Received December 21, 2021, accepted January 24, 2022, date of publication February 8, 2022, date of current version March 3, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3150093

Recent Trends in Underwater Visible Light Communication (UVLC) Systems

MOHAMMAD FURQAN ALI[1], (Graduate Student Member, IEEE), DUSHANTHA NALIN K. JAYAKODY[1,2], (Senior Member, IEEE), AND YONGHUI LI[3], (Fellow, IEEE)

[1]School of Computer Science and Robotics, National Research Tomsk Polytechnic University, 634050 Tomsk, Russia
[2]Centro de Investigaçă em Tecnologias—Autónoma TechLab, Universidade Autónoma de Lisboa, 1169-023 Lisbon, Portugal
[3]School of Electrical and Information Engineering, The University of Sydney, Camperdown, NSW 2006, Australia

Corresponding author: Dushantha Nalin K. Jayakody (djayakody@autonoma.pt)

This work was supported in part by the Cooperativa de Ensino Universitário (CEU), Portugal and in part by the Framework of Competitiveness Enhancement Program of National Research Tomsk Polytechnic University, Russia.

ABSTRACT In recent years, underwater visible light communication (UVLC) has become a potential wireless carrier candidate for signal transmission in highly critical, unknown, and acrimonious water mediums such as oceans. Unfortunately, the oceans are the least explored reservoirs in oceanogeographical history. However, natural disasters have aroused significant interest in observing and monitoring oceanic environments for the last couple of decades. Therefore, UVLC has drawn attention as a reliable digital carrier and claims a futuristic optical media in the wireless communication domain. Counterparts of traditional communications, the green, clean, and safe UVLC support high capacity data-rate and bandwidth with minimal delay. Nevertheless, the deployment of UVLC is challenging rather than terrestrial basis communication over long ranges. In addition, UVLC systems have severe signal attenuation and strong turbulence channel conditions. Due to the fact that, this study provides an exhaustive and comprehensive survey of recent advancements in UVLC implementations to cope with the optical signal propagation issues. In this regard, a wide detailed summary and future perspectives of underwater optical signaling towards 5G and beyond (5GB) networks along with the current project schemes, channel impairments, various optical signal modulation techniques, underwater sensor network (UWSN) architectures with energy harvesting approaches, hybrid communication possibilities, and advancements of Internet of underwater things (IoUTs) are concluded in this research.

INDEX TERMS Internet of underwater things (IoUTs), underwater wireless acoustic communication (UWAC), underwater wireless electromagnetic (RF) communication (UWRF), underwater wireless optical communication (UWOC), underwater wireless sensor networks (UWSN), underwater visible light communication (UVLC).

I. INTRODUCTION

The revolutionary evolution of underwater visible light communication (UVLC) towards the next-generation wireless network 5G and 5G beyond (5GB) vision would have an enhancement in overall system performance while satisfying the current requirements. From the perspective of VLC, data transmission is highly secure with very minimal interception. The 5GB is an advanced wireless communication networking approach that provides a downlink data rate of more than 1Gbps. Moreover, the drawback in 5GB is the high cost of infrastructural development [1]. On the other hand, the ongoing transition of VLC across the 6G wireless network has more eminence over 5G network such as enhanced machine-type communication (mMTC) and ultra-reliable & low-latency communication (uRLLC) [2]. However, a promising VLC technology has no interference as RF communication system does. Therefore, VLC has acceptability of benefits to deploy, where the RF wireless networks are less implemented such as medical fields, oil rigs and gas plants, nuclear power plants (NPPs), underwater communication and further numerous applications [3]. As the oceans are mysterious water reservoirs that need to be explored through various signal processing techniques and

The associate editor coordinating the review of this manuscript and approving it for publication was Xiaolong Li.

applications such as undersea monitoring, observing marine life, detecting oil and natural gas sources, early warning of tsunamis, floods, and underwater location coordinates for navigation purposes [4]. Under these conditions, underwater wireless communication (UWC) has become an essential approach to exploring undersea sectors and plays a significant role in order to provide the natural phenomenal underwater activities. The state-of-the-art UWC in coastal securities, fishing farms, marine transportation, and pollution control have been implemented for several decades [5]. UWC networks are necessarily vital approaches in inaccessible and unmanageable regions of the deep ocean, which are highly sought-after research areas among scientists, researchers, and academics. A comprehensive and detailed discussion on UWC as a potential method of wireless signal transmission is recorded as in [5]–[9]. In addition, the proposed deployable underwater communication technologies in existing surveys support the collection of the oceanographic data, observation of water pollution, undersea monitoring, immediate warning of floods & natural disasters, and the phenomena of melting ice sheets due to global warming caused by rising ocean levels are also discussed in [9].

Recent studies encourage exploring the oceanic environment by deploying UWC technologies such as electromagnetic waves (EM) in terms of RF, acoustic, and optical waves propagation. As RF waves highly attenuate by the seawater and change the properties conductor to dielectric at 250GHz frequency ranges [10]. Therefore, RF carriers are not feasible and cover short ranges of communication in an aquatic medium. As claimed by the existing underwater architectural system in literature, the frequency ranges of EM waves in underwater propagation is extremely low between $30 - 300Hz$ for military applications [11]. A large sized antenna is required in UWRF signaling for better performance in underwater mediums [12]. Similarly, RF waves are also operated as ultra-low frequencies (ULF) to proceed with low attenuation but at a very high budget and at a low data rate. it provides low data rates [13]. Most recently, a joint technical WMO-IOC Commission for Oceanography and Marine Meteorology (JCOMM) as an observing network of the Global Ocean Observing System (GOOS) has proposed a high-frequency radar network (HFR) in 2017s [14]. In [14], the proposed communication system has drawn an attention of HFR system, that is continuously observed and map of ocean currents up to 200km offshore site in the coastal area. It supports detecting the floating objects on the sea surface, such as fishing ships, buoys, floating nodes, boats, yachts, etc., and extremely helpful for rescue operations. In the HFR networking system, the signal propagation is held from the radar and the signal reception by the conduction ocean waves, measuring the Doppler shift and giving direction and velocity. A pictorial view is depicted the function of HFR by Fig.16.

At a glance, EM waves were initially used as low-frequency ranges to transmit signals on terrestrial-based communication for reliable communication to achieve high bandwidth. Though, in an underwater environment, RF waves propagate differently compared to terrestrial-based signaling and totally depend on water mediums. The advantageous feature of RF waves propagate with high velocity (similar to the optical waves) provide efficient communication among the network nodes. Underwater wireless RF (UWRF) experiences signal fading and easily attenuates over very short distances in underwater. It is challenging to transmit signals through RF waves in a highly turbid water medium. An impressive survey work is proposed on UWRF based communication in seawater, where the authors widely discussed the recent advances of RF waves for coastal and military applications [11].

Besides UWRF, the acoustic waves are received the utmost interest in signal propagation over long distances in underwater medium with the limited bandwidth [15]. The traditional acoustic wireless carriers propagate over long distances with a low speed of approximately $1500m/s$, and a meager data rate [12]. Generally, acoustic waves propagation speed is influenced by channel impairments. Conversely, the speed of acoustic waves increases tremendously due to fluctuation of the temperature and salinity of the water [8]. The affecting factors such as scattering, reflection, and absorption by suspended particles corrupt acoustic signals. Therefore, the main concern of UWC is the establishment and architectural design of underwater sensor networks (UWSNs) for obtaining proper communication among nodes. An exhaustively detailed review study of UWSN is summarized in [16]. Additionally, the shipbuilding industries are also increasingly interested in widespread communication through sensor network architectures. The possible UWSNs applications are over-viewed in various underwater applications such as observing strong influences of the aqueous medium, undersea nutrient production, natural oil retrieval, underwater transportation, and the impact of water climate regulation on ecological system [17]. In these corresponding applications, the sensor nodes such as autonomous underwater vehicles (AUVs), remotely operated underwater vehicles (ROVs) support the data collection with the onshore nodes (sub-station) [18]. The cluster of underwater sensor networks is depicted in Fig.1, Fig.14 and sensor network architecture in Fig.16.

Due to the limited data rate and bandwidth of UWRF and acoustic waves, an alternative optical signaling approach has become the most significant and reliable wireless carrier candidate for digital signaling in underwater [19]. For instance, in the first stage of optical signaling, fire, fire-smoke, fire beacons, torches, and reflecting sunlight were introduced. In the starting phase of optical signaling about 800 BC, the ancient Romans and Greeks used to transmit optical signals for communication purposes over long ranges [20]. During 1880s, the optical wave-based telephone (photophone) was invented by the famous scientist Alexander Graham Bell for signal transmission over 210m [21]. In this photophone, a parabolic mirror with a selenium cell was used as an optical signal receiver. In the end of the 19^{th} century, the continuous development of optical signaling, Heliographs were firstly proposed to deliver messages through optical waves in the battlefield for military applications [22]. Generally, the heliographs were assembled with a dual-layer of mirrors and directly used to control the light beam propagation. For further development of optical communication, lasers were introduced as an alternative for signal transmission to serve wireless carrier over long distances [12]. On the other hand, the demand for ocean exploration is hiking up for a couple of decades. For instance, a real-time data streaming fiber optics signaling is applicable for several underwater applications and proposed during 1970s [23]. However, the main drawback of fiber optics is highly cost setups and unpleasant for undersea species. Moreover, in connection with the limited propagation coverage and high attenuation, underwater signaling is highly challenging to fill the gap of the desired communication.

For consistent development of optical signaling, He-Ne laser (λ=632.8nm) was investigated as an optical signal carrier over the $30-40$km range during 1960s [23]. In the early ages of laser development, the very initial foundational laser link was established to control commercial traffic in Japan by Nippon Electric Company during 1970s [21]. This deployed laser link was firstly used for signal transmission over 14 km. Later on, full-duplex communication Free Space Optics (FSO) enabled He-Ne laser at 0.6325μm was introduced for communication between the cities of Yokohama and Tamagawa in Japan [21], [23]. To keep evolution going, FSO communication technology was proposed to transmit high data-rate signals with minimal delay over long distances among communication nodes, which is extensively discussed in [12] and [24]. Later, in the end of the 20^{th} century, the numerous developments have been documented for optical signaling. Kahn and Barry extended Gfeller and Bapst's work, where they demonstrated a laser of wavelength $780-950$nm with high data rates $50-70$Mbps [21], [25] [26].

In laser counterparts, the implementation of Light-emitting diodes (LEDs) in VLC are widely used as transmitters through an illumination nature that provides an ultrahigh bandwidth to achieve a high data rate. For optical signal transmission and receiving, LDs and LEDs are the potential tools and widely use in optical communication over very short, short, medium and long ranges as per the requirement of the applications [27]. Therefore, these LEDs are considered the main sources of optical signal contributors. Moreover, the various light sources, photosensors transmit and receive optical signals such as a laser diode (LDs), Avalanche photodiode (APD), p-n diode, etc. The consumption of LED seems to be a novel approach cause of its dual nature. LED turn-on and turn-off ability turns a new communication paradigm formally known as the visible light communication system. Although, the invention of LEDs received a remarkable extent of research for high data transmission of its dual nature as illumination and signal carrier [28]. The illumination phenomenon occurs based on the visible light wave spectrum at the wavelength $380-750$nm, which is used as a transmitter and an image sensor at the receiver end [29]. Historically, VLC was proposed by the Visible Light Communications Consortium Japan (VLCCJ), Japan Electronics & Information Technology Industries Association (JEITA) CP-1221, and CP-1222 during 2003s to 2007s [21]. For continuous development of VLC, the Visible Light Communications Associations (VLCA) was established in Japan for further standardization [30]. As Japan Traffic Management Technology Association (JTMTA) and VLCC conducted an experiment where they achieved 4800 kbps data rate over a distance of 300m. Overall, Japan had contributed the initiatives for the development of products based on VLC signal modulated technologies. Additionally, in 2012s, Casio Japan developed the new Apple application ''Picapicamera'' for users where the images could be sent instantly through VLC technology [27]. In contrast, the modulation schemes and dimming phenomenon supports possible VLC communication that has been widely investigated by IEEE 802.15.7 standard [31]. The optical wireless communication (OWC) IEEE 802.15.7r1 standardization is used for short-range communication as VLC implementation [32]. The new era of optical communication has become a more significant trade for digital wireless signaling media with the integration of different techniques, which are mentioned in Table 1. Subsequently, the optical camera communications (OCC) system is used as image sensors at the receiver end to provide triple functions simultaneously, i.e., illumination, data transmission, and wireless energy transfer [20].

All the above matter facts for real-time data streaming and high bandwidth signal propagation approaches are needed. Therefore, underwater optical wireless communication (UWOC) in terms of visible light, particularly the blue-green spectrum of wavelength (450-532)nm [20], has been chosen and is widely used for high data transmission underwater communication. In the UWOC, the hydrological optical beam experiences signal absorption due to electron transition and converted into another form of energy. It is noticeable that water offers transparency with blue-green light spectrum [20] rather than with other light spectrum wavelengths. Moreover, the ocean water offers less attenuation for the blue light spectrum while the green light spectrum is attenuated by coastal water [33]. The optical signal attenuation depends on the inherent optical properties (IOPs), and apparent optical properties (AOPs) of water medium [34]. Additionally, the physio-chemical properties of the water channel supports fading contribution due to absorption, optical scattering, and reflection caused by turbidity, pressure, temperature, and existing suspended material within the water environment [35]. As a result, underwater visible light communication (UVLC) has become a complementary approach compared to traditional acoustic communication in high data rates ranging from hundred Mbps to Gbps over short range applications. Even UVLC has received superiority over traditional underwater acoustic and EM signaling. As compared to the existing traditional

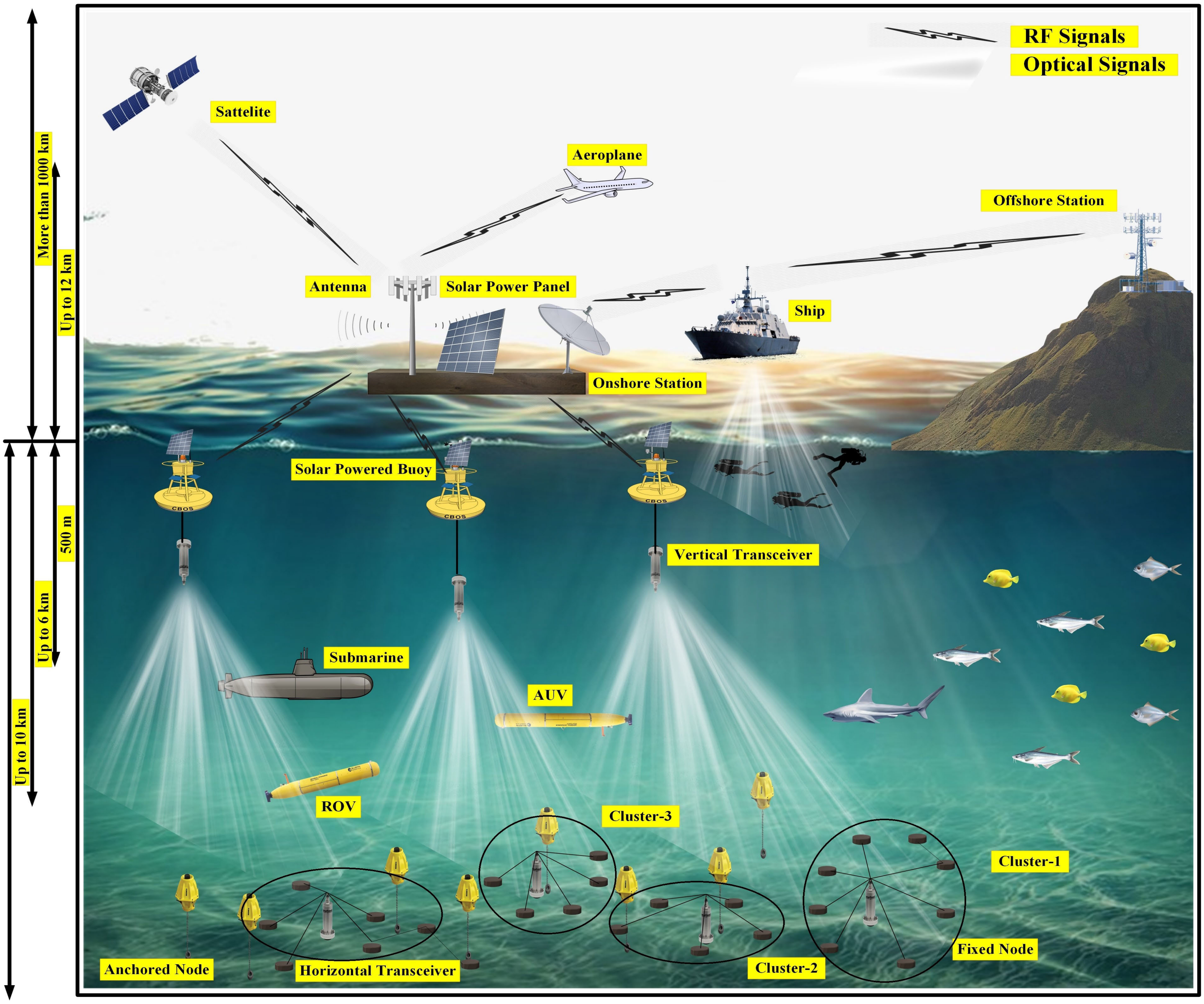

FIGURE 1. An overview of RF-VLC hybrid communication system where the oceanographic data collects by distinct types of underwater sensor network nodes architecture (1D, 2D, 3D, and 4D types of UWSNs architecture). The extracted data has been transferred to the offshore station for further analysis. In this type of scenario, the different internet of underwater things (IoUT) are included to communicate with each other by utilizing the latest wireless network or beyond. As depicted, the floating nodes collect the information along with the network nodes at the specified depth in the underwater medium.

UWC techniques, UVLC technology has advantages in harsh environments as it is handy to use, easy to deploy with low cost, and highly qualitative communication media [36]. A broad detailed scenario of UVLC and connecting nodes optically in an underwater environment is depicted in Fig.1.

Underwater signaling is entirely different from the terrestrial radio environment due to its energy costs and signal propagation phenomena. As a result, it is challenging to provide energy to power-hungry devices in underwater mediums. To cope with the energy harvesting (EH) issues, Simultaneously Wireless Information and Power Transfer (SWIPT) [37] and Simultaneously Light-Wave Information and Power Transfer (SLIPT) techniques [38], [39] are proposed in the literature in preference to powered up UWSNs. SWITP, wireless power transfer (WPT), and SLIPT will be widely discussed in further sections in this study. At a glance, EH is an optimum solution for power supply to activate the internet-enabled devices. Although, very few existing EH techniques are capable of supplying energy to the internet of underwater things (IoUTs). Several EH techniques are proposed in the open literature to power up underwater-based sensor nodes through RF and acoustic waves, which are mentioned in section IX.

Considering the EH scheme in acoustic communication, the Microbial Fuel Cell (MFC) and Acoustic Piezo-Electric (APE) techniques are the key enabling solutions for self-energizing nodes [40]. WPT and SWIPT techniques are investigated and introduced to provide energy with information transmission simultaneously over the wireless network [37]. Similarly, SLIPT has been announced as

TABLE 1. An overview of the different optical communication technologies along with the description of transceivers are used. In addition, the distinct characteristics and the possible applications of an individual technique are also summarized.

Type Optical Communication Technology	Spectrum Type	Transmitter Type	Receiver Type	Features	Applications
Visible Light Communication (VLC)	Visible Light	LED or Laser Diode (LD)	Photo-detector	Illumination and Communication Simultaneously with High Speed and Data-rate	Underwater Communication, Aviation, Hospitals, Indoor Localization
Free Space Optical (FSO) Communication	Visible, Near-Infrared, and Ultraviolet Light	Laser Diode	Photo-detector	High Data-rate Communication Over Long Ranges	Inter-chip Connectivity, Underwater Communication
Direct Detection and Ranging (DDR)	Near-Infrared, Visible Light	Laser Diode	Photo-detector	Information within the Remote area and Range can be found	Meteorology, Architectural Surveys
Optical Camera Communications (OCC)	Visible, and Infrared Light	LED	Image Sensor	A non-interference Communication	Intelligent Transport System
Light Fidelity (Li-Fi)	Visible, Infrared and Ultraviolet Light	LED	Photo-detector	A complementary technology where Illumination and Communication Simultaneously with High Speed and Data-rate	Smart Infrastructure connected with cloud

a futuristic wireless carrier candidate for EH and information transmission through light wave [41]. A more detailed summary and comparison between SWIPT and SLIPT is recorded in the literature in [42]. Furthermore, enabling the next-generation wireless network proliferates the communication system quality and efficiency. 5G enabled underwater wireless communication system will be the futuristic communication networking system that has been introduced recently in [35]. The authors in [43] and [44] are investigated the Filter bank multi-carrier (FBMC) and generalized frequency division multiplexing (GFDM) schemes which are considered as the latest reliable networking techniques for 5G applications in underwater. Improving the system quality of communication setup within the higher signal modulation techniques also significantly achieves a high data rate. The higher modulation techniques support a high degree of signal transmission between transceivers with minimum delay. The different types of optical signal modulation techniques are summarized in [45] and [21]. The hybrid links established for the long ranges of communication in different channel environmental conditions are used to deploy according to the requirement. A hybrid RF-UWOC system is investigated in [46]–[52]. Therefore, throughout this study, we present the various optical signal modulations, demodulations techniques, and their implementations in various wireless systems with recent trends in the underwater environment.

A. RELATED SURVEY LITERATURE

The various existing works are recorded based on UWC techniques and investigated with numerous emerging development methods in this domain. The existing related works are summarized by Table 4. For several decades, accelerating UWC to explore the underwater environment has become an alternative communication media that attracts human activities in an aqueous medium. Plenty of underwater wireless applications based on acoustic waves are investigated in existing works to explore the oceanic environment. However, the limited signal propagation speed and bandwidth recorded in underwater sound waves caused communication delay among nodes [12]. Therefore, the requirement for underwater acoustic communication setups for real-time monitoring and to access underwater applications are typically challenging. Based on underwater acoustic communication (UWAC), the most promptly military applications, especially in underwater acoustic communications among nodes such as submarine to the base station, submarine to ship, and submarine with military divers, are widely summarized in [53]. On the other hand, underwater optical signaling propagation reliably supports high bandwidth and high data-rate with minimal delay and latency. This is particularly appealing for real-time underwater applications [54]. To mitigate of its limitations, a hybrid mixed communication system design and evaluation of underwater optical-acoustic networks are investigated as in [55]–[59]. Similarly, for real-time scenarios, the performance of RF underwater communications operating system at frequency ranges 433MHz to 2.4GHz is investigated [60]. A range of existing hybrid underwater links are summarized in Table 4. Due to high signal propagation delay and very few kbps data rate in UWAC, counterparts of UWRF could be a complementary solution to receive high data rate and bandwidth range. For short distances, the RF conduction-based system design for voice communication in an aqueous medium has been recorded in [61].

Prior works are designed on theoretical propositions as a function of the physical properties of channels such as pressure, temperature, salinity, etc. A recent survey on UWOC is widely discussed about signal propagation-related issues based on the physical layer and localization technique in [13]. The authors in [62] investigated the path loss performance of a vertical UVLC link with the physical properties of the water channel considering n^{th} water layers. A UVLC system model considering LOS & non-LOS vertical configurations and the variation of refractive index is also presented in [63]. The survey [12] is exhaustively enlisted the critical factors of optical signals propagation in an underwater medium where the authors modeled the UWOC channels. However, the survey is provided a detailed summary of optical signal modulation and demodulation techniques according to the experimental setup of the system. UWOC wireless carriers as FSO and UVLC technology have been compared and widely discussed in [64]. The higher modulation techniques of UVLC have become attention for developing optical signals in the underwater environment. Due to this, a 16-QAM modulation scheme for underwater signaling was proposed in [65]. The authors in [65] are investigated the four types of different geometrical shaped 16-QAM constellation experimental approaches for improving the system efficiency. The most recent work based on the MIMO-OFDM scheme utilizing VLC in underwater is proposed as in [66] and [67], where the authors proposed the BER performance of the system under consideration of weak turbulence channel conditions. Another study is observed the BER performance over NOMA-based assisted UVLC link as in [68]. In hybrid communication, EH is an issue concerning nodes in active modes. An EH hybrid acoustic-optical underwater sensor networking system was investigated in [69]. The authors in [70], are introduced the possible underwater applications and the differences between the terrestrial-based wireless network (TWSNs) with the underwater sensor network nodes (UWSNs).

In the previous work [4], we reviewed the comparison among the three most significant UWC technologies and concluded the various advantages of UWOC over traditional wireless carriers. In this presented survey, we studied the recent advent of UVLC within different channel conditions. The following complementary sub-topics are widely summarized in this research as follows;

1) UVLC channel model is considered within the combined influence of weak to strong turbulence channel conditions along with the pointing error between transceivers;
2) The performance of underwater hybrid communication is obtained in different water types along with the simulation results;
3) The distinctive VLC higher modulation schemes support to improve channel performance and quality of services (QoSs);
4) The latest current project schemes to cope with the various underwater applications in marine industries all around the world;
5) A diverse study of IoUTs and implementation in different underwater locations for required applications are also summarized;
6) Integration of UVLC towards 5G and 5GB networking in UWC domain is concluded;
7) A SLIPT assisted scheme, based on time-switching and power switching methods to powered up UWSNs is highlighted in this research.

B. MOTIVATIONS AND CONTRIBUTIONS

Since humans footed on earth, oceanic reservoirs are least explored and are far-fetched to envisage the undersea environments. We tend to know more about the moon and mars rather than oceans existed on our earth. The interest growth of human activities in underwater is proposed the new research advances become familiarization with the natural oceanic phenomenal activities. Numerous UWC systems demand plenty of underwater applications for new research perspectives in this particular domain due to the immense development of industrialization. Traditional acoustic signaling is widely used for various underwater applications over long ranges. Nevertheless, a novel optical communication wireless media has been proposed recently to fulfill the requirement of desired data rate. Therefore, optical wireless signaling has become a potential wireless candidate for information transmission, and energy harvesting technology. However, UVLC is in its early age to cope with signal transmission and energy harvesting issues wirelessly in highly turbid water mediums. This study carries an exhaustive survey of UVLC towards 5GB futuristic networking system, the latest and current projects are running through the globe, channel modeling, UWSNs architectures, IoUTs enabled applications, and their contributions are perspectives. The main contributions and recent trends of UVLC through this study are as follows;

- The main purpose of this research is to provide a clear understanding of the main characteristic features of UVLC terminology towards future 5GB networking systems. In addition, the study also discusses signal processing extraction methodology with the possible solutions to the current factual challenges of improving the efficiency and potential wireless carriers of data communication in the underwater environment;
- An essential goal of this study includes a clear viewpoint of technical aspects of underwater networking architectural communication applicable for various applications and different higher modulation optical signal processing techniques among students, young scientists, and researchers to understand challenges and future directions in the corresponding domain;

- An extensive range of underwater applications requires communication techniques with high performance and reliability. Due to this, most of the significant channel impairments and challenges are widely studied. However, absorption, scattering, misalignment of transceivers (Pointing Error), and turbidity are the main influencing factors overlooked in single-hop, dual-hop, and hybrid multi-hop wireless communications;
- A wide detailed summary of VLC modulation, and demodulation techniques towards 5G enabled FBMC, and GFDM techniques are briefly summarized. UVLC enabled 5GB supports a proper connection among underwater-based internet-connected elements with the satellites or unmanned aerial vehicles (UAVs) for the sake of expanding human activities [1];
- This study is visualized the most distinctive type of UWSN architectures to power up the nodes through SWIPT and SLIPT schemes; the UWSNs architecture in both academic and industrial perspectives are majorly discussed;
- The discussion of this survey study provides a forum among the students, researchers, and engineers. In addition, the key fundamentals of this proposed survey are associated with professionals communication academics.

C. PAPER STRUCTURE

The remainder of the paper is organized into XV sections. An underwater wireless communication overview enabled with different communication media is presented in section II. We are discussing the fundamentals and propagation terminology of UVLC along with the types of waters, channel impairments in section III. The necessity of signal transmitter and receivers are summarized by section IV. Further, an exhaustive survey relating to the current project schemes and future deployments are widely summarized in section V. In section VI, there are plenty of computational methods discussed to provide a problematic solution of bulk data in optical signal processing. To cope with the channel impairments and signal fading factors have taken into account. Therefore the various UVLC system models are proposed and their overview is given in VII. The modulation schemes are the most practical terms to propagate digital signals. Due to this, the optical modulation and demodulation techniques are introduced in section VIII. Furthermore, deploying UVLC systems in critical environmental conditions is challenging and far-fetched to transfer energy to underwater-based sensor nodes. The SLIPT, SWIPT, and WPT wireless energy transfer and simultaneous information decoding schemes are broadly discussed in section IX. The aim of this study is to improve the performance and coverage range of UVLC by integrating with traditional UWC technologies. The various possible dual, triple, and multi-hop hybrid communication link system models are also presented in section X. For long-ranges communication coverage, the distinctive UWSNs architecture beneficial for various underwater applications is tabulated and introduced by section XI. Recent advancements of internet-connected devices underwater according to the requirements and advantages are also over-viewed in section XII. The implementation and future trends in UVLC towards 5G and 5GB are investigated in section XIII. Underwater optical wireless applications and recent advances are the impressive features of this study are summarized by section XIV. Finally, Section XV concludes the paper.

II. UNDERWATER WIRELESS COMMUNICATION AS AN OVERVIEW

UWC networks are challenging and become a significant approach to exploring an inaccessible unguided sector in the deep ocean with a wired and wireless connection. The deployable technologies allow to get familiar with the oceanic environment. Therefore, UWC accommodates an opportunity for oceanographic data collection and analysis, water pollution, underwater environmental monitoring, changes in currents, early warning of flood or tsunami, and observing the phenomena of ice sheet melting due to global warming cause of rising water level of oceans [4]. Nowadays in UWC, the three most significant distinctive technologies are employable for transmitting the information. These wireless carrier candidates are based on optical, sound, and electromagnetic waves based [5], [13]. The signal transmission is dependent on signal strength which is affected by the brutally chemical properties of the channel. The optical signal could be absorbed, scattered, and reflected caused by the chemical vitality of the channel, and suspended particles in a water environment [10]. Considering UWRF, which is used for short ranges, the signal decay happens by the hydrological properties and water channel. These water channel properties known as permittivity, conductivity, and permeability are directly responsible for the contribution of RF signal attenuation while increasing frequency ranges [37]. Since the saline seawater allows to propagate RF waves in few meters at extra low-frequency range of (30-300Hz), which is enabled to the transmission of few characters per minute to submarine [11]. Moreover, RF waves at the frequency range *MHz* to *GHz* accomplishes work efficiently in hybrid scenarios [4]. However, for shallow water scenarios, RF-enabled communication is called buoyant communication [5]. The UWRF system requires a costly and large sized information transmission antenna along with high energy-consuming transceivers [71]. In hybrid UWRF signaling, it offers a significant platform for the connection between underwater and terrestrial-based nodes. It also permits the exploration of the forbidden field of ocean and underwater environment. Extremely low frequencies (ELF) are used for long ranges underwater communication while the high frequencies (HF) strongly attenuate the cause of signal losses [72]. On the other hand, the frequency ranges as ultra-high frequency (ULF) to medium frequency (MF) are mainly used for a variety of underwater environments [73].

TABLE 2. The description of acronyms and notations are used in this study.

Acronym Notations	Definition	Acronym Notification	Definition
3H-RA	3-Hop-Reliability	FSO	Free Space Optics
5G	5th Generation	Gbps	Gigabytes per Second
6G	6th Generation	GFDM	Generalized Frequency Division Multiplexing
AI	Artificial Intelligence	GG	Gamma-Gamma distribution
AOPs	Apparent Optical Properties	GHz	Giga Hertz
APD	Avalanche Photo-diode	GMSD	Generalized Multiple Symbol Detection
APE	Acoustic Piezo-electric	GOOS	Global Ocean Observing System
ASC	Autonomous Surface Craft	GPS	Global Positioning System
ASR	Autonomous Submersible Robot	HFR	High Frequency Radar
ASVs	Autonomous Surface Vehicles	IM/DD	Intensity Modulation and Direct-Detection
AUEFM	Autonomous Exploration of European Flooded Mines	IOPs	Inherent Optical Properties
AUV	Autonomous Underwater Vehicle	IoUT	Internet of Underwater Things
BER	Bit-Error-Rate	ISI	Inter-Symbol-Interference
BQP	Biological-Inspired Quantum Photo-Sensor	JCOMM	Joint Technical WMO-IOC Commission for Oceanography and Marine Metrology
BS	Base Station	JEITA	Japan Electronics & Information Technology Industries Association
CAPEX	Capital Expenditure	JTMTA	Japan Traffic Management Technology Association
CAPEX	Operational Expenditure	LDs	Laser Diode
CBCs	Color Band Combinations	LEDs	Light Emitting Diodes
CDMA	Color Division Multiple Access	Li-Fi	Light Fidelity
CDOM	Color Division Organic Materials	LOS	Line-of-Sight
CM	Coherent Modulation	MBES	Multi-Beam Echo-Sounders
COUSIN	Cooperative Underwater Surveillance Network	Mbps	Megabyte per Second
CSK	Color Shift Keying	MCM-OFDM	Multi-Carrier Modulation OFDM
D2D	Device-to-Device	MFC	Microbial Fuel Cell
DDR	Direct-Detection and Ranging	MFTP	Maximum Flickering Time Period
DFB	Distributed Feedback Laser	MHz	Mega Hertz
DMT	Discrete Multi-tone	MIMO	Multi-Input-Multi-Output
DPPM	Differential Pulse Position Modulation	mMtc	Machine Type Communication
DSP	Digital Signal Processor	MPAPM	Multiple Pulse Amplitude and Position Modulation
EH	Energy Harvesting	M-PPM	Multiple Pulse Position Modulation
ELF	Extremely Low Frequency	MZM	Mach-Zender Modulator
E-PPM	Expurgated Pulse Position Modulation	NLOS	Non-Line of Sight
EU	European Union	NOMA	Non-Orthogonal Multiple Access

As far as long ranges in underwater signaling, acoustic waves are widely used and challenging communication technology to deploy in an underwater environment [74]. Nevertheless, in UWAC propagation, the speed of sounds deficient with high delay over long ranges [75]. According to [9] and [76], an impressive feature of UWAC offers an incremental speed propagation on raising the temperature of the water. An impressive increment (approximately 4m/s) has been recorded on rising 1°C of water temperature. Moreover, the salinity is also another cause of signal fading, and acoustic waves speed in enhanced by 1.4m/s while rising salinity 1 practical salinity unit (PSU). In respect to receiving signals over long distances under consideration of plane wave model or spherical wave model, emerging technology is widely known as UWSNs, which is alternative and a complimentary communication media solution, especially for military and naval tactical, operational applications [77].

III. FUNDAMENTALS OF UNDERWATER VISIBLE LIGHT COMMUNICATIONS

UVLC has become a unique advantageous technology in the new era of wireless signaling that has drawn attention as a dominant signal propagation over short ranges in the harsh underwater medium. Towards the next generation of 5GB wireless networking system, UVLC will be applicable for numerous undersea applications such as geographical mapping, underwater navigation, naval operations, data-retrieving among nodes, and high quality of UWSNs are also considered [119]. Additionally, UVLC has superiority including high data-rate, real-time steaming data transfer with high security compared with its counterpart traditional underwater signaling acoustic and RF signaling. Despite all of these advantages, several factors affect the signal propagation, such as absorption, scattering, and turbulence due to the IOPs and AOPs properties of water channel and

TABLE 3. Nomenclature and description of acronyms are used in this research.

Acronym Notations	Definition	Acronym Notification	Definition
FAP	Femto-cell Access Point	NPPs	Nuclear Power Plants
FBMC	Filter Bank Multi-Carrier	NRZ	Non-Return to Zero
FDMA	Frequency Division Multiple Access	OA-UWSNs	Optical-Acoustic Underwater Sensor Networks
FFIR	Fading-Free Impulse Response	OCC	Optical Camera Communication
FLS	Forward-Looking SONAR	OOK	On-Off Keying
FOV	Field of View	OPPM	Overlapping Pulse Position Modulation
P2P	Point to Point	TLS	Transmit Laser Selection
PAM	Pulse Amplitude Modulation	TWSNs	Terrestrial-Based Wireless Network
PAM-TDHP	Time-Domain Hybrid Pulse Amplitude Modulation	UASNs	Underwater Acoustic Sensor Network
PAPR	Peak to Average Power Ratio	UIoTs	Underwater Internet Connected Things
PLC	Power Line Communication	ULF	Ultra-Low Frequencies
PMEL	Pacific Marine Environmental Laboratory	uRLLC	Ultra-Reliable & Low Latency Communication
PPM	Pulse Position Modulation	USNs	Underwater Sensor Networks
PSU	Per Salinity Unit	USP	Underwater Sensor Positioning
PWM	Pulse Width Modulation	UUVs	Unmanned Underwater Vehicle
QAM	Quadrature Amplitude Modulation	UVLC	Underwater Visible Light Communication
QoE	Quality of Efficiency	UWAC	Underwater Wireless Acoustic Communication
QoS	Quality of Services	UWC	Underwater Wireless Communication
RADAR	Radio Detection and Ranging	UWOC	Underwater Wireless Optical Communication
RF	Radio Frequency	UWOSNs	Underwater Wireless Optical Sensors
RGB	Red-Green-Blue	UWRF	Underwater Wireless Radio Frequencies
RGBY	Red-Green-Blue and Yellow	UWRFSNs	Underwater Wireless RF Sensors
ROUV	Remotely Operated Underwater Vechicle	UWSNs	Underwater Sensor Networks
RTE	Radiative Transfer Theory	UXO	UneXploded Ordnance
sBES	Single Beam Echo-Sounders	V2V	Vehicle-to-Vehicle
Sbs (sBS)	Small cell Base Station	VLC	Visible Light Communication
SCFDM	Single Carrier Frequency-Division Multiplexing	VLCA	Visible Light Communication Association
SCM	Single Carrier Modulation	VLCCJ	Visible Light Communication Consortium Japan
SLAM	Simultaneous Location and Mapping	VPPM	Variable Pulse Position Modulation
SLIPT	Simultaneous Light-wave Information and Power Transfer	VR-MPPM	Variable-Rate Multi-Pulse Modulation
SSS-SONAR	Side-Scan SONAR	VSF	Volumetric Scattering Function
SWARM	Smart and Networking Underwater Robots in Cooperation Meshes	Wi-Fi	Wireless-Fidelity
SWIPT	Simultaneous Wireless Information and Power Transfer	WPT	Wireless Power Transfer
TDMA	Time-Domain Multiple Access		

nature of light [5], [9], [12], [34], [79]. The affecting factors cause signal fading, limiting a limited communication range for UVLC systems. Another degradation of signal fading is multi-path propagation that generates an inter-symbol interference (ISI). In this context, the fading-free impulse response (FFIR) of UVLC channel, which is a MIMO-UVLC system, has been recently investigated in [105]. In [105], the authors presented a thorough approach to UVLC channel characterization, performance analysis, and effective transmission along with the reception methods of the proposed system model. Moreover, in another study [120], the authors proposed a CDMA-UVLC approach based on assigning unique Optical Orthogonal Codes (OOC) for each underwater mobile user. An underwater cellular optical CDMA network and related applications of serial relaying mechanism has been recently proposed in [121] and [122]. The wireless signal transmission underwater is challenging, especially when optical transceivers are deployed. Acoustic and VLC are complementary deployable communication technologies to fulfill the desired communication gap in the wireless communication domain. However, acoustic link suffers signal attenuation and high signal propagation latency.

