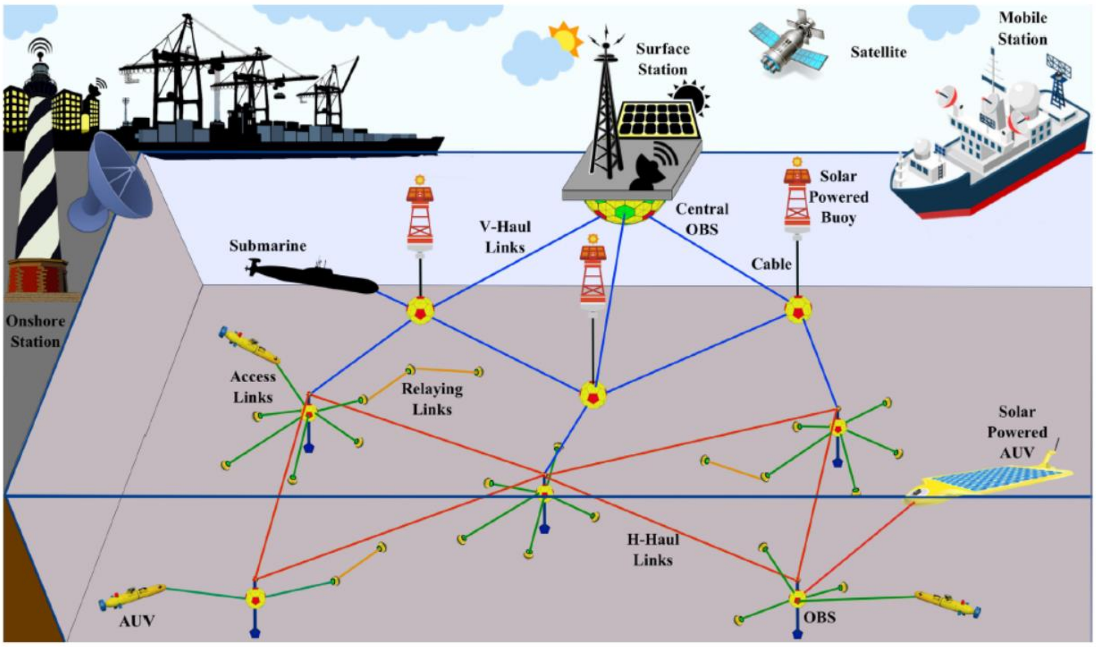

Figure 1: Basic pictorial 3D architecture of an underwater wireless sensor network (UWSN) (Nasir Saeed 2019) [11].

It is possible to use a preprogrammed software-defined network (SDN) in extraordinarily complex environment where number of multiple communication devices can communicate with each other. AUVs and ROVs can communicate with other underwater vehicles, underwater or floating buoys, floating devices, ships, and submarines using optical, RF or hybrid optical–acoustic communication links. Signal communication in such complex environment might userecent medium access control, routing, transport, and cross-layer networking protocols and also uses links between land stations to satellite, satellite to buoy or off shore platform, ship to land or to satellite, further the data can be exchanged through RF antennas placed at floating platform to land/on shore data collection and processing stations. This whole optical communication system which includes hybrid acoustic-optical underwater wireless sensor network can provide high-speed, low latency, energy efficient [12] communication links which can cover long range. Considering that the UWOC systems are in high demand for underwater applications, better knowledge of optical water channel and surrounding limitations for efficient data transmission and link establishment must be well studied.

3. Underwater Optical Communications System

An underwater optical communication system can be an option that may provide better solution for underwater communication with optical wave, wherein high data rates are possible. Optical communication technology delivers good performance in clear water and requires precise alignment of optical transducer due to the link establishment and the limitation on transmission ranges [13]. The medium behaves differently for RF and optical wave propagation in seawater: the water is a conductor for RF wave and act as a dielectric for optical wave propagation. The seawater changes from conductor to dielectric for certain frequencies [14]. In dielectric medium the RF wave shows lower attenuation compared to conductor medium, thus optical technology can provide higher data rates as compared to RF, for a limited propagation range up too few tens of meters. The speed of light is around 4 to 5 orders of magnitude greater than the speed of acoustic waves in fluids; due to this the Doppler spread and its effects are almost negligible in optical technology. The distance between the transmitter and the receiver must be short to establish the communication, due to challenging underwater environment, which is characterized by high attenuation, absorption, and scattering. Multi-scattering causes the optical wave to expand in the spatial, temporal, angular, and polarization domains. The high data rates are vulnerable to extremely high attenuation, absorption and scattering, there is studies have been reported that broadband optical communication links can be achieved over certain transmission ranges [15].

