Journal of Network and Computer Applications 148 (2019) 102446

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

Review

Survey on high reliability wireless communication for underwater sensor networks

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ARTICLE INFO

Keywords:
Underwater wireless sensor networks
Multimodal communication
Acoustic communication
Optical communication
Underwater routing protocol
Underwater MAC protocol

ABSTRACT

Underwater wireless sensor networks (UWSNs) have become an interesting research topic because the utilization of ocean resources and informatization is required. Communication technology is a fundamental and key part of an ocean network. However, as compared with the land environment, the marine environment is complex and changeable, and thus, communication in this environment is very difficult. This paper presents an in-depth discussion and review of underwater communication methods and network technologies, such as underwater acoustic communication, underwater optical communication, routing and medium access control (MAC) protocols, and underwater multimodal networks. The paper also discusses the realization of underwater high reliability communication technology, and a few challenges of underwater networks are addressed.

1. Introduction

The 21st century is the century of the ocean, and maritime nations urgently need to explore and protect the ocean. Ocean geological exploration, oil exploitation, and environmental monitoring require a stable underwater network. Meanwhile, ocean natural disaster warning systems and the breeding of ocean stock are also motivating the development of ocean informatization. The basis for achieving a highly reliable ocean network is an underwater point-to-point communication system that can achieve high speed, a low bit error rate (BER), a long communication radius, and low power consumption. Various methods for communication in the underwater environment have been proposed: underwater acoustic communication (UAC), underwater optical communication (UOC), electromagnetic communication, gravitational wave communication, quantum communication, and magnetic field communication. However, only UOC and UAC can in fact be applied to the underwater environment (Zeng et al., 2017) (Jiang, 2018a) and the remaining communication methods are still in the laboratory verification stage. UAC is currently the most mature communication method applied in the underwater environment. The speed of sound traveling underwater is up to 1500 m/s. The attenuation is extremely small and the acoustic attenuation coefficient between 1 Hz and 50 kHz is approximately 10^4 dB/m to 10^2 dB/m. The communication rate within 1000 m can reach a few m/s (Tuna and Gungor, 2017). Acoustic waves can travel thousands of kilometers at low frequencies and high power and provide the only means of achieving underwater long-distance communication. However, although UAC has the advantage of allowing long-distance communication, it also has many defects. For example, its transmission delay is long, because the propagation speed of underwater sound is five orders of magnitude lower than the speed of radio frequency (RF). The State Oceanic Administration requests that, at the time of a tsunami warning, the ocean observation network transmit the warning information within 3 s, because otherwise it would be meaningless. Clearly, UAC cannot meet this requirement. Another major flaw in UAC is the extremely scarce bandwidth resources. In the field of communications, the most important issue is the bandwidth. The direct benefit of a wider bandwidth is the significant increase in the transmission rate that it allows. In addition, the noise generated because of the versatile and complex characteristics of the underwater environment significantly interferes with UAC, and the mobility of the underwater nodes leads to the Doppler effect. Submarine boundaries, water boundaries, and different geographical environments in the ocean create the multipath effect, which poses significant challenges to high quality aquatic communications.

UOC is considered complementary to UAC. The rate of optical communication can reach several tens of m/s. However, because of the rapid attenuation of light in water, the distance light travels in underwater environments is only a few hundred meters. The Bluecom under-

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https://doi.org/10.1016/j.jnca.2019.102446
Received 30 May 2019; Received in revised form 30 August 2019; Accepted 16 September 2019
Available online 12 October 2019

water optical communication system can achieve a 20 Mbps transmission speed within 200 m underwater (Li et al., 2018). The Ambalux system can achieve a 10 Mbps transmission speed up to a distance of 400 m underwater (Zeng et al., 2017) (Khalighi and Uysal, 2014). With single-photon avalanche diodes, UOC can achieve a transmission distance of 500 m underwater in a relatively clean water environment (Shen et al., 2019). Although this allows high-speed underwater data transmission, UOC imposes stringent requirements on the water quality in the environment and on the two nodes that implement point-to-point communication. The first requirement is that the two communicating nodes be relatively stable. Meanwhile the transmitter and receiver should be accurately opposed; otherwise, data transmission will suffer devastating damage. The water quality in the environment significantly affects optical communications, because in turbid water the receiver cannot receive continuous optical signals. In other words, knowledge of the water quality in the environment is a prerequisite for determining whether UOC is applicable.

