Hybrid LD and LED-based underwater optical communication: state-of-the-art, opportunities, challenges, and trends [Invited]

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In this paper, the current research of an underwater optical wireless communication (UWOC) network is reviewed first. A hybrid laser diode (LD) and light-emitting diode (LED)-based UWOC system is then proposed and investigated, in which hybrid cluster-based networking with mobility restricted nodes is utilized to improve both the life cycle and throughput of the UWOC network. Moreover, the LEDs are utilized for the coarse alignment, while the LDs are used for high-precision positioning to reduce the difficulty of optical alignment. Finally, challenges and trends for UWOC are pointed out to provide some insight for potential future work of researchers.

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1. INTRODUCTION

With the development of the economy, the modern marine high-tech research, such as marine resources development, oceanographic research, seabed survey, and detection, has become a new research field in the world, and the research on related marine scientific technology has become the crucial issue for all countries in the world[1]. Underwater wireless communication technology is the basis and guarantee for the realization of ocean observation, resource detection, and environmental monitoring. Therefore, it is urgent to develop highly reliable and high-speed underwater wireless communication technology to process large amounts of underwater data with the latency as low as possible[2].

At present, underwater wireless communication technology mainly includes underwater wireless electromagnetic communication, underwater acoustic communication, and underwater optical communication[3]. However, the electromagnetic waves suffer from great attenuation in the water because of the absorption and scattering effects, which makes communications with electromagnetic waves underwater almost impossible[4]. Different from the electromagnetic wave, the acoustic wave has low loss in the water, which means its communication range in the water can be very long[5]. However, it also has several disadvantages. The acoustical communication channel has a narrow bandwidth, which means it can only handle a relatively low bit rate[6]. In addition, an acoustic wave is greatly affected by environmental factors such as sea water temperature, salinity, and pressure compared with underwater optical communication. Then, multi-path transmission is prone to occur, resulting in signal amplitude attenuation and inter-symbol interference, which seriously affects the establishment of communication processes[7]. Moreover, underwater acoustic signals are easy to be monitored, and it is difficult to meet the requirements of confidentiality in the communication process. Also, the acoustic wave speed in water is about 1500 m/s, which is slow and will lead to high latency in communication[8]. Thus, in order to accommodate a higher bit rate, another underwater wireless communication scheme with wider bandwidth should be investigated. A possible candidate is optical wireless communication. Specifically, for underwater optical wireless communication (UWOC), the blue/green light wavelengths are usually utilized because they suffer less attenuation in water compared to other colors. There are several advantages for the UWOC. The first is the high speed and wide spectrum. Because of the high frequency of the light wave and its strong information carrying capability, it can realize large-capacity underwater data transmission. The transmission bandwidth of light waves in water can reach hundreds of megahertz, which makes it possible to transmit large-capacity data quickly under water. The second advantage is the superior security. Optical communication has the characteristics of no electromagnetic radiation and strong anti-interference ability, resulting in the good underwater electronic countermeasure performance. The third advantage is the small size. Short wavelengths can greatly reduce the size and weight of transmitting and receiving equipment. The last advantage is the low power consumption.

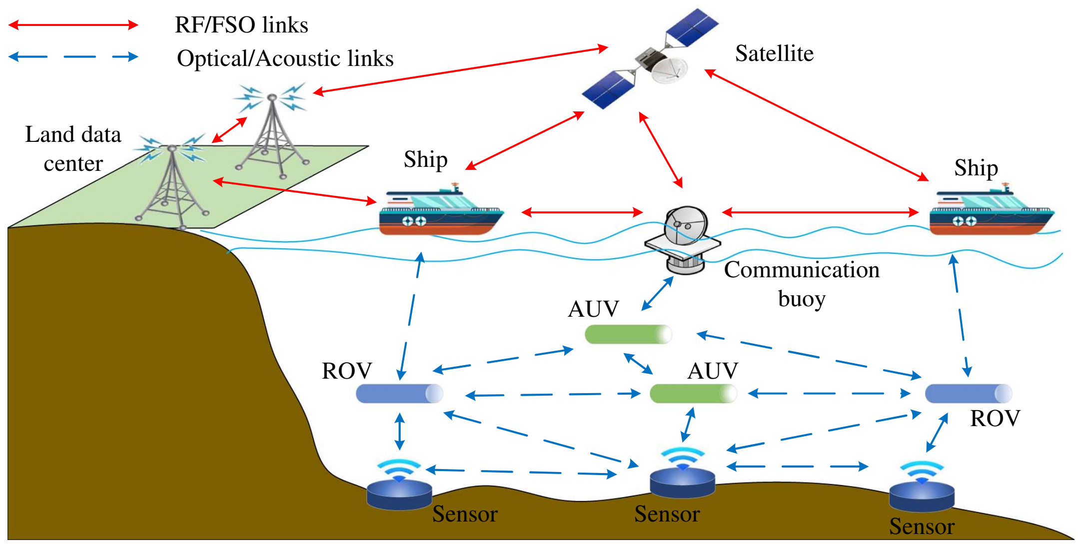

Fig. 1. Underwater wireless sensor network with aerospace and terrestrial communication.