The optical wave propagation distance is frequency depended. The blue-green optical band is much transparent to water and has lower optical attenuation; this information has been used to further develop and to improve blue-green light sources and detectors [4,16]. The water has two distinct features that affect light propagation in water: inherent optical properties (IOPs) and apparent optical properties (AOPs). Inherent optical properties depend only on the water medium, whereas apparent optical properties depend on the both water medium and light source characteristics [4,5,17].

For underwater optical wireless communication, the spectral absorption coefficient, and the spectral volume scattering function (VSF) are the most important IOPs [18]. In absorption process, the electromagnetic radiation is transforms into heat. Absorption occurs at chlorophyll in phytoplankton, by colored dissolved organic matter (CDOM), by water molecules itself, and by dissolved salts in water [17]. The absorption coefficient is denoted by a parameter $a(\lambda)$ [4], which measures spectral absorption coefficient per meter (in m^{-1}), at a given wavelength (λ). The scattering changes the direction of the photons. Scattering can be occurred by suspended particles, by salt ions in pure water, by particulate matter and or by turbulence in ocean. Scattering due to objects those are smaller than the wavelength of light is described by the Rayleigh scattering, whereas scattering due to objects which larger than the wavelength of light is described by Mie scattering. The spectral scattering coefficient is denoted by a parameter $b(\lambda)$, which measures spectral scattering coefficient per meter (in m^{-1}), at a given wavelength (λ).

Hanson and Radic [16] demonstrated 1-Gbit/ s data transmissions in a laboratory experiment with a simulated aquatic medium and scattering characteristic are similar to oceanic waters. Cochenour, Mullen, and Muth [19] measured the spatial as well as temporal effects of scattering on a laser communication link in turbid underwater environments. Using Monte Carlo simulations and measurement results, they predict longer-range underwater free-space optical performance with bandwidths greater than 5 GHz for a range of 64 m in clear ocean water which drops to 1 GHz for a range of 8 m in turbid harbor water. The authors [20 and 21], have examine the fundamental physics and natural variability of underwater optical attenuation and discuss the design issues of underwater optical communications associated with oceanic physics and parameter variability.

The various types of noise such as, optical background noise which may be gets introduced due environmental background, quantum shot noise may occurs due to random variations in the number of photons at optical receiver, optical excess noise may be caused by transmitter imperfections, excess noise may be generated in the process of amplifying the signal at the receiver, photo-detector dark current noise is caused by electrical current leakage from photo-detector and electronic noise may be introduced by electronic components [22]. These noises can hamper the performance of underwater optical communication system

In optical communications it is important to quantify channel characteristics for better signal transmission and detection method for a reliable communication. The channel maybe affected by inherent to physical properties and effects related to receiver aperture size. Unlike other technologies, the optical transducer requires special signal processing algorithms to track changes in the direction of the receiver field of view (FoV) and the optical transmitter beam. The possibility of channel interruption due to marine algae, blooms and other marine life should be detected to avoid transmission loss. Signal processing also plays a key role in communication link by filtering the received signal to counter environmental noise. Optical communications usually require line-of-sight link between transmitter and receiver, which involve direction tracking of light beam to maintain the communication link. The optical transducer can be configured in closed loop where the receiver can inform the transmitter with power and data-rate controls obtained from the backscattering estimation. The receiver can also estimate the angle of arrival and inform the transmitter to keep the alignment as precise as possible.

The main drawback related to underwater optical communications is their dependence on water turbidity. This environmental condition limits the propagation distance, which affect the longer communication links. It is time to re-evaluate the capabilities of Optical communication signaling in the underwater environment.