Underwater RF communication was considered for use in submarine communications. Because of the absorption of electromagnetic waves by water, RF waves can pass through a depth of only approximately 7 m (Qureshi et al., 2016). As the wavelength is lengthened, the electromagnetic wave penetration ability in water becomes higher, reaching 200 m. However, in ultra-low frequency RF communication, the transmission speed is reduced. Approximately half an hour is required to transmit a message, and the system can operate only in a simplex mode. Because of the long wavelength, the antenna of the transmitter should be up to tens of kilometers. This is evidently impossible in networking. We do not discuss the underwater applications of RF communication in this paper.

These communication technologies fundamentally determine the stability and reliability of underwater sensor networks. Of course, there are other factors that affect the reliability of underwater sensor networks, such as routing protocols and Mac protocols on the network layer. We will discuss these techniques in detail in subsequent chapters.

Our main contributions are as follow:

- The factors affecting the reliability of underwater network, including communication technology and network technology, are investigated and analyzed.
- We present a comprehensive survey of the state of the art in underwater communication and its development. The performance advantages of underwater multimodal networks and opinions on the future development of underwater networks are presented. Machine learning used for underwater data transmission is also examined.
- We discuss the AUV-assisted data transmission network innovatively. As a special underwater data transmission form, we analyze its advantages and problems in networking.
- We discuss the challenges and open issues facing the future development of underwater data transmission, including communication and networking, and propose some solutions that are feasible in our opinion.

The remainder of this paper is organized as follows. In Section II, we discuss underwater communication technology, consisting of UAC and UOC. In Section III, we examine networking in the underwater environment. Some challenges and open issues are presented in Section IV. Finally, Section V presents a few conclusions and perspectives on future research.

2. Ocean communication technology

This section discusses UAC and UOC in detail and reveals some factors that affect data transmission when different communication technologies are applied in underwater solutions.

2.1. Underwater acoustic communication

An underwater acoustic system was first widely used by the military at the end of the 19th century (Chen et al., 2018). In 1945, the US Navy Underwater Acoustics Laboratory designed a practical underwater telephone. Because of the technical limitations at the time, the single sideband modulation technique of the analog modulation system utilized by the underwater telephone used a carrier frequency of 8.33 KHz, and its communication distance could reach several kilometers. Subsequently, an underwater telephone utilizing frequency modulation technology, having a carrier frequency of kHz, was successfully developed. Because the analog modulation system cannot alleviate the signal fading and malformation caused by the special complexity of the underwater acoustic channel, the performance of the system was very limited. In the following decades, with the rapid development of signal processing technology and the gradual improvement in modulation technology, digital modulation technology was applied to UAC.

Currently, the development of UAC is limited by modulation technology. The earlier analog modulation digital sound process (DSP) and the current orthogonal frequency-division multiplexing (OFDM) modulation technology are both derived from land-based communication systems. These technologies can theoretically be used in underwater communication systems. Experiments and practical applications also prove this to be true. In 2008, Milica and Baosheng (Stojanovic, 2008) (Li et al., 2008), in their study of the application of OFDM technology to UAC systems, achieved a major breakthrough. Subsequently, Dang et al. (Aparicio et al., 2010) proposed OFDM interleave-division multiple access (OFDM-IDMA) communications over underwater acoustic channels, which renders the modulation technology of UAC more diverse. With the development of underwater communication modulation technology, UAC became more reliable. However, the underwater acoustic channel is recognized as one of the most uncompromising channel environments and its complexity and variability pose an insurmountable challenge for reliable information transmission.

2.1.1. Channel model

The establishment of the channel model has greatly benefitted the theoretical study of UAC and directly affected its quality. The underwater acoustic channel is time-varying and diverse, and the channel models in different water environments also differ. We list some underwater acoustic channel models and explain them further.

Milica Stojanovic et al. (Milica and Preisig, 2009) proposed a simple mathematical model for channel noise, multipath effects, and attenuation.

Path attenuation model:

$$A(l,f) = \frac{l}{l_r}^{k} \alpha(f)^{l-l_r} \tag{1}$$

where f is the signal frequency and l is the transmission distance with reference to some l_r. The path loss exponent models the spreading loss and its usual values are between two targets.

Noise model:

$$SNR(l,f) = \frac{S_l(f)}{A(l,f)N(f)} \tag{2}$$

where $S_l(f)$ is the power spectral density of the transmitted signal.