The semiconductor light source has good conversion efficiency, and thus, only a small amount of power can support wireless optical communication[9]. Therefore, the UWOC technology is considered as a promising and reliable candidate to accommodate the requirements of underwater high-speed communication[10].

In order to accommodate the ever growing requirements for high-efficiency and high-bandwidth data transmission in ocean exploration, the concept of underwater wireless sensor networks (UWSNs) is proposed. UWSN is an underwater self-organizing network. Through cooperative sensing, acquisition, and processing of the information of the perceived objects in the network coverage area by underwater wireless sensor nodes, the data information monitored and sensed by the nodes is transmitted to the surface base station (or buoy). Many distributed nodes are included in a UWSN, such as seabed sensors, communication buoys, autonomous underwater vehicles (AUVs) and remotely operated underwater vehicles (ROVs). Every node can complete sensing, processing, and communication transactions, thus maintaining the collaborative monitoring of the underwater environment[11]. In Fig. 1, the seabed sensors collect data and transmit them to the AUVs and ROVs via acoustic or optical links. Then, AUVs and ROVs transmit signals to the ships, communication buoys, and other underwater vehicles. Above the sea surface, the land data centers communicate with satellite and ships through radio frequency (RF) or free space optical (FSO) links.

The rest of this paper is organized as follows. In Section 2, the current research on the related technologies is reviewed. In Section 3, the implementation methods for the hybrid laser diode (LD) and light-emitting diode (LED)-based UWOC system are proposed. Future challenges and research trends are presented in Section 4. Finally, conclusions are drawn in Section 5.

2. CURRENT RESEARCH ON UWOC

A. Channel Model for UWOC

The UWOC has been investigated from many aspects. In the aspect of underwater optical channel model, the volume scattering function is analyzed in Ref. [12], and the spatial distribution of light energy in underwater visible communication is obtained. In Ref. [13], the Monte Carlo method based on the Henyey–Greenstein function is used to simulate the channel characteristics of underwater laser communication. A gamma–gamma function is proposed in Ref. [14] to model the impulse response of the underwater channel, and the impulse response parameters in coastal and port environments are obtained.

For UWOC, there are three primary interference sources: absorption, scattering, and turbulence[15]. The absorption and scattering of water will cause the attenuation of optical signals. The turbulence makes the underwater temperature and salinity fluctuate and then causes the random change of the refractive index of the transmission medium, which is the main cause of optical signal fading[16].

Absorption and Scattering. The impulse response function of the optical signal absorbed and scattered by sea water can be obtained by Monte Carlo simulation. The overall attenuation of absorption and scattering can be described by a extinction coefficient $c(\lambda)$, which can be expressed as

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

where λ is the wavelength of light. $a(\lambda)$ and $b(\lambda)$ represent the absorption coefficient and scattering coefficient of non-scattering light, respectively.

The overall absorption coefficient in sea water is split into four factors expressed as

Table 1. Absorption and Scattering Characteristics of Different Seawater Components

Component	Absorption Coefficient	Scattering Coefficient
Pure water	1. Unchanged at constant temperature and pressure. 2. The absorption of blue and green light is low.	1. Rayleigh scattering. 2. Related to λ.
CDOM	1. Vary with the concentration of CDOM. 2. The absorption of blue light is strong.	Can be neglected.
Plankton	1. Vary with the concentration of plankton. 2. The absorption of blue and red light is strong.	1. Mie scattering. 2. Vary with the concentration of plankton. 3. Decrease monotonously with λ.
Detritus	1. Vary with the concentration of detritus. 2. Decrease monotonously with λ.	1. Mie scattering. 2. Vary with the concentration of detritus. 3. Decrease monotonously with λ.

$$a(\lambda) = a_w(\lambda) + a_{\text{CDOM}}(\lambda) + a_{\text{phy}}(\lambda) + a_{\text{det}}(\lambda), \quad (2)$$

where $a_w(\lambda)$ is the pure seawater absorption, and $a_{\text{CDOM}}(\lambda)$, $a_{\text{phy}}(\lambda)$, and $a_{\text{det}}(\lambda)$ represent the absorption from the colored dissolved organic matter (CDOM), plankton, and detritus, respectively.