4. UWOC system architecture

The recent development in underwater optical communication technology has brought revolutionary change in new underwater communication technology over conventional technologies, which enables rapid and safe communication applications. The optical underwater communication system includes a “transmitter” which serves purpose for transmitting optical light signal with projection optics and beam steering elements in order to focus and steer the optical beam. While, at the “receiver” end the collecting optics collets light signals for a communication purpose. In underwater optical communications system, a transmitter can work as actuators at the transmitter end and receiver can work as a sensor. The transmitter is designed to convert an electrical input signal to an optical output signal using light source, whereas receivers convert optical input signals into electrical output signals. The recovered electrical signal is then allowed to pass through demodulator unit to regenerate original transmitted signal.

a. Transmitter:

The optical source can be either a laser or a light-emitting diode (LED). In the case of laser sources, as each technology has distinct characteristics, the selection of the most appropriate one depends on the system requirements. One technology is argon-ion lasers, in which the electrical to optical conversion is extremely inefficient [23]. Other technologies include diode-pumped solid-state (DPSS) lasers, InGaN lasers, whose devices are much more expensive than LEDs [23] and are susceptible to over-current problems, and tunable lasers, which can adapt the frequency of emission in order to have lower wave propagation attenuation according to the particular environmental characteristics. Another technology is the so-called laser modulators, whose data rates are extremely low (in the order of bps or kbps) and the propagation range is relatively longer (in the order of hundreds of meters) [23]. On the other hand, LEDs are cheaper optical sources when compared to lasers, but they have shorter propagation range [25]. The function of projection optics is to focus the beam toward a predefined direction. Beam steering is fundamental to the optical system performance.

Indeed, transmitter and receiver have to establish a point-to-point spatially aligned connection so that the optical signals that arrive at the receiver end have enough energy to be reliably decoded. In this context, the concept of smart optical systems is emerging in which transmitters are able to estimate water quality through the backscattered signal in order to adapt the transmission power, accordingly, thus improving the overall transmission process [25]. The smart transmitter might have an array of LEDs designed in hexagonal pyramid shape [25], where each LED has one lens. Each LED can be individually addressed for choosing an output direction, composing the switched beam steering mechanism at the transmitter side. Newly developed LEDs emit substantial light and are typically very inexpensive. Currently, LEDs can emit up to several watts of power into an angle of several tens of degrees. If these LEDs are placed in an array, the output power can be substantially greater. Laser diodes with their output frequency shifted into the 500- to 650-nm range can emit more power than LEDs but are more expensive.

b. Receiver:

Receivers are composed of collection optics and detector [23]. The collection optics can be a single lens, or an array of lenses, whose main role is to gather the transmitted rays. The detector is a photo sensor, whose main role is to convert optical signal into electrical signal. The objective of the transducer at the reception end is to collect the maximum number of photons that were transmitted. In order to improve the system performance, some relevant characteristics of the collection optics and of the detector have to be analysed and considered in the system design. One characteristic is the aperture size of the photo sensor. It is desirable to have a sensor with large aperture size. One photo sensor with this characteristic is the photo multiplier tube (PMT). These sensors, however, can be expensive and bulky [25], which is a disadvantage for some applications. Another alternative for increasing the aperture size is to use an array of lenses in front of the small collection area photo sensor. An ideal photo sensor should be cheap, small, robust, and power efficient [26], however, these requirements cannot be fulfilled simultaneously in the current technology stage. According to the system specifications, a particular type of photo sensor must be chosen. The main photo sensor types are [23, 24]: photo resistors, photo thyristors, phototransistors, photomultiplier tube (PMT), p-n photodiodes, avalanche photodiode(APD), photon detector selection, semiconductor photo sensors, and biologically-inspired quantum photo sensors(BQP).