TABLE 4. The table is summarized the most recent existing similar works along with the related contributions from the perspective of future directions. Furthermore, it has also mentioned the channel modeling, impairments, signal affecting factors, and the most widely deployable underwater applications.

Communication Technology	Propagation ranges and Latency	Contribution and Research Direction	Affecting Factors	Applications	Key References
Underwater Optical Wireless Communication (UWOC)	Moderate Distances (Up to several hundred meters) with low latency	• Surveys and latest project schemes to support the quality and efficiency of the communication system along with the future perspectives • UWOSNs architecture and proposed the different energy harvesting systems • Implementation of next generation of wireless networking system in underwater environment • A wide view of possible emerging wireless communication technologies in aqueous medium • A deployment scenario of IoUTs connected with distinct modulation schemes	• Absorption • Scattering • Turbidity • Suspended Particles and Color Division Organic Materials (CDOM) • Pointing Error	• Environmental Monitoring • Navigation • Surveillance • Military Purposes • Geo-Physics • Bio-Optical • Ocean Sampling	• [4] • [5] • [9] • [78] • [12] • [79] • [80] • [81] • [82] • [83] • [84] • [85]
Underwater Wireless Acoustic Communication (UWAC)	Horizontally covers up to 20km with high latency	• Existing Literature surveys, the latest project schemes are proposed to support long-range underwater wireless communication systems along with the future directions. • Underwater acoustic channel modeling, UASNs architectures, and future research challenges • The futuristic of underwater acoustic communication and research panoramas • The filter-bank multi-carrier communication for underwater acoustic channels to improve the efficiency and QoS	• Absorption • Scattering • Pressure • Temperature • Salinity of the Water Channel • Physio-Chemical Properties of Water	• Monitoring water quality • Navigation • Military Purposes • Natural Hazardous (Earthquakes & Floods)	• [4] • [5] • [9] • [74] • [86] • [87] • [88] • [89] • [90] • [91]
Underwater Wireless Electromagnetic Communication (UWRF)	Few meters (Up to 10 m) with low latency	• The contemporary Literature surveys, implementation of emerging project schemes most widely used for short and long-range communication in an underwater environment • The emerging techniques support to enhance the data rate and reduce the signal latency • UWSNs architecture and possible underwater applications for military and defense purposes are summarized • Underwater vehicle communication for shallow water, propagation of electromagnetic waves at MHz frequency ranges, and enabling mmWaves nodes architectures are proposed	• Conductivity • Permitivity of the Channel • Physio-Chemical Properties of Channel	• Operation of ROVs • UAVs Docking • Divers Communication • Underwater defence and military communication • Exporting and importing goods enabling applications • Underwater node localization and navigation	• [4] • [5] • [9] • [62] • [92] • [93] • [94] • [95] • [96] • [97] • [98] • [99]
Underwater Visible Light Communication (UVLC)	Several Tens of meters (Up to 50 m) with low latency	• The most recent trends and surveys of UWOC, along with the channel model widely discussed • The latest work and broad analysis of OFDM-MIMO deployment VLC LEDs underwater is presented • UVLC channel modeling in high turbidity channel conditions along with the misalignment phenomena of transceivers based system performance is investigated • UVLC through LEDs are used as a wireless candidate for divers communication, monitoring water pollution	• Inherent Optical Properties • Apparent Optical Properties • Turbulence • Pointing Error	• Divers & Submarine Communication link for Shallow water • Port & Coastal Securities • Oil & Gas field exploration	• [13] • [16] • [66] • [100] • [101] • [102] • [103] • [104] • [105]

TABLE 4. ***(Continued.)*** **The table is summarized the most recent existing similar works along with the related contributions from the perspective of future directions. Furthermore, it has also mentioned the channel modeling, impairments, signal affecting factors, and the most widely deployable underwater applications.**

Communication Technology	Propagation ranges and Latency	Contribution and Research Direction	Affecting Factors	Applications	Key References
Hybrid Acoustic-Optical	Few meters with Low latency	• The survey of possible UWC scenarios and hybrid acoustic-optical link for long-range communication is over-viewed • The evaluation of hybrid optical-acoustic network and realization and optimized for highly dense swarm within an optical transducer suitable for a wireless 3D networking operation • A novel optical-acoustic hybrid Underwater Wireless Sensor Network (OA-UWSN) techniques are proposed for transmitting control commands and node localization in an underwater environment	• Density • Temperature • Pressure • Absorption • Scattering • Salinity • Turbulence • Pointing Error • IOPs & AOPs Properties	• Real-Time Monitoring • High Capacity Video Streaming • Underwater Monitoring & Surveillance for Long-time • Ocean-data Collection	• [5] • [16] • [57] • [58] • [59] • [106] • [107] • [108]
Hybrid RF-UWOC	Long ranges	• An existing work and the possibility of high data transfer in underwater medium for various underwater applications • The review studies of RF-based macro-cell, small cell, Wi-Fi as well as optical-based VLC for different combinations of hybrid systems are presented • The secrecy outage performance and physical layer security in the context of IoUTs	• Terrestrial Fading & Underwater Apparent Optical Properties	• Military Surveillance • Ecological Monitoring • Climate Recording	• [16] • [48] • [49] • [52]
Hybrid RF-VLC	Long ranges	• Blue and green light wavelength has been chosen for UWC, due to this LEDs and LDs the two light sources combined with RF waves are widely discussed • An RF-VLC hybrid communication system is proposed for various underwater applications within different relay protocols in different water mediums • The performance analysis of RF-VCL system. The proposed system is introduced the marine life association with the terrestrial life	• Physio-Chemical Properties • Channel Conductivity • Permittivity • Permeability • Channel Turbulence • Salinity • IOPs & AOPs Properties	• Oceanic ecosystem monitoring • Maritime archaeology • Naval tactical operations • Surveillance and coastal securities • Water pollution monitoring	• [16] • [109] • [110] • [111] • [112] • [113] • [114]
Hybrid RF-FSO-RF	Long ranges	• The cascaded RF-FSO-VLC link is proposed for investigated system performance. In this cascaded system, the RF link is designed by Nakagami-m distribution fading, while the FSO and VLC links are modeled by GG distribution fading within strong turbulence channel conditions • The outage probability of the system and BER performance of triple-hop RF-FSO-VLC underwater cooperative system is investigated • The 3-Hop-Reliability UWSNs (3H-RA) model is investigated where an individual node maintains the received copy without any extra burden on the network	• Physio-Chemical Properties • Conductivity • Permitivity • Turbidity • Jitters and Pointing Error	• Satellite to underwater based node communication • Military and naval operational communication link • Underwater monitoring and observing network node localization • Lost treasure, oil & monitoring and investigation of natural resources	• [115] • [116] • [117] • [118]

The implantation of acoustic transceivers is expensive, bulky (highly challenging to deploy rather than optical setup), and high power consumption. The VLC link is considered as an alternative viable underwater signaling technology

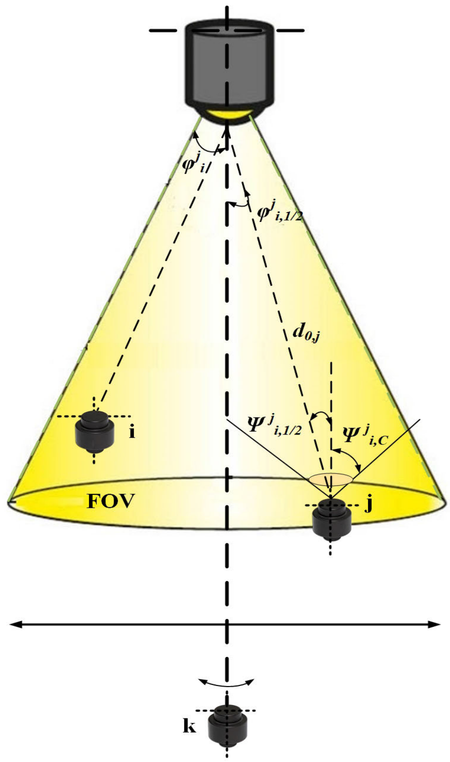

FIGURE 2. A pictorial view of Line of Sight (LOS) underwater optical signal propagation scenario. In this type of arrangement, the transceivers should be in the line of direction of the signal propagation. As depicted, the source node transmits signal towards receiving nodes through an optical beam. Moreover, the signals received only the nodes that are in the line of sight direction.

over moderate distances compared with acoustic and EM waves. To mitigate all the above facts, optical communication systems are defined as horizontal and vertical or slant links according to their implementation direction [123]. The horizontal links are proposed to improve the system performance and minimize the turbulence effects [63]. On the other hand, in the underwater vertical or slant link scenario, the transceivers are arranged in LOS link configuration [100].

A. UNDERWATER VLC CONFIGURATION LINKS

UWC is expected to achieve desirable receiving information in the underwater environment significantly. The design of a VLC link can be classified into three most significant categories such as i) UVLC Line of sight (LOS) link, ii) Retro-reflector assisted LOS link, and iii) Non-LOS configuration link.

- **UVLC Line of Sight Communication (LOS) Link:-** Generally, in optical communication LOS links are widely used; the LOS scenario is depicted by Fig.2. In this scenario, the deployable transceivers should be aligned and directly linked to one another in the line of direction of signal propagation. This type of combination supports and enhances the power efficiency, as well as immunity of the environmental distorting effects such as ambient and artificial light source [124]. Additionally, the LOS scenario is the most reliable approach for an underwater wireless communication system in terms of high data rate, better BER performance, improving system efficiency, and system performance. However, the drawback of LOS links is the mobility of transceivers due to water currents and the random flow of water waves. Even the received optical signals depend on the physical parameters of the experimental setup. According to [124], the LOS communication link by using laser diode wavelength 470nm is capable of covering 200m distance in the deep ocean that allowed 5Mbps data-rate transmission. On the other hand, in coastal ocean water, yellow-green LEDs are the optimal solution to deal with the signal scattering, and field of view (FOV) a wide-angle of beam causes increased attenuation. The propagation loss under Beer Lmabert's law can be defined as follows [125],

$$h_{ij}^{pl}(\lambda, d_{ij}) = exp\{-c(\lambda)d_{ij}\}, \quad (1)$$

where i, j are denoted the transmitter and receiver nodes, the euclidean distance between the transceivers and the total sum of absorption and scattering as extinction coefficient are defined as d_{ij} and $c(\lambda)$, respectively. The propagation losses depend on the path loss component as well as the geometrical parameters of the setup. Generally, the geometrical gain in optical LOS scenario can be written as [79],

$$h_{ij}^{gl} = \frac{A_i cos(\phi_{ij})}{2\pi(1 - cos(\theta_i)d_{ij}^2}, \quad (2)$$

where the receiver aperture area of nodes and the beam divergence angle of i^{th} transmitters are represented as A_i and θ_i, respectively. Furthermore, the channel conditions, which are the contribution of the path-loss and geometrical losses, are defined as follows [101],

$$h_{ij} = h_{ij}^{pl} + h_{ij}^{gl}. \quad (3)$$

The channel conditions h_{ij} is modified by replacing (1) and (2) into (3) given as follows,

$$h_{ij} = \frac{2\pi(1 - cos(\theta_i)d_{ij}^2)e^{\{-c(\lambda)d_{ij}\}} + A_i cos(\phi_{ij})}{2\pi(1 - cos(\theta_i)d_{ij}^2)}. \quad (4)$$

Furthermore, for approximation of the maximum achievable distance to achieve a specified bit-error-rate is investigated in [101], which can be defined as,

$$d_{ij} = \left[\frac{W\left(\frac{c(\lambda)}{2}(1-T)\left(\frac{D_r}{\theta_F}\right)h_{ij}^{\left(\frac{T-1}{2}\right)}\right)}{\frac{c(\lambda)}{2}(1-T)\left(\frac{D_r}{\theta_F}\right)^T} \right]^{\frac{1}{1-T}} \quad (5)$$

where W, D_r, T, and θ_F represent the Lambert-W function, the aperture diameter, the correction coefficient for data fitting with the simulation results, and divergence angle for full-width transmitted beam, respectively. For the LOS of laser diode, the divergence angle is generally

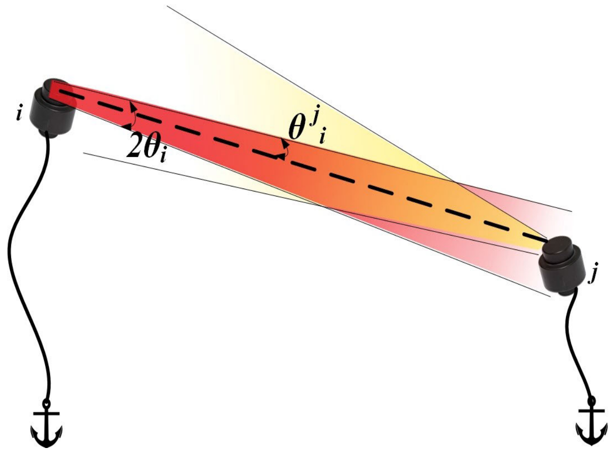

FIGURE 3. The retro-reflector LOS link is depicted where the reflector functioned as an interrogator. In this scenario, a continuous optical beam propagated by transmitter and strike and reflected by the receiver end.

planned for few milliradians, whereas LEDs fixed a divergence angle below 140 milliradians for diffusing light to a wide-angle [13]. At the receiver end, the received power (P_t^j) describes the product of transmission power efficiency, channel gain, propagation loss, and geometrical loss [79] of setup i.e.

$$P_t^j = P_t^i \eta_t^i \eta_r^j h_{ij}^{gl} \chi(\psi_i^j) h_{ij}^{pl} \left(c(\lambda), \frac{d_{ij}}{cos(\phi_i^j)} \right), \quad (6)$$

where P_t^j, P_r^j, η_t^i, η_r^j, $\chi(\psi_i^j)$ and ψ_i^j are denoted as the transmission and received signal powers, transceivers efficiencies, concentrator gain, and the incident angle concerning the receiver axis, respectively.

- **UVLC Retro-reflector-assisted LOS Link:** Optical retro-reflector type links are based on the back-scatter phenomenon principle consisting of a light source with an optical reflector. In this scenario, the capacity of the source is more powerful than the receiver node [125]. Although, the reflector is considered an interrogator with a basic anatomical design with minimal power availability. Consequently, the optical beam propagation source continuously emits a light beam during propagation of the light signal modulated and reflected by a local reflector then received by the destination. A UVLC retro-reflector LOS link is depicted by Fig.3. In more contrast, the retro-reflector scenario is sub-divided into two significant categories known as photon-limited and contrast-limited retro-reflector [5]. The photon-limited retro-reflector phenomena occurs in shallow waters such as lakes, deltas, and rivers either clear sea waters. In this scenario, the link range and the system capacity depends on the received falling photons at the detector end due to absorption phenomena. Although, the retro-reflector link is most widely used in turbid harbor water mediums, where signal scattering is considered an influential factor for system range and capacity. A contrast limitation for more specific uses underwater imaging applications is reducing the number of photons responsible for reducing the image contrast and quality. The reflector is capable of amplifying the modulated signal or light beam for the sake of better system performance in both scenarios as photon and contrast limited retro-reflectors [13]. Even, the retro-reflectors reflect the modulated beam and signals to the interrogator when the modulated signals are received on it [125]. In this retro-reflector design, if η_t, η_r, and η_{Ret} are the optical transmitter efficiency, receiver efficiency and retro-reflector efficiency, then the received power in retro-reflector link is given as follows [13], [125],

$$P_r^j = P_t^i \eta_t \eta_r \eta_{Ret} h_{ij} \chi(\psi_i^j) h_i^j \left(\lambda, \frac{2d_{ij}}{cos(\phi_i)} \right) \times \left[\frac{A_j cos(\phi_i^j)}{2\pi d_{ij}^2 (1 - cos(\theta_i))} \right] \left[\frac{A_r cos(\phi_{ij})}{\pi d_{ij} tan(\theta_r)^2} \right], \quad (7)$$

where the aperture receiver area of reflector, the divergence angle of the reflector, and the angle between the receiver trajectory of the source are denoted by A_r, θ_r, and ϕ_i^j, respectively.

- **UVLC Non-LOS Configuration Link:-** Non-line of sight (NLOS) optical signal propagation happens due to existing or suspended large scale particles or obstructions, even misalignment of the transceivers, and random orientation of the transceivers in underwater mediums. In this aspect, the reflected light from the sea surface or the bottom of water reservoirs (in shallow regions) could be beneficial to facilitate multi-point communication as depicted in Fig.4. In the NLOS scenario, the cone of light is emitted by the source with inner and outer angles θ_{min} and θ_{max} in an upward direction. This upward optical beam strikes with the water surface with an annular area A_{nn}, either a reflection of the light beam strikes with the ocean surface and reached the desired nodes. In contrast, if the transceivers are designed vertically upward, then the propagated beam partially refracts and partially reflects with the water surface. The reflected light beam propagates from the transmitter, which locates x distance apart water surface as depicted in Fig.4, where A_{nn} is defined as equal power density while apart at a distance x_0. The annular surface area can be written as follows [125],

$$A_{ann} = 2\pi (x + x_0)^2 \left[cos(\theta_{min}) - cos(\theta_{max}) \right], \quad (8)$$

where $(x + x_0)$ is defined as the radius of the spherical geometry, which means the uniform power density in free space. The received power at the specified destination in the NLOS scenario is expressed as [126],

$$P_r^j = P_t^i \eta_t^i \eta_j^r h_{ij}^{NLOS} \chi(\psi_i^j) h_{ij}^{pl} \left(c(\lambda), \frac{x + x_0}{cos(\phi_i^j)} \right). \quad (9)$$

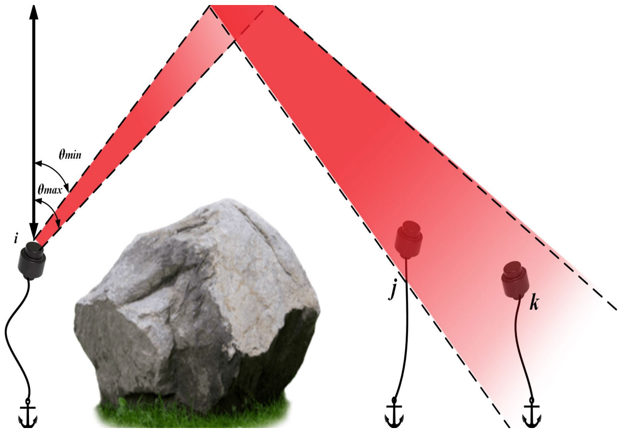

FIGURE 4. Non-Line of Sight optical signal propagation scenario has been depicted where, there is no possibility of the directed link in the underwater environment. The misalignment or the deflection of transceivers due to water current, the light beam strikes with sea surface or with the sea-floor (as in shallow water) then received at the receiver end.

B. THE NECESSITIES AND ADVANTAGES OF UVLC

UVLC has become a potential wireless candidate (transmission standard IEEE 802.15.7) for signal transmission in an underwater environment without any interference as in RF signaling. There are plenty of benefits to deploying VLC over traditional acoustic waves as very cost-effective, easy to install, high data transmission 3Gbit/s, real-time monitoring [105], and the collection of bathymetric data [127]. Under consideration of UVLC the blue-green colored optical wavelengths have been chosen for no-radiation and non-harmful for underwater species [128]. Numerous applications are deployed underwater where channel conditions emerge with a high-power LED-based VLC system. For real-time communication scenarios the underwater sensor network nodes (UWSNs) are connected with visible light sources and further communicate with the base station (BS) [129]. The sensors positioning system and localization in the UVLC system have been drawn attention in the literature in supporting and improving the system capacity and efficiency.

For instance in the initial stage of VLC, it was deployed intensively in mining sectors and further used as a wireless candidate in underground areas [130]. The electromagnetic waves as VLC counterparts, are absorbed and effortlessly attenuated by underground channels. Therefore, the evolution of VLC technology to bridge the gap in such complex applications as mining sectors, tunnel operations, and underwater communication. Due to this, most organizations are seeking further developments in the VLC communication systems. It turns the clock back as Disney Research had developed an in-light lightning system for their theme parks [131]. Huawei just recently signed an agreement with a German company Schnell Li-Fi to build optical hospitals that make the hospitals smarter and remotely operation could be possible through the wireless connected medical equipment [132]. These applications will support safer operations because visible light is free of interference compared to electromagnetic carriers. Another key driver is that the VLC (enabled LEDs) can deploy and make the oceans smarter, supporting an urgent need for efficient and highly secure communication. The micro-LEDs are being used for high data transmission in VLC systems. However, LEDs are tiny in size, and transmission power is relatively low compared to the laser. At a glance, lasers are not associated with the efficiency Doppler effect, which means they can reach higher power and higher power density even a very tiny device. Also, the laser operation in the stimulated emission regime has a much higher modulation bandwidth compared with LEDs. The requirement is to move from LED to laser source because lasers have more advantages over LEDs. A recently developed narrow bandwidth blue lasers-based distributed feedback laser (DFB) wave-guide structure has been proposed [133]. The DFB laser structure with III-layer nitride is still under development. An experimented wave-guide structure builds a high-speed DFB blue laser with enormous potential for future speed Li-Fi applications.

C. THE CHARACTERIZATION OF OCEANIC LAYERS

Generally, the deep oceans are categorized into three distinct zones for optical signaling, i.e., Euphotic, Disphotic, and Aphotic zones widely known as sunlight zone, twilight zone, and midnight zone, respectively, depicted in Fig.5. The range of the visible light signal, living organisms, and the variation of pressure concerning the depth is also summarized in Fig.5.

- Euphotic zone: The sunlight zone is the top layer of the water surface; enough amount of sunlight penetrates this zone. The green algae can survive due to the primary source of sunlight, and photosynthesis happens [134]. Moreover, the living creatures can be found in this zone [135]. The typical depth of this zone depends on water quality, such as the clarity or murkiness of the water. The depth of this zone varies in different in water types of waters. Euphotic zone can be quite deep up to hundreds of meters while it can be 15m meters in coastal ocean water in vertical column [5], [136]. Generally, the depth of the sunlight zone is approximated up to 200m from the water level. In this zone, the temperature fluctuates approximately 28^0C to freezing point -2^0C [137].
- Twilight Zone: The twilight zone is formally known as the Disphotic zone, which is beneath the Euphotic zone. The expected depth of this zone varies from 200m to typically 1km in the ocean [138]. At this level, a small amount of light visualize and rarely the algae alive in this zone. The very dim light falls and the dim blue light could penetrate this zone. There is not sufficient light to sustain the photosynthesis process in the disphotic zone. Some adaptable creatures can be found in the Twilight zone. The pressure increases and the temperature falls due to increasing depth.

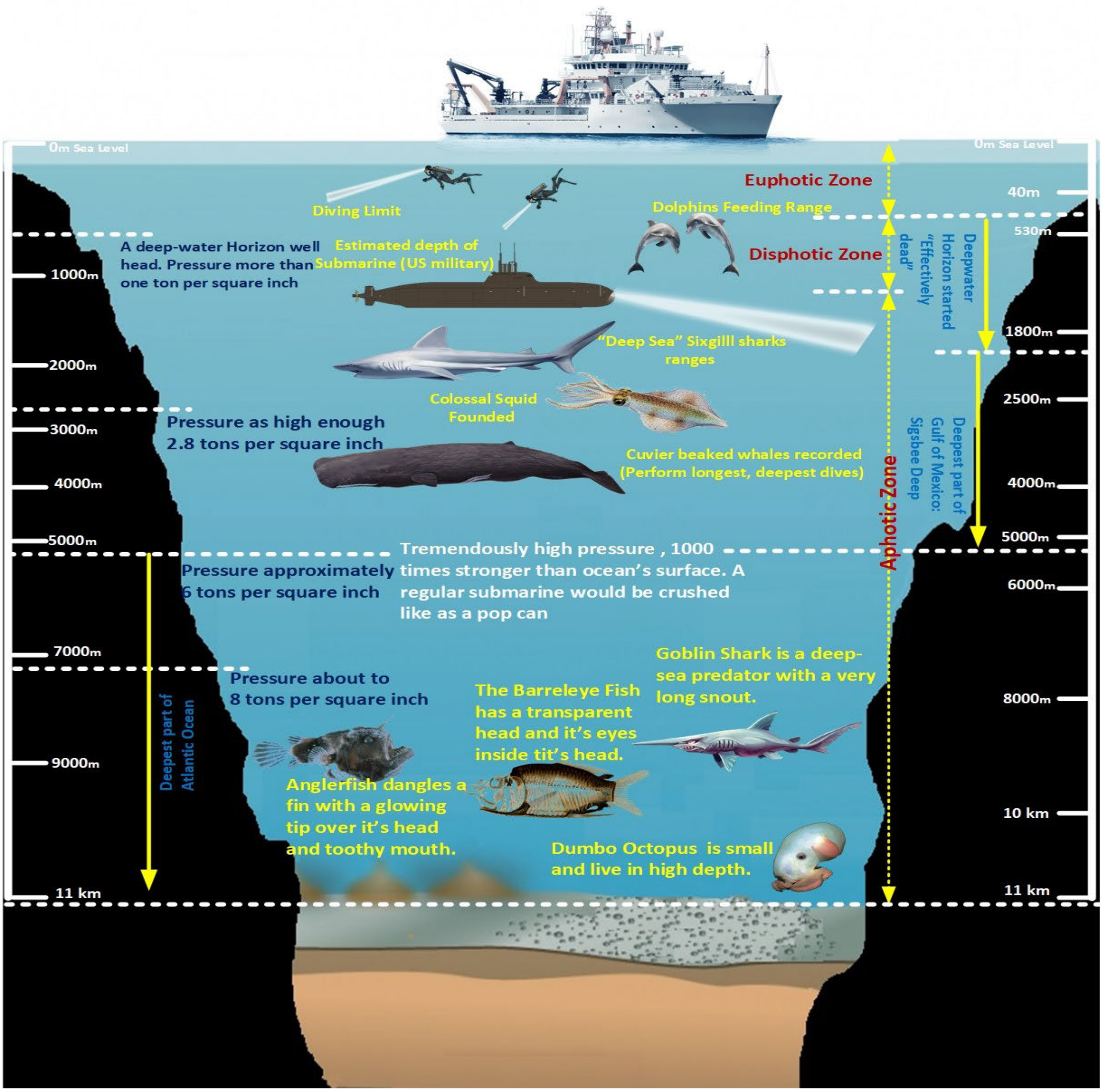

FIGURE 5. The pictorial view has shown the real optical signal propagation scenario at successive ocean depths. The ocean is categorized in three distinct categories as depicted according to the optical signal covering ranges. The natural properties of water in specific depths as pressure, temperature are summarized, along with the monitoring of marine life and the living creatures in an extraordinarily dark in dense aqueous medium. The typical visible light beam ranges, divers to divers communication, and communication link with the floating base station could be seen in this scenario.

- Mid-Night zone: A vast portion of the ocean belongs to this layer, known as the Aphotic zone. Approximately 90% of the ocean consists in the Midnight zone. It is entirely dark; there is no light extent this massive unguided water sector. The water pressure extremely low and below the freezing point. The depth of the midnight zone varies more than 1000m to 11km where is no light has taken place. The temperature fluctuates far from a chilling temperature of 4^0C to -15^0C or below. Rarely or more specific living organisms and creatures can be found in this zone [139].

D. DIFFERENT WATER TYPES, CHALLENGES & AFFECTING FACTORS IN UVLC SYSTEMS

Considering the channel conditions which affect optical signal propagation, the water has been categorized into different categories. According to [10], the three main types of waters exist and are classified for optical signaling as clearest water, intermediate water, and murkiest water. The geographical location of the clearest ocean water is located in the Mid-Pacific and Atlantic oceans, whereas intermediate water is possibly found in the Northern Pacific ocean. The North Sea and Eastern Atlantic oceans are the major water reservoirs of the murkiest water. Furthermore, another classification is commonly discussed in the open literature, which has been sub-divided into four distinctive categories: i) Pure seawater, ii) Clear ocean water, iii) Coastal ocean water, and finally, iv) Turbid harbor & estuary water. The light beam attenuates in these water differently. As in pure seawater the optical signals absorb because of the chemical composition, while the scattering loss occurs widely in clear ocean water due to its higher concentration of particles than pure seawater. A higher amount of particle concentration is founded in coastal ocean water rather than clear ocean water, which causes a higher rate of scattering and absorption of the light beam. Moreover, turbid harbor and estuary water has the highest concentration of particles.

The deployment of UWOC is more challenging as per channel condition requirements. The channel properties vary with distinct water types and geographical conditions [10]. Additionally, another classification while the propagation of light beam based on the environmental, geographical conditions, and the chemical vitality of the water is categorized. The subcategories are called as IOPs, and AOPs [140]. The IOPs are only medium dependents on existing substances and the composition of the medium [140], while AOPs depend on both the mediums and nature of the light beam. The AOPs are used to evaluate the ambient light levels for communication near the water surface. AOPs contribute radiance, irradiance, and reluctance. In more contrast, the spectral absorptive coefficient and volume scattering function are the two main factors that are considered in IOPs [141]. The transmission of the light beam experiences the absorption of photons by water and further converts them into another form of energy to increase the temperature of water molecules. In absorption phenomena the signal path-loss occurs where the beam intensity does weaken and the propagated photons absorb by the channel. The absorption occurs by chlorophyll in phytoplankton at colored dissolved organic matter (CDOM), by water molecules and existing salt contents [140]. Moreover, the CDOM matters are the combinations of the two components known as fulvic and humic acid as mentioned in [142]. In more detail, the absorption and scattering phenomena in different waters have been discussed in further subsections. The absorption effect is calculated in terms of wavelength and represented by $\alpha(\lambda)$. Though, scattering is defined as the randomness of photons with the direction of beam propagation. The optical signal scattering phenomena occur by the vitality of salt ions in pure water and collimated with particle matters. The scattering coefficient measurement per meter is denoted by $\beta(\lambda)$. Due to scattering and absorption, the energy of the optical beam falls and occurs the overall attenuation. The typical values of $\alpha(\lambda)$, $\beta(\lambda)$, and extinction coefficients $c(\lambda)$ in different water mediums are summarized in Table 5.

TABLE 5. The typical values of the contribution underwater absorption, scattering, and extinction coefficients. The data is applicable for different waters mediums [5], [82].

Classification of waters for UWC	$\alpha(\lambda)\ 10^{-3}$	$\beta(\lambda)\ 10^{-3}$	$c(\lambda) 10^{-3}$
Pure sea water	0.053	0.003	0.056
Clear Ocean water	0.069	0.08	0.15
Coastal Ocean water	0.088	0.216	0.305
Turbid Harbor water	0.295	1.875	2.17

- **Absorption & Scattering Phenomenon in UWC**:- Signal scattering in UVLC is the function that changes signal path, direction, and distance covered by photons in the underwater medium. The energy loss of optical beam by water (interaction between photon and water molecules) cause absorption, while the collision happens with suspended particles in UWOC. The optical signal absorption is an irreversible process where the photons lose their energy and improve the water temperature of water molecules. In more detail, if the photons strike with suspended particles and change their direction of propagation, scattering happens. The total energy loss of propagated optical beam due to absorption and scattering can be defined as the energy loss per meter. In addition to that an another cause of energy loss is inter-symbol interference (ISI), where the receiver aperture captures fewer incoming photons on its cross-sectional area. The extinction coefficient (summation absorption and scattering) is the signal loss phenomenon and directly affects the signal intensity and changes the direction of an optical beam. Concerning the physio-chemical properties of the channel and the geometrical model of absorption and scattering coefficient are proposed in [5] and [13]. Due to the harsh water channel conditions, the best way to understand the signal attenuation mechanism through a geometrical model of a water element is depicted by Fig.6. The optical beam energy is either absorbed by dangle particles or is transformed into heat energy, or raises water molecules thermal energy. Therefore, signal absorption affects signal strength, while the scattering phenomenon occurs the spreading photons randomly and strikes with the suspended particle. As a result, signals are partially received by detecting aperture or delayed to reach the destination. Thus, multi-path fading, time-jitter, and ISI occur in UWOC. To reduce ISI, the optimal multiple-symbol detection (MSD), as well as sub-optimal generalized MSD (GMSD) algorithms, are further investigated as in [105].

The recent surveys are detailed severe attenuation in optical signaling in harsh water cause absorption and scattering. Absorption and scattering are the two phenomenons responsible for signal fading caused by the suspended particles, the quality, and nature of water, dissolved organic matters affecting the signal strength, phase, and arrival angle of the received beam. The blue-green wavelength spectrum of visible light severs the minimum amount of absorption in pure seawater rather than coastal and turbid harbor water [143]. Moreover, light scattering is the cause of organic and inorganic matters due to the strong spatial and temporal

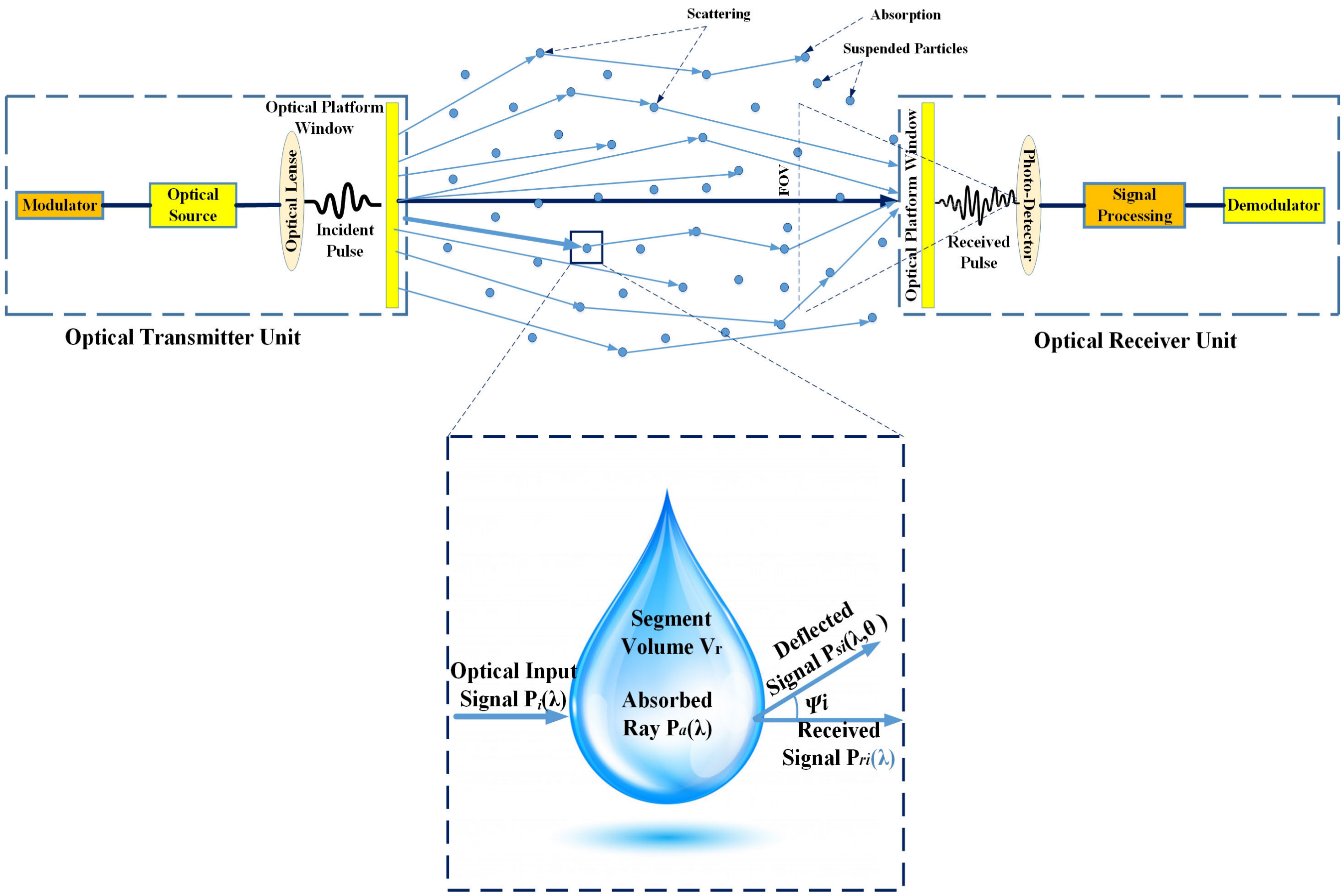

FIGURE 6. The signal affecting factors as absorption and scattering phenomena throughout the specified water segment and conversion of the single strength into another form of energy.

dispersion of photons, which may affect photon strength and intensity [144].