Multipath model:

$$H_p(f) = \frac{\Gamma_p}{\sqrt{A(l_p,f)}} \tag{3}$$

represents the frequency response of the p-th path.

Joaqun et al. (Aparicio et al., 2010) proposed a mathematical model of an acoustic channel located in a shallow water coastal environment. In the model, underwater acoustic attenuation, geometrical diffusion, absorption, signal bottom, and surface bounce are considered.

Geometric diffusion attenuation model:

$$TL_{geo} = k \times \log l \tag{4}$$

where k is a constant coefficient. In this model diffusion can be divided into circular diffusion and spherical diffusion, and the k value is then 10 and 20, respectively. l is the distance between the receiver and the transmitter.

Infrared energy is generated when the transmitter performs acoustic modulation. When the energy radiates outward, the sound wave is attenuated. The model is

$$TL_{abs} = \alpha \times l' \times 10^{-3} \tag{5}$$

$$\alpha = \frac{A_1 P_1 f^2}{f^2 + f_1^2} + \frac{A_2 P_2 f^2}{f^2 + f_2^2} + A_3 P_3 f^2 \tag{6}$$

where α is the attenuation coefficient. The model considers the pH, temperature, and salinity in the underwater environment as parameters.

Bottom and surface reflection loss models:

$$TL_{bot} = 10 \times \log\left[\frac{q \times \sin\theta_1 - (n^2 - \cos^2\theta_1)^{\frac{1}{2}})}{q \times \sin\theta_1 - (n^2 + \cos^2\theta_1)^{\frac{1}{2}})}\right]^2 \tag{7}$$

where $q = \frac{p_2}{p_1}$ and $n = \frac{c_1}{c_2}$

$$TL_{sur} = 10 \times \log \frac{1 + \frac{f}{f_1}^2}{1 + \frac{f}{f_2}^2} - (1 + \frac{90 - \omega}{60}) \times \frac{\theta}{30}^2 \tag{8}$$

In summary, the attenuation model can be written as

$$TL = -TL_{geo} - TL_{abs} + TL_{bot} + TL_{sur} \tag{9}$$

Dovietha et al. (Ha et al., 2017) proposed a Doppler power spectrum model for UAC channels.

$$S(f) = \frac{1}{1 + C(\frac{f - f_{D,max}}{f_{D,max}})^2} + Ae^{-(\frac{f - f_m}{w})^2} \tag{10}$$

BELLHOP model:

$$TL = -20lg|| \frac{p_s(r,z)}{p_s(r,z)\mid_{r-1}} \tag{11}$$

This model is used to calculate the propagation loss of a certain sound line (Porter and Jolla, 2010). where $p_s(r,z)$ is the sound pressure on a particular sound line.

Table 1 summarising the features of channel models.

The underwater acoustic channel model above includes several important models: path attenuation of acoustic frequency, noise, multipath, and Doppler. The path attenuation of UAC is affected by many factors, such as frequency, sea water temperature, salinity, depth, and pH, infrared scattering, and multipath scattering. The attenuation model proposed in (Milica and Preisig, 2009) uses the attenuation coefficient to fit the approximate function relationship between the underwater acoustic emitted signal and the received signal. Because of the fitting function relationship, the channel model shows a large divergence from the actual channel. However, this attenuation model has wider applicability than the attenuation model proposed by Milica. In general, noise in UAC constitutes additive noise. The simplest and most effective means to describe noise is the signal-to-noise ratio (SNR) (Milica and Preisig, 2009). The model summarized above is obtained by analyzing the motion state of underwater nodes. Although it is possible to build multipath and Doppler effect models, it remains difficult to solve the high BER of UAC. By relying on modulation technology, anti-channel attenuation and anti-noise techniques can be significantly improved. For Doppler and multipath effects, however, methods or algorithms other than modulation are needed to improve the communication performance, such as spread spectrum technology, equalization technology, and synchronization technology. In the next part, we explore the research on the multipath and Doppler effects.