Similarly, the scattering coefficient $b(\lambda)$ of underwater light propagation can also be expressed as a sum of different scattering factors, i.e.,

$$b(\lambda) = b_w(\lambda) + b_{\text{phy}}(\lambda) + b_{\text{det}}(\lambda), \quad (3)$$

where $b_w(\lambda)$, $b_{\text{phy}}(\lambda)$, and $b_{\text{det}}(\lambda)$ represent the scattering of the pure seawater, plankton, and detritus, respectively. Table 1 lists the absorption and scattering characteristics of different seawater components. In the visible spectrum range, the absorption of blue and green light in pure seawater is low, and the scattering coefficient will change due to the change of the refractive index caused by the flow, salinity, and temperature[17].

Then, the propagation loss factor L_c can be given as a function of the wavelength λ and transmission distance L, which can be formulated as

$$L_c = e^{-c(\lambda)L}, \quad (4)$$

and the channel impulse response of a UWOC system, which considers absorption and scattering can be given as

$$h_c = L_c \cdot h_i, \quad (5)$$

where h_i is the ideal channel impulse response.

Turbulence. The turbulence will cause the fading of the optical signals. Generally, different models are used for different turbulence intensities. For weak turbulence, the probability density function (PDF) of the impulse response h_t with turbulence can be given as

$$f(u) = \frac{1}{2u(2\pi\sigma_t^2)} \exp\left[-\frac{(\ln u - 2\mu_t)^2}{8\sigma_t^2}\right], \quad (6)$$

where σ_t^2 and μ_t are the variance and expectation of the turbulent channel, respectively. For moderate turbulence, the PDF of the impulse response can be formulated as

$$f(u) = \frac{2(AB)^{\frac{A+B}{2}}}{\Gamma(A)\Gamma(B)} u^{\frac{A+B-2}{2}} \gamma_{A-B}\left(2\sqrt{ABu}\right), \quad (7)$$

where $\Gamma(\cdot)$ and $\gamma(\cdot)$ represent the gamma function and Bessel function, respectively, and A and B are parameters related to the channel. For strong turbulence, the PDF of the impulse response can be given as

$$f(u) = e^{-u}. \quad (8)$$

Then, the overall channel impulse response h for the UWOC considering absorption, scattering, and turbulence can be represented as

$$h = h_c \cdot h_t. \quad (9)$$

B. Modulation Schemes

In terms of modulation schemes for visible light communication (VLC), orthogonal frequency division multiplexing (OFDM)-based modulation schemes can effectively address the issues of inter-symbol interference and narrowband interference caused by the multi-path effect of optical signals in UWOC and can improve the spectral efficiency of the system compared with single-carrier modulation, such as on–off keying (OOK)[18]. Direct current biased optical OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM) are the conventional VLC methods based on OFDM, but the energy efficiency and spectral efficiency are not high, respectively. To improve this, several hybrid modulation schemes have been proposed, such as asymmetrically clipped DC biased optical OFDM (ADO-OFDM)[19], hybrid ACO-OFDM (HACO-OFDM)[20], and layered ACO-OFDM (LACO-OFDM)[21].

In UWOC systems, the signal amplitude of VLC is limited, and the power of underwater equipment is restricted. The performance of the modulation scheme will change with the transformation of the underwater complex environment. Therefore, in order to achieve an efficient modulation scheme for underwater VLC, it is necessary to study the modulation schemes with high spectral efficiency and high energy efficiency, which are both limited in power and amplitude under different water conditions. Specifically, denote the channel capacity and the whole bandwidth as C and W. Then, the spectral efficiency of VLC systems, which is defined as the channel capacity per unit of bandwidth, can be given by

$$\eta_{\mathrm{SE}} = \frac{C}{W}. \tag{10}$$

The energy efficiency, which is defined as the ratio of the channel capacity over the mean power consumption, can be given by

$$\eta_{\mathrm{EE}} = \frac{C}{P}, \tag{11}$$

where P denotes the LED power cost[22]. Then, for each modulation scheme, the energy efficiency can be represented as a function of spectral efficiency by calculation, i.e.,

$$\eta_{\mathrm{EE}} = f(\eta_{\mathrm{SE}}), \tag{12}$$

where $f(\cdot)$ is different for various modulation schemes and water conditions. Then, the consumed energy per bit can be optimized by solving

$$\frac{\partial \eta_{\mathrm{EE}}}{\eta_{\mathrm{SE}}} = 0. \tag{13}$$

Thus, the optimal modulation scheme can be adaptively chosen with the minimum consumed energy per bit under different water conditions.

In addition, the performance changes of the bit error rate (BER), spectrum efficiency, and energy efficiency can be observed by adjusting the power ratio between odd and even subcarriers or between different layers. Specifically, for LACO-OFDM, the system performance is also related to the number of modulation layers. The power allocation scheme and modulation layer selection for each modulation scheme should be investigated to obtain the optimal system performance under different water conditions.