Authors	Year (Ref)	Modulation Scheme	Tx Type	Rx Type	Output Power	Link Range	Data Rate	BER
Hassan Makine Oubei (KAUST),)	2015 (1)	OOK-NRZ	520 Nm LD	APD	12 mW	7 m	2.3 Gbit/s	2.23×10−4
Hassan M. Oubei (KAUST)	2015(2)	16-QAM-OFDM	450-nm LD	APD	15 mW	5.4-m	4.8 Gbit/s	2.6 × 10−3
MEIWEI KONG (ZJU)	2016(3)	32-QAM OFDM	WDM–RGB LD	APD	35mW,15 mW, 1W	10-m	9.51-Gb/s	2.2 × 10−3, 2.0 × 10−3 and 2.3 × 10−3
CHAO SHEN (KUSAT)	2016(4)	NRZ-OOK	450-nm	Si APD	51.3 mW	12 and 20-m	2 and 1.5 Gb/s	2.8 × 10−5, and 3.0 × 10−3
YIFEI CHEN (ZJU)	2017 (5)	OFDM	520 Nm LD	APD	NA	21 m	5.5 Gbps	2.92×10−3, 2.92×10−3
XIAOYAN LIU (Fudan University)	2017(6)	NRZ-OOK	520 Nm LD	APD	19.40 mW	34.5 m	2.70 Gbps	3.4 × 10−3
JIEMEI WANG (USTC)	2019(7)	NRZ-OOK	520 Nm LD	APD	7.25 mW	100 m	500 Mbps	2.5 × 10−3
Tsai-Chen Wu (NTU)	2017(8)	16-QAM-OFDM	450-nm LD	PIN	26.15 mW	1.7m	12.4 Gbps	2.9 × 10−3
Yu-Fang Huang (NTU)	2018 (9)	16-QAM-OFDM	450-nm LD	PIN	120-mW	1.7 m.	14.8-Gbps	4.0 × 10−4
Frank Hanson(1Space and Naval Warfare Systems Center)	2007(10)	AM	532 nm LD	APD	7 mW	2 m	1 Gbps	NA
PENGFEI TIAN (Fudan Uni)	2017 (11)	OFDM	440 nm μ-LED	PIN/APD	1.1 mW	5.4 m	200 Mb/s	3.0 × 10−6
Joshua Baghdady (COMSET)	2016 (12)	OOK-NRZ	445-nm fiber-pigtailed LD	APD	NA	2.96 m	3 Gbit/s	2.073 × 10−4
K.	2015	IM/DD-	405 nm LD	APD	NA	4.8 m	1.45	9.1 × 10−4

Nakamura (Uni. of Yamanashi)	(13)	OFDM					Gbit/s	
Jing Xu (ZJU)	2016 (14)	QAM	520 nm LD	PIN	6 mW	2-m	1.118 Gb/s	2.98×10−3
JINGJING WANG (Qingdao UST)	2019 (15)	16-QAM	450-nm LD	PIN	NA	3 m	50 Mbps	7.11 × 10−4
Jing Xu (ZJU)	2016 (16)	32-QAM-OFDM	685 nm LD	APD	5.01 mW	6 m	4.883 Gb/s	3.20 × 10−3

Table 2: Recently developed UWOC systems with data transmission rates and distances

c. Optical Channel:

Water is transparent to the wavelengths of electromagnetic radiation that fall within the visible range of EM spectrum and is opaque to wavelengths above and below this band. However, once in the water, visible light is subject to both refraction and attenuation. Light rays that enter the water from air at any angle other than a right angle are refracted (i.e., bent) because the light waves travel at a slower speed in water than they do in air. The amount of refraction, referred to as the refractive index, is affected by both the salinity and temperature of the water. The refractive index increases with increasing salinity and decreasing temperature. This relationship allows the refractive index of a sample of seawater at a constant temperature to be used to determine the salinity of the sample.

Absorption & scattering:

The light that travels through the water is attenuated by absorption due phytoplankton, organic or inorganic matter present on the water and to convert it to other forms of energy, such as heat that warms or evaporates water, or is used by plants to fuel photosynthesis. Light which is not absorbed can be scattered by molecules and suspended particles present in the water. Scattered light is deflected into new directional paths and may wander randomly to eventually be either absorbed or directed upward and out of the water. It is this upward-scattered light and the light reflected from particles that determine the color of the oceans as seen from above.

Absorption restricts the transmission range of an underwater optical wireless link by causing the total propagation energy of an emitted light beam to continuously decrease. On the other hand, scattering spreads the photons toward random directions such that some portion of them is not received by the receiver as it has a finite aperture size, whereas the reception of some other portions may be delayed due to the following of different propagation paths. Thus, scattering leads to multi-path fading, time-jitter, and inter-symbol interference phenomena. The volume scattering function (VSF) can be interpreted as the scattered intensity per unit incident irradiance per unit volume of water and expressed as [27],

$$\vartheta\,(\lambda, \varphi) \ = \ \lim(d \to \ 0)\lim(\omega \to \ 0)P\ s\ (\lambda, \varphi)\ (d\_\omega) \text{ ------------- (1)}$$

Where, $P\ s$ (λ, φ) is the power of the scattered light beam into a solid angle.