2.1.2. Multipath effect, Doppler effect, and orthogonal frequency-division multiplexing technology research

The multipath effect, which exists in almost all land-based and underwater communication technologies, is an important factor that causes fast fading of signals. Because the signals of different paths arrive at the receiving machine at different times, in the case of a phase error the signal superimposition results in deformation or severe fading of the received signal, eventually leading to bit errors, which seriously affects the reliable transmission of data. Many methods exist for precluding multipath effects on land, such as those that improve the receiver ranging accuracy and the time domain equalization and those that utilize OFDM modulation. To improve the range accuracy and time domain equalization, positioning and time synchronization technologies are required. However, the dynamic topology of an underwater network makes it difficult to achieve accurate positioning and time synchronization in this environment (Awan et al., 2019) (Chen et al., 2018). OFDM modulation is the most effective means of achieving underwater multipath resistance and can improve the underwater data transmission rate. An ideal underwater acoustic network can be realized by combining medium access control (MAC) and security mechanisms (Jiang, 2018a; Jiang, 2018b; Tuna and Gungor, 2017; Jiang, 2019).

Although OFDM shows a superior performance in terms of multipath resistance, it is seriously affected by the Doppler effect. The Doppler effect in underwater communication is caused by a frequency shift due to the irregular motion of underwater nodes or vehicles. Doppler shift reveals that when the receiver is in front of the sound source (a node) displaced in a specific direction, the received signal wavelength is compressed as compared to that of the transmitter, and the frequency is higher, or vice versa. The Doppler effect increases sharply as the node moves faster. In severe cases, it causes bit errors and communication interruption. OFDM remains the most effective communication modulation technology for balancing the characteristics of underwater channels and environments. Research to improve the efficiency of OFDM technology in underwater communication is still in progress. Mahdi et al. comparatively studied the performance of fast Fourier transform (FFT) based and fractional Fourier transform (FRFT) based multiple-input multiple-output (MIMO) OFMD systems (Jiang, 2018b). Whereas the complexity of FRFT and FFT is the same, the performance of the former is better than that of the latter in all multipath underwater environments, and their performance is the same in a flat fading environment. Thus, the FRFT-based MIMO-OFDM system is a superior system. Because of the poor performance of non-coded OFMD systems in fading channels, Padmasree et al. studied the underwater performance of convolutionally encoded OFDM systems. The coded modem is shown in simulations to be superior to the MATLAB inbuilt function library, and the coding gains on the additive white Gaussian noise (AWGN) and Rayleigh channels are respectively 0.635 dB and 1.45 dB (at a BER of 10^{-1}). Experiments show that convolutional coded (CC) OFDM can produce a better performance under lower hardware conditions. Matched filter (MF), zero force (ZF), and minimum mean square error (MMSE) equalizers can be applied for channel equalization. However, each of these equalizers has disadvantages that affect the system communication performance: the performance of the MF is corrupted in a MIMO configuration, the ZF equalizer suffers from noise enhancement and high complexity, and the MMSE equalizer needs to estimate the SNR to operate correctly. Khaled et al. proposed a joint low complexity regularized ZF equalizer and carrier frequency offset compensation scheme. The proposed equalization algorithm adapts constant regularization parameters to ameliorate noise enhancement problems and system complexity. OFDM is sensitive to the Doppler effect. Compensation of the frequency by multiple OFDM systems is a general method of counteracting the Doppler effect, which is realized by applying subsampling and residual carrier frequency offset compensation. Shingo et al. proposed a technique that expands the sampling range and resamples by measuring the Doppler standard deviation. The conventional approach assumes that there is a constant Doppler shift in the com-

Table 1
Features of channel models.

Models	EF	PH	T	S	OC	HP	Description
Path attenuation model (Milica and Preisig, 2009)	✓	✓	✓	✓			Equation (1) only focuses on the signal attenuation between input and output, with a large error. Equation (5) independently studies the factors affecting signal attenuation, greatly improving the accuracy of the model.
Noise model (Milica and Preisig, 2009)	✓						A general model of noise used to measure the effect of noise on data transmission.
Multipath model (Aparicio et al., 2010)	✓				✓		Measure the effect of different paths under multipath effect on communication.
Doppler power spectrum model (Ha et al., 2017)	✓				✓		Analyze the intersymbol interference caused by the doppler shift.
BELLHOP model (Porter and Jolla, 2010)						✓	used to calculate the propagation loss of a certain sound line.