E. AFFECTING FACTORS IN UVLC SIGNALING

In the UWOC system, the absorption and scattering effects light pulses by existing suspended particles leading to photons path loss and intensity deviation. Both of these signal fading factors are wavelength-dependent per meter of signal propagation distances. Generally, these factors occur due to the interaction of the light beam with micro and macromolecules of water, algal sediments, and color division organic materials. In general, the organic particles are responsible for absorbing photons while inorganic particles are creditworthy for scattering [143]. Further, the CDOM strongly absorbs the light photons in the ultra-violate (UV) spectrum [144]. The total signal fading contribution by absorption $\alpha(\lambda)$ and scattering $\beta(\lambda)$ of optical beam energy loss describes in terms of extinction coefficient $c(\lambda)$ known as signal attenuation as $c(\lambda) = \alpha(\lambda) + \beta(\lambda)$. The extinction coefficient depends on the different water types. To formulate the expression for absorption and scattering, an elemental unit volume of water $\delta(V)$ with thickness $\delta(r)$ is considered and depicted by Fig.6. If the intensity of incident light-beam is denoted by $P_i(\lambda)$ with fixed wavelength λ collides with unitary elemental water volume. The incident beam is passing through the elemental volume and experiences absorption & scattering. The outcome beam is split into three fractions; as a certain amount of power, an incident beams $P_a(\lambda)$ absorbed and some extent of incident power $P_{si}(\lambda)$ will scatter at an angle ψ_i. The remaining apparent beam $P_{ri}(\lambda)$ passed through the element and detected by receiver. Thus, the energy conservation law and total incident power is calculated as the addition of all above fractions, i.e., $P_i(\lambda) = P_a(\lambda) + P_{si}(\lambda) + P_{ri}(\lambda)$. Furthermore, the absorbed signal power ratio $A(\lambda)$ and $B(\lambda)$ scattered signal power ratio are defined as,

$$A(\lambda) \equiv \frac{P_a(\lambda)}{P_i(\lambda)} \text{ and } B(\lambda) \equiv \frac{P_s(\lambda)}{P_i(\lambda)}. \tag{10}$$

In (10), the absorption and scattering ratios with the radius δr of an elemental water volume are infinitesimally small. Then taking the limits by an elemental water volume, the absorption and scattering coefficients can be written as [117],

$$\alpha(\lambda) = \lim_{\delta(r)\to 0} [\delta A(\lambda)/\delta(r)] = dA(\lambda)/dr, \tag{11}$$

$$\beta(\lambda) = \lim_{\delta(r)\to 0} [\delta B(\lambda)/\delta(r)] = dB(\lambda)/dr, \tag{12}$$

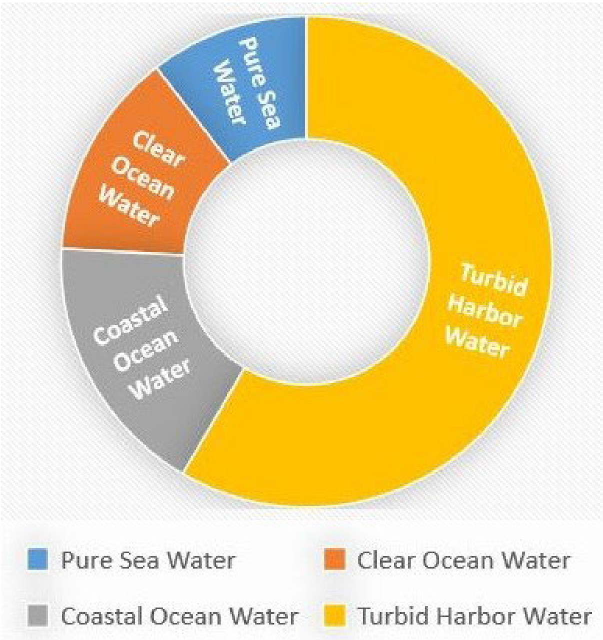

FIGURE 7. The most significant signal affecting factors as absorption and scattering phenomena occur while optical beam propagates underwater. The extinction coefficient is depicted in different water mediums.

Apart from the absorption and scattering, the seawater acts as a conductor medium for electromagnetic waves and offers dielectric properties for optical signaling [9]. In more precise terms, the seawater dramatically serves conductivity to dielectric at 250GHz frequency range [10]. However, underwater optical signals experience several extreme challenges and might be affected by fluctuation of scintillation index, scattering, absorption, dispersion, and temperature fluctuation due to the physio-chemical properties of the channel. Optical waves do not propagate simultaneously in water such as on a terrestrial basis, but accelerate exponentially in the water medium due to attenuation. The attenuation is the total contribution of signal fading, absorption, and scattering. In UWOC, scattering losses occur cause of discontinuity of the water molecules, while absorption occurs by the physical properties of channel conditions. In coastal ocean water, the optical signals are extremely corrupted by noise and path loss due to more scattering; the scattering event happens by the collision of the optical beam with the existing suspended particles and multiple reflections of angles [145]. The phenomena of absorption in UOWC have to be firmly taken into account cause several photons could reach the photo-detector or receiver end by passing harsh channel conditions.

Absorption is a high wavelength-dependent process where the transmitted photons are absorbed and converted into chemical or heat energy of the water. For instance, in [142] the authors have modeled absorption coefficient under consideration of absorptivity by pure seawater in terms of chlorophyll as a function of wavelength. The absorption by chlorophyll is defined as the change in light beam intensity per meter of path length. The total contribution of absorption is the chlorophyll and the color dissolved organic components (CDOMs) i.e., [146]–[148]

$$\alpha(\lambda) = \alpha_w(\lambda) + \alpha_{cl}(\lambda) + \alpha_f(\lambda) + \alpha_h(\lambda). \tag{13}$$

In (13), the absorption coefficient of water, chlorophyll absorption coefficient are represented by $\alpha_w(\lambda)$ and $\alpha_{cl}(\lambda)$. Moreover, the two CDOM components fulvic acid absorption coefficient $\alpha_f(\lambda)$, and humic acid absorption coefficient $\alpha_h(\lambda)$ are defined, respectively. The individual absorption and scattering components for different water mediums are calculated in (14) and (15) to model. As a result, we consider transmitting the blue-colored spectrum wavelength (450nm) of visible light.

The absorption coefficient by water types with respect to water concentration of ranges $0 \le w_c \le 15\ mg/m^3$, is calculated as follows,

$$\alpha_w(\lambda) = \alpha_w^0(\lambda)\left[\frac{w_c}{w_c^0}\right]^{a_w^0}, \tag{14}$$

where $w_c^0 = 1\ mg/m^3$ is the reference water concentration. For the different types of water the $a_w^0(\lambda)$ differentiate accordingly [142]. The water concentration for different water types such as for pure sea water, clear ocean water, coastal ocean water and turbid harbor water varies 0.0405λ, 0.114λ, 0.179λ and 0.266λ, respectively. According to [145], the absorption component due to chlorophyll $a_{cl}(\lambda)$ with respect to the chlorophyll concentration C_c^0 varies $0 \le C_c \le 12 mg/m^3$, and can be written as,

$$\alpha_{cl}(\lambda) = \alpha_c^0(\lambda)\left[\frac{C_c}{C_c^0}\right]^{0.0602}, \tag{15}$$

where the reference concentration of chlorophyll $C_c^0 = 1 mg/m^3$, and α_c^0 is equalized to 0.0602λ. Furthermore considering the CDOM components as, fulvic and humic acid absorption coefficients also formulated with respect to the chlorophyll concentration [146],

$$\alpha_f(\lambda) = \alpha_f^0 C_f \exp(-k_f\lambda), \tag{16}$$

$$\alpha_h(\lambda) = \alpha_h^0 C_h \exp(-k_h\lambda), \tag{17}$$

where the specific absorption coefficient for fulvic and humic acid component are a_f^0 and a_h^0 respectively. The concentrations of fulvic acid C_f and humic acid C_h in mg/m^3 can be expressed as follows [147],

$$C_f = 1.74098 C_c \exp\left[0.12317\left(\frac{C_c}{C_c^0}\right)\right], \tag{18}$$

$$C_h = 0.193348 C_c \exp\left[0.12343\left(\frac{C_c}{C_c^0}\right)\right]. \tag{19}$$

Due to suspended large and small scale particles underwater, the scattering phenomena occurs. The scattering coefficient $\beta(\lambda)$ defines the total signal loss due to the redirection of the photons. In contrast, the total scattering is the sum of scattering coefficient of water $\beta_w(\lambda)$, small particles $\beta_s(\lambda)$, and large particle $\beta_l(\lambda)$, respectively. The scattering function is wavelength and concentration-dependent. Therefore, total scattering can be calculated as [142], [146]–[148],

$$\beta(\lambda) = \beta_w(\lambda) + \beta_s(\lambda)C_s + \beta_l(\lambda)C_l, \tag{20}$$

where the small scale concentration C_s and C_l the concentration of large scale in g/m^3 can be calculated as [145]

$$C_s = 0.01739 C_c \exp\left[0.11631\left(\frac{C_c}{C_c^0}\right)\right] g/m^3, \tag{21}$$

$$C_l = 0.76284 C_c \exp\left[0.03092\left(\frac{C_c}{C_c^0}\right)\right] g/m^3. \tag{22}$$

Another noticeable optical property concerning signal scattering is known as albedo scattering, which is the ratio of scattering signal loss to the total signal losses [144]. The albedo scattering number is formed as, ω_0=(Scattering signals $\beta(\lambda)$)/(Total signal scattering $c(\lambda)$). The albedo number shows a significant scale factor to measure absorptivity or scattering of water medium, which varies from 0.25 to 0.8 for clear ocean water to turbid coastal water. The scattering phenomenon is stated as the detected optical information in terms of angular, temporal, and polarization which causes the degradation in the number of photons at the receiver end. The cause of suspended CDOM and inorganic particles, the scattering coefficient may be termed as the function of the volumetric scattering function β_v (VSF) over total angles (θ) as follows [149],

$$\beta(\lambda) = 2\pi \int_0^{\pi} \beta_{vsf}(\lambda; \theta)\sin(\theta)d\theta. \tag{23}$$

Moreover, the VSF is prescribed the normalization of $\beta(\lambda)$ by the scattering phase function. Therefore, the spectral VSF coefficient $\bar{\beta}_v(\theta, \lambda)$ is defined as follows,

$$\bar{\beta}_v(\theta, \lambda) = \frac{\beta_v(\lambda, \theta)}{\beta}. \tag{24}$$

Simultaneously, the optical beam propagated through the water channel and lost some fraction of its propagation energy in interaction with water molecules, number of biological substances, CDOM, etc. The are two signal-affecting mechanisms widely considered as absorption and scattering. The optical signals are severely affected by the channel turbidity due to the random fluctuation of the refraction index.

F. TURBULENCE

Turbulence is another cause of optical signal fading resulting from the random fluctuation in the refractive index. Plenty of valuable experimental results have recently been recorded in the open literature on characterizing underwater optical turbulence (UOT). In other words, turbidity is described as the varying changes in refractive index due to fluctuation of density, salinity, and pressure of underwater environment that affects optical signal propagation. It means the random variation in scintillation index induced turbidity in the channel environment. The consistency of oceanic turbulence occurs by wave current, physio-chemical properties of water, large, and small suspended particles. The wave currents are defined as weak to strong turbulence conditions based on Reynolds number. If Reynolds number $\rho \leq 1000$, then water flow is considered laminar or steady flow, with the minimal fluctuation in scintillation index. Whether, if it is $1000 \leq \rho \leq 2000$, then the flow has shown uncertainty, which means weak turbulence channel conditions. In the case where Reynolds number $2000 \leq \rho$ exceeds 4000, then it is considered as heavy turbulence channel conditions.

G. AFFECT OF NOISE IN UWOC

Noise is the factor that corrupts the signals, which directly affects the signal efficiency during communication. In UWOC, the noise occurs due to the reception of a random variation of photons propagation by transceivers. Different background noise sources are widely studied, such as quantum shot noise, optical-excess noise, optical background noise, photo-detector dark current noise, diffused extended background noise, background noise from sunlight, or other objects in the optical communication systems received at the receiver end. There are different types of noises in UWOC are recorded in existing literature [4], [5], [9], [150].

- **Optical Excess Noise:** The communication setup should be more accurate and reliable for information transmission purposes. However, some irregularities or faults in the experimental setup causes falling transmission accuracy. Due to inaccuracy of the transceivers noise occurrence, the glitches happen and corrupt the received signals defined as excess optical noise.
- **Background Noise:** In contrast to this noise, background noise is considered black-body radiation; the refracted sunlight is responsible as the main source of background noise. This type of noise majorly interfered by the sunlight, limiting the optical system performance for tens of meters (mostly in the Euphotic zone). The noise contribution of total background environment in the literature is recorded as in [4], [5], [9], and [150]. The total background noise power in optical signal propagation is defined as follows [150],

$$P_{BG} = P_{BG_{sol}} + P_{BG_{black-body}}. \tag{25}$$

For channel modeling, the background noise variance $\sigma_{BG}^2 = 2q\Re P_{BG}B$, depends on electronic signal bandwidth B, power of solar background $P_{BG_{sol}}$, and electron charge q, respectively. Furthermore, $P_{BG_{sol}}$ is expressed as,

$$P_{BG_{sol}} = A_R(\pi FOV)^2 \delta\lambda T_F L_{sol}. \tag{26}$$

In (26), the receiver aperture area, the optical filter transmissivity is presented by A_R, and T_F, respectively. However, the solar radiance also depends on downwelling irradiance E, underwater reflectance of downwelling irradiance R, the directional dependence of underwater radiance L_f, diffuse attenuation coefficient

K, and the underwater depth d. Therefore, the solar radiance L_{sol} is expressed by (27) as follows,

$$L_{sol} = \frac{ERL_f \exp(-Kd)}{\pi}. \quad (27)$$

Furthermore, the noise power of a black-body irradiance expressed as

$$P_{BG} = \frac{2hc^2 \gamma A_R (\pi FOV)^2 \delta\lambda T_A T_F}{(\lambda)^5 [e^{(hc/\lambda kT)} - 1]}, \quad (28)$$

where c, h, k, and γ are described as the speed of light, the Plank constant, the Boltzmann constant and the radiant factor. Moreover, the signal transmission factor in underwater is defined as $T_A = \exp(-\tau_0)$.

- **Photo-Detector Dark Current Noise:** The dark current noise is described and related to the photo-diode [35]. This type of noise occurs due to electrical current leakage from the photodetector. The variance of the dark current noise can be defined by (29), which is the function of electron charge q, the DC intensity I_{DC}, and electronic bandwidth [150],

$$\sigma^2_{DC} = 2qI_{DC}B. \quad (29)$$

- **Current Shot Noise:** This type of noise is generated while receiving the signals at the receiver end. If the signal power symbolized by P_s, then the shot noise variance can be written as [10],

$$\sigma^2_{ss} = 2qrP_sB. \quad (30)$$

- **Thermal Noise:** The random motion of electrons generates noise within the conductor medium due to a temperature rise. To model the thermal noise, if it considers The noise figure parameters $F = 4$, load resistance $R_l = 100\Omega$, and equivalent temperature $T_e = 290K$ are taken, then thermal noise variance given as [10], [150]

$$\sigma^2_{TH} = \frac{4kT_eFB}{R_l}. \quad (31)$$

In the UWOC system model, the sum of total noise variances is responsible for the system noise. Therefore, without any interference of optical signal, the noise variances of electrical current at the detector end is given as,

$$\sigma^2_I = \sigma^2_{TH} + \sigma^2_{DC} + \sigma^2_{BG} + \sigma^2_{ss}. \quad (32)$$

IV. TRANSCEIVERS FOR UVLC

A. TRANSMITTER AND TRANSDUCER

The function of optical transducers is to transform the modulated information into an optical or electrical or vice-versa signal pattern. The transducers are mounted on transceivers and fixed on a well-defined path for smooth signal propagation in an underwater medium. In another words, the transducers are designed to generate an optical signal from an electrical signal made from optical transmitters during optical beam propagation. On the other hand, an actuator can be used in UWOC [9] to generate the pulse of optical signal in electrical format at the receiver end. With the rapidly increasing interest in exploring aquatic media, UWOC plays a vital role in realizing a wide range of scientific, commercial, and coastal security applications. VLC is an alternative communication media as a UWOC implementation in the range of LEDs illuminating light sources. In UVLC, the transmitter transforms digital information into analog format over channel conditions. Generally, LEDs and LDs are used for signal transmission over high data rates and bandwidth. Another adhesive advantage is LED structure, where the photons are emitted spontaneously at different phases. In coherent radiation, the photons are stimulate by another photon that is radiated with phase correlation [151]. More precisely, LEDs excel as incandescent reliable light sources, power consumption devices, and efficient luminous tools. The LEDs efficiency operate 210 m/W more than the incandescent lamps efficiency [45]. The multi-functional transmitter-enabled LEDs emit light and information simultaneously with the optical dimming power this is most widely used; for efficient signal propagation while the optical transmitters do not use flickering phenomena. In a general aspect, the LEDs are designed for white-light emission sources and divided into two categories: blue and red-green-blue (RGB) emitting types of LEDs. Both types of LEDs emit different colors of light, as yellow-white light causes phosphorus polishing. Blue LEDs are considered more energy-efficient and widely use for light illuminating systems rather than blue LEDs. The blue-LEDs could achieve reliability for optical signal transmission by combining yellow color (RGBY).

In optical beam propagation, the VLC link depends on the dimming or switching nature of LEDs. The optical sources are categorized as laser transmitter type or an LED type optical transmitter. Consequently, the laser type of technological sources quiet different and are used according to the application requirement. An argon-ion laser is a well-known laser transmitter suitable for converting electrical signals into an optical format [10]. A transducer assists in converting and then transmitting all maximum quantities of photons toward the receiver or other nodes. For optical signal modulation, different types of laser modulators are being used. In general, the laser modulator is designed for low data rates over long-distance signal propagation, [9]. Compared to laser modulators, LEDs are cheaper though they cover very short ranges. The arrangement of an LED array is designed in a hexagonal type pyramidal shape for high-intensity and long-distance optical beam propagation, as proposed in [148]. In this type of pyramidal LED array structure, a single lens is used to illuminate the LED. This structure must be very compact for the output signals. For the sake of a signal, the direction can be created by switching an intense beam towards the destination.

B. OPTICAL RECEIVER

Optical receivers are the collection arrangements of all-optical signal transmission within a medium. In other words, receivers could be defined as the process of optical

TABLE 6. The latest underwater communication project schemes are currently running all around the world. Additionally, the future directions and the most significant contribution in the scientific community, underwater applications, and the results of the corresponding project schemes are summarized.

Project Name	Funded Under	Coordinated Body	Duration or Status	Contributions and Key Visions	Results or Publication
UNEXMIN (AUEFM) [154]	H2020-EU.3.5.3.	Miskolci Egyetem, Hungary	1^{st} February 2016 to 31^{st} October 2019 (Closed)	• Autonomous exploration of flood mines • 3D Mapping of specially for European oceans • A folk of robotics system provides a new technological platform that would have the capabilities of automated operations in mine explorations • The project contributes to boosting the miniaturization and adaption of sea robotic technology and interpreting geo-scientific data. item Several multiple autonomous deployments • Real-Time data acquisition • Reliable Navigation system • Communication among nodes along with the data fusion centre	• Dissertations-03 • Peer reviewed Articles-06 • Non-peer reviewed Article-01 • Mono-graphic Book-01 • Conferences-15
Surf3DSLAM [155]	FP7-PEOPLE-2009-RG - Marie Curie Action: "Reintegration Grants"	Universitat De Girona, Spain	1^{st} April 2001 to 31^{st} March 2013 (Closed)	• Development of AUV • High resolution sensors and low operational cost • Navigation and Exact position delectation • Localization of AUV in 3D underwater environment • Simultaneous localization and Mapping (SLAM) • Bathymetry and oceanographic data collection	• Articles-02
UnderWorld [161]	European Regional Development Fund (50%)	panish Ministry of Economy and Competitiveness (50%)	2013 to 2016	• Large scale of industries vitality in underwater, naval & military operation, seaport management infrastructures • Recommend to RF communication framework for shallow water cause the limited acoustic enabled system performances. • Goal to improve system quality setup towards future perspectives and alternative way of underwater signaling 1) Development of digital signals 2) Development of Antenna & Design 3) Advancement of communication system and development in low power regime 4) Enhance the underwater robotics and furhter development of UUVs for new paradigm underwater communication	• Articles-04

signal entities absorbed by the photodetector and the photons detection on its surface to generate an electrical signal called an optical receiver. The conversion process of photons energy into an electrical signal is performed through photoelectric effect. Otherwise stated, the received photons at the semiconductor junction diodes release either an electron or a hole. Subsequently, these released entities moved to the conductance and release their excessive energies [21]. The propagated optics are collected by a lens for the detection and demodulation process at the receiver end. A photo-sensor is used to convert optical signals for further analysis. Taking into account improving system performance, a photo-sensor is characterized as easily accessible, very cost-effective, robust, and small in size, along with the low current consumption [152]. To cope with these advantages, plenty of different types of photo-sensors are being used and summarized in recent surveys as [9], [152]. These photo-sensors are photo-resistors, phototransistors, photomultiplier tubes, avalanche photodiode (APD), p-n photodiodes, and a photon detector semiconductor, photo-sensors, and biologically-inspired quantum photo-sensors (BQP). PIN and avalanche photodiode (APD) are widely used as a photodetectors in optical communication [153].

V. CURRENT PROJECT SCHEMES ON UVLC

In this section, we provide the details of the most recent current project in underwater medium currently running

TABLE 6. *(Continued.)* **The latest underwater communication project schemes are currently running all around the world. Additionally, the future directions and the most significant contribution in the scientific community, underwater applications, and the results of the corresponding project schemes are summarized.**

Project Name	Funded Under	Coordinated Body	Duration or Status	Contributions and Key Visions	Results
subCULTron [156]	H2020-EU.1.2.2.	Universitaet Graz	1^{st} April 2015 to 31^{st} August 2019 (Details are not available)	• Development of high impact application area • Aim to betterment the communication among underwater nodes • Development of artificial mussels and interaction among nodes beneath water and water surface • Proposed a novel bio-inspired algorithm and energy harvesting in underwater scenarios • Development an artificial substrate underwater with the human society	• Reports -16 • Articles -03 • Conferences-13
TRIDENT [157]	FP7-ICT	Universitat Jaume I De Castellon, Spain	1^{st} March 2010 to 28^{th} (Closed) February 2013	• Proposed a new methodology for multipurpose underwater interventions tasks • Underwater Archaeology • Coastal and Ocean observatories • Oceanography and offshore industrial applications • Maritime rescue and marine applications	• More than 50 Publications
SWARMs [158]	H2020-EU.2.1.1.7.	Universidad Politechnical De Madrid, Spain	1^{st} July 2015 to 31^{st} July 2018 (Closed)	• Extensive and development of AUVs/ROVs research • Execution of maritime and offshore operations • Cost effective and increase safety pattern • Increase the mobility and accessibility of AUVs • Improve the serviceability of ROVs Achievement in different scenarios 1) Inspection, maintenance and repair of offshore infrastructure 2) Water pollution observation and monitoring 3) Offshore construction operations	• Reports -03 • Peer reviewed Articles-05 • Conferences-02
Sibiu-HCEV [159]	1) H2020-EU.3. 2) H2020-EU.2.3. 3) H2020-EU.2.1.	NIDO Robotics S.L., Spain	1^{st} February 2019 to 31^{st} July 2019 (Closed)	• Develop a cost-effective and easy to deploy an underwater floating robot • Autonomous surveillance an monitoring operations • Enabled optical and acoustical communication scenario • Improving the vision and localization • Development of combined vehicle-manipulator systems for underwater infrastructures inspection	• Not Available

worldwide. A wide detailed description are summarized in Table 6.

- Most recently, UNEXMIN project scheme [154] was launched and funded by the European Commission (EU) for 3D mapping and more widely autonomous exploration of European flooded mines (AUEFM) during the period of $2016 - 2019$. The main purpose of this project scheme was to develop a novel underwater robotic system for bathymetric, oceanographic, oceanic bathyscaphical data collection, and ocean exploration in 3D geographical imaging in real-time monitoring and video streaming. The Robotics Explorer is made by three robots named UX-1a, UX-1b, and UX-1c to adjoining for the purpose of valuable geological and mineralogical information collection. UX-1 is the first prototype was proposed to open the new technological lines and uncover mysterious challenges in this research project development. The first prototype was finished in April 2018 and has been tested at the Kaatiala mine (Finnland), Idrija mine (Slovenia), during 2018, and later in Urgeirca mine (Portugal), Ecton mine (England), Molnar Janos cave (Hungary) during 2019.
- The Surf3DSLAM project [155] was coordinated by the University de Girona, Spain, and proposed an innovative

TABLE 6. *(Continued.)* **The latest underwater communication project schemes are currently running all around the world. Additionally, the future directions and the most significant contribution in the scientific community, underwater applications, and the results of the corresponding project schemes are summarized.**

Project Name	Funded Body	Coordinated Body	Duration or Status	Contributions and Key Visions	Results
EUMarine-Robots [160]	H2020-EU.1.4.1.2.	Universidade Do Porto, Portugal	1^{st} March 2018 to 31^{st} August 2021 (Ongoing)	• The provision of access for researchers from academia and industries 1) State-of-the-art-infrastructure 2) Large-Scale sea experiments 3) Development and evaluation of operating concepts underwater applications 4) Data acquisition • Provide the uniform training for users • Enhance the better utilization of marine robotic infrastructures • Coping with the current and future marine challenges • Development of business strategies with the specific goals of ensuring the sustainability of the proposed infrastructures • The main Contribution 1) The extension of the Robotics Revolution 2) Cross-fertilization of ideas, tools, technologies, and methods 3) The efficient utilization of infrastructure in Europe	• Reports-06 • Peer Reviewed Articles -13 • Conferences - 12
Ocean-DAS [162]	H2020-EU.1.1.	Universidad De Alcala, Spain	1^{st} January 2020 to 30 June 2021 (Ongoing)	• Development and improve seismicity • Development of a low-cost monitoring seismcity in remote area of the ocean • Development of to detect range seismic waves • Easy to deploy the sensor arrays in underwater medium	• Not Available
COUSIN [163]	University of Sheffield, United Kingdom		1^{st} January 2021 to 31^{st} December 2023 (Ongoing)	• Reduce the cost underwater monitoring and surveillance system • Development of low-cost underwater acoustic network • Development of advance hybrid SONAR and RADAR based underwater monitoring system	• Not Available

research proposal for Probabilistic 3D Surface Matching for Bathymetry based Simultaneous Localization and Mapping (Surf3DSLAM) by deploying aquatic vehicles. The main challenges of this research project were navigation and detection of the exact position of the underwater vehicles. Further development of this project scheme proposed a remotely operated underwater vehicle (ROV) instead of AUV that supports low operational cost. The main objective of Surf3DSLAM was to accurately localize the ROVs and AUVs in 3D environmental space under the concept of simultaneous localization and mapping (SLAM). To associate SLAM within the 3D environment, the whole investigation was addressed as Surf3DSLAM. Surf3DSLAM framework mainly aimed to deploy AUVs for navigation purposes, replace other economical, efficient robotics vehicles, and further deploy for safe and precise surveys in an unguided aqueous environment.

- Most recently underwater activities are unveiling the mystery of occupied water territories and exploring natural mineral sources. Due to this, project scheme as Submarine Cultures Perform Long-Term Robotic Exploration of Unconventional Environmental (subCULTron) [156] was proposed and coordinated by the University Graz, Austria. This project was launched and aimed to achieve a long-lasting self-determination learning device, a self-configurable, self-maintainable underwater robotic tool in very high-impact-modified application areas in Italy. The main perspectives of this project are to develop a better quality of communication and energy harvesting among the underwater sensor nodes. The subCULTron is subdivided into few sections as the entitled project. The upper layer of sea surface in the proposed system, and the artificial objectives are introduced as the information collective robotic tools for long-run system exploration capabilities.

TABLE 6. *(Continued.)* **The latest underwater communication project schemes are currently running all around the world. Additionally, the future directions and the most significant contribution in the scientific community, underwater applications, and the results of the corresponding project schemes are summarized.**

Project Name	Funded Body	Coordinated Body	Duration or Status	Contributions and Key Visions	Results
TechOceanS [164]	H2020-EU.3.2.5.1.	National Oceanography Centre, UK	1^{st} October 2020 to 30^{th} September 2024 (Ongoing)	• Development of nine water observational technologies • Observation of water quality, Ocean biology and plastics monitoring • Improving underwater imaging of targeting sea-bed • Pelagic biology and plastics monitoring • Collection of thousands samples for further analysis • Artificial intelligence (AI)-based image processing method and information transmission	• Not Available
LD-UWC-VLC-LADCF [165]	Japan Society for the Promotion of Science (JSPS)	University of Yamanashi, Japan	1^{st} April 2020 to 31^{st} March to 2023	• Development of high speed underwater optical communication • Verification of effect distance extension in turbid water • Experimental evaluation and verification of construction of a laser beam array with propagation direction	• Not Available

The artificial robotic tool allows monitoring the marine environment, and the incredible natural oceanic environments, including biological materials such as algae, bacterium, and aquatic species. In contrast through subCULTron, a deployed artificial lily-pad on water surface communicates with human-culture and transmit energy along with the collected information from ship traffic. Apart from that, the artificial fish floats and exchanges information with mussels and lily-pad. The subCULTron is aimed to propose the real world for humans and animals in cohabitants of high impact such as venice canals and lagoon. Thus, the cultural evolution promotes a sub-culture development and an artificial society underwater along with the cultural services of human society over the water reservoir.

- The TRIDENT project scheme [157] formally known as Marine Robots, and Dexterous Manipulation for Enabling Autonomous Underwater Multipurpose Intervention Missions (MRDME-AUMIM) was proposed for multipurpose underwater challenges in highly turbid and complexity channel conditions. In other words, the development of novel methodology for marine robotics systems accommodates versatile dexterous adaption and the capabilities for operational activities in unguided underwater environments. This project scheme also has drawn attention to various specific skills in marine environments: navigation, bathymetric data, geographical mapping, vehicle-manipulator systems, dexterous manipulation, and the development of a wide range of intelligent control UWSNs architectural techniques. The project has been classified into two phases. In its first phase, the autonomous surface craft (ASC) is carried AUV towards the sector to be surveyed, while in the second phase, the assembly of ASC and AUV navigate the underwater targeted position.
- The latest project scheme [158] entitled Smart and Networking Under Water Robots in Cooperation Meshes (SWARMs) was funded by the EU and also coordinated by Universidad Politechnica de Madrid, succeeded to forward the extensive research of AUVs/ROVs to the next level. The further development of AUVs/ROVs research provides a solution to the threat of offshore industries. SWARM project aimed to expand a better utilization of robotics in underwater, various marine applications and offshore operations, which affects the assigned safety patterns and operational costs. The main attraction of the project research is to improve AUVs' autonomy and enhance the usability of ROVs in the underwater environment. Moreover, no specialized underwater vehicles are required; instead of AUVs/ROVs work in a cooperative network; as a result, it opens the doors for new futuristic underwater applications. At a glance, the achievements of SWARM could be demonstrated in several testing sites and numerous applications such as inspection and water pollution monitoring.
- Oceans and seas are the source of life on earth and the most significant water source for humankind. Nevertheless, these water reservoirs are affected by human interactive activities. Therefore, exploring these massive water mediums are necessary by deploying artificial devices or robots, called marine robots. In general, the vitality of marine robotics technology is an enormous significance in an extensive range of

functional underwater applications. These applications are mostly utilized to observe and monitor purpose and the life beneath the water surface, observation of water pollution, oil and gas rig observations, surveillance and coastal securities, fish farming, and early detection warning of natural disasters. Given this, an innovation of the project scheme Sibiu-HCEV [159], is introduced as the resolution of an intelligent hybrid high capacity electric underwater ROVs. The Sibiu-HCEV is an underwater floatable robot at different depths in an unguided water environment that is an innovative invention in underwater robotics technology to reduce risk to the capital expenditure (CAPEX) and operating expenditure (OPEX).

- Marine robotics industries are rapidly growing up to uncover the complexity of harsh oceanic environments. The marine robots have pulled back the curtains of the mysterious thesaurus of the deepest oceans. This underwater robotics industrial sector is a crucial, significantly cost-effective domain with considerable entry barriers to resources and developments. The project EUMarineRobots [160] is aimed to extend the underwater challenges into more depth, remotely operations, and in the very hostile marine environment. Additionally, the aim of EUMarineRobots are deploying for a full range of air and open international access to Europe. EUMarineRobots has an impressive research group from ten countries in marine robotics research infrastructure network. This network distinguishes the various technical infrastructures for diverse navigation beyond marine and in the marine robotic sectors.
- Since the early ages, underwater applications are based on acoustic links for long range communications. However, RF and optical waves are capable of supporting large bandwidth and high data rates but efficiently attenuated due to the physio-chemical vitality of the marine environment. The primary objectives of the project were recently proposed as UNDERWORLD [161] to re-evaluate the electromagnetic communication through UWSNs deployment for various underwater applications such as navigation, localization, natural disaster, detection of coral reefs, and coastal security purposes in real-time scenarios. This project aims to enhance industrialization in marine observatory systems, naval tactical operations, seaport management infrastructures, and underwater environmental monitoring. Moreover, underwater environmental monitoring in an aqueous medium is widely deployed with acoustic waves, but these applications apply in shallow waters such as rivers, dams, lakes, and remotely coastal areas. Throughout this project scheme. Another main contribution of this project is to improve the characteristics of antennas for two ways of communication among transceivers.
- Earthquakes, Tsunami, and floods are sudden natural events which occur due to an imbalance of water reservoirs and waves (water currents). These events are entirely impossible to control or prevent but can be detected earlier by deploying the sensors nodes or anchored architecture of UWSNs with the sea bottoms. The seismometers are used to sense the unacceptable seismic frequency at a standardized scale. These seismometers are highly detectable sensor nodes those capable for detecting and recording waves emitted by the most miniature earthquakes. It is far expensive to deploy seismometers at the ocean bottom to investigate water currents and seismic waves detection. Due to these issues, the novel project scheme funded by the EU entitled Ocean-DAS had recently proposed new tools for underwater seismology through ocean-bottom distributed acoustic sensors [162]. The main aim of Ocean-DAS is to develop a low-cost deployable alternatives for monitoring seismicity in remote areas of the oceans. The Ocean-DAS are enabled with the fiber optical wires for telecommunication which transforms the data into powerful seismic sensing arrays. Through the support of this opto-electronic unit, more than a 50km span could be monitored.
- The most recent project scheme is proposed entitled as Cooperative Underwater Surveillance Networks (COUSIN) funded by Engineering and Physical Sciences Research Council (EPSRC) [163] during 2021s to 2023s. The project scheme focuses on the underwater surveillance system for a specific country or region. The surveillance system is investigated for more precise benefits in various underwater applications in numerous fields such as pollution monitoring, coastal or harbor securities, import and export duties, human trafficking, smuggling, maintaining integrity, and detecting attacks on underwater infrastructure. The main expected contribution of this project scheme is to track, target and search for suspicious objects, and convey information to the base station for further investigation. The detectable target through this project scheme could be an artificial object such as UUV, surface vehicle, submarine, source of pollution, underwater species, active volcanos, oil & gas pipeline repaitment, ice objects, or divers, etc. Furthermore, surveillance and underwater monitoring are the main functions through the long-range acoustic link. For underwater geographical mapping and target detection, the SONAR waves are the key beneficial technologies while over the sea-surface detection, radio detection and ranging (RADAR) are the most widely used. The main objective of COUSIN is to design a low-cost underwater acoustic network to improve the underwater monitoring and surveillance system capabilities.
- The current ongoing project scheme entitled Technologies for Ocean Sensing (TechOceanS) [164] funded by the European Commission (EC) and coordinated by the National Oceanography Center, UK. TechOceanS is organized by the research group of ten universities in Europe. The oceans are affected by human beings by

flushing and trashing unwanted decomposable materials such as plastics that are threatening to harm underwater species. Due to human activities direct and indirect involvement in the underwater environment, the ice caps melt, and the water level rises. Therefore, an urgent need to deploy an advanced ocean observational technology through resistance to extract the decompose plastic materials. At first glance, the project has developed the scheme to monitor and observe ocean biology, chemical composition changes, and plastic monitoring through underwater vehicles nine pioneering technologies. The proposed novel solution by TechnOceanS is comprised of a group of five sensors; the two sensors are used for imaging data collection of the specified seabed, marine biology, and plastics. A sampler is used to collect thousands of particle samples for further analysis and the rest of use for a new artificial intelligence (AI)-based image processing method for data compression and information transmission.

- The most recent proceeding project scheme established for Long Distance Underwater Wireless Optical Communication System using Visible Light Laser Array with Directivity Control Function (LD-UWC-VLC-LADCF) [165], and funded by Japan Society for the Promotion Science (JSPS). The purpose of this scheme is to improve the quality of visible light signaling over long ranges in the underwater environment. In this research perspective, the main two challenges are extending the transmission distance in gigabit-class with high-speed UWOC. The first point is the verification of the effect of distance extension while multiple visible light laser are propagated propagating in a high turbid water medium. Secondly, the construction of a light beam in a particular direction through evaluating the experimental data available.

VI. COMPUTATIONAL METHODS

Nowadays, solving complex and huge data-based problems are typically possible without a real experimental setups. This is achieved through simulation-enabled computer science and engineering methodologies. Moreover, computational engineering methods support automaticity, design, and optimization of the complex problems. Therefore, the computational research methods provide the new advancements investigating the mythologies in computing such as algorithms, models, simulations, and system performances in order to understand the complexity of social, biological, technological, and everlasting patterns and their behaviors [166]. These computational research methodologies provide a solution for better understanding of random behavior of the system as follows:

- Automatically categorization and information extraction of the selected data-sets;
- Differentiate a bulk data into a specific group and particular level for the analysis;
- The system design and model of the emergence of new behaviors from individual-level interactions;
- A detailed explanation of emergence of a system network;
- Recognizes and refrigerates the thresholds within a complex system;
- Classifies and finds a the pattern within the massive data-sets for further analysis by using other techniques;
- Identify meaningful structural patterns within the webs of relationships.

In more detail, computational engineering methodologies are defined as the development and exploitation of more realistic computational models. As a result, the computational engineering methodology opens new perspectives and challenges of more sophisticated key problems of huge data structures. Additionally, computational methodologies are numerically mathematical and depends heavily on computer architectural system. It means that the numerical efficiency should be achieved by extracting the maximum amount of correct information from the minimum number of grid points, as well as establishing a linear proportionality between the incoming time and the unknown number. Due to this, several computational approaches are studied in this study as follows.