For a hybrid modulation scheme with scheme 1 and scheme 2, assume that scheme 1 needs to be demodulated first. Thus, the BER performance of scheme 1, denoted as $B_{e,1}$, can be obtained according to its modulation method. Then, the BER performance of scheme 2 in the hybrid modulation scheme can be derived as

$$\begin{aligned} B_{e,2} &= B_{e,1} B_{e,2|\bar{1}} + (1 - B_{e,1}) B_{e,2|1} \\ &= B_{e,2|1} + B_{e,1}(B_{e,2|\bar{1}} - B_{e,2|1}), \end{aligned} \tag{14}$$

where $B_{e,2|\bar{1}}$ and $B_{e,2|1}$ denote the conditional probability of error given that the signal of scheme 1 has been demodulated wrongly and successfully, respectively. Generally, under a high signal-to-noise ratio, $B_{e,1}$, $B_{e,2|\bar{1}}$, and $B_{e,2|1}$ could be small; thus, the second term in Eq. (14) is much smaller than $B_{e,2|1}$ and could be neglected. Hence, Eq. (14) is approximately estimated as

$$B_{e,2} = B_{e,2|1}, \tag{15}$$

which can be obtained according to the modulation method of scheme 2. Therefore, the overall BER performance of the hybrid modulation scheme can be derived as

$$B_e = \frac{N_1 \log_2 M_1 B_{e,1} + N_2 \log_2 M_2 B_{e,2}}{N_1 \log_2 M_1 + N_2 \log_2 M_2}, \tag{16}$$

where N_1 and N_2 are the occupied subcarriers by scheme 1 and scheme 2, respectively, while M_1 and M_2 denote the modulation orders of scheme 1 and scheme 2, respectively.

Thus, the optimization objective can be given as

$$\begin{aligned} \min_{\sigma_1,\sigma_2} \quad & B_e, \\ \text{s.t.} \quad & \int_{I_L}^{I_H} f_h(w)\mathrm{d}w \geq 1 - \varepsilon, \\ & P_h \leq P_0, \end{aligned} \tag{17}$$

where σ_1 and σ_2 denote the optimal electrical power for schemes 1 and 2, while $f_h(w)$ and P_h represent the PDF and power of the hybrid modulation scheme, and ε and P_0 are the maximum clipping ratio and restricted power, respectively. I_L and I_H represent the minimum and maximum allowed current values to ensure the approximately linear transfer characteristic, respectively.

3. HYBRID LD AND LED-BASED UWOC SYSTEM

According to the previous section, the most suitable optical modulation scheme is selected by the spectral efficiency and energy efficiency analysis reviewed in Section 2 to minimize the consumed energy per bit under different water conditions. Then, the power allocation factor under the current modulation scheme is selected by the power allocation scheme mentioned in Section 2 to minimize the overall BER. The design of the hybrid LED and LD system is carried out under the overall BER, clipping ratio, and power constraints as

$$\begin{cases} B_e \leq B, \\ R_t \leq R, \\ P_1 + P_2 \leq P, \end{cases} \tag{18}$$

where B_e and R_t represent the actual overall BER and clipping ratio of the system, and P_1 and P_2 denote the consumed power by the LED and LD, respectively, while B, P, and R are the maximum overall BER, power, and clipping ratio allowed by the system, respectively. After that, the hybrid LD and LED-based UWOC system is introduced in this section, in which a hybrid cluster-based networking with mobility restricted nodes is utilized to prolong the network life cycle and improve network throughput. Moreover, to reduce the difficulty of optical alignment, the LEDs are utilized for coarse alignment, while the LDs are used for high-precision positioning.

A. Underwater Mobility Restricted Network

Current research on UWOC networking mainly uses underwater fixed anchor nodes and fiber-optic cable connections. However, the underwater environment is complex and changeable, and the seabed is irregular, which leads to the high cost of anchor nodes and optical fiber placement. Thus, a more feasible mobility restricted network is considered in this paper, in which the nodes are fixed on the seabed by an anchor. The nodes themselves have no power device and can drift freely in a restricted area with the flow of water. With the maturity and cheapness of LED and LD devices, a large number of small size UWOC mobility restricted nodes can be conveniently put into the interested water areas through aircraft or surface vessels to achieve autonomous communication without highly complicated operations. Therefore, there is no need to lay optical cables for fixed connection, and the locations of the nodes are relatively fixed in a small area. The cost of a single node is moderate, and it has the ability to continuously monitor in a certain area, which can save a lot of power consumption and hardware costs.

UWOC can establish communication links by means of LED broadcasting or LD scanning through acquisition, pointing, and tracking (APT) response. For LEDs, the communication rate is low, the divergence angle is large, and it is easy to establish communication links. For LDs, it is just opposite where the communication rate is high, the divergence angle is small, and the establishment of communication links is difficult. Therefore, different communication modes can be chosen according to different requirements.