EF:empirical formulas,S:salinity,OC:ocean current,HP:hydraulic pressure.

munication data frame, but in actual environments the relative speed between the transmitter and receiver units fluctuates and the Doppler shift also fluctuates. This method can effectively address this issue and improve system performance, that is, the BER. Multicarrier modulation is a distinctive feature of OFDM systems, and orthogonality between carriers is a prerequisite for ensuring the good performance of an OFDM system. Sometimes orthogonality is lost between subcarriers on a time-varying channel, resulting in inter-carrier interference (ICI). Post-FFT and pre-FFT are two classification methods for handling this problem. The post-FFT method consists of block equalization or serial equalization of signals generated between the ICIs after signal demodulation (Esmaiel and Jiang, 2017; Abdelkareem et al., 2016; Wen et al., 2016; Nassiri and Baghersalimi, 2018; Ramadan et al., 2018). The pre-FFT method applies frequency offset compensation to the signal before signal demodulation to eliminate non-orthogonality between subcarriers (Yoshizawa et al., 2018; Han et al., 2018; Lin et al., 2018; Wu, 2018). Jing et al. proposed a combined weight calculation algorithm based on feature decomposition. As compared with the existing adaptive methods, the algorithm avoids the propagation of errors and eliminates the parameter tuning requirement. The method guarantees global optimality under the narrow-band Doppler hypothesis. The optimal weight vector of local FFT demodulation is obtained through the eigenvector associated with the smallest eigenvalue of the pilot detection error matrix. The algorithm can also be extended directly to subband calculations to offset the broadband Doppler effect.

In the above research studies, it was found that the most mature and popular technology for UAC is OFDM, mainly because OFDM can achieve high-speed data transmission and has a natural anti-multipath capability at a low acoustic wave propagation rate. Although the OFDM system is sensitive to the Doppler effect, the equalization techniques proposed in recent years can compensate for this defect. The results of research on OFDM coding and ICI and FRFT and FFT demodulation performance analysis have helped bring the underwater communication OFDM system closer to a perfect one and improve the reliability of underwater data transmission.

3. Ocean networking

3.1. Underwater routing

Underwater data transmission cannot utilize only simple point-to-point data transmission. To achieve data transmission, a reliable underwater network must be constructed in the designated ocean area by utilizing excellent communication technology. The routing protocol is the underlying protocol of a communication network and is important for implementing the network packet relay process. Extensive in-depth research on underwater routing protocols has been conducted, and dozens of underwater routing protocol algorithms exist. Because the construction and application of an underwater network are still in their infancy, there still exist few underwater networks that can be investigated experimentally. Because research on routing in a real environment is difficult, only a few routing protocols have been tested in such an environment. The high price of underwater network nodes is an additional reason why networks consist of only a few nodes (Diamant et al., 2018). The design of an underwater routing protocol is more complicated than that of a land-based routing protocol. The topology of land-based networks is a two-dimensional plane, while that of underwater networks is three-dimensional (Qiu et al., 2019a) (Qiu et al., 2019b) (Qiu et al., 2019c) (Qiu et al., 2018a) (Qiu et al., 2018b). Moreover, underwater routing is always dynamic, whereas subaerial routing is always static. Therefore, it is not suitable to copy completely a land routing protocol in an underwater network. In addition, underwater routing faces node movement, energy consumption, and other challenges (Mukhtiar et al., 2017) (AhmedSalleh and Channa, 2017) (Ghoreyshi et al., 2017). In particular, underwater routing suffers the same hole problem as land routing, which is more difficult to solve in underwater networks (Ghoreyshi et al., 2017) (Mukhtiar et al., 2017). In the following part, we examine and summarize the recently developed routing protocols so that the reader can understand the current state of the development of underwater routing protocols. Fig. 1 shows the model of an underwater sensor network.

3.1.1. Location-based routing protocols

In the early research on underwater routing, the existence or non-existence of node location information in the network was considered a main feature that divides underwater routing protocols into two different types. A typical representation of location-based routing is the vector based forwarding (VBF) protocol (Xie et al., 2006) and a typical representation of non-location-based routing is the depth-based routing (DBR) protocol (Yan et al., 2008). The purpose of the VBF protocol is to establish a valid data link from the source node to the sink node using the known location information of each node. The core idea is to establish a cylindrical virtual pipeline between the source node and the sink node; a node between the source node and the sink node in the pipeline is a candidate relay node for forwarding a packet. The size of the virtual pipeline established by the protocol is the key factor that affects the network. If the range of the pipeline is too large, the number of hops and the energy consumption increase excessively, whereas too short a range leads to communication interruption and packet loss. Although the protocol is highly adaptable in dynamic 3D underwater networks, important issues remain to be considered: node energy consumption and sparse networks. To address these two problems, Jornet et al. proposed the hop-by-hop (HH) VBF protocol (Nicolaou et al., 2007) and Nicolaou et al. proposed the focused beam routing (FBR) (Jornet et al., 2008) protocol. HH-VBF solves the performance problem of VBF in a sparse network. The method adopts a hop-by-hop virtual pipeline. After the source node forwards data to the next hop according to its virtual pipeline, the source node does not participate in subsequent data forwarding. The next hop node establishes its own independent pipe