A. MONTE-CARLO COMPUTATIONAL METHOD

The probabilistic format of the computational method is widely known as the Monte-Carlo simulation. In UWOC, this computational method is used to track the number of photons emitted by an optical source within the underwater medium. A high bandwidth underwater optical communication channel by utilizing Monte-Carlo simulation is widely discussed in [167]. The simulation approach of photons propagation is rigorous within turbid medium, in a more detailed description, Monte-Carlo simulation computational methods are used to provide the specific details of the propagated photons geometry as mentioned in [168] and [169]. Generally, the optical signals propagation depends on the medium waves. This is an alternative computational approach to eliminate the unbounded error growth in co-variance equation computationally as described in [170].

B. NUMERICAL MODELING OF WAVE PROPAGATION

As aforementioned, that the optical beam spreads in an underwater medium and depends on the water flow (channel conditions). The different types of water flow have been categorized and summarized according to the flow pattern in [171]. Laminar flow is defined as where the fluid particles move along in a well-defined path and each water layer slides smoothly over the adjacent layer. While the turbulent flow is defined as the zig-zag flow pattern of water particles. The laminar flow changes into turbulent flow if the Reynold's number is more than that 4000. The Reynold's condition satisfies as laminar flow below 2000, otherwise turbulent flow [172]. Due to this, the optical beam propagation experiences a huge loss due to turbulence, signal absorption, and scattering by the suspended particles within the medium. Therefore, the necessity is to model the turbulence channel. Moreover, a numerical method for free surface flow that builds for nonlinear shallow water equation and utilizes a non-hydrostatic pressure term to describe short waves are presented in [173].

C. BEER LAMBERT's LAW

Computational methods are employed as the most significant solution for optical signaling in underwater mediums. An ordinary simulation method is widely employs for optical signaling in an aqueous medium known as Beer Lambert's law. This law is described the optical signal attenuation due to the existence of suspended particles underwater. It is mathematically defined as the function of optical received signal power, the Euclidean distance apart from the transceivers, and the extinction coefficient of the medium. This type of channel model is used for optical signaling for any type of water availability, especially, for path loss fading. The mathematical expression of Beer Lambert's law is shown below:

$$P_r(\lambda, d) = P_t \exp -c(\lambda)d, \tag{33}$$

where P_r and P_t are denoted as the received and transmitted optical signal strength at the receiver and transmitter ends. Also, the extinction coefficient $c(\lambda)$ is the sum of total optical signal absorption and scattering which are the optical wavelength dependents. The experimental values of extinction coefficient, for the readers references are widely discussed in [5], [82], [84], [86], and [174]. Additionally, due to transceivers physical parameters, geometrical losses are also considered for diffused LDs and semi-collimated light sources LEDs. Therefore, the modified Beer-Lambert law is the function of path loss (h_{pl}) and geometrical losses (h_{gl}) are given as [101],

$$\begin{aligned} h_l \approx & \quad h_{pl} + h_{gl}, \\ = & \left(\frac{D_r}{\theta_F}\right)^2 d_t^{-2} exp\left(-c\left(\frac{D_r}{\theta_F}\right)^\tau d_t^{1-\tau}\right). \end{aligned} \tag{34}$$

The contributed channel condition coefficient h_l in terms of path loss and geometrical losses are presented in (34). In (34), the receiver aperture diameter D_r, full-width transmitter beam divergence angle θ_F, and correction coefficient τ are defined. According to [101], the maximum achievable distance between communication nodes to obtain the BER performance of the vertically point-point system is given as follows,

$$d = \left[\frac{W\left(\frac{c}{2}(1-T)\right)\left(\frac{D_R}{\theta_{1/e}}\right)\left(\frac{1}{Q(BER)}\sqrt{\frac{2\sigma_n^2}{P_t r^2 \eta^2}}\right)^{\left(\frac{T-1}{2}\right)}}{\frac{c}{2}(1-T)\left(\frac{D_R}{\theta_{1/e}}\right)^T}\right]^{\frac{1}{1-T}}. \tag{35}$$

where W, Q, η, and T are defined as the Lambert-W function, error function, electrical to optical conversion efficiency, and correction coefficient.

D. RADIATIVE TRANSFER DIFFERENTIAL THEORY AND COMPUTATIONAL METHOD

Radiative transfer theory (RTE) deals with computing derivatives of radiometric measures with respect to desired visual of geometrical parametrization, and facilitates the gradient-based optimization in various applications [175]. Additionally, the RTE is deployable in neutron transportation, astrophysics, and biomedical image analysis [175], [176]. Furthermore, the energy conservation-based radio transfer theory is used to model the optical waves in participating media. For better RTE understanding the assumptions are made, if considers the test volume $V \subseteq \mathbb{R}^3$ with the corresponding boundary ∂V, and the interior radiance field $L(s, \omega)$ is defined over the position $s \in V/\partial V$, and light-transport directions $\omega \in \mathbb{S}^2$. Then, the RTE equation given as follows [175],

$$L = (K_T K_C + K_S)L + L^{(0)}, \tag{36}$$

where, K_T, K_C, and K_S are denoted as the transport operator, collision operator, and interfacial scattering operator, respectively. Additionally, the Reynolds transport theorem is also an alternative method to solve computational problems. The Reynolds theorem for f scalar value function is defined for n-dimensional manifold ω parameterized with some $\pi \in \mathbb{R}$ as (37). If it is an assumption that $\Gamma(\pi) \subset V(\pi)$ be an $(n-1)$ dimensional manifold given by the union of the external boundary $\partial V(\pi)$ and the internal one containing the discontinuous locations of f. Then, Reynold's theorem could be specified as follows [177],

$$\begin{aligned} \partial_\pi \left(\int_{V(\pi)} f dV(\pi)\right) \\ = \int_{V(\pi)} \dot{f} dV(\pi) + \int_{\Gamma(\pi)} < n, \dot{x} > \Gamma(\pi). \end{aligned} \tag{37}$$

Furthermore, $\dot{f} := \partial_\pi$, $\dot{x} := \partial_\pi x$, dV and $d\Gamma$ denotes the standard measures associated with V and $\Gamma 0$; Moreover $< \cdot, \cdot >$ indicated the dot (inner product between two vectors.) Furthermore, n is the normal direction at each $x \in \Gamma(\pi)$.

E. THE DATA ASSIMILATION ALGORITHMS FOR NUMERICAL MODELS

The data assimilation refers to the procedure of incorporating data into a model simulation to improve the upcoming predictions. The predictions of the system behavior can be defined by the measurement of the physically numerical based model. More specifically, the system should be more simplified for a better understanding of computational methods. In many applications, the data assimilation approaches are accurate to describe the dynamic behavior of the system. Utilizing the data assimilation techniques the measurement and model outcomes are used to obtain an optimal estimation of the state of the system. However, the main hurdles in advanced data assimilation schemes are the bulky computational load that is required for solving a real problem. On the other hand, the assimilation algorithm is an essential tool to obtain efficient variational data for further analysis. Due to this, More accurate data assimilation methods are variational data assimilation and Kalman filtering computational method is widely used. Data assimilation for minimization computational method widely discussed in [178] as follows,

$$X_{k+1} = f(X_k, p, k) + B(k, p)u_k, X_0 = x_0 \tag{38}$$

where X_k is the system state, u_k is the input of the system, f is a nonlinear function, p is a vector containing the uncertain parameters, and $B(k)$ is an input matrix. Besides, the Kalman filter assimilation computational method could be written as,

$$X_{k+1} = F(k)X_k + B(k)u_k + G(k)W_k, \tag{39}$$

where the Gaussian noise process is denoted by W_k with zero mean and covariance matrix $Q(k)$ and $G(k)$ is the noise input matrix.

VII. UVLC CHANNEL MODELLING

Modeling of UWOC channel leads to a better understanding of optical signal propagation and supports exploring aqueous mediums. UVLC is considered an alternative communication media to meet the requirements in high data rate, large bandwidth, and high communication speed to deploy in various underwater applications. Moreover, for long ranges UVLC communication, the necessity is to design a system for efficient signal transmission. Generally, the signal absorption reduces the signal strength that is attenuated in the transmitted signal. Despite that, the scattering phenomena is responsible for the optical beam deflection from its initial position, this contributes to signal fading. As a result, Monte-Carlo simulation is being used, which is an alternative approach to deal with the statistical methodology for the evaluation of channel characteristics by generating a number of random photons and further obtained the simulation performance interaction of each photon within the medium [179].

Optical signal propagation is categorized into two main streams based on the type of detection techniques. They are: non-coherent intensity modulation and direct detection (IM/DD) signal modulation technique. However, the IM/DD is generally used as an optical signal modulation scheme to decode information at the receiver. In non-coherent systems, the detector directly detects information through emitted light. Another aspect of the signal detection technique is the coherent detection, where a local oscillator (LO) is being used to mix optical signals before detection which improves the receiver sensitivity [180]. In more contrast, coherent and heterodyne detection techniques are widely discussed as in [29]. A local oscillator uses incoherent detection scheme

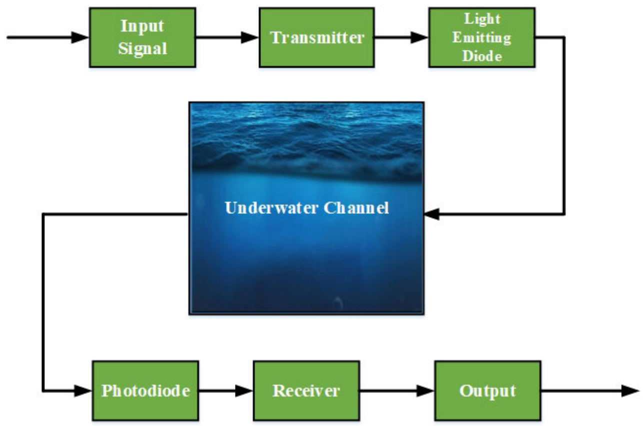

FIGURE 8. The flow chart to design the underwater wireless signal model in underwater.

which comprises of the received signal to the carrier beam detected by the photodetector. Furthermore, the coherent detection scheme is also sub-categorized into two main classes as heterodyne and homodyne detection [21]. The LO operates as the same frequency with the optical signal in the homodyne detection scheme, while the frequency could be different in the heterodyne detection scheme. In the VLC setup, the system consists of an optical transmitter for signal modulation by LED illumination phenomena. On the other hand, a receiver enables a photosensitive diode for the decoding process from the detected light power. The block diagram consists of a transmitter and a receiving system depicted by Fig. 8. The different approaches use to model the undersea VLC system.

A. OCEANIC TURBULENCE CHANNEL MODELING

The most influential optical signal phenomenon is channel turbidity. Turbulence occurs due to random fluctuation in the refractive index of the water medium caused by the variation in temperature and salinity. Therefore, turbulence phenomena affects the performance of optical signal propagation in an aqueous medium. The affecting performance and channel modeling of highly turbid water mediums are presented in existing literature [100], [102], [181]–[183]. The fluctuation in the refractive index is directly related to the nature of the water channel as a function of temperature, salinity, pressure, and density. Due to increasing underwater depth, the temperature decreases and pressure increases; nevertheless, the water is slightly compressible affecting highly pressurized and dense water environments. Taking into account underwater turbulence, the scintillation index (σ_I^2) leads turbidity which is the main cause of optical signal fading. In more detail, the broad study of modified underwater optical turbulence (UOT) model is investigated mathematically by (40), as shown at the bottom of the next page, [184].

As stated UOT spectrum model in (40), where κ, ϵ and C_0, C_1 is defined the magnitude of the spatial frequency, dissipation rate of turbulent kinetic energy per unit mass of fluid and fluid constants, respectively. Moreover, Kolmogorov microscale length η is represented ratio of kinematic viscosity (ν) and ϵ. The dissipation rate of mean-squared refractive index χ_n, the thermal expansion coefficient α, and saline contraction coefficients are given as,

$$\chi_n = \alpha^2 \chi_T + \beta^2 \chi_S - 2\alpha\beta \chi_{TS}. \tag{41}$$

Considering plane and spherical wave models of scintillation index (σ_I^2) for different Gaussian beams are widely discussed in [185]–[187]. However, the scintillation index is defined as the variance of the received signal normalized intensity I, which is expressed in [8],

$$\sigma_I^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}. \tag{42}$$

As varying scintillation index causes heavy turbulence, that can be highly affect of optical signal propagation. It means the more unsatisfactory performance of the system and degrades the system efficiency. Various existing works are recorded to channel models in weak and heavy turbidity channel conditions. In existing research, plenty of statistical channel models under weak turbulence intensity fluctuation and mathematically are defined PDFs for turbulence. The experimental model under lognormal distribution is mentioned as in [100], [188]–[190]. Therefore, the probability density function (PDF) of turbulence channel condition under lognormal distribution is given as follows,

$$f_I(I) = \frac{\exp\left(-\frac{(\ln(I) - 2\mu_n)^2}{8\chi_n^2}\right)}{\sqrt{8\pi \chi_n^2 h^2}}. \tag{43}$$

In spite of strong turbulence channel conditions, UVLC channel model into successive j^{th} number of water layers, and following Gamma-Gamma (GG) distribution model is proposed as in [33] and [114],

$$f_{I_j}(I_j) = 2\frac{(\alpha_j\beta_j)^{\frac{(\alpha_j+\beta_j)}{2}}}{\Gamma(\alpha_j)\Gamma(\beta_j)}(I_j)^{\frac{(\alpha_j+\beta_j)}{2}-1} K_{\alpha_j-\beta_j}(2\sqrt{\alpha_j\beta_j I_j}), \tag{44}$$

where the Gamma function and modified Bessel function of the second kind are denoted by $\Gamma(\cdot)$ and $K_{(\alpha_j-\beta_j)}(\cdot)$, respectively. The PDF in (44), for normalization conditions it satisfies the equality of turbulence channel coefficient as $\mathbb{E}\{I_J\}^2 = 1$. Besides of it, the scintillation index for GG distribution is given as [191],

$$\sigma_{I_j}^2 = \frac{1}{\alpha_j} + \frac{1}{\beta_j} + \frac{1}{\alpha_j\beta_j}. \tag{45}$$

Furthermore, under-consideration of j^{th} vertical water layers, the large and small scale factors for the plane wave model are defined by α_j and β_j respectively. The α_j and β_j can be written as follows [33], [183],

$$\alpha_j = \left[exp\left(\frac{0.49\chi_{I_j}^2}{\left(1 + 1.11\chi_{I_j}^{\frac{12}{5}}\right)^{\frac{7}{6}}} \right) - 1 \right]^{-1}, \tag{46}$$

$$\beta_j = \left[exp\left(\frac{0.51\chi_{I_j}^2}{\left(1 + 0.69\chi_{I_j}^{\frac{12}{5}}\right)^{\frac{5}{6}}} \right) - 1 \right]^{-1}. \tag{47}$$

In (46)-(49), χ_I^2 represents the scintillation index which is known as Rytov variance [102]. Consequently, under-consideration of plane wave model, the large scale factor α, and small scale factor β for multiple water layers can be written as [192], [193],

$$\alpha_k = \left[exp\left(\frac{0.49\chi_{I_k}^2}{\left(1 + 0.18d^2 + 0.56\chi_{I_k}^{\frac{12}{5}}\right)^{\frac{7}{6}}} \right) - 1 \right]^{-1}, \tag{48}$$

$$\beta_k = \left[exp\left(\frac{0.51\chi_{I_k}^2 (1 + 0.69\chi_{I_k}^{\frac{12}{5}})^{\frac{-5}{6}}}{\left(1 + 0.9d^2 + 0.62d^2\chi_{I_k}^{\frac{12}{5}}\right)^{\frac{5}{6}}} \right) - 1 \right]^{-1}. \tag{49}$$

In above expressions (48) and (49), the Rytove variance is calculated for k^{th} environment layers as $\chi_{I_k}^2 = 1.23{C_n}^2 k^{7/6} L^{11/6}$. Herewith, the optical wave number is denoted by $k = 2\pi/\lambda$. In (48) and (49), $d = 10D\sqrt{\frac{5\pi}{\lambda z}}$, with D which is the receiver aperture diameter and the optical wavelength (λ). It is noteworthy that the refraction index is denoted by ${C_n}^2$ which varies from $10^{-13} m^{-2/3}$ (strong turbulence regime) to $10^{-17} m^{-2/3}$ (weak turbulence regime) with uncertainties values $10^{-15} m^{-2/3}$ in terrestrial based communication [194]. Moreover, the Rytov variance $\chi_{I_k}^2 \gg 1$ depends for large scale cells for plane wave model while $\chi_{I_k}^2 \ll 1$ for small scale cells.

$$\Phi_n(\kappa) = \left(\frac{\alpha^2 \chi_T C_0}{4\pi\kappa^2\omega^2}\right) \sqrt[3]{\frac{1}{\epsilon\kappa^5}} \left[1 + C_1\left(\sqrt[3]{\kappa^2\eta^2}\right)\right] \left[\omega^2 \exp\left(\frac{-C_0\delta}{P_T\sqrt{C_1^2}}\right) + d_r \exp\left(\frac{-C_0\delta}{P_S\sqrt{C_1^2}}\right) - \omega\,(d_r + 1)\exp\left(\frac{-0.5C_0\delta}{P_T S\sqrt{C_1^2}}\right)\right] \tag{40}$$

However, in (46) and (47) the Rytov variance is modeled [184, Eq. (22)] as follows,

$$\chi_{I_j}^2 = 8\pi^2 k_0^2 d_0 \int_0^1 \int_0^\infty \kappa \Phi_n(\kappa)\left\{1 - cos\left[\frac{d_0\kappa^2}{k_0}(\xi - \xi^2)\right]\right\} \times[1 + C_1(\kappa\eta)^{\frac{2}{3}}]\Big(\omega^2 \exp(-A_T\delta) + d_r \exp(-A_S\delta) - \omega(d_r + 1)\exp(-A_{TS}\delta)\Big) d\kappa d\xi, \quad (50)$$

in (50), the parameters d_0, κ, $\Phi_n(\kappa)$, and ξ, η, C_0, C_1 are defined as the link distance, magnitude of the spatial frequency, spectrum model, & normalized distance variable, Kolmogorov micro-scale length, and constants with relative strength of temperature and salinity ω with eddy diffusivity ratio d_r. Additionally, the coefficients $A_T = C_0C_1^{-2}P_T^{-1}$, $A_S = C_0C_1^{-2}P_S^{-1}$ are temperature, salinity and Prandtl numbers dependent along with $\delta = 1.5C_1^2(\kappa\eta)^{45} + C_1^3(\kappa\eta)^2$, respectively.

B. POINTING ERRORS AND NON-LOS COMMUNICATION LINK

Pointing error is another issue in optical signal propagation that contributes to the signal fading in the underwater environment. Due to the random water current flow and movement of floating nodes, a uniform constant tracking pointing system necessary to maintain for a reliable communication link. Generally, the pointing error is defined and considered with the two essential categories as bore-sight and jitter [195]. For more detail, in [195] the authors are defined the bore-sight determines on a stable displacement transceiver (between detector center and the beam center), whereas jitter is the random displacement process between of beam center at the detector plane [196].

Under consideration of Gaussian beam model for jitter phenomenon, if the optical beam propagates through the distance z between the source and destination along with the collected beam at the detector end with beam radius a. Then, the collected power at the receiver is given as [100], [195] [197],

$$h_p(R; z) \approx A_p \exp\left(-\frac{2R^2}{\Omega_{zeq}^2}\right). \quad (51)$$

In (51), R denotes the random radial displacement at the receiver that could be further expressed as $R = \sqrt{R_x^2 + R_y^2}$ with R_x^2 and R_y^2 are the horizontal and vertical components. The fraction of the collected power is denoted by A_p at $R = 0$. The fraction of the collected power $A_p = [\text{erf}(v)^2]$ and $v = \sqrt{\frac{\pi}{2}}\left(\frac{D_R}{2w_z}\right)$ are defined the ratio between aperture radius along with beam-width w_z. The equivalent beam width defined as $\Omega_{zeq}= w_z\sqrt{\frac{\sqrt{\pi}erf(v)}{2v\exp{-v^2}}}$ where erf denotes the error function. The beam-width at distance z given as $w_z \approx w_0\sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2}\right)}$. The spot size of the Gaussian beam wave and beam wavelength are denoted by w_0 and λ, respectively. The probability density function (PDF) of pointing error h_p can be expressed as follows,

$$f_{h_p}(h_p) = \frac{\zeta^2}{A_p^{\zeta^2}} h_p^{\zeta^2-1}, 0 \le h_p \le A_p \quad (52)$$

where the ratio of equivalent beam radius with pointing error displacement standard deviation at the receiver end is presented by $\zeta = \frac{\Omega}{2\sigma_s}$. On the other hand, if neglecting the pointing error, then the observation the misalignment of the transceivers is modeled by utilizing the beam spread function (BSF) as [85].

VIII. MODULATION, DEMODULATION, AND CHANNEL CODING TECHNIQUES FOR UVLC

VLC signal modulation is totally different from terrestrial-based communication cause of non-encoding features in phase, and amplitude [198]. In general, the accomplishment of LEDs in the VLC system has triple features as illumination, high-speed data communication, and energy harvesting simultaneously [27]. The Maximum Flickering Time-Period (MFTP) of the light should be minimized for the minimal flickering phenomena [31]. On the other hand, the dimming process control of light supports the potential energy conservation purposes [31]. Generally, VLC modulation techniques deploy under IM/DD, and coherent modulation (CM) based scheme, which is further classified as a single carrier modulation (SCM), multi-carrier modulation (MCM), and color domain-based modulation (CDBM) schemes [3]. The various type of VLC modulation schemes are summarized by the Table 7. Moreover, the pictorial classification of VLC modulation techniques is depicted by Fig. 9. It is noteworthy that IM/DD modulation schemes are less suitable for high-data-rate applications [21]. For that reason, there is an alternative option Mach-Zehnder Modulator (MZM) which is used to modulate the intensity of the continuous optical waves and widely use for laser beams propagation [199]. Although the CM scheme offers more advantages over IM/DD enabled system in detection performance and minimize the background noise, the better sensitivity of the receiver, low cost, and complexity to install setup [200]. Modulation schemes are the most critical ways to expand bandwidth, such as OOK, pulse position modulation (PPM), and pulse width modulation (PMW) have advantages regarding system complexity when using to enhance the performance of the VLC system. However, the Discrete Multitone (DMT) modulation, OFDM modulation, and Carrier-less Amplitude Phase (CAP) modulation have better spectral efficiency [27].

A. SINGLE CARRIER MODULATION SCHEME

In SCM, the communication setup leads to improve channel capacity. Nevertheless, the system complexity is increased

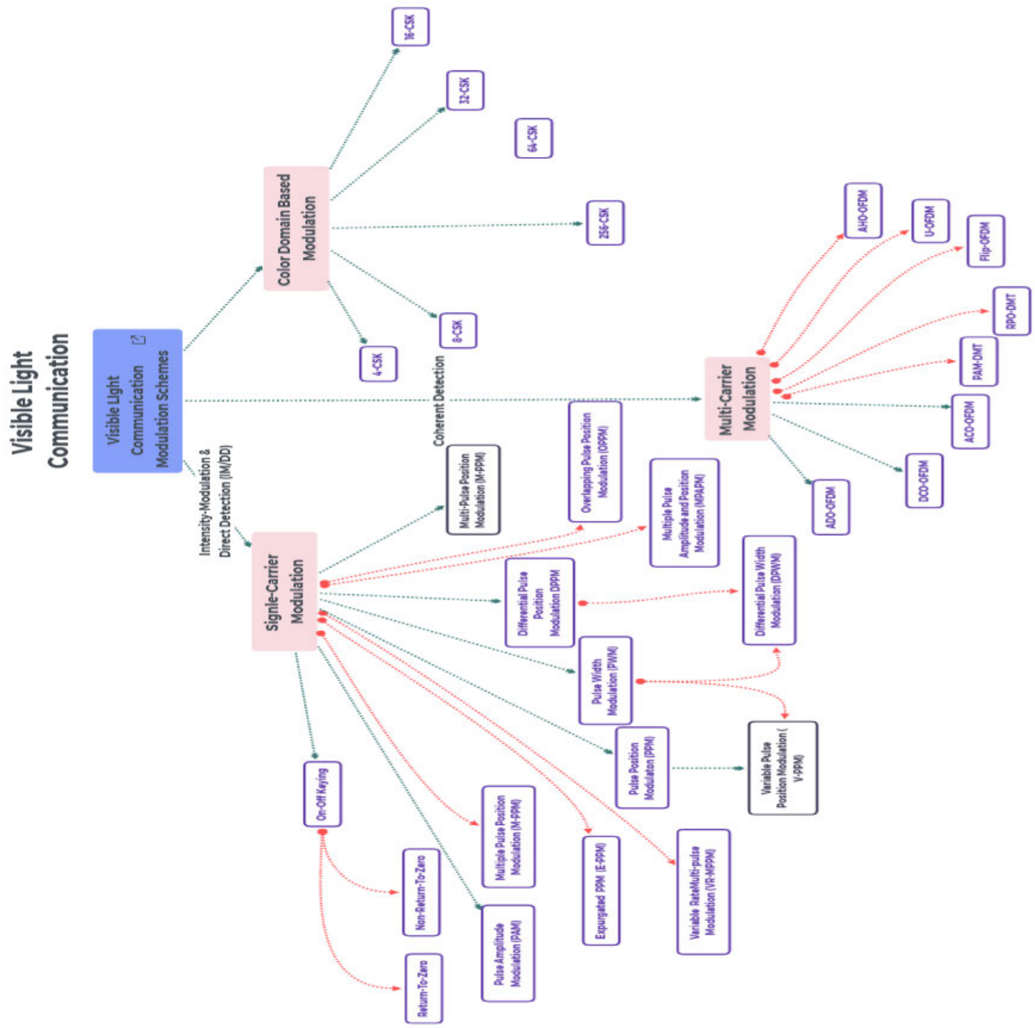

FIGURE 9. The tree construction of optical signal modulation schemes under consideration IM/DD. The classification is also categorized under three distinct categories: single-carrier modulation (SCM), Multi-carrier modulation (MCM), and color-domain-based modulation (CDM) techniques. Each of the categorized optical signal schemes for the specific signal modulation and encoding scenario. Nevertheless, the basic single-carrier modulation scheme is widely used in the existing literature.

due to the cost factor. The IM/DD setups have several benefits as easy to install, very cost-effective, and less complex as compared with the coherent system. The photo-detectors are used to convert optical signals into electrical signals under IM/DD technique. As the dimming process is widely noticed in optical signaling consequently, several dimming processes have been proposed in [201]. Furthermore, the PPM, DMT, and OOK are also proposed to accommodate dimming phenomena [202]. Generally, for regular system model design, signal carrier modulation (SCM) schemes are widely used. In consideration of SCM- IM/DD, several modulation techniques are investigated such as OOK, PAM, variable pulse position modulation (VPPM) and differential pulse position modulation (DPPM) pulse position modulation (PPM), pulse width modulation (PWM) and color shift keying (CSK), etc., [21], [27] and are mentioned in Table 7.

B. OOK MODULATION SCHEME UNDER CONSIDERATION IM/DD

IM/DD scheme is well known and easy to install, and a cost-effective signal propagation scheme. In this scheme, the signals have to propagate through the source directly or by the external modulator. Despite the receiver side, the signal information is demodulated through the direct detection process; therefore, the whole system is named as intensity-modulation & direct-detection. An ordinary process to modulate optical signal information through light and the intensity regulated by the OOK scheme. The illumination of LEDs are turned ''off'' and ''on'' phenomena according to the bit-stream as the digital numbers ''0'' and ''1'' [27]. Such as the presence and absence pulse phenomena of light intensity depending on the bit duration. The LEDs are not completely turned off in the ''off states''; nevertheless, the

TABLE 7. Consider the underwater optical modulation techniques, the single carrier modulation scheme (SCM), and color shift keying (CSK) are summarized in this table. The research objectives, design system model, and future directions are also briefly described.

Modulation Techniques	Type of Modulation	Research Objectives	References
Single Carrier Modulation (SCM)	OOK 1) RZ-OOK 2) NRZ-OOK	1) BER performance for P2P and Hybrid communication system 2) An optical underwater system is proposed over 34.5m distance received 2.70Gbps data-rate through a green laser diode utilizing with NRZ-OOK modulation scheme	• [24] • [182] • [203]
	PAM	1) Average BER performance of P2P VLC system within strong GG turbulence channel conditions and pointing error effect 2) BER performance of P2P VLC system within weak Log-normal turbulence channel condition 3) Asymptotic BER performance of generalized TLS selection over weak Log-normal turbulence channel condition 4) Diversity gain analysis of optical system over strong GG turbulence channel condition along with the pointing errors	1) [100] 2) [204] 3) [205] 4) [206]
	1) L-PPM 2) M-PPM	1) Investigate the spectra, power efficiency and bandwidth of L-PPM and M-PAM 2) The system model, BER performance and comparison with existing OOK, L-PPM and M-PAM schemes 3) The proposed alternative way of reducing the sampling rate for wideband signals along with the basic theory of compressive sampling-based on PPM	1) [207] 2) [208] 3) [209]
	L-PWM	1) The system model and comparison with existing OOK and PPM schemes 2) Investigate the spectra, power and bandwidth efficiency of L-PPM	• [208]
Color Shift Keying (CSK)	1) 3-CSK 2) IEEE 802.15.7 CSK	1) Proposed a novel symbol sequence transmission technique 2) The analytical expression for BER and designed parameters for 3-CSK are also optimized 3) Several color band combination (CBCs) of multilevel CSK techniques are proposed (CBC-1,CBC-2,CBC-7,CBC-8,CBC-9)	• [210] • [211]

signal intensity level decreases in this state. The OOK scheme uses and is divided into the pulse format with a return to zero (RZ) and without a return to zero (NRZ), [29]. In a more vast discussion, the format contains the digital bits "1" in NRZ while the RZ format occupies the remaining parts of the bits represented by "0". The performance of the OOK modulation technique severely degrades and can be improved by updating the higher modulation schemes as followed in Table 7.

C. PULSE MODULATION SCHEMES

Aforementioned, the OOK modulation technique is an essential signal modulation scheme that supports low data rates with low performances. Pulse amplitude modulation (PAM) is more tolerant of the effect of the multi-path channel as mentioned in [27]. PAM modulation scheme is the process where the message is encoded in terms of amplitude of the optical pulse. Despite the PAM scheme, OOK is recorded as widely used under consideration of IM/DD optical communication scheme because of its simplicity and resilience to the intrinsic nonlinearities of laser origin. Even, in pulse position modulation (PPM) scheme, the division of symbol k is transmitted into an equal time slot within the 2^M constellation symbol M. A single pulse in PPM scheme during each symbol period suffers from low data-rate [45]. To cope up with this issue in PPM, a pulse

TABLE 7. *(Continued.)* **In this table, the underwater optical modulation techniques under consideration, a Multi-carrier modulation - OFDMA (MCM-OFDM), is described succinctly. Moreover, the research objectives, design system model, and future directions are also briefly described.**

Modulation Techniques	Type of Modulation	Research Objectives	References
Multi Carrier Modulation-OFDM (MCM-OFDM)	ACO-OFDM	1) A comprehensive detailed comparison among ACO-OFDM, DCO-OFDM, and ADO-OFDM along with the BER performance of each technique 2) A novel hybrid ACO-OFDM and OOK modulation schemes to improve better QoS with high efficiency	1) [212] 2) [213]
	DCO-OFDM	1) A novel clipping signal transmission technique, ACO-OFDM and DCO-OFDM under IM/DD system 2) Observation of channel capacity under IM/DD through ACO-OFDM 3) To enhance the system performance, a novel receiver is proposed to exploit the subscribers to collect subsidiary diversity with coding gain which leads the BER performance of the sytem 4) A layered asymmetrically clipped optical OFDM and the influence of thermal noise, inter-layer interference and clipping distortion on system performance is investigated	1) [214] 2) [215] 3) [216] 4) [217]
	ADO-OFDM	1) An amplify-and-forward relay protocol enabled VLC system is investigated by utilizing ADO-OFDM towards the next generation of a wireless network for the concern to improve system performance 2) An novel heterogeneous Attocell ADO-OFDM scheme clipped with DC-biased optical OFDM for the global network to avoid co-channel interference is proposed 3) The comparative betterment between asymmetrically and symmetrically clipped optical (ASCO)-OFDM and ADO-OFDM study is carried out and the generation of probability density function is derived	1) [218] 2) [219] 3) [220]
	PAM-DMT	1) A discrete multi-tone (DMT) Volterra series based post nonlinear equalization experimental demonstration through 450nm laser in UWOC system receiving 16.6 Gbps data rate 2) A 8-PAM encrypted data with 1.08 Gb/s over 1.2 m transmission experimentally demonstrated 3) A detailed study is proposed based on PAM-TDHP using transmission data-rate with distance-adaptive UWOC system	1) [221] 2) [222] 3) [223]

width modulation (PWM) scheme is investigated as in [231], where it deals with dimming control cause of lower intensity control and varies with the pulse width proportion of the instantaneous values of the signals. Therefore, for multi-pulse in each symbol-time transmission the multi-pulse modulation (M-PPM) scheme was proposed [29]. On the other hand, in [3], authors comprised as PAM required more power for large bandwidth while PPM suffers low spectral efficiency.

Continuously developing of optical pulse modulation schemes, a differential pulse position modulation (DPPM) scheme is introduced to improve the overall throughput spectral efficiency of PPM [232]. However, the DPPM is based on a very short pulse duration width for an alternative signal propagation. Due to this, the combination of DPPM and PWM in the form of DPWM has achieved a higher bandwidth efficiency than PPM and OOK. The most significant advantage of DPWM is that it solves the narrow pulse problem and has low power efficiency. To control the brightness of the LED in the PPM scheme, a Variable PPM (VPPM) is proposed as in [233]. However, the VPPM

TABLE 7. *(Continued.)* In this table, the underwater modulation techniques under consideration, a multi-carrier modulation - OFDMA (MCM-OFDM), is described succinctly. Moreover, the research objectives, design system model, and future directions are also briefly described.

Modulation Techniques	Type of Modulation	Research Objectives	References
	AHO-OFDM	1) A novel scheme is proposed as hybrid asymmetrical clipped optical (ACO-OFDM) and PAM-DMT signals inverted; then the combination is being used to signal transmission 2) An efficient dimming VLC control system is introduced as SCFDM. The fundamental contribution of dual SCFDM dimming control systems including AHO-SCFDM and DCO-SCFDM are proposed	1) [224] 2) [225]
	RPO-OFDM	1) A novel topology and implementation of RPO-OFDM compatibility by using signal transmission by a string of LEDs 2) A combined RPO-OFDM and fast optical-OFDM (O-OFDM) approach based on slow PWM dimming signal is proposed. The combination of RPO-OFDM and O-OFDM contributes to the adequate LED brightness a) Using RPO-OFDM exceeds the limitation of data-rate by the frequency of the PWM signal b) BER performance is durable at a fraction of the luminaire dimming range	1) [226] 2) [227]
	U-OFDM & Flip-OFDM	1) A novel multi-carrier modulation scheme as U-OFDM is proposed for optical communication and improvement over other multi-carrier schemes 2) U-OFDM demonstrated better demodulation as compared with DCO-OFDM within AWGN channel 3) A wide detail comparison among classical optical OFDM schemes 4) An approach is investigated to obtain the desired data-rate through clipping of flip-OFDM under an average optical power constraints.	1) [228] 2) [228] 3) [229] 4) [230]

combines PWM and 2-PPM, which control the brightness and data transmission along with the controlling dimming level to flickering position. As a result, the multiple Pulse Position Modulation (MPPM) has gained a more power-efficient scheme than OOK, PAM, and PPM. Taken into an account of optimum power and bandwidth efficiency, a hybrid Multiple Pulse Amplitude and Position Modulation (MPAPM) signal propagation scheme is proposed in [234]. However, an Overlapping Pulse Position Modulation (OPPM) [235] is proposed for improving bandwidth efficiency and high data-rate in MPPM. Utilizing VPPM for data transmission, the system offers complexity; an alternative approach, a Variable Rate Multi-pulse Modulation (VR-MPPM) [233], is investigated to cope with the complex issues to achieve both data rate and brightness control simultaneously. Furthermore, an expurgated PPM (E-PPM) modulation scheme is proposed to improve the performance of a peak-power limited M-ary communication system mentioned in Table 7.

D. COLOR DOMAIN BASED SHIFT KEYING (CSK) MODULATION

Color Phase Shift Keying (CSK) is defined by VLC IEEE 802.15.7 standard to improve system performance compared with other modulation schemes [45]. The IEEE standards for the CSK scheme are categorized into three sub-categories based on data rates known as PHY-I operates 11.67 to 266.6 kb/s, PHY-II operates on 1.25 to 96 Mb/s and PHY-III that is operated on 12 to 96 Mb/s [31]. CSK modulation is the color space chromaticity dependent on utilizing the three colors intensities as Green, Red, and Blue LED of the source. The main principle of multi-color LED is the color shift keying where the VLC beam implemented as 4-CSK, 8-CSK, and 16-CSK modulation schemes light sources. The 3-Color CSK [210] and 4-CSK modulation schemes are proposed based on IEEE 802.15.7 standard [211]. The different CSK modulation schemes have been proposed in [236]–[238] and Table 7.

E. COHERENT & MULTI-CARRIER MODULATION TECHNIQUES

Despite IM/DD modulation scheme, the coherent scheme employs both phase and amplitude signals to modulate corresponding information. A local oscillator is used to convert the optical signals at the receiver end, which are referred to *homodyne* and *hetrodyne* detection mechanism. As a result, the coherent modulation scheme supports a high spectral efficiency and background noise resistivity but more channel complexity. However, multi-carrier modulation schemes are followed OFDM, where orthogonal sub-carriers are used as data transmission. A particular fading channel is converted into a flat fading channel as in the OFDM technique and using as a single tap equalizer. The different types of OFDM-based optical modulation schemes are proposed in open literature [239], [240]. The various multi-carrier modulation schemes are summarized in Table 7. The signals are converted from parallel format into serial ones for demodulation by using IFFT and then further transmitting to the LED transmitter. At the receiver end, the signal demodulation process happens by photo-diode (PD). Several multi-carrier modulation techniques are discussed in further Tables and subsections.