B. Hybrid LD and LED-based Cluster-based Networking

Node clustering is an effective way to prolong network lifetime and improve network throughput. According to the location information of the nodes and the energy of the remaining nodes, the UWOC network can increase the network throughput while reducing and balancing the energy consumption of the nodes through a reasonable multiple access control (MAC) protocol. The idea of clustering is to divide UWSN into one or more than one cluster. One node in each cluster is chosen as the cluster head (CH) node, while the rest of the nodes are non-CH (NCH) nodes, so that they can manage resources and route interconnections more reasonably. The hierarchical network based on clustering structure reduces the complexity of communication by localizing routing and control information, which improves the system throughput and network expansion ability. The communication between intra-cluster and inter-cluster nodes can be coordinated by the selected CH nodes to improve the utilization of network resources.

As shown in Fig. 2, the whole monitoring network in the offshore area includes RF and satellite links above the water surface, surface base stations, and underwater UWOC mobility restricted networks. UWOC nodes connected with anchors can be randomly scattered by aircraft or ships in the offshore areas, which need to be monitored, and drift passively with the current in a restricted area, forming a UWOC mobility restricted network. After clustering, the mobility restricted nodes below the water surface are divided into CH nodes and NCH nodes. The structures of all nodes are the same. In the process of network operation and cluster maintenance, the CH and NCH nodes may change roles to balance the energy consumption. The NCH and CH nodes are connected by a single hop. The cluster association line shown by a dotted line in Fig. 2 represents the CH corresponding to NCH when it accesses the cluster. Without loss of generality, it can be considered that the surface base station is equipped with a global positioning system, which has enough energy to support platform movement and ground transmission. Generally, a CH node is fixed under the surface platform for data collection and instruction issuance. The system is

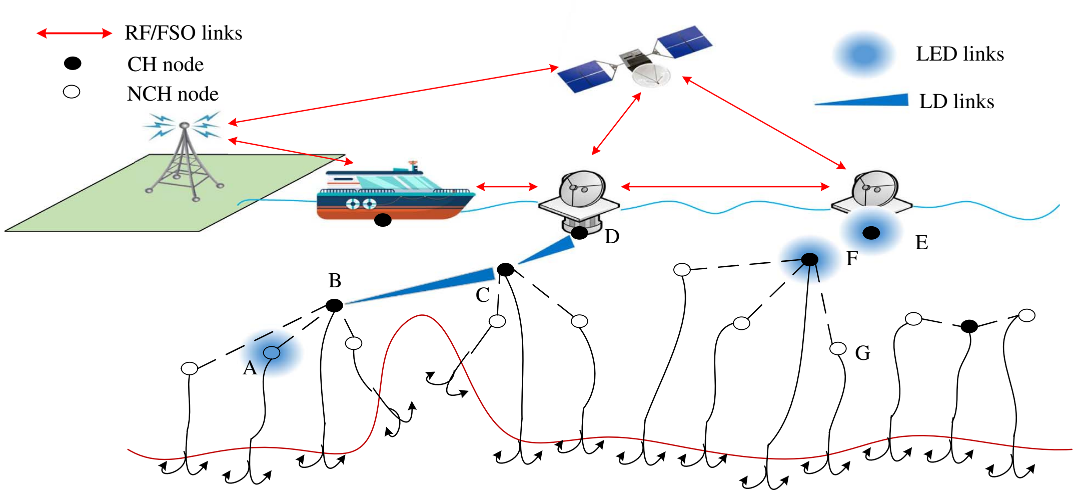

Fig. 2. Structure of the mobility restricted network with cluster-based networking.

divided into uplinks and downlinks. The uplink is the link from the UWOC mobility restricted nodes to CH nodes of the surface base station (in the order of A → B → C → D in Fig. 2), while the downlink communication is the reverse process of uplink communication, i.e., the transmission process from the CH nodes of the surface base station to underwater CH or NCH nodes (in the order of E → F → G in Fig. 2).

The divergence angle of the LED is large, and it is easy to establish links, while the communication rate of the LD is high, and link establishment is difficult. Therefore, from the data transmission point of view, due to the asymmetry of uplink and downlink data, different transmission methods can be adopted. Because of the small amount of downlink transmission data, the downlink transmission from CH nodes to CH nodes and from CH nodes to NCH nodes (e.g., the process of E → F or F → G) adopts an LED light source. The uplink process will be different. Because of the small amount of data needed to be transmitted by a single NCH node in the uplink, the transmission from NCH nodes to CH nodes in the uplink (such as the A → B process) uses an LED light source. However, because the CH node in the uplink gathers information from multiple NCH nodes and has a large amount of data, the transmission of CH nodes to CH nodes in the uplink (such as the process of B → C or C → D) uses an LD light source.