The scattering coefficient can be obtained by integrating VSF over all the directions, i.e., $b(\lambda) \ = \ \vartheta(\lambda, \varphi)\ d\omega$. Furthermore, the scattering phase function (SPF) can be expressed by normalizing the VSF by the scattering coefficient [27], i.e., $\vartheta\,(\lambda, \varphi) \ = \ \vartheta(\lambda, \varphi)\ b(\lambda)$, which is commonly represented by the Henyey-Greenstein (HG) phase function [12] . HG phase function is a convenient approximation of the ocean scattering functions. They are helpful in reducing complexity in the calculations but can significantly influence the delay spread [28]. Extinction coefficient which is the sum of absorption and scattering coefficients can be formulated based on a geometric model proposed in [5], given as

$$c(\lambda) = \ a\ (\lambda) + \ b(\lambda) \text{ ------------- (2)}$$

	beam attenuation coefficient c (m^{-1})	Absorption coefficient a (m^{-1})	Scattering coefficient b(m^{-1})	Beam Extinction coefficient/length $(a + b)^{-1}$ (m)	Spectral single-scattering albedo ω_o=(b/c)
Pure sea water	0.043	0.0405	0.0025	23.26	0.581
Clear ocean waters	0.151	0.114*	0.037	6.62	0.245
Coastal ocean waters	0.398	0.179*	0.219	2.51	0.550
Turbid harbor waters	2.190	0.366*	1.824	0.46	0.833

Table 3: Inherent optical properties for the waters, Data reproduced from [29], for 514 nm,

*Estimated by Petzold (1972) at λ= 530 nm.

Where, *a* (λ), *b* (λ), and *c*(λ) are in units of m^{-1}. These coefficients heavily depend on water types and depths. Based on their influence on the inherent optical properties, the oceanic water types are classified by Petzold [29] in Table 3,

Water molecules, dissolved salts, organic substances, and suspended particulates combine to cause the intensity of available light to decrease with depth. Observations of light attenuation in ocean waters indicate that not only does the intensity of solar radiation decrease with depth but also the wavelengths present in the solar spectrum are not attenuated at the same rates. Both short wavelengths (ultraviolet) and long wavelengths (infrared) are absorbed rapidly and are not available for scattering. Only blue-green wavelengths that penetrates at much higher depth, and, because the blue-green light is most available for scattering, the oceans appear blue to the human eye. Changes in the color of the ocean waters are caused either by the color of the particulates in suspension and dissolved substances or by the changing quality of the solar radiation at the ocean surface as determined by the angle of the Sun and atmospheric conditions. In the clearest ocean waters only about 1 percent of the surface radiation remains at a depth of 150 meters (about 500 feet). No sunlight penetrates below 1,000 meters (about 3,300 feet). There are many ways of measuring light attenuation in the oceans. A common method involves the use of a Secchi disk, a weighted round white disk about 30 cm (about 12 inches) in diameter.

	violet		blue green			yellow	orange	red
wavelength (micrometer)	0.30	0.40	0.46	0.50	0.54	0.58	0.64	0.70
oceanic water, most transparent	16%	4%	2%	3%	5%	9%	29%	42%
oceanic water, least transparent	57%	16%	11%	10%	13%	19%	36%	55%
coastal water, average		63%	37%	29%	28%	30%	45%	74%

Table 4: According to Jerlov the loss of light (in percent) in one meter of sea water is given in above table.

The Secchi disk is lowered into the ocean to the depth where it disappears from view; its reflectance equals the intensity of light backscattered from the water. This depth in meters divided into 1.7 yields an attenuation, or extinction, coefficient for available light as averaged over the Secchi disk depth. The light extinction coefficient, x, may then be used in a form of Beer's law, $Iz = I0exz$, to estimate Iz, the intensity of light at depth z from I_0, the intensity of light at the ocean surface. This method gives no indication of the attenuation change with depth or the attenuation of specific wavelengths of light. A photocell may be lowered into the ocean to measure light intensity at discrete depths and to determine light reduction from the surface value or from the previous depth value. The photocell may sense all available wavelengths or may be equipped with filters that pass only certain wavelengths of light. Since Iz and I_0 are known, changing light intensity values may be used in Beer's law to determine how the attenuation coefficient changes with depth and quality of light. Measurements of this type are used to determine the level of photosynthesis as a function of radiant energy level with depth and to measure changes in the turbidity of the water caused by particulate distribution with depth.