- DCO-OFDM:- Generally, OFDM uses RF communication which cannot be directly accessible to use in VLC because of the real and unipolar values of optical signals [241]. Therefore the conversion is needed; firstly, the bipolar signals are transformed into unipolar format and then the non-positive integers should be clipped. Generally, the RF-OFDM signals are converted into optical-OFDM by the Hermitian symmetry method. In contrast, the DC-bias converts into bipolar OFDM, which is known as DCO-OFDM. The mathematical expression of DC bias is given as [241],

$$B_{DC} = \mu\sqrt{E\{x(t)^2\}}, \tag{53}$$

where DC bias is defined by B_{DC} of $10\log_{10}(\mu^2+1)$dB. The proportionality constant and standard deviation of unclipped signals are represented by μ and $\sqrt{E\{x(t)^2\}}$, respectively. On the other hand, the expression for clipping operation can be written as follows [241],

$$x(t) = \begin{cases} x_0(t), & \text{if } x_0(t) > 0 \\ 0, & \text{if } x_0(t) \leq 0. \end{cases}$$

The continuous development of LED carries new trends in optical communication. It is obvious that in DCO-OFDM, the power efficiency decreases while the modulation sequence increases. This makes it less compatible with several VLC applications. Therefore, a substitutional modulation technique is required. The novel substitutional technique is investigated only heterogeneous subcarriers for operation and also removes subcarriers known as ACO-OFDM [213]. In contrast, the drawback of ACO-OFDM spectral efficiency is that half of DCO-OFDM causes half of the subcarriers rejection. PAM-DMT [221] has become an alternative methodology based on Fourier transform properties. In PAM-DMT, the real part of the signals is ignored while considering the imaginary values of the received signals. Moreover, for unipolar OFDM, the Flip-OFDM was also proposed [230]. The recently proposed Flip-OFDM technique is classified into two classes. In this classification, the second class is the replica of the original one. It means both of the classes contain the equivalency under DC bias-based modulation techniques. Therefore, in DCO-OFDM, the spectral efficiency falls up to half rather than ACO-OFDM.

F. HYBRID MODULATION TECHNIQUES

In optical signaling, long distances coverage is challenging. For covering, long-range communication hybrid links are the key solution approaches for further wireless communication and mentioned in Table 4 and Table 4. A single LED is used to transmit the signal in the further development of hybrid links instead of multiple arrays of LEDs. To deal with the issues in hybrid communication, spatial optical OFDM (SO-OFDM) is proposed. The SO-OFDM has received better BER performance than DCO-OFDM [241]. On the contrary, the reverse polarity optical OFDM (RPO-OFDM) is also introduced to control LED illumination in the VLC system [227]. The combined PWM technique deals with the real values in optical OFDM to control dimming phenomena in the VLC system.

IX. OPTICAL ENERGY HARVESTING (OEH)

The integration of IoTs, is a novel approach for wireless signaling in an underwater environment through IoUTs [70]. Optical waves can carry information and transfer energy simultaneously to power up the batteries of communication nodes. Even, to deploy an underwater communication setup is much more challenging than terrestrial-based communication. Therefore, the UVLC techniques are the potential wireless candidates for communication and energy transmitting media within the communication networks. Due to this, simultaneously, light-wave information and power transfer (SLIPT) has been proposed as a potential wireless candidate for communication and power transmission through optical link connectivity [242]. Compared with simultaneous wireless information and power transmission (SWIPT), SLIPT performs better in specific channel condition requirements. This section provides an overview of SLIPT methodology through time, power, and spatial space dependency. Moreover, the LEDs are capable of transmitting signals in underwater environments with conveniently low-cost rather than RF signaling [20].

Internet-connected devices are the power-hungry tools those need to harvest energy being in an active mode. WPT is quite challenging among wireless nodes, specifically underwater. Although this, WPT has gained research attention in the most recent years [41], [243]–[245]. Initially, the idea of WPT came up during the 1890s [246]. Later on, the integration of WPT was triggered by SWIPT, where only electromagnetic waves carry information and power in different required application scenarios. SWIPT has become a futuristic digital energy transmitting technology in the wireless communication domain. However, RF-energy harvesting (RF-EH) systems experienced major technical problems due to transceiver circuits and suffered from relatively low efficiency. It is noteworthy that EM waves propagate over few meters in the underwater environment. Consequently, to get rid of the radiation rate of EM waves, it is replaced by VLC enabled light sources such as laser diode and LEDs. A hybrid RF and light-wave power transfer scheme with the color diversity of optical beam has been recorded in [247]. The authors in [247], are proposed a novel RF-VLC ultra-small cell network and the proposed system model consists of multiple terminal devices along with an optical angle-diversity transmitter with a multi-antenna RF access point. For shallow water communication, the fading of the optical signal due to the limited sunlight or background light effect is the leading cause of EH harvesting efficiency.

SLIPT methodology can be a complementary energy harvesting (EH) approach to transfer energy via visible light in IoUT networking system. For instance, the RF/VCL hybrid communication and EH scheme is proposed in [248], where the authors designed a VLC link to harvest energy at the relay and furthered this harvested energy by transferring it with the base station through an RF link. However, a more sophisticated optical transceivers setup is required in the SLIPT scenario based on modulation and demodulation schemes, including the time, power, and space splitting format.

A. SWITCHING TECHNOLOGIES

As the main concern of the SLIPT scenario, the switching technique has played the most significant role in transmission power and simultaneously information transmission. Generally, time, power, and space switching schemes are proposed in the open literature [249]. In the time switching aspect, the receiver acts to decode information in the time slot t, whether the reaming time slot $(1 - t)$ is assigned for the harvesting energy. Furthermore, the received signals split into photo-voltaic and photo-conductive modes of receiving as well as decoding the signals. In addition, the low-power hybrid system can perform the function of switching between two solar cell modes in the cooperative communication aspect. While in power splitting mode, the receiving terminal self charges and detects the incident light beam information. The light beam splits into dual power factors as α and $(1 - \alpha)$, respectively. The power factor $P\alpha$ is responsible for EH; else remaining power fraction $P(1-\alpha)$ is assigned for information decoding. In this power splitting scenario, the power splitting component could function passively; the reason is splitting the incident beam divides into two portions. Nevertheless, in this scenario, it is considering n^{th} number of transceivers in a communication system and functioning for energy harvesting capabilities and information decoding. In this type of system architecture, the spatial splitting approach applicable. In this anticipated system design, each transmitter node is independent of each others and could transmit the signal and energy received by each receiving node. Furthermore, the time switching SPLIT approach could be utilized within this scenario for the same receiver, which acts as "Energy Harvester" and "Signal Decoder" over different periods. These two switching techniques would be beneficial to deploy in critical environments such as undersea and underground communication and wireless energy transfer.

For long-range communication, the UWSNs are deployed within a particular depth in an undersea environment. Being in an active mode of sensor networks to replace the batteries and transfer energy wirelessly is quite challenging. To cope up with this issue, a novel hybrid SWIPT and SLIPT wireless power transfer techniques are investigated [247]. RF and light-wave power transfers are complement to each other in their relative profits and losses during signal propagation. An alternatively switchable process towards the 5GB wireless network to transfer power in shallow waters over moderate depth in underwater mediums is summarized in this section.

SWIPT and SLIPT are the EH utility process where signal energy is converted into usable electric energy. An EH-system harvests the energy from nature such as solar energy, wind, rising temperature, and vibrational EH approaches are recorded in [250]. As, we are surrounded by an electronic world, embedded devices, remote sensors, and low-power electronic devices are necessarily required for power transfer and batteries to store the electrical capacity. Due to the limitations of the battery lifespan, they should be replaced as per requirement. In underwater SLIPT, the signal recognition and simultaneously receiving energy is a novel approach amongst researchers. The most significant advantage of the EH scheme is the applicability for remote locations and harsh water channel conditions. This type of EH technology is cost-effective, improves safety and reliability [251]. In the SLIPT scenario, it offers high bandwidth, extremely high speed, and energy efficiency. Furthermore, the movement of the renewal traditional EH technologies towards to SLIPT is the solution for environmentally friendly technology, which belongs to the class of green communication [252].

B. SLIPT IN UNDERWATER COMMUNICATION

An underwater SLIPT scenario is depicted by Fig. 10. Throughout the proposed system model, the received signal splits into two chunks simultaneously, which are responsible for energy harvesting and information decoding. At the receiver end the received signals are converted into AC and DC components. The AC component is responsible for the signal decoding while the DC component uses for the EH purposes [253].

According to Fig. 10, in the SLIPT system model, if $m(t)$ represents the modulated electrical signal and A denotes the peak amplitude. If, $+A_I$ assigns for a bit "1" while $-A_I$

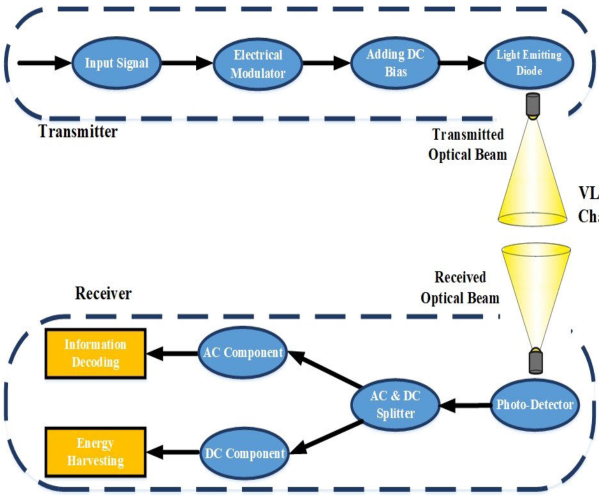

FIGURE 10. The basic schematic diagram of underwater-based SLIPT system, where the energy harvesting (EH) and information decoding (ID) process happens through LED luminaries. Furthermore, the AC and DC components are responsible for EH and ID within different switching techniques.

for "0" in modulation and demodulation of VLC signal. In consideration of modulation process to control the optical intensity of LED with the DC bias ψ, the peak amplitude for each bit is given as [41],

$$A_I \leq min(\psi - I_L, I_H - \psi), \tag{54}$$

where I_L and I_H are denoted the minimum and maximum input bias current. Furthermore, in the point-to-point communication scenario, the harvested energy is modified and given by [41], [254],

$$\begin{aligned} E_{EH} &= fI_{DC}V_t \\ &= fTrIP_tBV_t ln\left(1 + \frac{rIhP_t\psi}{I_0}\right), \end{aligned} \tag{55}$$

where f, I_{DC}, V_t, T, r, P_t, and I_0 are defined as the fill factor of solar panel, the DC component $I_{DC} = rIP_t\psi$, the thermal voltage, time duration during energy harvesting, the photo-detector resistivity, the power component, and the dark saturation current of solar panel, respectively.

- **Time-Switching (TS) SLIPT Receiver Architecture** The TS receiver architecture is a disjoint scheme as well as the splitting factors t and $(1 - t)$ denoted for the optimization in the SLIPT system. According to the splitting factor, the ability to gain the idea of exploit harvested energy with adequate BER performance. Moreover, the TS mechanism represents separate two-time frames for EH and information decoding (ID). Furthermore, TS can use for only one function at a time, energy transfer or receiving signal [253]. The TS-SLIPT block diagram architecture under the SPLIT system is depicted by Fig.11.
- **Power-Switching (PS) SLIPT Receiver Architecture** The PS receiver architecture is another combined scheme as received current distributed into two phases. The DC component of the current phase uses for EH, while the AC component of the current phase uses for information decoding purposes. Compared with the TS-SLIPT scheme, the PS design could reach high efficiency in EH at the receiver end. Additionally, the PS-SLIPT mechanism works at the same time with different power domains for EH and ID [42]. Fig.12 shows the block diagram of the PS-SLIPT receiver architecture.

C. SLIPT AND SWIPT SCHEMES

The authors in [42] widely discussed which comprised both of futuristic SLIPT and SWIPT schemes. In both schemes, the authors obtained the behavior of system BER & outage performances along with amount of harvested energy. Therefore, the BER and outage performances in the SLIPT scheme perform better than the SWIPT scheme at the consecutive photodetector sensitivity and power splitting factors. On the contrary case according to [42], the EH in SWIPT shows superior performance rather than indoor enabled SLIPT technology.

X. HYBRID UNDERWATER WIRELESS COMMUNICATION

Optical communication as VLC is a promising complementary approach instead of RF and acoustic waves signal transmission in the underwater medium over short distances. Enabling next generation of wireless network 5GB optical communication technique allows the massive number of connectivity of IoUTs. In recent years there is a growing interest in deploying VLC as a communication link in underwater integrated with existing RF and acoustic waves. Therefore, hybrid RF-VLC and FSO-VLC wireless communication links are proposed and showed impressive system performances expect to deploy individual point-to-point or point-to-multi-point communication links. A wide detailed summary of various hybrid communication techniques are depicted by Fig.1 and Fig.13. In RF-UWOC hybrid communication system [48] an electromagnetic link combines with an optical link, while in underwater FSO-VLC system [255] enables both of optical links for signal propagation. Additionally, a dual-hop acoustic-optical link is widely used for signal propagation in the underwater medium over long-ranges [256]. In hybrid underwater communication aspect various signal transmission techniques are developed and use to enable with FSO, VLC, sonar, and underwater acoustic waves. It is challenging to deploy an optical communication hybrid network system towards to 5GB and connecting IoUTs. Optical wireless communication link supports highly secure signal propagation media under visible light (VL), infra-red (IR), and ultraviolet (UV) frequency bands. Nowadays, numerous optical wireless communication systems are being developed under consideration above three optical frequency bands. In a hybrid link scenario, RF and acoustic waves are not required line-of-sight (LOS) nor short ranges but support high mobility and better performance in NLOS conditions. The hybrid approaches are integrated with two

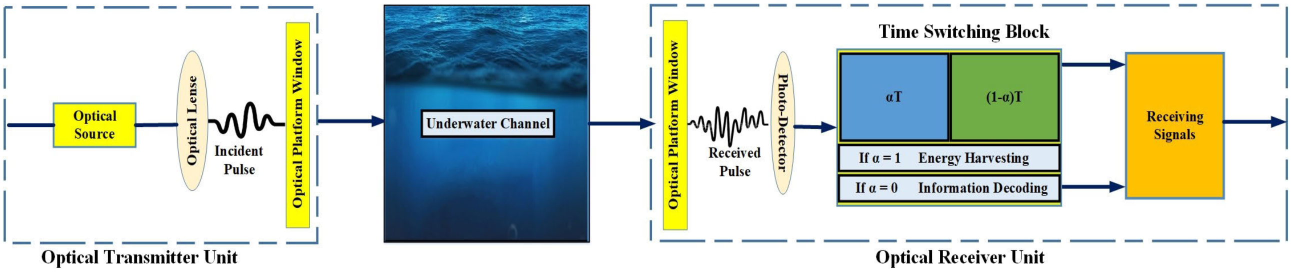

FIGURE 11. The Time-Switching block diagram where the received signal splits into two corresponding factions at the receiver end, and α is defined as a split factor. The fraction αT is responsible for energy harvesting if $\alpha = 1$. While, if $\alpha = 0$, then, the fraction $(1 - \alpha)T$ being used for information decoding under SLIPT Time-switching scheme.

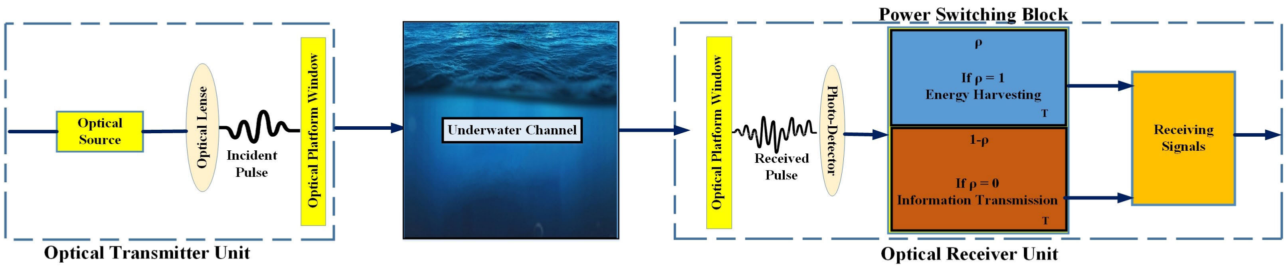

FIGURE 12. The Power-Switching scheme block diagram where the received signal splits into two corresponding factions at the receiver side and ρ is defined as a power-split factor. The fraction ρ is responsible for energy harvesting (if $\rho = 1$). While, if $\rho = 0$, then the fraction $(1 - \rho)$ is used for information decoding under SLIPT power-switching scheme.

multi-hops different wireless communication technologies such as RF-VLC [257], [258], RF-FSO [47], [48], and PLC-VLC [259], [260] are investigated in the open literature to provide various advantages as per requirement and deployment. Additionally, a hybrid wireless communication system facilitates the integration of multiple wireless carrier candidates to cover long-ranges communication along with better system performance that overcome the limitation of an individual technology.

A. RF/FSO DUAL-HOP HYBRID COMMUNICATION LINK

FSO has become an alternative solution for a wireless communication system with high bandwidth over long distances. Terrestrial FSO is most widely used as a LOS wireless communication approach that operates within $850-1550$ nm of optical spectrum wavelength. Due to strong channel conditions, the FSO links are attenuated by atmospheric conditions, especially atmospheric turbulence, fog, snow, and dust limiting channels. Plenty of FSO based applications are recorded in open literature as in [171]. Mostly, in the FSO system the channel turbulence phenomenon is a highly noticeable event of the fluctuation of the scintillation index. The turbulence effect occurs due to the flexibility of refractive index variation inhomogeneities in an atmosphere where the temperature and pressure fluctuates. RF waves attenuate easily in an underwater environment and propagate over short distances. In hybrid communication over long ranges RF waves signify as a promising signal transmission technique. Therefore, RF-FSO underwater is a potential solution for acquiring high bandwidth over long distances. In this section, an RF-FSO hybrid communication system model is proposed to obtain the system performance. A source node S communicates with an underwater-based destination D through a floating buoy. The floating buoy works as a decode-and-forward (DF) relay protocol R and depicted by Fig.13. The source node transmits the RF signals with an average signal power P_s. Further, the relay receives the transmitted signals re-generates then forwards to the destination D through FSO link. In another aspect, if we use the AF relay protocol, the relay received a signal copy from S and amplifies then forward to D. Additionally, we consider the RF-FSO combination follows Rayleigh flat fading and FSO link is experienced by strong turbulence channel conditions for communication between R and D. For strong turbulent channel conditions, the fading is modeled through Gamma-Gamma distribution.

In hybrid communication relaying technique has been widely promoted for signal transmission over long ranges. Due to the limitation of FSO signaling on terrestrial based communication, the channel impairments have to be taken into account. As turbulence and pointing errors are the main cause of optical signal fading, the hybrid communication link is widely studied in literature and the performance investigated through different modulation and demodulation techniques. In an underwater communication scenario, optical communication is a permissible communication media for signal transmission. Thus, a number of RF-Optical [46]–[48], [50], [51] and acoustic-optical [69], [256], [261], [262] hybrid communication systems are investigated.

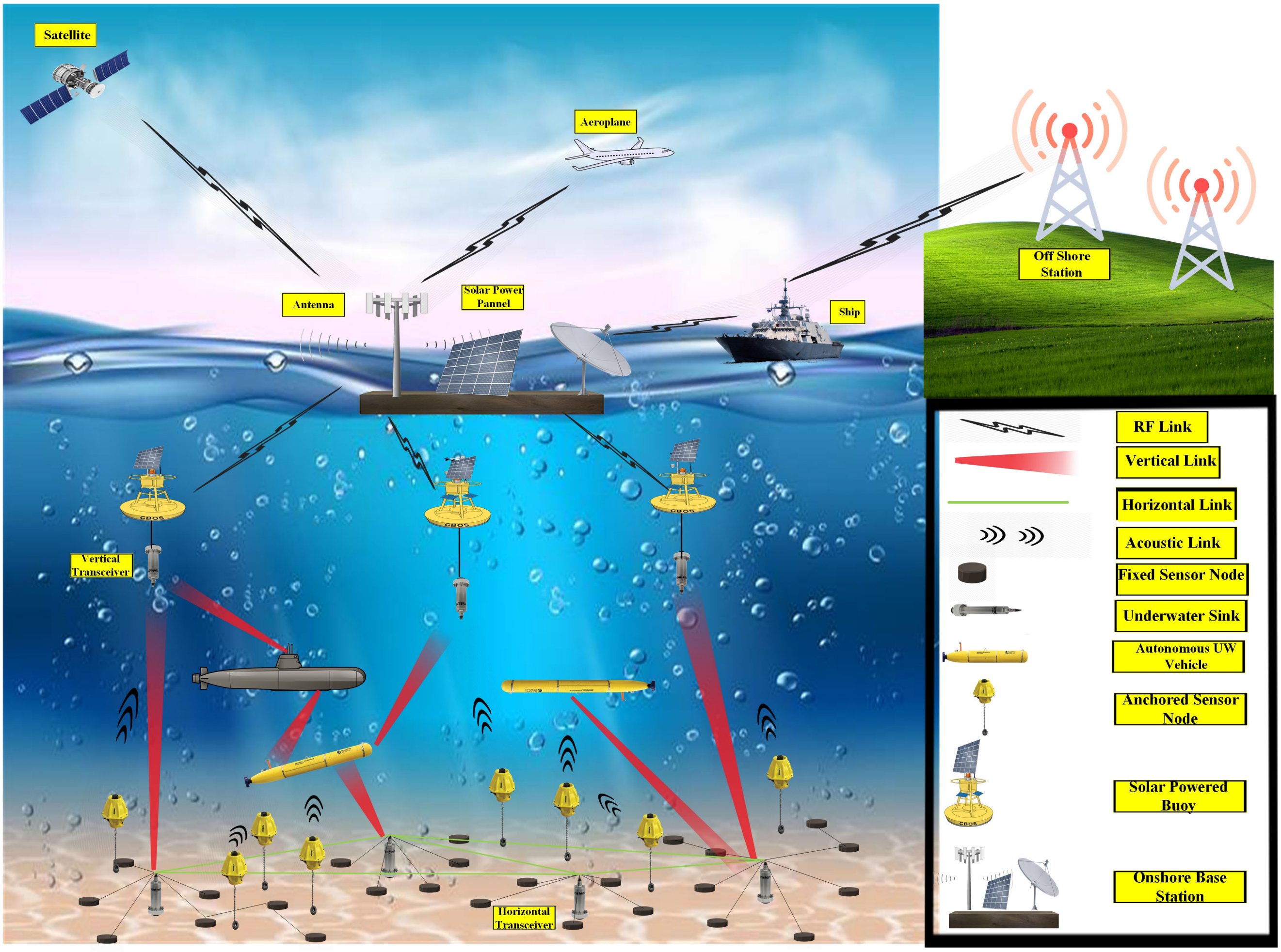

FIGURE 13. A hypothetical scenario of hybrid RF-optical, Acoustic-optical, and Acoustic-RF link in an underwater environment where each node communicates with the other. The monitoring and collect oceanographic data has to transfer an off-shore-based station for further analysis. The fixed and anchored nodes monitor the undersea environment while the floating nodes deployable monitoring for the water streams, water pollution, geo-chemical process, localization, etc. The architecture of underwater sensor network nodes is also depicted where 1D to 4D UWSNs architecture deployed and enabled with a unique wireless hybrid link towards the next generation 6G and beyond wireless networking system.

B. RF/VLC DUAL-HOP HYBRID COMMUNICATION LINK

In optical communication aspect VLC shows an impressive performance for signal transmission over short distances. VLC uses LED luminaries, which are very cost-effective, easy to install, and 100 Gbps data can be achieved. Similarly, VLC also affects by strong channel conditions, especially sunlight. VLC integrated with RF and a hybrid RF-VLC combination shows better performance in different waters. A dual-hop hybrid RF-VLC underwater communication link proposed in [114]. The system model consists of three or more nodes for signal transmission where a relay function re-generates or amplifies signal information and further communicates with the underwater-based destination. In [114], the system model is assumed in half-duplex mode with a single antenna at relay, while the nodes are fixed. Moreover, the relay should mount two directional antennas in full-duplex mode, where one antenna receives the transmitted signals from source and the other antenna towards to the destination for further communication with the destination. The BER performance of RF-VLC dual-hop hybrid cooperative communication system [257] in different water types under strong channel conditions are depicted by Fig.14.

C. FSO/VLC DUAL-HOP HYBRID COMMUNICATION LINK

The traditional underwater communication media is modeled by acoustic waves that supports low data rate and bandwidth with high delayed signal propagation. FSO-VLC combination full-fill the acceptability of desired communication requirements with a highly achievable data rate. This hybrid communication could be operating in half and full-duplex mode as both are optical links and sever almost the same channel impairments. The high turbulence channel conditions, current water waves, misalignment, and physio-chemical properties such as pressure, temperature, and salinity affects FSO and VLC links. A hybrid FSO-VLC

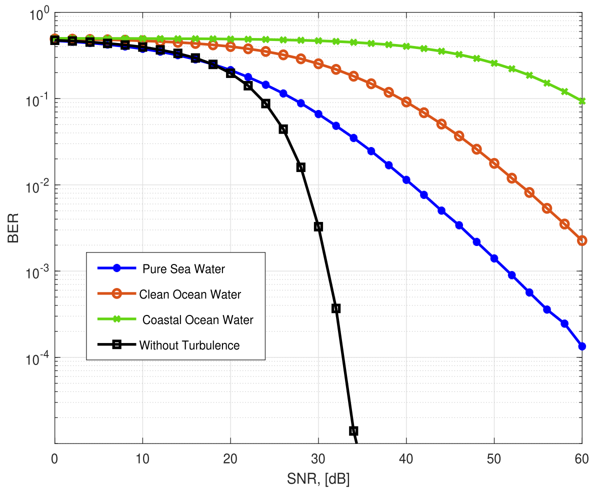

FIGURE 14. The BER performance of a dual-hop hybrid RF-VLC communication system in different water mediums.

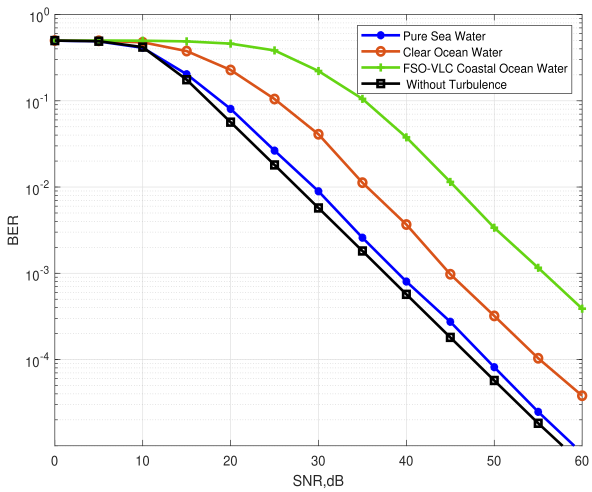

FIGURE 15. The BER performance of a dual-hop hybrid FSO-VLC communication system in different water mediums.

combination is proposed in the open literature, where an AUV communicates with terrestrial based station through a floating buoy that functions as a relay to assist received information from the source-based station. The BER performance of an investigate FSO/VLC dual-hop hybrid communication system [257] in different water types is depicted by Fig.15.

D. PLC/VLC DUAL-HOP HYBRID COMMUNICATION LINK

Another approach of hybrid underwater communication VLC link combined with power line communication (PLC) technology. A telecommunication technology PLC is based on the use of power grids for high-speed information transmission. The low transmission speed and poor noise immunity are the bottlenecks of this technology. Rather than this, the advent of PLC strengthens digital signal processors (DSP), making it possible to use more complex signal modulation methods such as OFDM modulation. PLC can be used to create a small base station where the main requirements for the network are ease of implementation, device mobility, and easy scalability. The small cell base station (CBS), e.g., femtocell access point (FAP) are used as a small cellular base station that serves 6-8 users. In hybrid PLC-VLC combined communication link a small power grid antenna connects with the small base station (SBS) through line cable. The signal is transmitted from SBS to the antenna via cable and further this antenna mounts by LEDs for further signal transmission to divers or UWSNs in shallow water.

E. OPTICAL-ACOUSTIC AND RF-ACOUSTIC DUAL-HOP HYBRID COMMUNICATION LINK

The study of acoustic waves involves the discovery and deployment of sound waves transmission in fluid media. Acoustic waves are generally defined as mechanical and longitudinal vibrational ripples that can travel through solid, liquid, or gas mediums in a wave patterns. Underwater acoustic is an alternative signal propagation method of sound in water, especially over long ranges undersea. Sound waves are the most effective energy transmission wireless carriers that propagate over long distances in the ocean. Moreover, acoustic waves can tolerate the pressure and the temperature of the deep oceans. Neither RF nor optical waves are suitable for long-range transmissions in an underwater environment as acoustic waves [263]. Usually, the speed of acoustic waves is comparably low (Approximately 1500 m/s) [74]. Although, according to the layer clarification the speed varies in cold water and lower than normal water. Acoustic waves are used for long-ranges transmissions approximately up to $15 - 20$ km, but these waves cannot achieve high bandwidth signals undersea. Due to low frequency, bandwidth, speed, and additionally the received signals are delayed at the destination [264], [265].

However, the sound waves depend on the compressibility and density of the medium. In [266], an acoustic sound speed profile (SSP) system model has been proposed for 1 km as follows,

$$c = 1448.96 + 4.591T - 0.591T^2 + 0.00029T^3 + (1.340 - 0.01T)(S - 35) + 0.0163z, \quad (56)$$

where the temperature in ^{0}C, salinity in PSU, depth in meters, and speed of sound in m/s are denoted by T, S, z, and c, respectively.

Sound waves propagate according to water current concerning every instant of time. An empirical model is described as a function of physical water properties such as temperature, salinity, and pressure varies with depth. Stratification of these parameters lead to stratification of wave motion, which entails the existence of specific profiles. Mackenzie has developed a mathematical formula in applied science during 1981s [267]. As already discussed, underwater optical communication is an alternative approach that refers to transmit signals in an aqueous medium. VLC communication has more superiority in comparison to acoustic waves but over short distances. To fulfill the gap of long-range communication, a hybrid optical-acoustic communication system is considerable. In this type of system model, the underwater-based mobile station transmits the acoustic signals and further convert into optical format for decoding purposes at the targeted node.

XI. UNDERWATER SENSOR NETWORKS ARCHITECTURE

Recently, there have been growing interests in underwater wireless sensor networks (UWSNs). The fundamental source of ocean exploration underwater sensor architecture is defined as a group of sensor nodes that are established undersea to exchange information wirelessly with the base station (BS) and floating vehicles (nodes). The growing interest of UWSNs for a wide variety of purposes about oceanography, monitoring marine life, seismic surveillance, oil-fields exploration, military applications, and deep-sea activities. In this regard, the necessity of UWSNs contributes a significant role in UWC. Generally, UWSN nodes are enabled with acoustic and optical links for data transmission within various applications. Energy conservation and self battery powered is a critical issue in UWSN technology. This survey estimates the target position and improves energy efficiency in hibernating and an active mode of underwater sensor nodes (USNs). The network of underwater sensors fixed with a certain depth or with the bottom of the deep ocean for early detection warning of an earthquake, tectonic plate movements, and active volcanos before striking the coastal and residential areas. The floating nodes are used to detect ice sheet melting and rising water level phenomenon, coral reef, water pollution, and physio-chemical properties of water. The development of floating nodes AUV supports to improve the quality of geographical mapping and navigation systems in underwater sectors. Localization is another significant application of UWSNs for tracking location or Global Positioning System (GPS) in harsh water mediums [268]. The integration of sensor nodes architecture has permitted to allow communication, localization, and GPS. In an underwater environment, navigation and localization are the two most significant challenges for mobile robots, floating nodes, and different underwater applications.

Aforementioned, acoustic and optical signal-based sensor networking systems are the most widely used for various underwater applications. Through the proposed underwater applications the acoustic and optical transponders are used to navigate an AUV. The sound navigation and ranging (SONAR) enabled AUV methodology has been proposed with the two basic configurations introduced as side-scan SONAR (SSS) and Forward-Looking SONAR (FLS) in [269] and [270]. The above SSS and FLS are used for monitoring marine life and detection for underwater environmental changes [271]. While an array of sensor nodes with a camera or without a camera can be implemented for long ranges navigation and imaging systems [272].

A. SIMULTANEOUS LOCATION AND MAPPING (SLAM)

SLAM is an AUV-enabled imaging technique and an essential solution for mapping unknown locations within the unknown environment to develop a consistent geographical mapping of an underwater environment [271]. In contrast, the SLAM imaging AUV-based technology that supports constructing a 3D image in different color frames is widely discussed in [273]. The authors in the above-proposed work defined a color-coding representation for the reconstruction of unknown mapping sectors, where each color code has its specified distance measurement between AUV and obstacles. The various methods are presented in the literature of SLAM to the reconstruction of the unknown sectors in underwater environment [271], [274]–[277]. Each method has its inadequacies and strengths according to the desired interaction, inspection, and navigation implementation. Furthermore, underwater SLAM is differentiated into acoustic-based, and vision-based categories [278]. The acoustic-based underwater SLAM is used for intense unknown segments, while the vision-based SLAM is suffered from limited visibility and background noise by natural sources in shallow waters. Therefore, a high-definition FLS SLAM could be a promising alternative solution in geographical mapping to mitigate the problematic solution.

B. UNDERWATER ACOUSTIC SENSOR NETWORK

UASNs is an approach that supports the exploration of extremely dark and highly deep oceans. UASNs deploy for various underwater applications such as for detection submarines and unmanned operations for military purposes. The UWSNs architecture is categorized into fixed 2D and mobility 3D sensors. In the 3D type of architectural sensor system, the motion of nodes controls the internal navigation system. The floating nodes are free to move underwater with the drift and unpropelled type of portable devices such as unmanned underwater vehicles (UUVs), AUVs, ROVs, drifters, and gliders. The main function of these devices is to collect oceanographic data from an aqueous medium. The various types of UWSNs are summarized by Table 8. The drifter operates mostly through the ground, which drifts with wind and surface waves to acquire the possible measurement of marine sectors, further sharing the collected data with the base station through satellite. Moreover, the gliders are driven by the buoyant force and connected with the floating buoy or the cluster head for sharing collected data. In existing work, there are the two main groups of UASNs known as content-based and scheduled-based protocols proposed in [279]. UASNs are classified into two categories as content-based and scheduled-based nodes. The Content-based nodes exchange signals to each other, while scheduled-based nodes eliminate the exchange of aggregated data between transmission nodes. Alternatively stated content-based nodes do not meet the desired gap and are critically suitable for UWC. In contrast, due to high propagation latency and narrow bandwidth, the

TABLE 8. The various types of underwater sensor network nodes (UWSNs) architectures established in the open literature to cope with issues of highly delay, low bandwidth, heavy turbulence channel conditions. The architectures are enabled for the required underwater applications from short to long ranges.

Underwater Sensor Architecture	Communication Technology	Possible Applications	Possible Range	References
1D Type	• Acoustic communication • RF communication • Optical laser or visible light communication	• Environmental Monitoring • Observing Temperature, Humidity, Pressure etc., • Vibration and Motion of Tectonic Plates or Coral-Reef Observation • Data-Retrieval with Sensor Networks nodes	• Shallow water	• [280] • [281]
2D Type	• Acoustic communication • RF communication • Optical laser or visible light communication	• Monitoring underwater activities • Handling fish farming • Water quality and water pollution • Underwater Exploration	• Moderate distances	• [98] • [97] • [281] • [282]
3D Type	• Acoustic communication • RF communication • Optical laser or visible light communication	• 3D localization • Underwater navigation for specific nodes such as submarine and divers • Observing marine environment • Observing underwater mines and minerals • Hybrid data communication	• Long ranges	• [281] • [283] • [284] • [282] • [285]
4D Type	• Acoustic communication • RF communication	• Boarder and coastal securities • Navigation and surveillance • Seismic monitoring and ocean sampling • ROVs, Autonomous submersible robots (ASR), Underwater floating vehicles, UUVs, AUVs, ships, and even submarines can be used for data collection and retrieving	• Long ranges	• [281]
Array of Hydrophones	• Acoustic communication	• Coastal and tactical surveillance • Imaging and video acquisition • Geographical mapping • Offshore and oil exploration • Pollution monitoring • Oceanographic data collection • Rescue operations	• Long ranges	• [286] • [287] • [288] • [289] • [290]

scheduled-based nodes such as TDMA and FDMA are less suitable. However, CDMA is a more suitable approach for UAN to be deployed in underwater medium [268].

C. ARCHITECTURE OF UNDERWATER SENSOR NETWORK NODES (UWSNs)

UASN is commonly used for underwater exploration but quite adequate to meet the demand for real-time streaming and high data rate scenario. RF wave-based underwater sensor network nodes (UWRFSNs) are the potential approachable technique TO full-fill the requirement of various underwater applications. In this section, the discussion is carried out of the different types UWSNs along with their deployment challenges.

- **1D-UWSNs Architecture:** The single dimension (1D) UWSNs are the self-employed types of deployable networks underwater. In this type of sensor network, the individual node is self-configured by itself. In this type of architecture, each node has the capability of sensing and it is responsible for processing collection data within the remote area [281]. The sensor node could be fixed with a seabed or a floating buoy responsible for collecting the useful oceanographic data and further shared with the BS. In another scenario, the floating buoy could be the buoyant type of node that floats a certain depth underwater and then float towards the BS for information transmission. AUVs also function as self-configured individual nodes; they can floats at any horizontal and vertical depth to sense the data and share it with the onshore data center. The 1D-UWSNs type of architecture enables acoustic, EM, and optical communication-based wireless signaling technology.

The 1D-UWSNs are widely deployable for single-hop communication where the nodes directly communicate with the BS; in VLC scenario 1D type of UWSNs usable for plenty of underwater applications in shallow waters such as rivers, dams, lakes, etc.