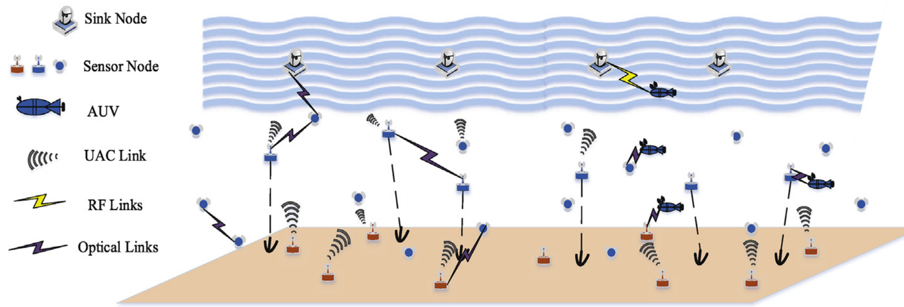

Fig. 1. Model of underwater sensor network.

to the sink node until the packet is successfully forwarded to the next hop node. The FBR protocol is a routing protocol based on power layering and uses different transmission power levels in the forwarding process. In the routing process, the sender node sends a packet request with a specific transmission power level to its neighbor. If the sender node receives a clear to send (CTS) packet from the neighbor, it sends the packet to the neighbor node with the CTS response; otherwise, if the CTS is not received, the transmission power level increases to the next power level. This process is repeated until the CTS package is successfully received. However, the constant exchange of request to send (RTS)/CTS packets causes delays. In addition, FBR also suffers positioning problems.

3.1.2. Non-location-based routing protocols

In underwater networks, it is sometimes difficult to determine node location information. A routing protocol based on location information depends very strongly on the underwater positioning algorithm, which presents a difficult challenge in an underwater network. Therefore, routing protocols based on non-location information are of practical value. The first non-location information-based routing protocol for the underwater environment was DBR, which was proposed by Yan et al. (2008). The protocol considers only one parameter, node depth, in data forwarding. In the network model, the sink node is located on the water surface and the underwater nodes are distributed at different randomly assigned depths. After generating the data packet, the node forwards the data packet upward according to the depth and continuously calculates the depth difference between the node and the adjacent nodes during the forwarding process to ensure that the data packet can be forwarded only upward. Because the protocol uses only depth as the standard for data forwarding, a node at a shallower depth participates excessively in the data forwarding, and thus it consumes more energy and becomes inoperative more quickly. In addition, the DBR protocol does not provide a more effective next hop node selection decision. The H2-DBR protocol (Wahid and Kim, 2012) and the energy efficient DBR (EEDBR) protocol that was subsequently proposed solve the above problems and greatly improve the performance of the DBR protocol. In 2014, Wahid et al. developed the DBR protocol to achieve a reliable energy-efficient routing protocol based on physical distance and residual energy (R-ERP2R). This underwater routing protocol is in general based on physical distance (Khasawneh et al., 2018). It replaces the depth calculation in the DBR protocol with the calculation of the physical distance between the source node and the adjacent node. Such an algorithm is more adaptable and is suitable for the underwater clustering sensor network. It comprehensively considers the energy consumption of underwater nodes and so on, and thus, the performance of the protocol is better than that of EEDBR in terms of network data forwarding and network lifetime.

3.1.3. Energy-based routings

In the past two years, the research on routing protocols based on location and non-location information has continued to progress. In 2018, Majid and Ahmad proposed the reliable and energy efficient pressure-based routing (RE-PBR) protocol (Khasawneh et al., 2018) and the improved VBF protocol (Mazinani et al., 2018). The RE-PBR protocol introduces parameters such as residual energy, link quality indicator (LQI) values, and SNR. The link quality values were added to the relay routing decision algorithm for the first time. Simulation experiments show that the end-to-end delay and network lifetime are significantly improved as compared with those achieved by EEDBR and DBR. As compared to the original VBF protocol, Ahmad's improved VBF protocol considers the residual energy, and he innovatively proposed a dynamic virtual pipeline approach to improve the VBF performance. The protocol considers information such as residual energy and the node position changes as a parameter to determine the virtual pipe radius of the source node dynamically to accommodate an unstable underwater environment. To improve the survival time of underwater networks further, Nouman et al. proposed a DBR-based enhanced energy harvesting DBR protocol (EH-DBR) (Khan et al., Hafeez), which charges nodes by collecting energy in the acoustic wave communication frequency band using data packets. In theory, the lifetime of an underwater network can be extended indefinitely. Many studies have considered the energy consumption problem of underwater nodes, which also indicates that the problem of node energy consumption in the field of underwater communication networks is a fundamental problem. In recent years, there have been dozens of studies reported in the literature on communication networks or node energy consumption problems, and many routing protocols (Jin et al., 2018; Bu et al., 2018; Karim et al., 2018; Khan et al., 2018; Faheem et al., 2018; Khasawneh et al., 2018; Basagni et al., 2018) have been proposed and improved.