5. UWOC System Links

The UWOC links configurations can be classified into three major categories, 1) Point to Point (P2P) line of sight (LoS), 2) Diffused line of sight (LoS), 3) non line of sight (NLoS), and 4) retro-reflective UWOC links.

a. Point to Point Line-of-Sight (P2P LoS) Communication Link

P2P LoS link is the most straightforward and commonly used link configurations in UWOC as shown in Figure 2. Clear waters are more transparent to blue-green region of EM band show low absorption and scattering and can provide long distance communication using P2P LoS UWOC link. Current UWOC studies are focused on visible light wavelengths in the range of 400–520 nm and a line-of-sight (LoS) configuration. In point to pint (P2P) configuration the transmitted light is directly falls on the receiver plane. The LoS configuration requires sophisticated PAT mechanisms and strict alignment between the transmitter and the receiver [30], as LoS UWOC employs light source such as lasers which has very narrow divergence angle, because of this LoS requires precision pointing between transmitter and a receiver. As signal gets faded or lost when system encounters turbulent water environment, or when both the transmitter and the receiver lost their position, the performance of the LoS system drastically decreases.

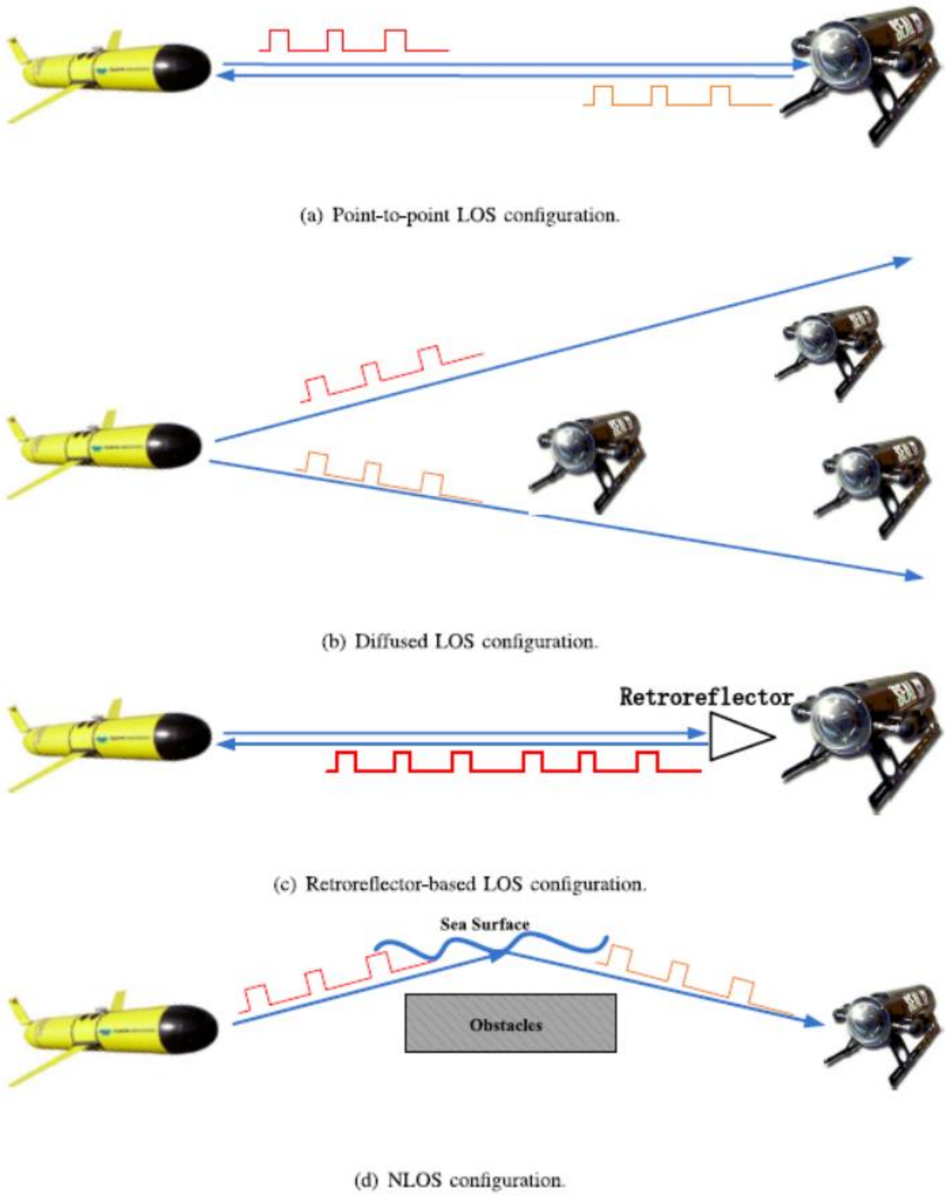

Figure 2: Various UWOC Communication links (Zeng Z. 2017) [36]