- **2D-UWSNs Architecture:** The 2D type of UWSN is referred as a group of sensor networks (cluster) where the nodes communicate with the cluster head. The fixed or anchored cluster head collects the sensed data from each node and further transmits it to the vertical buoyant transceiver of the BS. In 2D-UWSN architecture, it is considered that each node communicates with the cluster head horizontally and communicates with the vertical buoyant node as well. Thus, this type of node architecture is called 2D-UWSNs, based on acoustic, EM, and optical waves-based wireless signaling technology for long ranges in an underwater environment. In the UVLC scenario, all local and cluster head nodes link and transmit the information with the remote station. The 2D type of UWSNs architecture is proposed in [291] for the purpose of short-term aquatic exploration applications and extensively discussed. The 2D-type of UWSNs is depicted in Fig.1.
- **3D-UWSN Architecture:** The 3D type of UWSN describes the network architecture where the sensor cluster nodes are deployed in different depths in underwater medium. Due to different depths, the clusters communication links established are variable in 3D space geometry in undersea. The communication link among the sensor nodes would be in three dimensions space for the mobility of data transmission. Additionally, in 3D-UWSNs, the cluster communicates among the neighboring clusters at varying depths, and the cluster network nodes communicate with their cluster head. All the cluster heads collect the sensed data by their local sensors and further transmit it to the buoyant node or with the BS. The 3D type of UWSNs can be deployed for underwater applications requirement based on acoustic, EM, and optical communication [281]. Moreover, the 3D underwater sensor network localization has been widely discussed in [282]. In UVLC enabled sensor network communication, the high probability of real-time monitoring and achieving high data rate. The 3D-type of UWSNs is depicted in Fig.1.
- **4D-UWSN Architecture:** The 4D type of sensor network architectural system is designed by combining anchored sensor nodes with the floating or mobile UWSNs nodes at different underwater depths. The 4D-UWSN architecture is deployable for long ranges communication among the nodes. Mostly, the mobile UWSNs consist of ROVs for the data collection from an anchored or fixed nodes at the seabed in varying depth. The ROVs can be submersible robots, vehicles, ships, and even submarines. Each node can relay information with ROV and depending on the distance between the node and ROV. Furthermore, the signal transmission is the distance-dependent between underwater sensor nodes and ROV [292]. The 2D-type of UWSNs is depicted in Fig.16.

XII. RECENT DEVELOPMENT OF INTERNET OF UNDERWATER THINGS (IoUTs)

The network of the internet of underwater things (IoUTs) is a potential novel approach for data collection within the underwater environment that has to be transferred with the BS for further analysis. IoUTs is a group of wireless network-enabled smart devices and could be a wide range of underwater sensor nodes architecture. The different types of UWSNs architectures are discussed in the earlier sections for various underwater application purposes. The system architecture of IoUT has received attention for developing smart ocean and innovative business surrounded by smart interconnected underwater water objects [70]. The most widely deployable IoUTs are discussed as follow and depicted by Fig.16.

A. SEA GLIDERS AND AUTONOMOUS UNDERWATER VEHICLES

The Internet-connected devices structure provides a pretty reasonable communication bridge among the nodes. For underwater communication purposes, wirelessly connected devices are recognized as the internet of underwater things (IoUTs). These devices could be identified as network nodes, AUVs, moving gliders, ROVs and floating buoys, etc. Whereas sea gliders and AUVs provide the measurement of oceanic environment over long-ranges especially for bathymetric data collection. The thrust and movement of the sea-gliders are used as an electrically driven propellers and are operated by an installed battery that provides upthrust with buoyancy for forwarding or upward motion. The AUVs and sea-gliders are designed to cover thousands of miles for several months within underwater mediums. These devices sink up to 1km from the sea surface due to their energy capacity limits. Furthermore, these types of nodes are deployed for oceanographic data collection and GPS purposes. An architecture of IoUTs that involves the multiple wave gliders for acoustical observation is proposed [293]. The internal sensors of sea-gliders determine the direction of vehicle when it dives underwater. The external sensor scans the ocean to collect the data. The movement of sea-gliders, AUV, UUV, and ROVs, is shown in Fig.16.

B. UNDERWATER ANIMAL TELEMETRY

Animal telemetry is another effective approach for ocean exploration and uses to observe the marine environment. This tagging technology enables us to get to know about the marine life inhabitants and their interaction with coastal shelf ecosystem to polar seas and the open oceans [294]. Animal telemetry supports observing the exploration summary of the vast oceans, underwater environmental changes, and marine pollution. The air-sea interface is necessary to understand the observation and oceanic exploration of daily water

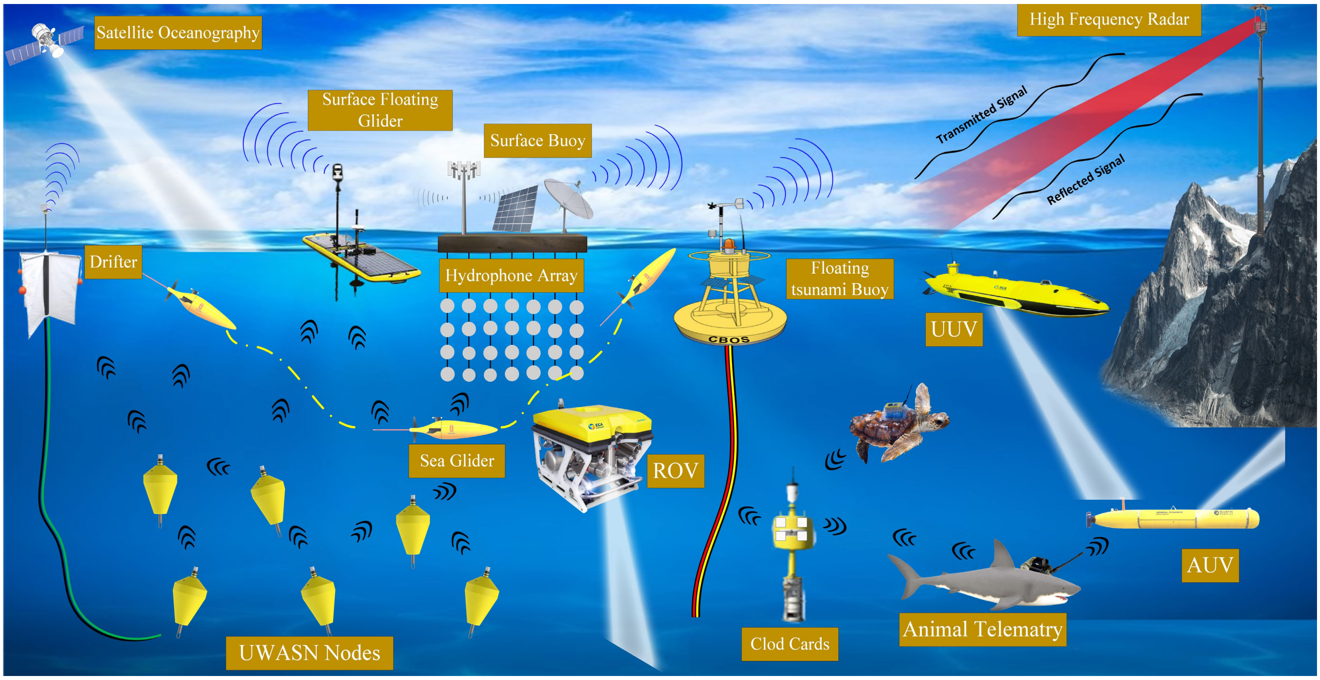

FIGURE 16. A hieroglyphic overview of the Internet of Underwater Things (IoUTs) in diversified possible underwater applications. Each Internet-connected tool functioned differently for a specific purpose. As floating nodes, sea gliders, Unmanned underwater vehicles (UUVs), Remotely operated vehicles (ROVs) are used for long-range communication, localization, bathymetric data-collection, and real-time monitoring. On the other hand, the high-frequency radar, a floating drifter, geographical satellite, surface floating gliders, and Tsunami buoy are used for continuously observation and mapping ocean currents, oceanographic imaging and geographical mapping, and early detection warning of the tsunami and tectonic plates movement. Moreover, the clod cards and animal telemetry are usable for studying the underwater flow pattern and observation of the marine environment.

conditions, driving global climate changes, biogeochemical cycle process, heavy wind and water currents to exchange the momentum and other micro-particles [294]. The various IoUTs such as HFR, satellites, drifters, and autonomous surface vehicles (ASVs) are widely used to observe the air-sea interface. To mitigate such challenges, the development of a small communicating device that can be mounted on the floating seabird back that contained a sensing data unit with a battery is capable of measuring the water surface, water currents, and winds over the sea [294]–[297]. For more details about animal telemetry, a pictorial view is referred to for this approach in Fig.16.

C. A DEEP DETECTABLE TSUNAMI BUOY

Tsunamis and earthquakes are sudden events and highly impossible to control. Nevertheless, these events are predictabled by deploying an early detectable device called a tsunami buoy. The primary function of a tsunami buoy is the detection and monitoring of the high level ocean water waves (Tides). The tsunami events are generated by undersea earthquakes that bureau of meteorology confirms. The tsunami buoys are deployed for observation and recorded the changes in sea level and bottomless oceans. It enhances the capability for early detection warning of tsunamis and floods before hitting the land. The buoy splits into two major components: the pressure sensor anchored with the sea bead and a surface buoy that floats on the water surface. The anchored sensors at the sea-bed are used to measure the changes in the height of the water column (the height h of the water column is the function of water pressure p as $p = \rho gh$). In more contrast, the measured water column height utilized for communication purposes with the floating buoy (works as a relay) through sound waves and further relayed via satellite to the tsunami warning center [298]. The function of the tsunami buoy is depicted in Fig.16.

D. UNDERWATER FLOATING DRIFTERS

Through the immense development of drifters, observing the global ocean currents and their effects are the main concerns. Recent advancements of drifters support the ocean circulation patterns in real-time monitoring the deployment of the drifters possibly in shallow water by a ship or another source. On the deployment of the drifter when it floats, the transmitter is activated and starts to share the collected oceanographic data with the satellite, this collected data is further to transmitted with the offshore BS for analysis. Other inbuilt sensors at drifters are responsible for collecting the various types of data such as water surface temperature, wind, ocean color, pressure, and salinity [299]. The data synchronization with the satellite has been depicted in Fig.16.

E. UNDERWATER HYDROPHONES

Generally, the signal propagation effects by channel impairments; noise is one of signal corrupting factors. The array of hydrophones are designed to be deployed for noise detection in an aqueous medium. Also, the hydrophones produce a limited voltage signal over high-frequency ranges while receiving the underwater sound from any direction. Deployment of an array of hydrophones amplifies and records the received noise more precisely. Omni-directional and Hemi-directional hydrophones support to collect the sound from a particular direction; it is also to track underwater the movement of underwater species. Therefore, hydrophones are the fundamental tools for plenty of undersea acoustic applications such as Sono-buoys, wired hydrophones, and autonomous hydrophones [287]. In addition, the NOAA's Pacific Marine Environmental Laboratory (PMEL) under NOAA's National Marine Sanctuaries also frequently uses hydrophones [300]. In addition to that NOAA's PMEL derives a long-term datasets for the global ocean acoustic environment. It has been utilized to identify and evaluate acoustic influences of human activities and natural disasters such as the eruption of an underwater volcano and glacial earthquakes in the marine environment [301]. The deployment of hydrophones in the underwater scenario has shown in Fig.16.

F. CLOD CARDS USE THE MEASUREMENT OF WATER FLOW

The clod cards are ice-shaped identical trapezoidal geometries and made by alabaster or plaster of Paris (gypsum blocks) and utilize to analyze underwater flow patterns. The ingredients of clod cards or made by the combination of the 100ml of freshwater with 80gm plaster of Paris powder manufactured by the Hobby Craft Trading limited, Dorest UK [302]. In [302], the clod cards were sanded at the bottom of the water bodies to accomplish a consistent weight of 12.5 ± 1.5 gm. Every individual plaster cube must be glued with the plastic plate size 3x8cm with silicone cement in this strategy. To measure the exact water flows analysis, the four clod cards established in four cardinal directions in front of their faces are fixed to a straight pole for at least 24 hours. The requirement of clod cards deployment in predetermined sites for various underwater applications such as divers, ROVs, and floating nodes. After a limited and fixed time duration (approximately 1 to 2 days), the clod cards have to be retrieved, dried at 40^0C, and reweighed to calculate the decay and the strong water flow. Conversely, the exact weight loss of the plaster of Paris is determined from each card and sent to the laboratory for further analysis. As a result, it can be concluded that the clods who lost more weight are exposed to greater water flow than those who lost less weight. Accordingly, the cloud card can be used to measure several other essential parameters from the ocean. An implementation of a clod card has been depicted in Fig.16.

G. SATELLITE OCEANOGRAPHY

The weather observational satellite is the most significant tool to share constructive information with the base station. Additionally, the satellite plays a vital role in ocean observation research and functions as an intermediate communication node for information transmission between the underwater and offshore base stations. For oceanographic data collection, environmental satellites are widely used to capture images and calculate the surface temperature of oceans. It is also used to know the water patterns and further shared the collected data with the terrestrial-based stations for analysis. For real-time video, steaming could be possible by utilizing satellites in different color coding techniques for water flow analysis. It supports determining the impact of floods and tsunami along the coastal area along with the detection of algal blooms. In the most recent years, remote sensing technology-enabled with the satellite that has boosted for data synchronization with altimetry (study to measures the height of sea surface), scatterometry (study to measures wind speed and direction), as well as the bathymetric (study of the ocean floor) approaches. These are the technologies that make the smart satellite for ocean observation, monitoring, and GPS. Additionally, to monitor early detection warnings to evacuate the coastal area and develop major storms, such as hurricanes and tornadoes, geosynchronous environmental satellites are being used. The most important information of coral reefs, coastal habitats, and similar environments can be analyzed by the satellite photography [303]. In Fig.16, an environmental satellite is depicted for ocean mapping.

H. REMOTELY OPERATED VEHICLES (ROVs)

ROVs are accessed remotely and functioned similarly as a robot. This type of node has been designed for underwater exploration and deployment for various underwater applications to find the lost ships, repair and monitor gas pipelines, habitat mapping, etc. Specifically, the ROVs are equipped with sensors and sampling tools for data collection at variable distances from the oceans. A network cable is used to detect and observing the objects by illuminating the light, establishes a communication link between the base station and floating node to controls commands of the proper node movement. The ROV is a well-equipped floating vehicle enabled with advanced features that contain a lighting system with a camera at the frontal portion for videography to record a better sub-aquatic panorama. It is especially utilized in the aquatic medium for the contribution of geology education and sea life learning [304]. The exploration and functioning of ROV in an underwater medium have shown in Fig.16.

XIII. INTEGRATION OF ADVANCE AND NEXT GENERATION COMMUNICATION TECHNOLOGY

Currently, with the immense enhancement of data traffic in telecommunication industries, a large number of regular users have been observed. An alternative communication media has an essential role in the wireless networking era to fulfill the requirements of further innovations, research, and further development of new emerging communication technologies. The development of optical communication applications in visible light has become an immense growth in different fields. Nowadays, the trade of VLC applications became more reliable and highly efficient in acquiring indoor and outdoor scenarios. VLC uses the limited frequency ranges about $430 - 790$THz at the wavelength ranges $380 - 750$nm. The benefit of this frequency range is the compatibility with the human eye with no effect on an electrical circuit. The basic concept in VLC signaling is the information modulation happens at the receiver end while demodulation is held by a photo-detector and decodes the signal from received information under fluctuation of the light intensity. The communication link is enabled with a lighting system as LED, which offers a considerable bandwidth with a desirable high data rate. Cellular technologies have changed and support improving the system qualities and performances. To proliferate smart internet-connected devices, emerging advanced future wireless networks play an ample role for an efficient and reliable communication link among the network architectural nodes as 5G networks have shown superior performances as a key enabling wireless technology. Also, the 5GB and 6G would be offered an immense performance while linked with the multiple nodes. The latest 5GB wireless network would significantly impact various wireless connected applications such as intelligent transportation, device-to-device (D2D) communication, underwater optical communication, and internet-connected devices. The most recent survey on 6G wireless network carried out an outperform study about VLC enabling communication signaling through laser and LEDs [305].

A. 5G NETWORKING SYSTEM IN UNDERWATER

5G wireless communication system has been designed to offer a significant improvement, especially for enhancing the system capacity, spectral efficiency, and energy efficiency of the communication system. For efficient and reliable wireless communication, 5G is widely accepted to combine the small cell, picocells, and macrocells [306]. The commercial use of 5G during 2019s established a collaborative communication system on a terrestrial basis, excluding the underwater environmental communication. The deployment of a 5G wireless network underwater will be an innovative step to improve data extraction from an aqueous medium for further analysis. As being improving the system capacity and essential assets of high data rate underwater wireless communication technology, optical communication towards 5G is the key solution that attracts the scientific community. Although, the most recent experimental study and the performance evaluation of 520nm wavelength laser-diode towards 5G is presented as [307]. In [307], the authors analyzed the performance of an underwater optical system under consideration of varying salinity conditions in pure water. Facing these issues, the Generalized Frequency Division Multiplexing (GFDM) is proposed as a novel underwater wireless network candidate towards the next generation standard based on multi-branch multi-carrier filter bank in [43]. It is presented and generalized the traditional OFDM technique with several advantages as minimal peak to average power ratio (PAPR). Minimizing PAPR is one of the key advantage features in GFDM over OFDM and a significant parameter to analyze the performance characteristics of the communication system [308]. As recorded the limited bandwidth in underwater acoustic, OFDM suits for communication purposes. In contrast, OFDM offers a profitable integration over single-carrier modulations against the frequency selective fading [309]. Therefore, to come up for all these issues, the requirement to deploy multi-carrier transmission schemes. GFDM [310] and filter bank multi-carrier (FBMC) [311] are proposed the new promising emerging communication techniques towards 5G applications.

B. PREDICTABLE 5G AND BEYOND (5GB) NETWORKING SYSTEM IN UNDERWATER

The forthcoming next-generation 5G and beyond (5GB) communication will indeed offer numerous advanced services with ultra-high capabilities, an extensive number of device connectivity, very ultra-low energy consumption, and latency along with ultra-high security, extremely high quality of services (QoS), and high-resolution experience (HRE) [312]. The 6G networks are anticipated to accommodate and exceeded performance in comparison with 5G. Thus, the exceptionally high data will greatly impact networking users and the critical factor for more complex future challenges in various sectors such as in healthcare, long-range communication, vehicle-to-vehicle (V2V) communication, underwater communication, etc. Though, the prediction to launch the 6G communication system is anticipated till 2030s [313]. Indeed, the 6G wireless communication network will provide the next level of signal transmission qualitative performance compared with 5G communication. The recent advances of and application of optical communication technologies towards 5G/6G are summarized in detail [314]. An extremely high data rate up to 100Gbps by deploying VLC has been confirmed in [315] and [316]. Internet of underwater things (IoUTs) is the essential part of an underwater communication system connected with a standardized communication network for data extraction in the real-time scenario from the underwater environment. The implementation of 6G integrating UWC will be a revolutionary step to explore aqueous mediums as IoUTs connected with VLC. The most significant aim is predicted to connect underwater-based nodes with satellites for global coverage and observation all around the globe.

C. INTERNET OF UNDERWATER THINGS (IoUTs)

IoUTs refer to internet-connected devices that can easily and legitimately retrieve information through cabled or wireless-enabled connectivity. UIoTs claims to be an extension and development phase of IoTs, which allows the extraction of anonymous information from smart ocean [317]. IoUTs are enabled by the most recent developments of AUVs, ROVs, smart underwater sensor networks, and routing protocols. The architecture of UIoTs depicted in Fig.1 and Fig.13, enable numerous applications in an underwater environment in terms of sensing, monitoring, and identify underwater objects. In underwater internet of things (UIoTs), the sensor network nodes collect data and communicate with the cluster head. Furthermore, the received data has to transmit with a base station for subsequent analysis. The IoUTs structure enables the UVLC link to be classified into two major categories: horizontal and slant communication systems. Described in more detail, the horizontal link has been an extensively focused study on increasing data rate and signal propagation length along with reducing underwater turbulence effects while slant links formed high depth considering wave height wind speed, sea surface slope, and heavy turbulence conditions. On the other hand, in the vertical link for high depth, pressure increases up to 10bar for each k^{th} layer (each layer for $k = 10m$) in addition temperature decreases from 25^0C to freezing point, the above matter facts due to varying salinity which affects the refractive index.

XIV. UNDERWATER OPTICAL WIRELESS NETWORK APPLICATIONS

Oceans are mysterious and challenging water bodies to explore. Plenty of natural disasters such as volcanic eruptions, earthquakes, and tsunamis occur by imbalanced water phenomena that could be observed and monitored by deploying communication links. To address the requirement of current emerging underwater applications which have been used in the context of rising water level, environmental monitoring, marine life, early detection tsunami, oil and gas rigs exploration, volcanic eruptions, coastal securities, and sliding tectonic plates, jointly with various hybrid wireless communication systems. Moreover, undersea wireless communication over long distances, UWSN plays an essential role in data transmission. The traditional acoustic modems are widely used in long-range UWC, whether low speed (approximately 1500 m/s) in such complexity of water channel conditions [318].

In more contrast, for high depth, the floating nodes AUVs, and UAVs are used to transfer information from source to destination. RF waves transmission show poor performance in an underwater environment cause the EM waves propagation depend on the intrinsic properties of the channel. Contrarily, the water medium has more density, permittivity, and higher electrical conductivity than air. Therefore, RF waves easily attenuate when propagating over successive distances [94]. For such transmission scenarios, a high data rate cooperative dual-hop RF-UVLC and FSO/UVLC systems are needed to be deployed [48], [180] [319]. As, VLC provides a high capacity of data rate over moderate distances, an acceptable wireless media for underwater mapping, and real-time video streaming with high resolution and various UVLC applications as follows.

A. OCEAN FLOOR BATHYMETRY

The study of exploring the ocean floor is referred to the depths and shape of the underwater terrain [320], as stated bathymetry is the most significant investigation that deploys in numerous underwater applications. Additionally, the collection of geographical and oceanographic data analysis updates of weather and natural hazards on our earth. The massive water reservoirs are still unmapped, unexplored, and unobserved sectors. Only a very few oceanic portions have been mapped systematically by direct measurement [127]. The rest of the unexplored fraction of oceans are predicted by the satellite altimeter data, which is the approximated estimation structure of the seabed. A newly sounding technique is proposed that supports measuring ocean depth over less than 18% of the seafloor resolution about 1km [321]. Furthermore, the two most significant seafloor mapping techniques are proposed as Single Beam Echo-Sounders (SBES) [127], [322] and Multi-beam Echo-Sounders (MBES) [127], [323], respectively. The use of the two-way travel time of sound waves methodologies are used for measurement sea depth directly, where the sound waves strike with the seabed. On the other hand, in the MBES system, the enabled fan generates sound waves for further data collection. These sound waves are responsible for re-echoing signals generated in areas of the strait perpendicular to that fan, leading to the ocean floor mapping. Therefore, the established system receives hundreds of beams capable of mapping the narrow sectors up to 150 degrees.

B. UNDERWATER ENVIRONMENTAL EXPLORATION AND MONITORING

Most of the underwater environmental monitoring applications are related explicitly to observing manual and habitable activities in the oceanic environment. By deploying the UWSNs, the water pollution, water flows, and lives could be monitored. Additionally, the tectonic plate movement, underwater thunderstorms, earthquakes, and new formation of lands due to the eruption of volcanoes (the lava plays a significant role in forming a chunk of the island, etc.) being monitored. The floating nodes at different depths can observe and collect data of the 3D geometry of open oceans and terrains as human beings are highly interested in exploring the underwater environment since their existence. The scientific community is a witness in the exploration of less than 5% of oceans. A vast number of underwater applications are immersed by floating nodes as AUVs, ROVs, and UUVs for monitoring and observing the marine lives along with the three-dimensional geographical data within real-time scenario [283]. The study of monitoring water quality, pollution, impurities underwater is more challenging. Various water samples are being used to monitor water quality regarding the pH level, oxygen (O_2), and ammonium nitrate (NH_3). Moreover, the underwater monitoring also includes water macrophytes or hydrophytes, marine species, coral reefs, and algae for further analysis. In more contrast, environmental monitoring is also a fundamental approach through IoUT enabled applications which include the physio-chemical properties of water such as pressure, temperature, and variation in underwater are the main concerns [324].

The continuous monitoring of underwater helps to check remotely the pH water level. The water pollution monitoring is also substantial for the ecological system, especially for undersea species. IoUT provides an opportunity to explore the bottomless underwater reservoirs to discover lost human civilizations and lost treasure. Moreover, to identify the roughness of the seafloor, natural minerals, oil, and gas treasures. Many lost-treasure discoveries were made through the IoUTs.

C. NAVIGATION & SURVEILLANCE

Oceans are highly complex and unguided water bodies which are 95% unexplored in scientific research. As a result, underwater navigation is more complicated than terrestrial basis. UWSNs are appropriate and the most suitable technological approach that supports navigation in hulking aqueous mediums. Especially, for navigation the 3*D* underwater sensor network (USN) localization system is investigated in [282]. In [282], the authors propose the superiority of 3D Underwater Sensor Positioning (USP) systematic planning, which is beneficial for improving localization capabilities over existing 3D sensor architectures with predictable, balanced communication underwater. An AUV-assisted localization scenario of USNs roaming across the underwater sensor fields is presented in [325]. A wide range of localization of acoustic network nodes in the underwater medium is summarized in open literature as in [326]–[332]. Since optical communication is a novel technique to implement the localization and navigation purposes. Therefore, the authors in [333] investigated the connectivity of underwater wireless optical sensor networks (UWOSNs) as the influential factor to the system performance. Most recently, an extensive study based on received signal strength to the centralized localization scheme is proposed in [13]. Counterpart surveillance is a more efficient tool for node detection for military purposes or coastal securities. AUVs are used as emerging communication nodes for surveillance and retrieving information for defense operations. A most recent survey summarized the AUV capabilities for underwater communication in [271]. The authors in [271] are widely discussed the possible underwater application through AUV such as signal transmission, localization, and navigation purposes where the RF waves are incapable of retrieving the digital information.

D. NAVAL-MINE RECONNAISSANCE

As we know that underwater environments are highly deepest and massive water reservoirs, countless mines in oceans could be found by deploying UWSNs connecting with ships safe voyage or floating and operational activities. A recent work is proposed to design an underwater mine detection system in [334]. The authors have suggested a model minefield that includes the type of mines to be detected and mine-clearing operations by deploying the sonar waves in the various depth of the oceanic environment. Another impressive work in the open literature, where the authors have proposed the detection of underwater mines in real-time scenarios [335]. In [335], an AUV floats at different depths with sonar waves transmission along with a camera for real-time observation. Naval mines are also a real threat to maritime and naval tactical operations. Underwater-based mines hide or buried by the high altitude of tides and water currents, even covered by muddy soil at the sea bottom [336]. In most of the conditions, the naval mines are undetectable by low-frequency ranges. To cope with this issue, the challenge is that a high-frequency range of sonar should be mounted through an AUV to detect or bathymetric data of naval mines. For instance, the ECA Group deals with the issues within an innovative technological solution to perform complex missions in hostile or harsh environments [336]. According to SOACYS, the first prototype in the form of a 5 to 40m longship is used to collect oceanic data 1 Teabyte within 2400km of survey lines [337]. This small ship prototype is used for various applications such as UneXploded Ordnance (UXO), debris, boulders, pipelines/cables, marine archeology, sedimentary studies, etc.

E. BORDER & COASTAL SECURITIES

The border and coastal securities applications are mainly used to observe unwanted activities in coastal areas such as entry port security, land border security, and maritime border security. Taking account of these issues, USWNs an emerging technique for various military operations and are used for military communication purposes. These integral networking signals have a key role in providing such facilities to the military as surveillance, intelligence, localization, targeting positions, and tracking nuclear, biological, and chemical weapons. A high capacity command control communication system of ASELSAN is used to enhance situational awareness, accurate decision making, and faster response qualities in coastal and border security system solutions [338].

F. SEISMIC MONITORING AND OCEAN SAMPLING

The oceans are extremely large water reservoirs that change over the time. The sensor nodes are the main advantageous communication networking tools for sampling and observing the underwater environment, collecting oceanographic data, and transmitting signals to the source (e.g., base stations, etc.). The floating sensor nodes could be deployed at high depth for ocean mapping and underwater sampling activities. Furthermore, earthquakes, tsunami, and floods are sudden and unexpected events that cause major catastrophy worldwide. Sudden slip of bedrock causes seismic waves that shake the ground. UWSNs are dedicated to monitoring seismic activities and recording data for early detection warning [339].

G. FUTURE DIRECTION

UVLC has drawn attention to the futuristic deployment of UWC, which opens the doors of advanced wireless communication systems towards 5GB networking system in the nearest future. Currently, it is possible to transmit the data at high speed as well as the wireless energy transfer through the illumination phenomena of LEDs. UVLC has a fruitful future perspectives due to the wide range of popularity of LEDs all around the world [42]. Therefore, UVLC has shown potential acceptability for next-generation 5GB networking systems for further developments in the digital wireless generation of communication phase. LEDs are very cost-effective optical signaling elements that have more superiority over traditional wireless communication media. The light spectrum of the optical beam visible light and LED illumination is a comfortable illusion for aquatic species. Therefore, the essentiality for promising extensive research is required for more advanced, very cost-effective light-emitting and photon receiving detectors. The less expensive, tiny in size, less power consumption, and high compatibility with neighboring optical network UVLC claim the most significant wireless carriers. The traditional acoustic and RF wireless candidates are lagging behind for underwater signaling with low data-rate (few kbps); therefore UVLC fills the gap (Mbps to Gbps data transmission rates) of desired communication. In more contrast, the IoUT networks support the mobility of the devices in a very divisive medium within 3D channel coverage. Plenty of UWC applications enabled with ROVs, UUVs, and AUVs are widely employable with VLC format. The hybrid communication systems with 5GB networks are capable of connecting an enormous number of devices on terrestrial to underwater-based internet connecting things for further exploration of unguided oceanic sectors. The predictable scenario is establishing the underwater environment of the satellite becoming a universal digital communication sphere. As a substitute, UVLC supports high data rates (3Gb/s DMT VLC transmissions) [340] over short distances with low latency.

XV. CONCLUSION

UVLC approach builds up a wireless connection between terrestrial and floating nodes in an underwater environment. The possible solution to cope with the challenges and affecting factors of signal propagation are widely studied in this research. UVLC has become the most significant trade for signaling in aqueous mediums towards the futuristic 5GB wireless networking systems. The most recent advances through the current project schemes all around the globe to enhance the interest in marine industries along with various underwater applications are the main perspectives. The UVLC technological critics of signal propagation and channel impairments are the main issues due to the various types of underwater-based hybrid communication scenarios are summarized in this paper. Additionally, the architectural design of UWNs with higher modulation techniques is quite challenging to deploy over long-range communication in marine industries. Due to this, the different types of hybrid communication approaches are investigated according to requirements and geographical environments. The IoUTs play an ample role as a backbone in communication among transceivers. In the IoUT networks, the modems may contain some advanced signal tools for the purpose of achieving reliable high-data rates with diminishing influential factors such as noise and channel impairments in the correspondence of physical layers. This study contributes the solution of various range of channel impairment challenges and provides an overview of the latest projects schemes along with the future perspectives towards the 5GB networking system in this particular domain.

REFERENCES

[1] S. Dang, O. Amin, B. Shihada, and M.-S. Alouini, ''What should 6G be?'' *Nature Electron.*, vol. 3, no. 1, pp. 20–29, Jan. 2020.

[2] S. Ariyanti and M. Suryanegara, ''Visible light communication (VLC) for 6G technology: The potency and research challenges,'' in *Proc. 4th World Conf. Smart Trends Syst., Secur. Sustainability (WorldS)*, Jul. 2020, pp. 490–493.

[3] S. Idris, A. M. Aibinu, G. Koyunlu, and J. Sanusi, ''A survey of modulation schemes in visible light communications,'' in *Proc. 3rd Int. Conf. Trends Electron. Informat. (ICOEI)*, Apr. 2019, pp. 1–7.

[4] M. F. Ali, D. N. K. Jayakody, Y. A. Chursin, S. Affes, and S. Dmitry, ''Recent advances and future directions on underwater wireless communications,'' *Arch. Comput. Methods Eng.*, vol. 27, no. 5, pp. 1–34, 2019.

[5] H. Kaushal and G. Kaddoum, ''Underwater optical wireless communication,'' *IEEE Access*, vol. 4, pp. 1518–1547, 2016.

[6] S. Zhu, X. Chen, X. Liu, G. Zhang, and P. Tian, ''Recent progress in and perspectives of underwater wireless optical communication,'' *Prog. Quantum Electron.*, vol. 73, Sep. 2020, Art. no. 100274.

[7] M. Jouhari, K. Ibrahimi, H. Tembine, and J. Ben-Othman, ''Underwater wireless sensor networks: A survey on enabling technologies, localization protocols, and internet of underwater things,'' *IEEE Access*, vol. 7, pp. 96879–96899, 2019.

[8] X. Sun, C. H. Kang, M. Kong, O. Alkhazragi, Y. Guo, M. Ouhssain, Y. Weng, B. H. Jones, T. K. Ng, and B. S. Ooi, ''A review on practical considerations and solutions in underwater wireless optical communication,'' *J. Lightw. Technol.*, vol. 38, no. 2, pp. 421–431, Jan. 15, 2020.

[9] C. M. G. Gussen, P. S. R. Diniz, M. L. R. Campos, W. A. Martins, and J. N. Gois, ''A survey of underwater wireless communication technologies,'' *J. Commun. Inf. Sys.*, vol. 31, no. 1, pp. 242–255, 2016.

[10] M. Lanzagorta, ''Underwater communications,'' *Synth. Lectures Commun.*, vol. 5, no. 2, pp. 1–129, 2012.

[11] M. Rhodes, ''Electromagnetic propagation in sea water and its value,'' in *Proc. Mil. Syst. SEAS DTC Tech. Conf.*, 2007, pp. 1–6.

[12] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, ''A survey of underwater optical wireless communications,'' *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 204–238, 1st Quart., 2016.

[13] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, ''Underwater optical wireless communications, networking, and localization: A survey,'' *Ad Hoc Netw.*, vol. 94, Nov. 2019, Art. no. 101935.

[14] H. Roarty, T. Cook, L. Hazard, D. George, J. Harlan, S. Cosoli, L. Wyatt, E. A. Fanjul, E. Terrill, M. Otero, and J. Largier, ''The global high frequency radar network,'' *Frontiers Mar. Sci.* vol. 6, p. 164, Dec. 2019.

[15] G. S. Spagnolo, L. Cozzella, and F. Leccese, ''Underwater optical wireless communications: Overview,'' *Sensors*, vol. 20, no. 8, p. 2261, Apr. 2020.

[16] K. Chen, M. Ma, E. Cheng, F. Yuan, and W. Su, ''A survey on MAC protocols for underwater wireless sensor networks,'' *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1433–1447, Mar. 2014.

[17] Z. Guo, Z. Li, and F. Hong, ''USS-TDMA: Self-stabilizing TDMA algorithm for underwater wireless sensor network,'' in *Proc. Int. Conf. Comput. Eng. Technol.*, Jan. 2009, pp. 578–582.

[18] M. Teng, L. Ye, Z. Yuxin, J. Yanqing, C. Zheng, Z. Qiang, and X. Shuo, ''An AUV localization and path planning algorithm for terrain-aided navigation,'' *ISA Trans.*, vol. 103, pp. 215–227, Aug. 2020.