3.1.4. VH-based routing protocols

The information void hole (VH) problem is an important issue in the performance of underwater networks and also presents a major challenge for routing protocol developers. Only a few of the many papers reviewed considered underwater VH problems. In general, most routing protocols can make one of two decisions when encountering a VH: the first is to abandon the data packet after multiple automatic-repeat-request (ARQ) protocols have not responded, and the second is to increase the network overhead to bypass the information hole. These methods cannot solve the VH problem perfectly but can effectively reduce the complexity of the routing algorithm. In recent years, many research results on information holes have been reported. In (Ghoreyshi et al., 2018), the first complete stateless opportunistic routing protocol (SORP) was proposed. It adopts the passive participation method and locally detects holes and captured nodes in different areas of the network topology during routing. It also adopts a new scheme, implementing an adaptive forwarding area that can be adjusted and replaced according to the local density and position of the candidate forwarding node, thereby improving energy efficiency and reliability. Nadeem et al. proposed two protocols to handle VHs: the interference-aware routing protocol (Intar) and the reliable and interference-aware routing protocol (RE-Intar). There are only a few differences between the two proto-

Node ID	Depth	Number of neighbors	Distance to sink	Hop count from sink

Fig. 2. Hello packet.

cols. The protocol establishes a data link in two steps. In the first step, the source node broadcasts a HELLO message to find all the paths that can reach the sink node and stores them. The HELLO packet includes ID, NumNeighbor, Timestamp, DistNeighbor, and HopSink (Fig. 2).

After the available data link has been updated, the source node determines the next hop node by calculating the cost function value (*CF*):

$$CF(j) = \frac{Dist(i,j)}{Hop(j) \times Neighbor(j)} \tag{12}$$

where $Hop(j)$ is the number of hops of the j-th potential forwarding node (PFN) from the sink, $Neighbor(j)$ is the number of neighbors of the j-th PFN, and $Dist(i,j)$ is the distance between the j-th PFN and source node i. The difference between the RE-Intar protocol and the Intar protocol is that depth information is added to the former HOLLE. The protocol can effectively solve the information hole problem and shows a certain improvement in network performance.

3.1.5. Routing protocols based on machine learning

Machine learning is currently a hot research topic, and learning algorithms are compatible with underwater communication networks. The application of machine learning methods to underwater networks has become an important means of solving their key problems. Because traditional terrestrial protocols cannot adapt to the underwater environment, the performance of non-intelligent routing protocols in underwater networks is always unsatisfactory. Obaida et al. proposed a Q-learning-based efficient and balanced energy consumption data gathering routing protocol, QL-EEBDG (Karim et al., 2018). The protocol is based on reinforcement learning, which is aimed to balance the energy consumption of some aggregation nodes in the network, so that a node does not cause a network interruption or large-scale reduction in network coverage because of its rapid death due to its excessive use.

A serious flaw exists in reinforcement learning, called the dimension crisis. Reinforcement learning does not require data for training. The process of making decisions is the process of learning the environment. A Q-value table is used to store the current environment information. When the environment state has only one dimension, the Q-value table needs only one row and N columns to record all the information. When the environment state is two-dimensional, an N*N table is needed to record information. When there are three dimensions, a three-dimensional cube array is needed to record the data. Then, what about four dimensions? Reinforcement learning has been difficult to handle. However, the environment under the ocean is complex, the number of states can reach thousands, and the dimensions can reach tens of dimensions. Obaida et al.'s reinforcement learning-based routing algorithm allows each node to record the Q values of neighboring nodes based on the reward function, which very significantly reduces the information stored in the Q-value table. However, the direct problem is that network energy optimization constitutes local, not global, optimization. Based on the problems caused by the reinforcement learning mentioned above, Su et al. proposed a deep Q-learning (DQN) based energy and latency aware routing protocol, DQELR (Javaid et al., 2019). The protocol uses the minimum energy consumption and the shortest delay as the objective function of the network, so that the network maintains a short delay under the condition of a dynamic topology and its lifetime is maximized. Deep reinforcement learning is a combination of reinforcement learning and deep neural networks. Deep neural networks can realize feature extraction of high-dimensional information, which can perfectly overcome the dimension crisis of reinforcement learning.