b. Diffused Line-of-Sight (LoS)Communication Link

Diffused LoS link configuration employs diffused light source like high power LED's with large divergence angle. Large divergence angle broadcasting enables communication between single transmitter nodes to multiple receivers' nodes. The advantage of diffused LoS link configuration over P2P LoS configuration is that it does not require precision pointing between transmitter and a receiver. However, the diffused LoS link configuration undergoes, light attenuation due to large diffusion angle. Short communication distance, low data rate, power consumption and efficiency are the main limitations of Diffused LoS link configuration.

c. Non-Line-of-Sight (NLOS) Communication Link

However, one of the most challenging task is to maintain the alignment between optical transmitters and receiver in the real oceanic environment, due to ocean turbulence [31,32], turbidity [33], and obstacles [31] in the water channel which can cause a severe signal loss, and fading, in LoS UWOC links. To overcome this problem, a non-line-of-sight (NLOS) UWOC link was proposed. The NLoS link can be configured through a light reflection from water surface or from suspended particles present in the water channel [34,35]. As a result, the NLOS UWOC link can relive the strict pointing, acquisition, and tracking (PAT) requirements of LOS UWOC. Compared with surface-reflection NLOS, light-scattering-based NLOS circumvents the problem of signal fading caused by wave-induced variations in the water surface. In a light-scattering-based NLOS UWOC link, the photons emitted from the transmitter will be redirected multiple times by the minute particles in the water before being detected by the receiver. Therefore, it is feasible that the strict PAT requirements of LOS UWOC could be fully relaxed [30].

d. Retro-reflective Communication Link

Retroreflector-based LOS arrangement, as appeared in Figure 2, can be represented as one of the point-to-point LOS arrangement. This setup is reasonable for duplex UOWC frameworks with underwater sensor nodes with limitation over power consumption. In the retro-reflector bases communication link, the transmitted light ray is reflected back from a retro-reflector, the information is encoded on a reflected beam to which the retroreflector responses to the transceiver. As there are no other optical light sources in the retroreflector end, the power consumption and weights are extremely reduced. The drawback of this configuration is that the transmitted and reflected light beams may interface each other which may result in degrading SNR and BER which reduces systems performance. Multiple reflections may lead to attenuation of optical received signal.

6. Conclusions

In the recent years due to the potential of UWOC in high-speed and flexible underwater communication applications has led to continuous research and developments. Although bandwidth is always in the focus of communication system research, the improvement in the communication distance is also challenging task in UWOC systems design and developments. For the construction of the entire UWOC system, a deep understanding of the characteristics of underwater optical channels is the primary work of UWOC research. It is also necessary to meet the challenges of underwater optical transmission and evaluate the performance of UWOC. For the link loss caused by absorption and scattering in an underwater optical channel, designing a transmitter with good bandwidth performance, strong and stable power, and a receiver with high sensitivity and strong anti-interference ability is the basic strategy to achieve long-range UWOC. Combining the characteristics of optical channels, design a suitable modulation format to improve spectrum efficiency and power efficiency, and then increase the communication rate. For performance distortion caused by factors such as time-domain expansion caused by seawater scattering, limited bandwidth of UWOC system devices, and non-linear characteristics, a series of signal processing techniques such as coding and equalization are needed to optimize.

In addition, the increase in the speed of the optical multiplexing technology and the extension of the link distance by the single photon detection technology are all worthy of attention. Compared with the positive effects of scattering, the rational configuration of input and output will play a greater role in solving the problem of optical alignment, and adaptive optics will also help solve this problem. The use of advanced test platforms can help analyze the problems of scattering, turbulence, and waves that are common in actual seawater, and prepare for the practical application of UWOC. On these foundations, the combination of UWOC and other communication methods will help form a large-scale integrated land, sea, and air communication network. In addition, UWOC's potential security issues and networking issues also deserve sufficient attention from researchers.

7. References:

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