[19] A. Amantayeva, M. Yerzhanova, and R. C. Kizilirmak, "Multiuser MIMO for underwater visible light communication," in *Proc. Int. Conf. Comput. Netw. Commun. (CoCoNet)*, Aug. 2018, pp. 164–168.
[20] A. Al-Kinani, C.-X. Wang, L. Zhou, and W. Zhang, "Optical wireless communication channel measurements and models," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1939–1962, 3rd Quart. 2018.
[21] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling With MATLAB*. Boca Raton, FL, USA: CRC Press, 2019.
[22] M. Uysal, C. Capsoni, Z. Ghassemlooy, A. Boucouvalas, and E. Udvary, *Optical Wireless Communications: An Emerging Technology*. Graz, Austria: Springer, 2016.
[23] F. E. Goodwin, "A review of operational laser communication systems," *Proc. IEEE*, vol. 58, no. 10, pp. 1746–1752, Oct. 1970.
[24] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 2231–2258, Jun. 2014.
[25] J. M. Kahn and J. R. Barry, "Wireless infrared communications," *Proc. IEEE*, vol. 85, no. 2, pp. 265–298, Feb. 1997.
[26] J. B. Carruther and J. M. Kahn, "Angle diversity for nondirected wireless infrared communication," *IEEE Trans. Commun.*, vol. 48, no. 6, pp. 960–969, Jun. 2000.
[27] N. Chi, *LED-Based Visible Light Communications*. Beijing, China: Springer, 2018.
[28] Y. Taniyasu, M. Kasu, and T. Makimoto, "An aluminium nitride light-emitting diode with a wavelength of 210 nanometres," *Nature*, vol. 441, pp. 325–328, May 2006.
[29] Z. Ghassemlooy, D. Wu, M.-A. Khalighi, and X. Tang, "Indoor non-directed optical wireless communications-optimization of the Lambertian order," *J. Electr. Comput. Eng. Innov.*, vol. 1, no. 1, pp. 1–9, 2013.
[30] G. Strasser, K. Takagi, S. Werner, U. Hollenbach, T. Tanaka, K. Yamamoto, and K. Hirota, "A verification of the ITTC/ISO speed/power trials analysis," *J. Mar. Sci. Technol.*, vol. 20, no. 1, pp. 2–13, Mar. 2015.
[31] S. Rajagopal, R. Roberts, and S.-K. Lim, "IEEE 802.15.7 visible light communication: Modulation schemes and dimming support," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 72–82, Mar. 2012.
[32] M. Uysal, F. Miramirkhani, O. Narmanlioglu, T. Baykas, and E. Panayirci, "IEEE 802.15.7r1 reference channel models for visible light communications," *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 212–217, Jan. 2017.
[33] M. Elamassie and M. Uysal, "Vertical underwater vlc links over cascaded gamma-gamma turbulence channels with pointing errors," in *Proc. IEEE Int. Black Sea Conf. Commun. Netw. (BlackSeaCom)*. Sochi, Russia: IEEE, Jun. 2019, pp. 1–5.
[34] C. D. Mobley, "The optical properties of water," *Handbook Opt.*, vol. 1, no. 43, pp. 3–43, 1995.
[35] M. F. Ali, D. N. K. Jayakody, T. D. P. Perera, K. Srinivasan, A. Sharma, and I. Krikidis, "Underwater communications: Recent advances," in *Proc. Int. Conf. Emerg. Technol. Inf. Commun. (ETIC)*, vol. 6, 2019, pp. 97–102.
[36] X. Wu and N. Chi, "The phase estimation of geometric shaping 8-QAM modulations based on K-means clustering in underwater visible light communication," *Opt. Commun.*, vol. 444, pp. 147–153, Aug. 2019.
[37] T. D. P. Perera, D. N. K. Jayakody, S. Affes, M. Chidambaranathan, and C. Yury, "Wireless-powered hybrid terrestrial and underwater cooperative communication system," in *Proc. 15th Int. Conf. Distrib. Comput. Sensor Syst. (DCOSS)*, May 2019, pp. 502–506.
[38] M. Uysal, S. Ghasvarianjahromi, M. Karbalayghareh, P. D. Diamantoulakis, G. K. Karagiannidis, and S. M. Sait, "SLIPT for underwater visible light communications: Performance analysis and optimization," *IEEE Trans. Wireless Commun.*, vol. 20, no. 10, pp. 6715–6728, Oct. 2021.
[39] J. I. D. O. Filho, A. Trichili, B. S. Ooi, M.-S. Alouini, and K. N. Salama, "Toward self-powered internet of underwater things devices," *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 68–73, Jan. 2020.
[40] B. S. Srujana, Neha, P. Mathews, and V. P. Harigovindan, "Multi-source energy harvesting system for underwater wireless sensor networks," *Proc. Comput. Sci.*, vol. 46, pp. 1041–1048, Jan. 2015.
[41] P. D. Diamantoulakis, G. K. Karagiannidis, and Z. Ding, "Simultaneous lightwave information and power transfer (SLIPT)," *IEEE Trans. Green Commun. NetW.*, vol. 2, no. 3, pp. 764–773, Sep. 2018.
[42] S. S. Morapitiya, M. F. Ali, S. Rajkumar, S. K. Wijayasekara, D. N. K. Jayakody, and R. U. Weerasuriya, "A SLIPT-assisted visible light communication scheme," in *Proc. 16th Int. Conf. Distrib. Comput. Sensor Syst. (DCOSS)*, May 2020, pp. 368–375.
[43] J. Wu, X. Ma, X. Qi, Z. Babar, and W. Zheng, "Influence of pulse shaping filters on PAPR performance of underwater 5G communication system technique: GFDM," *Wireless Commun. Mobile Comput.*, vol. 2017, pp. 1–7, Jan. 2017.
[44] P. Amini, R.-R. Chen, and B. Farhang-Boroujeny, "Filterbank multicarrier for underwater communications," in *Proc. 49th Annu. Allerton Conf. Commun., Control, Comput. (Allerton)*, Sep. 2011, pp. 639–646.
[45] L. U. Khan, "Visible light communication: Applications, architecture, standardization and research challenges," *Digit. Commun. Netw.*, vol. 3, no. 2, pp. 78–88, May 2016.
[46] I. S. Ansari, F. Yilmaz, and M.-S. Alouini, "Impact of pointing errors on the performance of mixed RF/FSO dual-hop transmission systems," *IEEE Wireless Commun. Lett.*, vol. 2, no. 3, pp. 351–354, Jun. 2013.
[47] E. Illi, F. E. Bouanani, D. B. da Costa, P. C. Sofotasios, F. Ayoub, K. Mezher, and S. Muhaidat, "Physical layer security of a dual-hop regenerative mixed RF/UOW system," *IEEE Trans. Sustain. Comput.*, vol. 6, no. 1, pp. 90–104, Jan. 2021.
[48] E. Illi, F. E. Bouanani, D. B. da Costa, F. Ayoub, and U. S. Dias, "Dual-hop mixed RF-UOW communication system: A PHY security analysis," *IEEE Access*, vol. 6, pp. 55345–55360, 2018.
[49] N. Ishpuniani, M. Aggarwal, and N. Garg, "Outage analysis of dual hop FSO system with multiuser scheduling over gamma-gamma turbulence," *Int. J. Eng. Trends Technol.*, vol. 35, no. 6, pp. 237–242, May 2016.
[50] T. A. Tsiftsis, G. K. Karagiannidis, and S. A. Kotsopoulos, "Dual-hop wireless communications with combined gain relays," *IEE Proc. Commun.*, vol. 152, no. 5, pp. 528–532, Oct. 2005.
[51] E. Illi, F. E. Bouanani, D. B. da Costa, F. Ayoub, and U. S. Dias, "On the secrecy performance of mixed RF/UOW communication system," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2018, pp. 1–6.
[52] A. M. Salhab, "A new scenario of triple-hop mixed RF/FSO/RF relay network with generalized order user scheduling and power allocation," *EURASIP J. Wireless Commun. Netw.*, vol. 2016, no. 1, pp. 1–20, Dec. 2016.
[53] L. Xu and T. Xu, *Digital Underwater Acoustic Communications*. New York, NY, USA: Academic, 2016.
[54] K. M. Awan, P. A. Shah, K. Iqbal, S. Gillani, W. Ahmad, and Y. Nam, "Underwater wireless sensor networks: A review of recent issues and challenges," *Wireless Commun. Mobile Comput.*, vol. 2019, pp. 1–20, Jan. 2019.
[55] T. Hu and Y. Fei, "MURAO: A multi-level routing protocol for acoustic-optical hybrid underwater wireless sensor networks," in *Proc. 9th Annu. IEEE Commun. Soc. Conf. Sensor, Mesh Ad Hoc Commun. Netw. (SECON)*, Jun. 2012, pp. 218–226.
[56] S. Han, Y. Noh, R. Liang, R. Chen, Y.-J. Cheng, and M. Gerla, "Evaluation of underwater optical-acoustic hybrid network," *China Commun.*, vol. 11, no. 5, pp. 49–59, May 2014.
[57] L. J. Johnson, R. J. Green, and M. S. Leeson, "Hybrid underwater optical/acoustic link design," in *Proc. 16th Int. Conf. Transparent Opt. Netw. (ICTON)*, Jul. 2014, pp. 1–4.
[58] C. Moriconi, G. Cupertino, S. Betti, and M. Tabacchiera, "Hybrid acoustic/optic communications in underwater swarms," in *Proc. OCEANS*, May 2015, pp. 1–9.
[59] C. Lodovisi, P. Loreti, L. Bracciale, and S. Betti, "Performance analysis of hybrid optical–acoustic AUV swarms for marine monitoring," *Future Internet*, vol. 10, no. 7, p. 65, 2018.
[60] S. M. Maher, Z. M. Ali, H. H. Mahmoud, S. O. Abdellatif, and M. M. Abdellatif, "Performance of RF underwater communications operating at 433 MHz and 2.4 GHz," in *Proc. Int. Conf. Innov. Trends Comput. Eng. (ITCE)*, Feb. 2019, pp. 334–339.
[61] A. Zoksimovski, D. Sexton, M. Stojanovic, and C. Rappaport, "Underwater electromagnetic communications using conduction–channel characterization," *Ad Hoc Netw.*, vol. 34, pp. 42–51, 2015.
[62] S. M. T. Islam and A. Ashok, "Empirical characterization of vertical channel in underwater visible light communication," in *Proc. Int. Conf. Underwater Netw. Syst.*, Oct. 2019, pp. 1–8.
[63] N. Anous, M. Abdallah, M. Uysal, and K. Qaraqe, "Performance evaluation of LOS and NLOS vertical inhomogeneous links in underwater visible light communications," *IEEE Access*, vol. 6, pp. 22408–22420, 2018.

[64] Z. Ghassemlooy, S. Arnon, M. Uysal, Z. Xu, and J. Cheng, "Emerging optical wireless communications-advances and challenges," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1738–1749, Sep. 2015.

[65] F. Hu, P. Zou, F. Wang, X. Wu, and N. Chi, "Optimized geometrically shaped 16QAM in underwater visible light communication," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2018, pp. 1–3.

[66] A. K. Chaudhary, S. Shukla, and S. Singh, "Analysis of underwater wireless communication using visible light LEDs," in *Proc. IEEE Int. Students' Conf. Elect., Electron. Comput. Sci. (SCEECS)*, Feb. 2020, pp. 1–4.

[67] H. Jiang, H. Qiu, N. He, W. Popoola, Z. Ahmad, and S. Rajbhandari, "Performance of spatial diversity DCO-OFDM in a weak turbulence underwater visible light communication channel," *J. Lightw. Technol.*, vol. 38, no. 8, pp. 2271–2277, Apr. 15, 2020.

[68] M. Jain, N. Sharma, A. Gupta, D. Rawal, and P. Garg, "Performance analysis of NOMA assisted underwater visible light communication system," *IEEE Wireless Commun. Lett.*, vol. 9, no. 8, pp. 1291–1294, Aug. 2020.

[69] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, "Energy harvesting hybrid acoustic-optical underwater wireless sensor networks localization," *Sensors*, vol. 18, no. 1, p. 51, 2018.

[70] C.-C. Kao, Y.-S. Lin, G.-D. Wu, and C.-J. Huang, "A comprehensive study on the internet of underwater things: Applications, challenges, and channel models," *Sensors*, vol. 17, no. 7, p. 1477, 2017.

[71] J. Zhang, L. Dai, Y. Zhang, and Z. Wang, "Unified performance analysis of mixed radio frequency/free-space optical dual-hop transmission systems," *J. Lightw. Technol.*, vol. 33, no. 11, pp. 2286–2293, Jun. 1, 2015.

[72] U. S. Navy. (2003). Extremely Low Frequency Transmitter Site Clam Lake. Wisconsin. Accessed: Apr. 25, 2010. [Online]. Available: http://enterprise.spawar.navy.mil/UploadedFiles/fs_clam_lake_elf2003.pdf

[73] X. Che, I. Wells, G. Dickers, P. Kear, and X. Gong, "Re-evaluation of RF electromagnetic communication in underwater sensor networks," *IEEE Commun. Mag.*, vol. 48, no. 12, pp. 143–151, Dec. 2010.

[74] M. Stojanovic and J. Preisig, "Underwater acoustic communication channels: Propagation models and statistical characterization," *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 84–89, Jan. 2009.

[75] J. K. Gaurav Mishra, "A survey of underwater communication, 2018," *Int. Res. J. Eng. Technol.*, Mar. 2018.

[76] L. Liu, S. Zhou, and J.-H. Cui, "Prospects and problems of wireless communication for underwater sensor networks," *Wireless Commun. Mobile Comput., Underwater Sensor Netw., Archit. Protocols*, vol. 8, no. 8, pp. 977–994, 2008.

[77] X. Mei, H. Wu, N. Saeed, T. Ma, J. Xian, and Y. Chen, "An absorption mitigation technique for received signal strength-based target localization in underwater wireless sensor networks," *Sensors*, vol. 20, no. 17, p. 4698, Aug. 2020.

[78] J. A. Simpson, B. L. Hughes, and J. F. Muth, "Smart transmitters and receivers for underwater free-space optical communication," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 5, pp. 964–974, Jun. 2012.

[79] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, "Underwater optical wireless communications, networking, and localization: A survey," 2018, *arXiv:1803.02442*.

[80] R. C. Smith and K. S. Baker, "Optical properties of the clearest natural waters (200–800 nm)," *Appl. Opt.*, vol. 20, no. 2, pp. 177–184, Jan. 1981.

[81] F. A. Tahir, "Open ocean underwater wireless optical communication: Chlorophyll and depth dependent variation in attenuation," Ph.D. dissertation, Dept. Elect. Electron. Eng., Universiti Tun Hussein Onn Malaysia, Parit Raja, Malaysia, 2015.

[82] F. Hanson and S. Radic, "High bandwidth underwater optical communication," *Appl. Opt*, vol. 47, no. 2, pp. 277–283, 2008.

[83] T. Dickey, M. Lewis, and G. Chang, "Optical oceanography: Recent advances and future directions using global remote sensing and *in situ* observations," *Rev. Geophys.*, vol. 44, no. 1, pp. 1–39, 2006.

[84] L. Johnson, R. Green, and M. Leeson, "A survey of channel models for underwater optical wireless communication," in *Proc. 2nd Int. Workshop Opt. Wireless Commun. (IWOW)*, Oct. 2013, pp. 1–5.

[85] C. Gabriel, M.-A. Khalighi, S. Bourennane, P. Leon, and V. Rigaud, "Misalignment considerations in point-to-point underwater wireless optical links," in *Proc. MTS/IEEE OCEANS*, Jun. 2013, pp. 1–5.

[86] I. F. Akyildiz, D. Pompili, and T. Melodia, "Challenges for efficient communication in underwater acoustic sensor networks," *ACM SIGBED Rev.*, vol. 1, no. 2, pp. 3–8, Jul. 2004.

[87] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: Research challenges," *Ad Hoc Netw.*, vol. 3, no. 3, pp. 257–279, Mar. 2005.

[88] M. Chitre, S. Shahabudeen, and M. Stojanovic, "Underwater acoustic communications and networking: Recent advances and future challenges," *Marine Technol. Soc. J.*, vol. 42, no. 1, pp. 103–116, 2008.

[89] M. Chitre, S. Shahabudeen, L. Freitag, and M. Stojanovic, "Recent advances in underwater acoustic communications & networking," in *Proc. OCEANS*, 2008, pp. 1–10.

[90] P. Amini, R.-R. Chen, and B. Farhang-Boroujeny, "Filterbank multicarrier communications for underwater acoustic channels," *IEEE J. Ocean. Eng.*, vol. 40, no. 1, pp. 115–130, Jan. 2015.

[91] P. Kumar, V. K. Trivedi, and P. Kumar, "Recent trends in multicarrier underwater acoustic communications," in *Proc. IEEE Underwater Technol. (UT)*, Feb. 2015, pp. 1–8.

[92] U. West Lothian, "Electromagnetic propagation in sea water and its value in military systems," in *Proc. SEAS DTC Tech. Conf.*, 2007, pp. 1–6.

[93] L. A. Belov, S. M. Smolskiy, and V. N. Kochemasov, *Handbook of RF, Microwave, and Millimeter-Wave Components*. Norwood, MA, USA: Artech House, 2012.

[94] M. Dautta and M. I. Hasan, "Underwater vehicle communication using electromagnetic fields in shallow seas," in *Proc. Int. Conf. Electr., Comput. Commun. Eng. (ECCE)*, Feb. 2017, pp. 38–43.

[95] A. I. Al-Shamma'a, A. Shaw, and S. Saman, "Propagation of electromagnetic waves at MHz frequencies through seawater," *IEEE Trans. Antennas Propag.*, vol. 52, no. 11, pp. 2843–2849, Nov. 2004.

[96] A. Palmeiro, M. Martin, I. Crowther, and M. Rhodes, "Underwater radio frequency communications," in *Proc. OCEANS*, Jun. 2011, pp. 1–8.

[97] I. Wells, A. Davies, X. Che, P. Kear, G. Dickers, X. Gong, and M. Rhodes, "Node pattern simulation of an undersea sensor network using RF electromagnetic communications," in *Proc. Int. Conf. Ultra Modern Telecommun. Workshops*, Oct. 2009, pp. 1–4.

[98] X. Che, I. Wells, P. Kear, G. Dickers, X. Gong, and M. Rhodes, "A static multi-hop underwater wireless sensor network using," in *Proc. 29th IEEE Int. Conf. Distrib. Comput. Syst. Workshops*, Jun. 2009, pp. 460–463.

[99] S. Jiang and S. Georgakopoulos, "Electromagnetic wave propagation into fresh water," *J. Electromagn. Anal. Appl.*, vol. 3, no. 7, pp. 261–266, 2011.

[100] M. Elamassie and M. Uysal, "Vertical underwater VLC links over cascaded gamma-gamma turbulence channels with pointing errors," in *Proc. IEEE Int. Black Sea Conf. Commun. Netw. (BlackSeaCom)*, Jun. 2019, pp. 1–5.

[101] M. Elamassie, F. Miramirkhani, and M. Uysal, "Channel modeling and performance characterization of underwater visible light communications," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, May 2018, pp. 1–5.

[102] M. Elamassie, S. M. Sait, and M. Uysal, "Underwater visible light communications in cascaded gamma-gamma turbulence," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2018, pp. 1–6.

[103] A. K. Das, A. Ghosh, A. M. Vibin, and S. Prince, "Underwater communication system for deep sea divers using visible light," in *Proc. Photon. Global Conf. (PGC)*, Dec. 2012, pp. 1–3.

[104] T. Szili, B. Matolcsy, and G. Fekete, "Water pollution investigations by underwater visible light communications," in *Proc. 17th Int. Conf. Transparent Opt. Netw. (ICTON)*, Jul. 2015, pp. 1–4.

[105] M. V. Jamali, P. Nabavi, and J. A. Salehi, "MIMO underwater visible light communications: Comprehensive channel study, performance analysis, and multiple-symbol detection," *IEEE Trans. Veh. Technol.*, vol. 67, no. 9, pp. 8223–8237, Sep. 2018.

[106] N. Farr, A. Bowen, J. Ware, C. Pontbriand, and M. Tivey, "An integrated, underwater optical/acoustic communications system," in *Proc. OCEANS*, May 2010, pp. 1–6.

[107] J. Wang, W. Shi, L. Xu, L. Zhou, Q. Niu, and J. Liu, "Design of optical-acoustic hybrid underwater wireless sensor network," *J. Netw. Comput. Appl.*, vol. 92, pp. 59–67, Aug. 2017.

[108] Z. Zeng, "A survey of underwater wireless optical communication," Ph.D. dissertation, Dept. Elect. Eng., Univ. British Columbia, Vancouver, BC, Canada, 2015.

[109] X. Wu, D. Basnayaka, M. Safari, and H. Haas, "Two-stage access point selection for hybrid VLC and RF networks," in *Proc. IEEE 27th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2016, pp. 1–6.

[110] M. F. Ali, T. D. P. Perera, V. S. Sergeevich, S. A. Irfan, U. E. Viktorovna, and W. Zhang, A. Camponogara, and D. N. K. Jayakody, "Selection relay based RF-VLC underwater communication system," in *Machine Learning, Deep Learning and Computational Intelligence for Wireless Communication*. Singapore: Springer, 2021, pp. 177–192.

[111] W. Guo, Q. Li, H.-Y. Yu, and J.-H. Liu, "A parallel transmission MAC protocol in hybrid VLC-RF network," *J. Commun.*, vol. 10, no. 1, pp. 80–85, 2015.

[112] M. Hammouda, S. Akin, A. M. Vegni, H. Haas, and J. Peissig, "Link selection in hybrid RF/VLC systems under statistical queueing constraints," *IEEE Trans. Wireless Commun.*, vol. 17, no. 4, pp. 2738–2754, Apr. 2018.

[113] D. A. Basnayaka and H. Haas, "Hybrid RF and VLC systems: Improving user data rate performance of VLC systems," in *Proc. IEEE 81st Veh. Technol. Conf. (VTC Spring)*, May 2015, pp. 1–5.

[114] A. Gupta, N. Sharma, P. Garg, D. N. K. Jayakody, C. Y. Aleksandrovich, and J. Li, "Asymmetric satellite-underwater visible light communication system for oceanic monitoring," *IEEE Access*, vol. 7, pp. 133342–133350, 2019.

[115] P. Sarma, R. Deka, and S. Anees, "Performance analysis of DF based mixed triple hop RF-FSO-UWOC cooperative system," in *Proc. IEEE 92nd Veh. Technol. Conf. (VTC-Fall)*, Nov. 2020, pp. 1–5.

[116] S. Anees, P. S. S. Harsha, and M. R. Bhatnagar, "On the performance of AF based mixed triple-hop RF/FSO/RF communication system," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Oct. 2017, pp. 1–6.

[117] T. Ali, L. T. Jung, and I. Faye, "Three hops reliability model for underwater wireless sensor network," in *Proc. Int. Conf. Comput. Inf. Sci. (ICCOINS)*, Jun. 2014, pp. 1–6.

[118] R. Deka and S. Anees, "Cascaded RF-FSO-VLC system using DF relays," *Int. J. Innov. Technol. Exploring Eng.*, vol. 8, no. 10, pp. 1–6, 2019.

[119] S. Tang, Y. Dong, and X. Zhang, "Impulse response modeling for underwater wireless optical communication links," *IEEE Trans. Commun.*, vol. 62, no. 1, pp. 226–234, Jan. 2014.

[120] F. Akhoundi, J. A. Salehi, and A. Tashakori, "Cellular underwater wireless optical CDMA network: Performance analysis and implementation concepts," *IEEE Trans. Commun.*, vol. 63, no. 3, pp. 882–891, Mar. 2015.

[121] M. V. Jamali, A. Chizari, and J. A. Salehi, "Performance analysis of multi-hop underwater wireless optical communication systems," *IEEE Photon. Technol. Lett.*, vol. 29, no. 5, pp. 462–465, Mar. 1, 2017.

[122] M. V. Jamali, F. Akhoundi, and J. A. Salehi, "Performance characterization of relay-assisted wireless optical CDMA networks in turbulent underwater channel," *IEEE Trans. Wireless Commun.*, vol. 15, no. 6, pp. 4104–4116, Jun. 2016.

[123] A. S. Hamza, J. S. Deogun, and D. R. Alexander, "Classification framework for free space optical communication links and systems," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1346–1382, 2nd Quart., 2019.

[124] L. J. Johnson, F. Jasman, R. J. Green, and M. S. Leeson, "Recent advances in underwater optical wireless communications," *Underwater Technol., Int. J. Soc. Underwater*, vol. 32, no. 3, pp. 167–175, Nov. 2014.

[125] S. Arnon, "Underwater optical wireless communication network," *Opt. Eng.*, vol. 49, no. 1, Jan. 2010, Art. no. 015001.

[126] S. Arnon and D. Kedar, "Non-line-of-sight underwater optical wireless communication network," *J. Opt. Soc. Amer. A, Opt. Image Sci.*, vol. 26, no. 3, pp. 530–539, 2009.

[127] A.-C. Wölfl, H. Snaith, S. Amirebrahimi, C. W. Devey, B. Dorschel, V. Ferrini, V. A. I. Huvenne, M. Jakobsson, J. Jencks, G. Johnston, G. Lamarche, L. Mayer, D. Millar, T. H. Pedersen, K. Picard, A. Reitz, T. Schmitt, M. Visbeck, P. Weatherall, and R. Wigley, "Seafloor mapping—The challenge of a truly global ocean bathymetry," *Frontiers Mar. Sci.*, vol. 6, p. 283, Jun. 2019.

[128] M. A. A. Ali and A. Ali, "Characteristics of optical channel for an underwater optical wireless communications based on visible light," *Austral. J. Basic Appl. Sci.*, vol. 9, no. 23, pp. 437–445, 2015.

[129] M. A. A. Ali and S. K. Rahi, "Line of sight (LoS) underwater wireless optical communication based on LED," in *Proc. 9th Int. Symp. Telecommun. (IST)*, Dec. 2018, pp. 270–274.

[130] F. Seguel, I. Soto, P. Adasme, N. Krommenacker, and P. Charpentier, "Potential and challenges of VLC based IPS in underground mines," in *Proc. 1st South Amer. Colloq. Visible Light Commun. (SACVLC)*, Nov. 2017, pp. 1–6.

[131] M. R. Mine, J. V. Baar, A. Grundhofer, D. Rose, and B. Yang, "Projection-based augmented reality in Disney theme parks," *Computer*, vol. 45, no. 7, pp. 32–40, Jul. 2012.

[132] O. News. *Huawei France and Schnell Team up to Bring Li-Fi to Hospitals, Telecompaper*. Accessed Mar. 15, 2021. [Online]. Available: https://oltnews.com/huawei-france-and-schnell-team-up-to-bring-li-fi-to% -hospitals-telecompaper

[133] Z. Deng, J. Li, M. Liao, W. Xie, and S. Luo, "InGaN/GaN distributed feedback laser diodes with surface gratings and sidewall gratings," *Micromachines*, vol. 10, no. 10, p. 699, Oct. 2019.

[134] *Layers of the Ocean*, N. W. Service, Jan. 2021. Accessed: Jan. 31, 2021. [Online]. Available: https://www.weather.gov/jetstream/layers_ocean

[135] (2021). U. M. O. P. UCMP. *The Marine Biome*. Accessed: Jan. 31, 2021. [Online]. Available: https://ucmp.berkeley.edu/exhibits/biomes/marine.php#oceans

[136] (2021). M. BIO. *Marine Zones*. Accessed: Jan. 31, 2021. [Online]. Available: https://marinebio.org/oceans/marine-zones

[137] (2021). M. BIO. *The Ocean & Temperature*. Accessed: Jan. 31, 2021. [Online]. Available: https://marinebio.org/oceans/temperature

[138] (2021). O. Network. *Twilight Zone*. Accessed: Jan. 31, 2021. [Online]. Available: https://www.oceanscape-aquarium.org/twilight-zone.html

[139] (2021). O. Network. *Midnight Zone*. Accessed: Jan. 31, 2021. [Online]. Available: https://www.oceanscape-aquarium.org/midnight-zone.html

[140] J. Simpson, "A 1 Mbps underwater communications system using LEDs and photodiodes with signal processing capability," Ph.D. dissertation, North Carolina State Univ., Raleigh, NC, USA, 2008.

[141] C. Gabriel, M.-A. Khalighi, S. Bourennane, P. Leon, and V. Rigaud, "Monte-Carlo-based channel characterization for underwater optical communication systems," *J. Opt. Commun. Netw.*, vol. 5, no. 1, pp. 1–12, 2013.

[142] A. N. Z. Rashed and H. A. Sharshar, "Performance evaluation of short range underwater optical wireless communications for different ocean water types," *Wireless Pers. Commun.*, vol. 72, no. 1, pp. 693–708, Sep. 2013.

[143] L. K. Gkoura, G. D. Roumelas, H. E. Nistazakis, H. G. Sandalidis, A. Vavoulas, A. D. Tsigopoulos, and G. S. Tombras, "Underwater optical wireless communication systems: A concise review," in *Turbulence Modelling Approaches–Current State, Development Prospects, Applications*. Rijeka, Croatia: InTech, 2017.

[144] S. K. Sahu and P. Shanmugam, "A theoretical study on the impact of particle scattering on the channel characteristics of underwater optical communication system," *Opt. Commun.*, vol. 408, pp. 3–14, Feb. 2018.

[145] M. Garcia, S. Sendra, M. Atenas, and J. Lloret, "Underwater wireless ad-hoc networks: A survey," in *Mobile Ad Hoc Networks: Current Status and Future Trends*. Boca Raton, FL, USA: CRC Press, 2011, pp. 379–411.

[146] C. Christopoulou, H. G. Sandalidis, and N. Vaiopoulos, "Performance of an underwater optical wireless link with a randomly placed or moving receiver," *IEEE J. Ocean. Eng.*, vol. 46, no. 3, pp. 1068–1079, Jul. 2021.

[147] A. Vavoulas, H. G. Sandalidis, and D. Varoutas, "Underwater optical wireless networks: A K-connectivity analysis," *IEEE J. Ocean. Eng.*, vol. 39, no. 4, pp. 801–809, Jan. 2014.

[148] V. I. Haltrin, "Chlorophyll-based model of seawater optical properties," *Appl. Opt.*, vol. 38, no. 33, pp. 6826–6832, 1999.

[149] A. Sokolov, M. Chami, E. Dmitriev, and G. Khomenko, "Parameterization of vol. scattering, function of coastal waters based on the statistical approach," *Opt. Exp.*, vol. 18, no. 5, pp. 4615–4636, 2010.

[150] S. Jaruwatanadilok, "Underwater wireless optical communication channel modeling and performance evaluation using vector radiative transfer theory," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1620–1627, Dec. 2008.

[151] S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices*. Hoboken, NJ, USA: Wiley, 2006.

[152] H. Brundage, "Designing a wireless underwater optical communication system," Ph.D. dissertation, Massachusetts Institute of Technology, 2010.

[153] T. Cevik and S. Yilmaz, "An overview of visible light communication systems," 2015, *arXiv:1512.03568*.

[154] UNEXMIN. *Autonomous Underwater Explorer for Flooded Mines*. The UNEXMIN, Accessed: Mar. 15, 2021. [Online]. Available: https://www.unexmin.eu/the-project/the-ux-1-robot/

[155] Surf3DSLAM. *Probabilistic 3D Surface Matching for Bathymetry Based Simultaneous Localization and Mapping of Underwater Vehicles*. The Surf3DSLAM, Accessed: Mar. 15, 2021. [Online]. Available: https://cordis.europa.eu/project/id/276778

[156] SubCULTron. *Submarine Cultures Perform Long-Term Robotic Exploration of Unconventional Environmental Niches*. The subCULTron. Accessed: Mar. 15, 2021. [Online]. Available: https://cordis.europa.eu/project/id/640967

[157] Trident. *Marine Robots and Dexterous Manipulation for Enabling Autonomous Underwater Multipurpose Intervention Missions*. The Trident. Accessed: Mar. 15, 2021. [Online]. Available: https://cordis.europa.eu/project/id/248497

[158] SWARMs. *Smart and Networking UnderWAter Robots in Cooperation Meshes*. The SWARMs. Accessed: Mar. 15, 2021. [Online]. Available: http://www.swarms.eu/

[159] SubCULTron. *Sibiu HCEV: An Intelligent Hybrid High Capacity Electric Underwater Remotely Operated Vehicle*. The Sibiu HCEV. Accessed: Mar. 15, 2021. [Online]. Available: https://cordis.europa.eu/project/id/855006

[160] EUMarineRobots. *Marine Robotics Research Infrastructure Network*. The EUMarineRobots. Accessed: Mar. 15, 2021. [Online]. Available: https://cordis.europa.eu/project/id/731103

[161] (2016). *Under World Project*. Accessed: Mar. 15, 2021. [Online]. Available: http://www.underworldproject.eu/the-project

[162] Ocean-DAS. *Ocean-Bottom Distributed Acoustic Sensors: New Tools for Underwater Seismology*. The Ocean-DAS. Accessed: Mar. 15, 2021. [Online]. Available: https://cordis.europa.eu/project/id/875302

[163] COUSIN. *Cooperative Underwater Surveillance Networks (COUSIN)*. The COUSIN. Accessed: Mar. 15, 2021. [Online]. Available: https://app.dimensions.ai/details/grant/grant.9530716

[164] TechOceanS. *Technologies for Ocean Sensing (TechOceanS)*. The COUSIN. Accessed: Mar. 15, 2021. [Online]. Available: https://app.dimensions.ai/details/grant/grant.9414204

[165] U. O. Y. J. Research organization. *Long Distance Underwater Wireless Optical Communication System Using Visible Light Laser Array With Directivity Control Function (LD-UWC-VLC-LADCF)*. The LD-UWC-VLC-LADCF. Accessed: Mar. 15, 2021. [Online]. Available: https://app.dimensions.ai/details/grant/grant.9195926

[166] H. Liu, J. Salerno, and M. J. Young, *Social Computing and Behavioral Modeling*. Boston, MA, USA: Springer, 2009.

[167] C. Gabriel, M.-A. Khalighi, S. Bourennane, P. Leon, and V. Rigaud, "Channel modeling for underwater optical communication," in *Proc. IEEE GLOBECOM Workshops (GC Wkshps)*, Dec. 2011, pp. 833–837.

[168] S. Raychaudhuri, "Introduction to Monte Carlo simulation," in *Proc. Winter Simul. Conf.*, Dec. 2008, pp. 91–100.

[169] L. Wang and S. L. Jacques, "Monte Carlo modeling of light transport in multi-layered tissues in standard C," Ph.D. dissertation, Dept. Navy, Univ. Texas, MD Anderson Cancer Center, Houston, Univ. Texas, Austin, TX, USA, 1992, pp. 4–11.

[170] G. Evensen, "Sequential data assimilation with a nonlinear quasi-geostrophic model using Monte Carlo methods to forecast error statistics," *J. Geophys. Res.*, vol. 99, no. C5, pp. 10143–10162, 1994.

[171] A. A. B. Raj, J. A. V. Selvi, and S. Durairaj, "Comparison of different models for ground-level atmospheric turbulence strength (cn 2) prediction with a new model according to local weather data for fso applications," *Appl. Opt.*, vol. 54, no. 4, pp. 802–815, 2015.

[172] R. Rajput, *A Textbook of Fluid Mechanics and Hydraulic Machines*. New Delhi, India: S. Chand Publishing, 2015.

[173] G. Stelling and M. Zijlema, "Numerical modeling of wave propagation, breaking and run-up on a beach," in *Advanced Computational Methods in Science and Engineering*. Berlin, Germany: Springer, 2009, pp. 373–401.

[174] J. H. Smart, "Underwater optical communications systems part 1: Variability of water optical parameters," in *Proc. MILCOM IEEE Mil. Commun. Conf.*, Oct. 2005, pp. 1140–1146.

[175] C. Zhang, L. Wu, C. Zheng, I. Gkioulekas, R. Ramamoorthi, and S. Zhao, "A differential theory of radiative transfer," *ACM Trans. Graph.*, vol. 38, no. 6, pp. 1–16, 2019.

[176] M. I. Mishchenko, L. D. Travis, and A. A. Lacis, *Multiple Scattering of Light by Particles: Radiative Transfer and Coherent Backscattering*. Cambridge, U.K.: Cambridge Univ. Press, 2006.

[177] S. K. Harouna and E. Mémin, "Stochastic representation of the Reynolds transport theorem: Revisiting large-scale modeling," *Comput. Fluids*, vol. 156, pp. 456–469, Oct. 2017.

[178] B. Koren and K. Vuik, *Advanced Computational Methods in Science and Engineering*. Berlin, Germany: Springer-Verlag, 2009, vol. 71.

[179] C. D. Mobley, B. Gentili, H. R. Gordon, Z. Jin, G. W. Kattawar, A. Morel, P. Reinersman, K. Stamnes, and R. H. Stavn, "Comparison of numerical models for computing underwater light fields," *Appl. Opt.*, vol. 32, no. 36, pp. 7484–7504, Dec. 1993.

[180] E. Zedini, I. S. Ansari, and M.-S. Alouini, "Performance analysis of mixed Nakagami-*m* and gamma–gamma dual-hop FSO transmission systems," *IEEE Photon. J.*, vol. 7, no. 1, pp. 1–20, Dec. 2014.

[181] M. Elamassie, M. Al-Nahhal, R. C. Kizilirmak, and M. Uysal, "Transmit laser selection for underwater visible light communication systems," in *Proc. IEEE 30th Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2019, pp. 1–6.

[182] M. Elamassie and M. Uysal, "Performance characterization of vertical underwater VLC links in the presence of turbulence," in *Proc. 11th Int. Symp. Commun. Syst., Netw. Digit. Signal Process. (CSNDSP)*, Jul. 2018, pp. 1–6.

[183] M. Elamassie and M. Uysal, "Vertical underwater visible light communication links: Channel modeling and performance analysis," *IEEE Trans. Wireless Commun.*, vol. 19, no. 10, pp. 6948–6959, Oct. 2020.

[184] M. Elamassie, M. Uysal, Y. Baykal, M. Abdallah, and K. Qaraqe, "Effect of eddy diffusivity ratio on underwater optical scintillation index," *J. Opt. Soc. Amer. A, Opt. Image Sci.*, vol. 34, no. 11, pp. 1969–1973, 2017.

[185] O. Korotkova, N. Farwell, and E. Shchepakina, "Light scintillation in oceanic turbulence," *Waves Random Complex Media*, vol. 22, no. 2, pp. 260–266, 2012.

[186] H. Gerçekcioğlu, "Bit error rate of focused Gaussian beams in weak oceanic turbulence," *J. Opt. Soc. Amer. A, Opt. Image Sci.*, vol. 31, no. 9, pp. 1963–1968, 2014.

[187] Y. Ata and Y. Baykal, "Scintillations of optical plane and spherical waves in underwater turbulence," *J. Opt. Soc. Amer. A, Opt. Image Sci.*, vol. 31, no. 7, pp. 1552–1556, 2014.

[188] A. Bhowal and R. S. Kshetrimayum, "Performance analysis of one-and two-way relays for underwater optical wireless communications," *OSA Continuum*, vol. 1, no. 4, pp. 1400–1413, 2018.

[189] M. Sharifzadeh and M. Ahmadirad, "Performance analysis of underwater wireless optical communication systems over a wide range of optical turbulence," *Opt. Commun.*, vol. 427, pp. 609–616, Nov. 2018.

[190] W. Liu, Z. Xu, and L. Yang, "SIMO detection schemes for underwater optical wireless communication under turbulence," *Photon. Res.*, vol. 3, no. 3, pp. 48–53, Oct. 2015.

[191] M. V. Jamali, A. Mirani, A. Parsay, B. Abolhassani, P. Nabavi, A. Chizari, P. Khorramshahi, S. Abdollahramezani, and J. A. Salehi, "Statistical studies of fading in underwater wireless optical channels in the presence of air bubble, temperature, and salinity random variations (long version)," 2018, *arXiv:1801.07402*.

[192] G. K. Varotsos, A. N. Stassinakis, H. E. Nistazakis, A. D. Tsigopoulos, K. P. Peppas, C. J. Aidinis, and G. S. Tombras, "Probability of fade estimation for FSO links with time dispersion and turbulence modeled with the gamma–gamma or the I-K distribution," *Optik*, vol. 125, no. 24, pp. 7191–7197, Dec. 2014.

[193] G. K. Varotsos, H. E. Nistazakis, M. P. Ninos, G. S. Tombras, A. D. Tsigopoulos, and C. K. Volos, "DF relayed FSO communication systems with time dispersion over gamma gamma turbulence and misalignment," in *Proc. 6th Int. Conf. Modern Circuits Syst. Technol. (MOCAST)*, May 2017, pp. 1–4.

[194] M. Aggarwal, P. Garg, and P. Puri, "Analysis of subcarrier intensity modulation-based optical wireless df relaying over turbulence channels with path loss and pointing error impairments," *IET Commun.*, vol. 8, no. 17, pp. 3170–3178, Nov. 2014.

[195] F. Yang, J. Cheng, and T. A. Tsiftsis, "Free-space optical communication with nonzero boresight pointing errors," *IEEE Trans. Commun.*, vol. 62, no. 2, pp. 713–725, Feb. 2014.

[196] R. J. Watkins, H.-J. Chen, B. N. Agrawal, and Y. S. Shin, "Optical beam jitter control," *Proc. SPIE*, vol. 5338, pp. 204–213, Jun. 2004.

[197] A. A. Farid and S. Hranilovic, "Outage capacity optimization for free-space optical links with pointing errors," *J. Lightw. Technol.*, vol. 25, no. 7, pp. 1702–1710, Jul. 1, 2007.

[198] D. Tsonev, S. Videv, and H. Haas, "Light fidelity (Li-Fi): Towards all-optical networking," *Proc. SPIE*, vol. 9007, Dec. 2013, Art. no. 900702.