C. Hybrid LD and LED-based Alignment

The precise location of nodes is the premise of effective clustering and the guarantee of high-speed network communication. The loss of wireless light in underwater propagation decreases exponentially with distance, so the presence of large location estimation error will reduce the effectiveness of clustering and increase network energy consumption. UWOC nodes need precise alignment to achieve high-speed data transmission when using an LD to communicate, and the nodes need to get the exact location information of each other in order to provide favorable conditions for alignment. However, unlike the underwater fixed anchor node, the location of the mobility restricted node may change with the drift of water flow, and the stability of the communication link may be affected by the complex underwater environment, which puts forward higher requirements for node alignment.

Especially because of the large divergence angle and light spot of LEDs, it is easy for LEDs to align, but the small divergence angle and light spot of LDs will increase the difficulty of APT realization and alignment in communication. Therefore, in order to improve the accuracy of APT of LDs, a hybrid UWOC alignment based on LEDs and LDs is proposed, in which LEDs with larger divergence angle are used for underwater coarse alignment to get the approximate location of nodes. On this basis, the LDs with smaller divergence angle can achieve further precise alignment. This UWOC alignment technology, which combines the two communication modes of LEDs and LDs, can reduce the difficulty of underwater LD alignment and realize the wireless transmission of underwater high-speed data over a long distance. Furthermore, when the wave condition is extremely poor, the method of multiple alignments can be used. First, the LED is used to align roughly and then lock its coarse direction. Next, the LD is used to align precisely and then lock its accurate direction. Then, the LD is unlocked and used to roughly align again, continuing to iterate until a better alignment is achieved.

4. CHALLENGES AND TRENDS

A. Dual Selective Channel

Challenges. Due to the complex composition of seawater, the throughput of the UWOC is affected by many factors. On the one hand, the absorption and scattering effects of different substances dissolved or floating in seawater make the signal attenuation change with the frequency. Meanwhile, the underwater optical channel has the characteristics of non-flatness in the frequency domain due to the frequency selective fading caused by the multi-path effect. On the other hand, the time-selective fading is caused by the relative position change of the transceiver. Ocean turbulence causes the light drift, scintillation, and waveform distortion. Therefore, the underwater optical channel is non-stationary in the time domain. Thus, in a real environment, the underwater optical channel is a kind of non-flat and non-stationary channel, which poses a serious challenge to the stability, robustness, and reliability of the UWOC system. In addition, for FSO links, changes in actual outdoor temperature can lead to defocusing and signal fading. On the other hand, the temperature of sea water will fluctuate in different depths and seasons, which will further cause different refractive indices of light propagating underwater, making the signal received by the receiver have greater jitter and fading, and reducing the communication performance of the UWOC system.

Trends. Due to the non-flat and non-stationary characteristics of the underwater visible channel, the existing channel estimation methods will be inaccurate in high spectral efficiency and fast time-varying channels. How to estimate the channel accurately in dual selective channels has become a new research field. Possible research methods are presented here. Because the underwater optical channel is sparse in parameter domain, frequency domain, and special transform domain, a multi-parameter channel estimation method based on Bayesian compressed sensing can be studied to improve the channel estimation accuracy. On the other hand, based on the significant time-domain channel variation rules and the joint sparsity of the sampling domain for time-domain non-stationary channels, the base expansion model and structured compressed sensing theory can be used to design scientific and reasonable observation matrices and multi-dimensional observation vectors, so as to obtain a parametric channel estimation method suitable for non-flat and non-stationary underwater optical channels. Furthermore, theories and experiments cannot cover all the changes, e.g., temperature. Therefore, in the future, a variety of typical and representative sea-water optical channel scenarios should be investigated. Different scenarios will consider different temperature changes, so as to theoretically analyze the law of optical signal transmission in seawater.

B. Shape Design of Nodes

Challenges. The rapid response of APT is needed in UWOC. The conventional node design based on underwater acoustic communication is no longer suitable. The spherical-like polyhedron structure judges the incident direction of light by the angle relationship formed by the facades of the node shape, which can reduce the difficulty of APT implementation and the hardware requirements of the photo-detector (PD). However, the number of facades of spherical-like structures needs to be moderate, and the angle relationship between facades has a direct impact on judging the direction of incident light. If the angle between facades is too large (fewer facades), the shape of the node tends to be sharp (similar to a triangular pyramid, cube structure), which makes it difficult for the node to judge the precise direction of incident light. If the angle between facades is too small (too many facades), the shape of the node will become a more smooth spherical structure, which will not only cause the node to flip under water and lead to unstable communication, but also increase the cost of hardware and design. In addition, water flow and other factors can make nodes spin, which will reduce the efficiency of information transmission between nodes.

Trends. Considering the deployment cost, single-node cost, volume, and energy consumption, a new node design method is needed to ensure the rapid APT response and self-localization of the nodes, even in the underwater dynamic environment, such as overturn and inversion. A possible research direction is given here. According to the possibility that the incident light of an LD arrives from the upper, middle, and lower directions, the shape of the node can be designed as a three-layer spherical-like structure, and the principle of "tumbler" can also be used for reference to reduce the possibility of upside-down reversal of nodes under the action of the current. In addition, the angle relationship between each facade of the polyhedron should be further designed so that each facade can quickly judge the approximate direction of the incident light according to the geometric relationship formed by the facade after receiving the optical signal, so as to reduce the difficulty of alignment in the APT process. In the process of node shape design, it is necessary to comprehensively consider the movement rules and stress situation of the nodes in water. In addition, the detection area of the PD is very small, which makes it difficult for transmitters and receivers to align accurately. But, multiple-input multiple-output (MIMO) can be used to solve this problem. In this wireless optical MIMO system, the PDs can receive signals from multiple LEDs, thus improving the communication quality.

C. High-precision Location for Underwater Nodes

Challenges. High-precision positioning of CH nodes is the basis of fast APT response and the guarantee of high-speed communication for LDs. Large alignment deviation will seriously affect the communication rate of LDs. However, the conventional location method based on ranging is difficult to directly apply to an underwater optical positioning environment. Conventional received signal strength (RSS)-based optical ranging requires at least four anchor nodes to receive optical signals in order to achieve three-dimensional positioning, and each anchor node in RSS-based ranging will cause different measurement errors due to bubbles, turbulence, and background light noise in water, which makes the overall positioning effect poor. Conventional time of arrival (TOA)-based ranging and positioning requires that unknown nodes keep precise time synchronization with each anchor node. Conventional angle of arrival (AOA)-based ranging and positioning needs to obtain the accurate information of pitch angle and tilt angle of each anchor node in advance, which is undoubtedly difficult for mobility restricted nodes in the UWOC system. More importantly, these conventional methods require multiple anchor nodes to transmit optical signals in the form of high-power LED broadcasting. It is difficult to use low-power LD light sources, because it may cause information asynchrony due to the different APT response times of each anchor node and affect positioning performance. In addition, these methods usually require anchor nodes to be fixed underwater and use wired optical fiber connections to interact with each other. However, anchor nodes in mobility restricted networks cannot obtain each other's information, so it is difficult to use these methods to meet the location requirements in underwater mobility restricted networks.

Trends. In view of the underwater mobility restricted network with unstable anchor nodes, the high-precision ranging and positioning method based on a single CH node will be gradually adopted in the future. The single CH node localization means that only a single CH node is used as an anchor node to locate unknown nodes, and the localization accuracy can reach sub-meter or even centimeter level. A possible implementation method is given here. The conventional AOA method uses multiple anchor nodes to send and a single unknown node to receive to locate and estimate. In order to achieve high-precision positioning of the single CH node, the idea of "one sending, multiple receiving" in the array signal processing and classical MIMO system can be used for reference[23]. The interior of the node facade is designed as an optical array unit consisting of multiple receiving prisms and detectors, and the angle estimation is realized by using the geometric relationship of the optical array and the principle of AOA ranging and positioning.

D. Energy Efficient MAC Algorithm

Challenges. In the energy-constrained UWOC network, due to the dynamic and complex characteristics of underwater environment, it is impossible to establish stable communication links in time or to maintain stable links in a certain period of time, so it has delay-tolerant characteristics, which is called a delay-tolerant UWOC network. In the process of uplink data transmission from CH nodes to CH nodes, on the one hand, the complex and dynamic marine environment will increase the difficulty of implementing APT for CH nodes. Even if fast APT response is achieved through node design and high-precision positioning, the communication link of CH nodes will be interrupted frequently or even be completely unable to communicate due to the intermittent occlusion of LD collimated beams caused by underwater bubbles, fish swarms, and aquatic organisms or interference of strong background light.

Trends. In order to ensure efficient data transmission, slot optimization of the delay-tolerant UWOC network will become a research difficulty in the future. Its focus is to determine whether the current CH node is a node with poor link quality or no urgent transmission needs (called a delay-tolerant node) and how to make efficient use of the slots of delay-tolerant nodes. Essentially, it is a problem of time resource allocation, that is, how to allocate the slot resources occupied by delay-tolerant nodes to adjacent CH nodes for their data transmission according to the characteristics of the delay-tolerant UWOC network. In order to satisfy the real-time requirement of data transmission and reduce the extra overhead caused by repeated retransmissions due to data transmission failure in the delay-tolerant UWOC network, it is necessary to design a reasonable MAC protocol. Thus, it can reduce the collision of data packets, network interference, and the overhead of retransmitting due to packet loss, so as to balance the energy consumption of nodes, prolong the network lifetime, and ensure efficient data transmission. In addition, artificial intelligence and machine learning can be utilized in the design process of the MAC protocol to further optimize the efficiency of the MAC algorithm across multiple dimensions.