[199] Z. Wang, Q. Wang, W. Huang, and Z. Xu, *Visible Light Communications: Modulation Signal Processing*. Hoboken, NJ, USA: Wiley, 2017.

[200] S. Trisno, *Design and Analysis of Advanced Free Space Optical Communication Systems*. College Park, MD, USA: Univ. Maryland, 2006.

[201] J.-Y. Wang, J.-B. Wang, M. Chen, and X. Song, "Dimming scheme analysis for pulse amplitude modulated visible light communications," in *Proc. Int. Conf. Wireless Commun. Signal Process.*, Oct. 2013, pp. 1–6.

[202] E. Cho, J.-H. Choi, C. Park, M. Kang, S. Shin, Z. Ghassemlooy, and C. G. Lee, "NRZ-OOK signaling with LED dimming for visible light communication link," in *Proc. 16th Eur. Conf. Netw. Opt. Commun.*, Jul. 2011, pp. 32–35.

[203] X. Liu, S. Yi, X. Zhou, Z. Fang, Z. Qiu, L. Hu, C. Cong, L. Zheng, R. Liu, and P. Tian, "34.5 m underwater optical wireless communication with 2.70 Gbps data rate based on a green laser diode with NRZ-OOK modulation," *Opt. Exp.*, vol. 25, no. 22, pp. 27937–27947, Oct. 2017.

[204] M. Elamassie and M. Uysal, "Performance characterization of vertical underwater VLC links in the presence of turbulence," in *Proc. 11th Int. Symp. Commun. Syst., Netw. Digit. Signal Process. (CSNDSP)*, Jul. 2018, pp. 1–6.

[205] M. Elamassie and M. Uysal, "Asymptotic performance of generalized transmit laser selection over lognormal turbulence channels," *IEEE Commun. Lett.*, vol. 24, no. 8, pp. 1762–1766, Aug. 2020.

[206] M. Elamassie, S. M. Sait, and M. Uysal, "Finite-SNR diversity gain analysis of FSO systems over gamma-gamma fading channels with pointing errors," *IEEE Commun. Lett.*, vol. 25, no. 6, pp. 1940–1944, Jun. 2021.

[207] T. Y. Elganimi, "Performance comparison between OOK, PPM and PAM modulation schemes for free space optical (FSO) communication systems: Analytical study," *Int. J. Comput. Appl.*, vol. 79, no. 11, pp. 22–27, Oct. 2013.

[208] Y. Fan and R. J. Green, "Comparison of pulse position modulation and pulse width modulation for application in optical communications," *Opt. Eng.*, vol. 46, no. 6, Jun. 2007, Art. no. 065001.

[209] S. S. Gishkori, "Compressive sampling for PPM and FSK modulated signals," Delft Univ. Technol., Delft, The Netherlands, Tech. Rep. CAS-2009-1394584, 2009.

[210] A. E. Tzikas, A. Sahinis, S. E. Trevlakis, S. A. Tegos, P. D. Diamantoulakis, and G. K. Karagiannidis, "3-color shift keying for indoor visible light communications," *IEEE Commun. Lett.*, vol. 23, no. 12, pp. 2271–2274, Dec. 2019.

[211] R. Singh, T. O'Farrell, and J. P. David, "Performance evaluation of IEEE 802.15. 7 CSK physical layer," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2013, pp. 1064–1069.

[212] S. D. Dissanayake and J. Armstrong, "Comparison of ACO-OFDM, DCO-OFDM and ADO-OFDM in IM/DD systems," *J. Lightw. Technol.*, vol. 31, no. 7, pp. 1063–1072, Apr. 1, 2013.

[213] F. Yang, J. Gao, and S. Liu, "Novel visible light communication approach based on hybrid OOK and ACO-OFDM," *IEEE Photon. Technol. Lett.*, vol. 28, no. 14, pp. 1585–1588, Apr. 20, 2016.

[214] S. D. Dissanayake, K. Panta, and J. Armstrong, "A novel technique to simultaneously transmit ACO-OFDM and DCO-OFDM in IM/DD systems," in *Proc. IEEE GLOBECOM Workshops (GC Wkshps)*, Dec. 2011, pp. 782–786.

[215] X. Li, R. Mardling, and J. Armstrong, "Channel capacity of IM/DD optical communication systems and of ACO-OFDM," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2007, pp. 2128–2133.

[216] J. Dang, Z. Zhang, and L. Wu, "A novel receiver for ACO-OFDM in visible light communication," *IEEE Commun. Lett.*, vol. 17, no. 12, pp. 2320–2323, Dec. 2013.

[217] X. Zhang, Q. Wang, R. Zhang, S. Chen, and L. Hanzo, "Performance analysis of layered aco-ofdm," *IEEE Access*, vol. 5, pp. 18366–18381, 2017.

[218] Z. Na, Y. Wang, M. Xiong, X. Liu, and J. Xia, "Modeling and throughput analysis of an ADO-OFDM based relay-assisted VLC system for 5G networks," *IEEE Access*, vol. 6, pp. 17586–17594, 2018.

[219] X. Huang, F. Yang, and J. Song, "Novel heterogeneous attocell network based on the enhanced ADO-OFDM for VLC," *IEEE Commun. Lett.*, vol. 23, no. 1, pp. 40–43, Jan. 2019.

[220] N. Wu and Y. Bar-Ness, "Lower bounds on the channel capacity of ASCO-OFDM and ADO-OFDM," in *Proc. 49th Annu. Conf. Inf. Sci. Syst. (CISS)*, Mar. 2015, pp. 1–5.

[221] C. Fei, X. Hong, G. Zhang, J. Du, Y. Gong, J. Evans, and S. He, "16.6 Gbps data rate for underwater wireless optical transmission with single laser diode achieved with discrete multi-tone and post nonlinear equalization," *Opt. Exp.*, vol. 26, no. 26, pp. 34060–34069, Dec. 2018.

[222] Y. Zhou, J. Shi, J. Zhang, and N. Chi, "Spectral scrambling for high-security PAM-8 underwater visible light communication system," in *Proc. Asia Commun. Photon. Conf. (ACP)*, Oct. 2018, pp. 1–3.

[223] T. Kodama, M. Aizat, F. Kobori, T. Kimura, Y. Inoue, and M. Jinno, "Time-domain hybrid PAM for data-rate and distance adaptive UWOC system," 2021, *arXiv:2103.11789*.

[224] Q. Wang, Z. Wang, and L. Dai, "Asymmetrical hybrid optical OFDM for visible light communications with dimming control," *IEEE Photon. Technol. Lett.*, vol. 27, no. 9, pp. 974–977, May 1, 2015.

[225] T. Zhang, J. Zhou, Z. Zhang, Y. Lu, F. Su, and Y. Qiao, "Dimming control systems based on low-PAPR SCFDM for visible light communications," *IEEE Photon. J.*, vol. 10, no. 5, pp. 1–11, Oct. 2018.

[226] A. Mirvakili, V. J. Koomson, M. Rahaim, H. Elgala, and T. D. Little, "Wireless access test-bed through visible light and dimming compatible ofdm," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2015, pp. 2268–2272.

[227] H. Elgala and T. D. Little, "Reverse polarity optical-OFDM (RPO-OFDM): Dimming compatible OFDM for gigabit VLC links," *Opt. Exp.*, vol. 21, no. 20, pp. 24288–24299, 2013.

[228] D. Tsonev, S. Sinanovic, and H. Haas, "Novel unipolar orthogonal frequency division multiplexing (U-OFDM) for optical wireless," in *Proc. IEEE 75th Veh. Technol. Conf. (VTC Spring)*, May 2012, pp. 1–5.

[229] Z. Wang, T. Mao, and Q. Wang, "Optical OFDM for visible light communications," in *Proc. 13th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Jun. 2017, pp. 1190–1194.

[230] Z. Yu, R. J. Baxley, and G. T. Zhou, "Achievable data rate analysis of clipped flip-OFDM in optical wireless communication," in *Proc. IEEE Globecom Workshops*, Dec. 2012, pp. 1203–1207.

[231] H.-J. Jang, J.-H. Choi, Z. Ghassemlooy, and C. G. Lee, "PWM-based PPM format for dimming control in visible light communication system," in *Proc. 8th Int. Symp. Commun. Syst., Netw. Digit. Signal Process. (CSNDSP)*, Jul. 2012, pp. 1–5.

[232] D. Shiu and J. M. Kahn, "Differential pulse-position modulation for power-efficient optical communication," *IEEE Trans. Commun.*, vol. 47, no. 8, pp. 1201–1210, Aug. 1999.

[233] M. Rouissat, R. A. Borsali, and M. E. Chikh-Bled, "A new modified MPPM for high-speed wireless optical communication systems," *ETRI J.*, vol. 35, no. 2, pp. 188–192, Apr. 2013.

[234] Y. Zeng, R. Green, and M. Leeson, "Multiple pulse amplitude and position modulation for the optical wireless channel," in *Proc. 10th Anniversary Int. Conf. Transparent Opt. Netw.*, Jun. 2008, pp. 193–196.

[235] Y. Wu, C. Yang, A. Yang, and Y.-N. Sun, "OPPM and PWM concatenated modulation for LED indoor communication," in *Proc. Symp. Photon. Optoelectronics*, May 2012, pp. 1–3.

[236] V. K. Papanikolaou, P. P. Bamidis, P. D. Diamantoulakis, and G. K. Karagiannidis, "Li-Fi and Wi-Fi with common backhaul: Coordination and resource allocation," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2018, pp. 1–6.

[237] R. Singh, T. O'Farrell, and J. P. David, "Higher order colour shift keying modulation formats for visible light communications," in *Proc. IEEE 81st Veh. Technol. Conf. (VTC Spring)*, May 2015, pp. 1–5.

[238] N. Murata, H. Shimamoto, Y. Kozawa, and Y. Umeda, "Performance evaluation of digital colour shift keying for visible light communications," in *Proc. IEEE Int. Conf. Commun. Workshop (ICCW)*, Jun. 2015, pp. 1374–1379.

[239] M. S. Islim, D. Tsonev, and H. Haas, "A generalized solution to the spectral efficiency loss in unipolar optical OFDM-based systems," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2015, pp. 5126–5131.

[240] J. Zhou and W. Zhang, "A comparative study of unipolar OFDM schemes in Gaussian optical intensity channel," *IEEE Trans. Commun.*, vol. 66, no. 4, pp. 1549–1564, Apr. 2018.

[241] S. Kumar and P. Singh, "A comprehensive survey of visible light communication: Potential and challenges," *Wireless Pers. Commun.*, vol. 109, no. 2, pp. 1357–1375, Nov. 2019.

[242] J.-Y. Wang, Y. Qiu, S.-H. Lin, J.-B. Wang, Q. Wang, and B. Zhang, "Performance analysis and improvement for secure VLC with SLIPT and random terminals," *IEEE Access*, vol. 8, pp. 73645–73658, 2020.

[243] H. Tabassum and E. Hossain, "Coverage and rate analysis for co-existing RF/VLC downlink cellular networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 4, pp. 2588–2601, Apr. 2018.

[244] D. A. Basnayaka and H. Haas, "Design and analysis of a hybrid radio frequency and visible light communication system," *IEEE Trans. Commun.*, vol. 65, no. 10, pp. 4334–4347, Oct. 2017.

[245] J. Fakidis, S. Videv, S. Kucera, H. Claussen, and H. Haas, "Indoor optical wireless power transfer to small cells at nighttime," *J. Lightw. Technol.*, vol. 34, no. 13, pp. 3236–3258, Apr. 21, 2016.

[246] T. D. P. Perera, D. N. K. Jayakody, S. K. Sharma, S. Chatzinotas, and J. Li, "Simultaneous wireless information and power transfer (SWIPT): Recent advances and future challenges," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 264–302, 1st Quart.,2018.

[247] H.-V. Tran, G. Kaddoum, and C. Abou-Rjeily, "Collaborative RF and lightwave power transfer for next-generation wireless networks," *IEEE Commun. Mag.*, vol. 58, no. 2, pp. 27–33, Feb. 2020.

[248] H. Tran, G. Kaddoum, P. D. Diamantoulakis, C. Abou-Rjeily, and G. K. Karagiannidis, "Ultra-small cell networks with collaborative RF and lightwave power transfer," *IEEE Trans. Commun.*, vol. 67, no. 9, pp. 6243–6255, Sep. 2019.

[249] T. D. P. Perera and D. N. K. Jayakody, "Analysis of time-switching and power-splitting protocols in wireless-powered cooperative communication system," *Phys. Commun.*, vol. 31, pp. 141–151, Dec. 2018.

[250] D. Altinel and G. K. Kurt, "Energy harvesting from multiple RF sources in wireless fading channels," *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 8854–8864, Nov. 2016.

[251] S. Sudevalayam and P. Kulkarni, "Energy harvesting sensor nodes: Survey and implications," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 3, pp. 443–461, Sep. 2011.

[252] H. G. Sandalidis, A. Vavoulas, T. A. Tsiftsis, and N. Vaiopoulos, "Illumination, data transmission, and energy harvesting: The threefold advantage of VLC," *Appl. Opt.*, vol. 56, pp. 3421–3427, Apr. 2017.

[253] P. D. Diamantoulakis and G. K. Karagiannidis, "Simultaneous lightwave information and power transfer (SLIPT) for indoor IoT applications," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–6.

[254] S. Ghasvarianjahromi, M. Karbalayghareh, P. D. Diamantoulakis, G. K. Karagiannidis, and M. Uysal, "Simultaneous lightwave information and power transfer in underwater visible light communications," in *Proc. IEEE 30th Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2019, pp. 1–6.

[255] L. Yang, Q. Zhu, S. Li, I. S. Ansari, and S. Yu, "On the performance of mixed FSO-UWOC dual-hop transmission systems," *IEEE Wireless Commun. Lett.*, vol. 10, no. 9, pp. 2041–2045, Sep. 2021.

[256] D. Zhang, I. N'Doye, T. Ballal, T. Y. Al-Naffouri, M.-S. Alouini, and T.-M. Laleg-Kirati, "Localization and tracking control using hybrid Acoustic–Optical communication for autonomous underwater vehicles," *IEEE Internet Things J.*, vol. 7, no. 10, pp. 10048–10060, Oct. 2020.

[257] M. F. Ali, T. D. P. Perera, V. S. Sergeevich, S. A. Irfan, U. E. Viktorovna, W. Zhang, A. Camponogara, and D. N. K. Jayakody, "Selection relay-based RF-vlc underwater communication system," in *Machine Learning, Deep Learning and Computational Intelligence for Wireless Communication*. Singapore: Springer, 2021, pp. 177–192.

[258] J. Al-Khori, G. Nauryzbayev, M. M. Abdallah, and M. Hamdi, "Secrecy performance of decode- and-forward based hybrid RF/VLC relaying systems," *IEEE Access*, vol. 7, pp. 10844–10856, 2019.

[259] M. Jani, P. Garg, and A. Gupta, "On the performance of a cooperative PLC-VLC indoor broadcasting system consisting of mobile user nodes for IoT networks," *IEEE Trans. Broadcast.*, vol. 67, no. 1, pp. 289–298, Mar. 2021.

[260] M. Jani, P. Garg, and A. Gupta, "Performance analysis of a mixed cooperative PLC–VLC system for indoor communication systems," *IEEE Syst. J.*, vol. 14, no. 1, pp. 469–476, Mar. 2020.

[261] R. Diamant, F. Campagnaro, M. de Filippo de Grazia, P. Casari, A. Testolin, V. Sanjuan Calzado, and M. Zorzi, "On the relationship between the underwater acoustic and optical channels," *IEEE Trans. Wireless Commun.*, vol. 16, no. 12, pp. 8037–8051, Dec. 2017.

[262] F. Campagnaro, F. Guerra, P. Casari, R. Diamant, and M. Zorzi, "Implementation of a multi-modal acoustic-optical underwater network protocol stack," in *Proc. OCEANS*, Apr. 2016, pp. 1–6.

[263] S. Al-Dharrab, M. Uysal, and T. M. Duman, "Cooperative underwater acoustic communications [accepted from open call]," *IEEE Commun. Mag.*, vol. 51, no. 7, pp. 146–153, Jul. 2013.

[264] M. F. Ali, D. N. K. Jayakody, T. D. P. Perera, K. Srinivasan, A. Sharma, and I. Krikidis, "Underwater communications: Recent advances," in *Proc. Int. Conf. Emerging Technol. Inf. Commun. (ETIC)*, Bhutan, 2019, pp. 97–102.

[265] P. C. Etter, *Underwater Acoustic Modeling: Principles Techniques and Application*. London, U.K.: E & FN Spon, 1991.

[266] F. B. Jensen, W. A. Kuperman, M. B. Porter, and H. Schmidt, *Computational Ocean Acoustics*. New York, NY, USA: Springer, 2011.

[267] J. Aparicio, A. Jiménez, F. J. Álvarez, C. De Marziani, J. Urena, and C. Diego, "Underwater acoustic relative positioning system based on complementary set of sequences," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat. (IPIN)*, Sep. 2011, pp. 21–23.

[268] X. Su, I. Ullah, X. Liu, and D. Choi, "A review of underwater localization techniques, algorithms, and challenges," *J. Sensors*, vol. 2020, pp. 1–24, Jan. 2020.

[269] M. F. Fallon, M. Kaess, H. Johannsson, and J. J. Leonard, "Efficient AUV navigation fusing acoustic ranging and side-scan sonar," in *Proc. IEEE Int. Conf. Robot. Automat.*, May 2011, pp. 2398–2405.

[270] N. Hurtós, D. Ribas, X. Cufí, Y. Petillot, and J. Salvi, "Fourier-based registration for robust forward-looking sonar mosaicing in low-visibility underwater environments," *J. Field Robot.*, vol. 32, no. 1, pp. 123–151, Jan. 2015.

[271] J. González-García, A. Gómez-Espinosa, E. Cuan-Urquizo, L. G. García-Valdovinos, T. Salgado-Jiménez, and J. A. E. Cabello, "Autonomous underwater vehicles: Localization, navigation, and communication for collaborative missions," *Appl. Sci.*, vol. 10, no. 4, p. 1256, Feb. 2020.

[272] G. Nootz, E. Jarosz, F. R. Dalgleish, and W. Hou, "Quantification of optical turbulence in the ocean and its effects on beam propagation," *Appl. Opt.*, vol. 55, no. 31, pp. 8813–8820, 2016.

[273] H. Durrant-Whyte and T. Bailey, "Simultaneous localization and mapping: Part I," *IEEE Robot. Autom. Mag.*, vol. 13, no. 2, pp. 99–110, Jun. 2006.

[274] Y. Lu and D. Song, "Visual navigation using heterogeneous landmarks and unsupervised geometric constraints," *IEEE Trans. Robot.*, vol. 31, no. 3, pp. 736–749, Jun. 2015.

[275] H. Carrillo, P. Dames, V. Kumar, and J. A. Castellanos, "Autonomous robotic exploration using occupancy grid maps and graph slam based on Shannon and rényi entropy," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, May 2015, pp. 487–494.

[276] M. Pizzoli, C. Forster, and D. Scaramuzza, "REMODE: Probabilistic, monocular dense reconstruction in real time," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, May 2014, pp. 2609–2616.

[277] C. Brand, M. J. Schuster, H. Hirschmüller, and M. Suppa, "Stereo-vision based obstacle mapping for indoor/outdoor slam," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2014, pp. 1846–1853.

[278] J. J. Garcia-Luna-Aceves, "Name-based content routing in information centric networks using distance information," in *Proc. 1st ACM Conf. Inf.-Centric Netw.*, 2014, pp. 7–16.

[279] W. L. Lee, A. Datta, and R. Cardell-Oliver, "Flexitp: A flexible-schedule-based tdma protocol for fault-tolerant and energy-efficient wireless sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 19, no. 6, pp. 851–864, Jun. 2008.

[280] E. A. Karagianni, "Electromagnetic waves under sea: Bow-tie antennas design for Wi-Fi underwater communications," *Prog. Electromagn. Res. M*, vol. 41, pp. 189–198, 2015.

[281] E. Felemban, F. K. Shaikh, U. M. Qureshi, A. A. Sheikh, and S. B. Qaisar, "Underwater sensor network applications: A comprehensive survey," *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 11, Nov. 2015, Art. no. 896832.

[282] A. Y. Teymorian, W. Cheng, L. Ma, X. Cheng, X. Lu, and Z. Lu, "3D underwater sensor network localization," *IEEE Trans. Mobile Comput.*, vol. 8, no. 12, pp. 1610–1621, Dec. 2009.

[283] T. Shaneyfelt, M. A. Joordens, K. Nagothu, and M. Jamshidi, "RF communication between surface and underwater robotic swarms," in *Proc. World Autom. Congr.*, Sep. 2008, pp. 1–6.

[284] K. P. Hunt, J. J. Niemeier, and A. Kruger, "RF communications in underwater wireless sensor networks," in *Proc. IEEE Int. Conf. Electro/Inf. Technol.*, May 2010, pp. 1–6.

[285] M. F. Hossain, M. B. Wali, K. S. Munasinghe, and A. Jamalipour, "Three dimensional (3D) underwater sensor network architectures for intruder localization using EM wave," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2016, pp. 1–6.

[286] B. Lawal, S. S. A. Ali, and A. B. Awang, "Massive MIMO systems for underwater acoustic communication," in *Proc. IEEE Int. Conf. Underwater Syst. Technol., Theory Appl. (USYS)*, 2016, pp. 159–164.

[287] X. Zhao and D. Pompili, "AMMCA: Acoustic massive MIMO with carrier aggregation to boost the underwater communication data rate," in *Proc. 10th Int. Conf. Underwater Netw. Syst. (WUWNET)*, 2015, pp. 1–5.

[288] J. D. Holmes, W. M. Carey, D. K. Wilson, J. F. Lynch, and D. K. Wilson, "Results from an autonomous underwater vehicle towed hydrophone array experiment in Nantucket sound," *J. Acoust. Soc. Amer.*, vol. 120, no. 2, pp. EL15–EL21, Aug. 2006.

[289] J. Pan, "Comparison of mid-oceanic earthquake epicentral differences of travel time, centroid locations, and those determined by autonomous underwater hydrophone arrays," *J. Geophys. Res.*, vol. 110, no. B7, pp. 1–21, 2005.

[290] S. Zhu, N. Jin, L. Wang, X. Zheng, S. Yang, and M. Zhu, "A novel dual-hydrophone localization method in underwater sensor networks," in *Proc. IEEE/OES China Ocean Acoust. (COA)*, Jan. 2016, pp. 1–4.
[291] A. Shantaram, H. Beyenal, R. Veluchamy, and Z. Lewandowski, "The challenges of building scalable mobile underwater wireless sensor networks for aquatic applications," *Environ. Sci. Technol*, vol. 39, no. 13, pp. 5037–5042, 2005.
[292] M. C. Domingo and R. Prior, "Energy analysis of routing protocols for underwater wireless sensor networks," *Comput. Commun*, vol. 31, no. 6, pp. 1227–1238, Apr. 2008.
[293] H. Lan, Y. Lv, J. Jin, J. Li, D. Sun, and Z. Yang, "Acoustical observation with multiple wave gliders for internet of underwater things," *IEEE Internet Things J.*, vol. 8, no. 4, pp. 2814–2825, Feb. 2021.
[294] R. Harcourt, A. M. M. Sequeira, X. Zhang, F. Roquet, K. Komatsu, M. Heupel, C. McMahon, F. Whoriskey, M. Meekan, G. Carroll, and S. Brodie, "Animal-borne telemetry: An integral component of the ocean observing toolkit," *Frontiers Mar. Sci.*, vol. 6, p. 326, Jun. 2019.
[295] Y. Yonehara, Y. Goto, K. Yoda, Y. Watanuki, L. C. Young, H. Weimerskirch, C.-A. Bost, and K. Sato, "Flight paths of seabirds soaring over the ocean surface enable measurement of fine-scale wind speed and direction," *Proc. Nat. Acad. Sci. USA*, vol. 113, no. 32, pp. 9039–9044, Aug. 2016.
[296] Y. Goto, K. Yoda, and K. Sato, "Asymmetry hidden in birds' tracks reveals wind, heading, and orientation ability over the ocean," *Sci. Adv.*, vol. 3, no. 9, Sep. 2017, Art. no. e1700097.
[297] K. Yoda, K. Shiomi, and K. Sato, "Foraging spots of streaked shearwaters in relation to ocean surface currents as identified using their drift movements," *Prog. Oceanogr.*, vol. 122, pp. 54–64, Mar. 2014.
[298] L. Zhao, F. Yu, J. Hou, P. Wang, and T. Fan, "The role of tsunami buoy played in tsunami warning and its application in south China sea," *Theor. Appl. Mech. Lett.*, vol. 3, no. 3, 2013, Art. no. 032002.
[299] J. Jaffe and C. Schurgers, "Sensor networks of freely drifting autonomous underwater explorers," in *Proc. 1st ACM Int. Workshop Underwater Netw.*, 2006, pp. 93–96.
[300] (2021). *Acoustic hydrophones*. Accessed: Jun. 15, 2021. [Online]. Available: https://sanctuaries.noaa.gov/science/sentinel-site-program/grays-reef/noise.html
[301] (2020). N. O. NOAA and A. Administration. *Underwater Hydrophones*. Accessed: Nov. 25, 2020. [Online]. Available: https://oceanservice.noaa.gov/facts/hydrophone.html
[302] M. N. Githaiga, A. M. Frouws, J. G. Kairo, and M. Huxham, "Seagrass removal leads to rapid changes in fauna and loss of carbon," *Frontiers Ecol. Evol.*, vol. 7, p. 62, Mar. 2019.
[303] J. Marra, *Introduction to Satellite Oceanography*. China: Limmol.e-Lectures, 2014, doi: 10.4319/lol.2014.jmarra.6.
[304] (2020). I. E. Commision. *Underwater Vehicles Play Major Role Ex Environments*. Accessed: Nov. 26, 2020. [Online]. Available: https://etech.iec.ch/issue/2019-01/rovs-auvs-and-aivs
[305] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, and P. Fan, "6G wireless networks: Vision, requirements, architecture, and key technologies," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 28–41, Sep. 2019.
[306] Y. Fu, M. D. Soltani, H. Alshaer, C.-X. Wang, M. Safari, S. McLaughlin, and H. Haas, "End-to-end energy efficiency evaluation for a beyond 5G wireless communication network," China, Tech. Rep., Jul. 2020.
[307] G. He, Z. Lv, C. Qiu, and Z. Liu, "Performance evaluation of 520 nm laser diode underwater wireless optical communication systems in the presence of oceanic turbulence," in *SID Symp. Dig. Tech. Papers*, vol. 51, 2020, pp. 47–50.
[308] F. Schaich and T. Wild, "Waveform contenders for 5G-OFDM vs. FBMC vs. UFMC," in *Proc. 6th Int. Symp. Commun., Control Signal Process. (ISCCSP)*, May 2014, pp. 457–460.
[309] W. Jinqiu, Q. Gang, and K. Pengbin, "Emerging 5G multicarrier chaotic sequence spread spectrum technology for underwater acoustic communication," *Complexity*, vol. 2018, pp. 1–7, Oct. 2018.
[310] G. Fettweis, M. Krondorf, and S. Bittner, "GFDM–Generalized frequency division multiplexing," in *Proc. IEEE 69th Veh. Technol. Conf. (VTC Spring)*, Apr. 2009, pp. 1–4.
[311] T. Ihalainen, A. Viholainen, T. H. Stitz, and M. Renfors, "Generation of filter bank-based multicarrier waveform using partial synthesis and time domain interpolation," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 57, no. 7, pp. 1767–1778, Jul. 2009.
[312] M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, "5G: A tutorial overview of standards, trials, challenges, deployment, and practice," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 6, pp. 1201–1221, Jun. 2017.
[313] S. A. H. M. M. Mehedi, A. M. Hasan, M. A. Sadiq, H. Akhtar, and L. S. R. Islam, "A systematic review on practical considerations, recent advances and research challenges in underwater optical wireless communication," *Int. J. Adv. Comput. Sci. Appl.*, vol. 11, no. 7, 2020.
[314] M. Z. Chowdhury, M. Shahjalal, M. K. Hasan, and Y. M. Jang, "The role of optical wireless communication technologies in 5G/6G and IoT solutions: Prospects, directions, and challenges," *Appl. Sci.*, vol. 9, no. 20, p. 4367, Oct. 2019.
[315] C. H. Chang, C. Y. Li, H. H. Lu, C. Y. Lin, J. H. Chen, Z. W. Wan, and C. J. Cheng, "A 100-Gb/s multiple-input multiple-output visible laser light communication system," *J. Lightw. Technol.*, vol. 32, no. 24, pp. 4121–4127, Dec. 15, 2014.
[316] D. Tsonev, S. Videv, and H. Haas, "Towards a 100 Gb/s visible light wireless access network," *Opt. Exp.*, vol. 23, no. 2, pp. 1627–1637, Jan. 2015.
[317] M. C. Domingo, "An overview of the internet of underwater things," *J. Netw. Comput. Appl.*, vol. 35, no. 6, pp. 1879–1890, 2012.
[318] J. Heidemann, M. Stojanovic, and M. Zorzi, "Underwater sensor networks: Applications, advances and challenges," *Philos. Trans. Roy. Soc. London A, Math. Phys. Sci.*, vol. 370, no. 1958, pp. 158–175, Jan. 2012.
[319] A. H. Abd El-Malek, A. M. Salhab, S. A. Zummo, and M.-S. Alouini, "Enhancing physical layer security of multiuser SIMO mixed RF/FSO relay networks with multi-eavesdroppers," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2016, pp. 1–7.
[320] (2021). N. O. Services. *What is Bathymetry?*. Accessed: Feb. 3, 2021. [Online]. Available: https://oceanservice.noaa.gov/facts/bathymetry.html
[321] L. Mayer, M. Jakobsson, G. Allen, B. Dorschel, R. Falconer, V. Ferrini, G. Lamarche, H. Snaith, and P. Weatherall, "The nippon foundation—GEBCO seabed 2030 project: The quest to see the World's oceans completely mapped by 2030," *Geosciences*, vol. 8, no. 2, p. 63, Feb. 2018.
[322] L. A. Mayer, "Frontiers in seafloor mapping and visualization," *Mar. Geophys. Researches*, vol. 27, no. 1, pp. 7–17, Mar. 2006.
[323] M. F. Glenn, "Introducing an operational multi-beam array sonar," *Int. Hydrographic Rev.*, vol. 47, no. 1, pp. 35–39, 1970.
[324] C. Alippi, R. Camplani, C. Galperti, and M. Roveri, "A robust, adaptive, solar-powered WSN framework for aquatic environmental monitoring," *IEEE Sensors J.*, vol. 11, no. 1, pp. 45–55, Jan. 2011.
[325] M. Erol, L. F. M. Vieira, and M. Gerla, "AUV-aided localization for underwater sensor networks," in *Proc. Int. Conf. Wireless Algorithms, Syst. Appl. (WASA)*, Aug. 2007, pp. 44–54.
[326] J. E. Garcia, "Positioning of sensors in underwater acoustic networks," in *Proc. OCEANS*, Sep. 2005, pp. 2088–2092.
[327] V. Chandrasekhar, W. K. Seah, Y. S. Choo, and H. V. Ee, "Localization in underwater sensor networks: Survey and challenges," in *Proc. 1st ACM Int. Workshop Underwater Netw.*, 2006, pp. 33–40.
[328] V. Chandrasekhar and W. Seah, "An area localization scheme for underwater sensor networks," in *Proc. OCEANS*, May 2006, pp. 1–8.
[329] Y. Guo, Q. Han, and X. Kang, "Underwater sensor networks localization based on mobility-constrained beacon," *Wireless Netw.*, vol. 26, no. 4, pp. 2585–2594, May 2020.
[330] W. Cheng, A. Y. Teymorian, L. Ma, X. Cheng, X. Lu, and Z. Lu, "Underwater localization in sparse 3D acoustic sensor networks," in *Proc. 27th Conf. Comput. Commun. (INFOCOM)*, Apr. 2008, pp. 236–240.
[331] Z. Zhou, Z. Peng, J.-H. Cui, Z. Shi, and A. C. Bagtzoglou, "Scalable localization with mobility prediction for underwater sensor networks," *IEEE Trans. Mobile Comput.*, vol. 10, no. 3, pp. 335–348, Mar. 2011.
[332] Z. Zhou, J.-H. Cui, and S. Zhou, "Localization for large-scale underwater sensor networks," in *Proc. Int. Conf. Res. Netw.* Vienna, Austria: Springer, 2007, pp. 108–119.
[333] N. Saeed, A. Celik, M.-S. Alouini, and T. Y. Al-Naffouri, "Performance analysis of connectivity and localization in multi-hop underwater optical wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 18, no. 11, pp. 2604–2615, Nov. 2018.
[334] S. Khaledi, H. Mann, J. Perkovich, and S. Zayed, "Design of an underwater mine detection system," in *Proc. Syst. Inf. Eng. Design Symp. (SIEDS)*, Apr. 2014, pp. 78–83.

[335] Y. Rzhanov, L. Linnett, and A. Settery, "A model for the synthesis of a seabed scene and the detection of objects on the seabed using a sonar simulation," in *Proc. 32nd ISATA Conf. 1999*, Vienna, Austria, Jun. 1999.
[336] (2021). E. Group. *ECA Group to Detect Buried Sea Mines-Always Moving One Step Ahead in Naval Mine Countermeasures*. Accessed: Mar. 13, 2021. [Online]. Available: https://www.ecagroup.com/en/business/eca-group-to-detect-buried-sea-mines-always-moving-one-step-ahead-in-naval-mine-countermeasures
[337] *ECA Group to Detect Buried Sea Mines*, E. Group, Toulon, France, Jun. 2020.
[338] *Aselsan Coastal/Border Security System*, A. Group, Ankara, Turkey, Nov. 2016.
[339] K. Maraiya, K. Kant, and N. Gupta, "Application based study on wireless sensor network," *Int. J. Comput. Appl.*, vol. 21, no. 8, pp. 9–15, May 2011.
[340] N. Chi, Y. Zhou, Y. Wei, and F. Hu, "Visible light communication in 6G: Advances, challenges, and prospects," *IEEE Veh. Technol. Mag.*, vol. 15, no. 4, pp. 93–102, Dec. 2020.

MOHAMMAD FURQAN ALI (Graduate Student Member, IEEE) received the B.Tech. degree from Uttar Pradesh Technical University, Lucknow, India, in 2013, and the M.Sc. degree (Hons.) from National Research Tomsk Polytechnic University, Russia, in 2018, where he is currently pursuing the Ph.D. degree in computer science and wireless communication engineering with the School of Computer Science and Robotics. He is also working as a Research Engineer. His research interests include optical communication, underwater visible light communication (UVLC), 5G wireless networking, the Internet of Things (IoTs), and hybrid-cooperative underwater wireless communication. He received the Gold Medal for his M.Sc. program.

DUSHANTHA NALIN K. JAYAKODY (Senior Member, IEEE) received the M.Sc. degree in electronics and communications engineering from the Department of Electrical and Electronics Engineering, Eastern Mediterranean University, Turkey, under the University Full Graduate Scholarship, and the Ph.D. degree in electronics and communications engineering from University College Dublin, Ireland.

From 2014 to 2016, he was a Postdoctoral Research Fellow with the University of Tartu, Estonia; and the University of Bergen, Norway. Since 2016, he has been a Professor with the School of Computer Science and Robotics, National Research Tomsk Polytechnic University (TPU), Russia. He also serves as the Head for the Research and Educational Center on Automation and Information Technologies and the Founder for the Tomsk Infocomm Laboratory, TPU. Since 2019, he has been serving as the Head for the School of Postgraduate and Research, Sri Lanka Technological Campus (SLTC), Padukka, Sri Lanka, and the Founding Director for the Centre of Telecommunication Research, SLTC. He is also supervising/supervised 15 Ph.D. students, and many master's and undergraduate students. He held visiting and/or sabbatical positions at the Centre for Telecommunications Research, The University of Sydney, Australia, in 2015; and Texas A&M University, in 2018. He has published nearly 200 international peer-reviewed journal and conference papers and books. His research interests include PHY and NET layer prospective of 5G communications technologies, such as NOMA for 5G; cooperative wireless communications; device to device communications; LDPC codes; and unmanned aerial vehicle. In his career, so far, he has attracted nearly 6M research funding. He is a fellow of IET. He has received the Best Paper Award from the IEEE International Conference on Communication, Management and Information Technology (ICCMIT) in 2017 and the International Conference on Emerging Technologies of Information and Communications, Bhutan, in March 2019. In July 2019, he received the Education Leadership Award from the World Academic Congress in 2019. In 2017 and 2018, he received the Outstanding Faculty Award by TPU. He also received the Distinguished Researcher in Wireless Communications in Chennai, India, in 2019. He has organized or co-organized more than 25 workshops, special sessions, and IEEE conferences. He currently serves as an Area Editor for the *Physical Communication* journal (Elsevier), *Information* journal (MDPI), *Sensors* (MDPI), and *Internet Technology Letters* (Wiley). Also, he serves on the Advisory Board of multidisciplinary journal *Sci* (MDPI). In addition, he serves as a reviewer for various IEEE TRANSACTIONS and other journals.

YONGHUI LI (Fellow, IEEE) received the Ph.D. degree from the Beijing University of Aeronautics and Astronautics, in November 2002. From 1999 to 2003, he was affiliated with Linkair Communication Inc., where he held a position of the Project Manager with responsibility for the design of physical layer solutions for the LAS-CDMA system. Since 2003, he has been with the Centre of Excellence in Telecommunications, The University of Sydney, Australia, where he is currently a Professor with the School of Electrical and Information Engineering. His current research interests include wireless communications, with a particular focus on MIMO, millimeter wave communications, machine to machine communications, coding techniques, and cooperative communications. He holds a number of patents granted and pending in these fields. He received the Best Paper Award from the IEEE International Conference on Communications (ICC) in 2014, the IEEE Wireless Days Conferences (WD) in 2014, and IEEE PIMRC 2017. He was a recipient of the Australian Queen Elizabeth II Fellowship in 2008 and the Australian Future Fellowship in 2012. He is also an Editor of the IEEE TRANSACTIONS ON COMMUNICATIONS and the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY. He also served as a Guest Editor for several special issues of IEEE journals, such as IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS Special Issue on Millimeter Wave Communications.