Furthermore, in the case of restricted energy supply, some intelligent wake-up mechanisms can be introduced, which do not need to keep the PD in use all the time, thus prolonging the working time of the PD as much as possible under the same energy conditions. Besides, new energy harvest technologies, such as utilizing ocean currents and solar energy, could be introduced into the UWOC systems too.

E. Cross-medium Communication

Challenges. At present, the wireless communication that crosses the sea surface is mainly divided into two sections. The first part is the communication between the underwater nodes and the surface base stations, which can use UWOC or underwater acoustic communication. The second part is the communication between the surface base stations and the land base stations, which can use RFs for communication. Obviously, this method requires multiple relays and multiple base stations to support, which will bring a lot of extra expense. In addition, laser-based UWOC systems with line-of-sight cannot support stable air–water/water–air interface communication due to the strict optical alignment requirement, which makes it difficult to support the cross-medium communication.

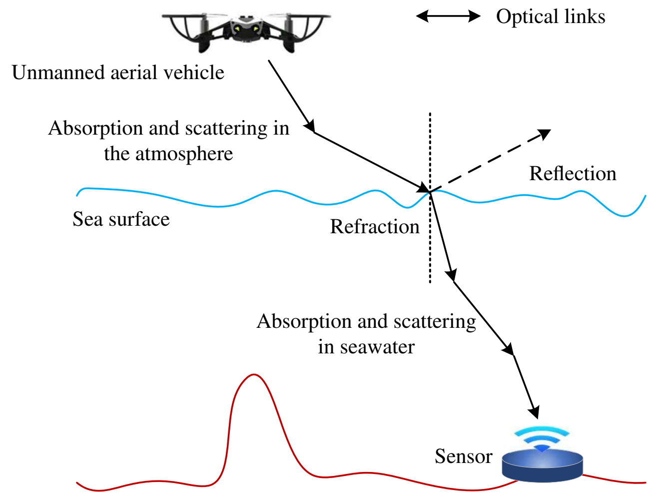

Fig. 3. Direct optical communication between underwater nodes and atmospheric communication targets.

Trends. In view of the above topics, future research on direct communication between underwater nodes and atmospheric communication targets, such as laser cross-medium communication technology, will be carried out, as shown in Fig. 3. A laser cross-medium transmission channel is a complex transmission channel. The sea surface always fluctuates under the influence of various factors. The incident angles of light passing through the sea surface are different, so the refraction direction is different, which leads to beam drift, spot distortion, and intensity fluctuation, resulting in the uneven distribution of light intensity in time and space, and introducing certain noise to the receiving end, which becomes an important problem restricting the effective transmission of light signals in the cross-medium environment. In the cross-medium optical communication system, the uplink and downlink channels are not simply reversible. Future research trends will include research on optical signal transmission methods on seawater/atmosphere communication links, defining the boundary conditions of laser cross-medium transmission and the corresponding cross-medium transmission methods, as well as establishing theoretical models of cross-medium transmission in wireless optical communication. Furthermore, to solve the misalignment caused by the variation of the refractive index in the medium, the first method is to use a number of inexpensive semiconductor lasers to emit beams, similar to MIMO systems, which can work even if part of the PDs are not aligned. Thus, the data transmission rate of the whole communication system can be guaranteed, and the stability and security of the system can be ensured. The second method is to increase the divergence angle of the LD appropriately. Although this method will sacrifice the transmission distance, it can ensure the system performance.

F. MIMO Technology

Challenges. On the one hand, the underwater optical communication environment is complex, and the transmitted signal is greatly affected by water absorption, scattering, and turbulence. Therefore, there is large channel fading in an underwater channel, which will greatly reduce the reliability of transmission. On the other hand, in order to achieve higher data rates, the capacity of the UWOC system needs to be further improved.

Trends. In order to further enhance the system capacity of the underwater optical communication system and meet the requirements of high-speed and reliable transmission of the UWOC, it is necessary to consider introducing MIMO into UWOC systems. In order to give full play to the role and advantages of MIMO technology in underwater visible communication, it is necessary to further design the transmission scheme of underwater optical MIMO systems based on spatial expansion to meet the requirements of different water quality and scenarios. According to the characteristics of UWOC and for different water quality, scattering degrees, and turbulence intensity, the research can be carried out from three aspects: spatial multiplexing, spatial modulation, and beam shaping. Different schemes will get different diversity or multiplexing effects.

5. CONCLUSIONS

In this paper, the channel model, the modulation schemes of the UWOC, is reviewed first. Then, a hybrid LD and LED-based UWOC system is investigated. The corresponding hybrid cluster-based networking with mobility restricted nodes and hybrid LD and LED-based alignment is utilized to prolong the network life cycle, improve network throughput, and reduce the difficulty of optical alignment, respectively. Finally, the challenges and trends of UWOC are concluded, including dual selective channel, shape design of nodes, high-precision location, MAC algorithm, cross-medium communication, and MIMO technology.

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