Table 2
Routing protocol.

CAT	Description
Layered Network	AD: Low complexity, Easy to implement, Low demand for network topology. DA: Difficult to control energy consumption and deal with voids
Clustering Network	AD:Strong scalability, Balanced energy consumption DA:The algorithm complexity is slightly higher, and the network performance is greatly affected by the protocols
Multimodal Network	AD:Effectively improve network performance DA:It has higher requirements on network topology and requires better resource allocation algorithm
AUV	AD:An effective method for big data transmission DA:High network latency

The input state and action in the DQELR protocol are approximately 1300 tuples, and the neural network uses a five-dimensional model (including the bias term b1) and three hidden layers of fully connected networks. This protocol can approximate the optimal solution globally, and the experimental results are slightly improved as compared with those of the Q-learning-based energy-efficient and lifetime-aware routing (QELAR) and VBF protocols (Faheem et al., 2018) (Xie et al., 2006). The studies in the literature also indicated a problem: because a neural network requires a large amount of data for training, the protocol needs a reinforcement learning algorithm to learn the environment in real time, and the learning process has a long delay, it may take a few hours or more for the neural network to reach a convergence state. To avoid this problem, the DQELR protocol adopts a combination of offline and online training; the convergence of the algorithm is greatly accelerated through the offline training before the protocol is formally applied. The underwater network models given in (Faheem et al., 2018) (Xie et al., 2006) are dynamic network node models. The proposed routing protocol should be able to guarantee fully the reliable data transmission of the network with strong adaptability when the network topology changes dynamically. In addition, Nadeem et al. also utilized reinforcement learning to avoid the occurrence of void nodes in routing protocols by using the adjacent node technique, QLEEBDG-AND (Javaid et al., 2018). The application of the machine learning method to underwater routing, which provides each node in the network with a certain intelligent decision-making ability, is an effective solution for underwater routing and is also a hot research topic. Finally, we provide the classification diagram of a routing protocol and summarising advantages, and disadvantages of the categories described in Table 2. We classify existing routing protocols as shown in Fig. 3.

3.2. Medium-access control protocols

The medium-access control (MAC) protocol is a key technology for network access and thus has been widely studied for many years as a classic problem in wired and wireless networks. Useful research studies have been conducted on the MAC protocol of underwater acoustic sensing networks. These studies can be divided according to the channel access strategy that they addressed: resource allocation, resource competition, or hybrid.

The resource allocation type MAC protocol is divided into three main types: frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). FDMA realizes multiple access by frequency division, the orthogonal FDMA (OFDMA) protocol adopts orthogonal frequency division technology to optimize channel allocation, the CDMA protocol realizes multiple access by spreading coded allocation, and the TDMA protocol realizes multiple access by dividing the time frame, reducing packet conflict (Sozer et al., 2000).

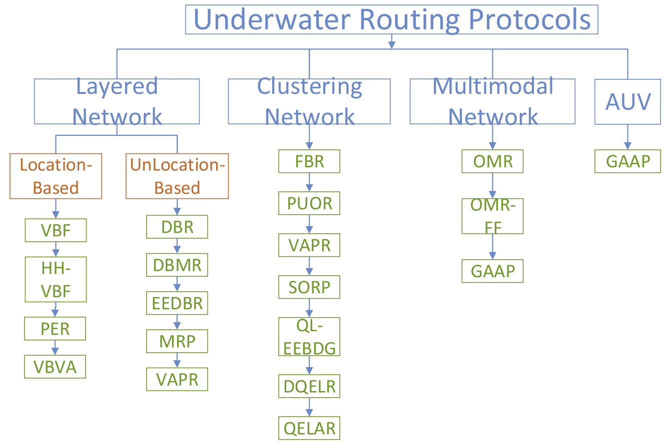

Fig. 3. Routing protocol for underwater wireless sensor networks.

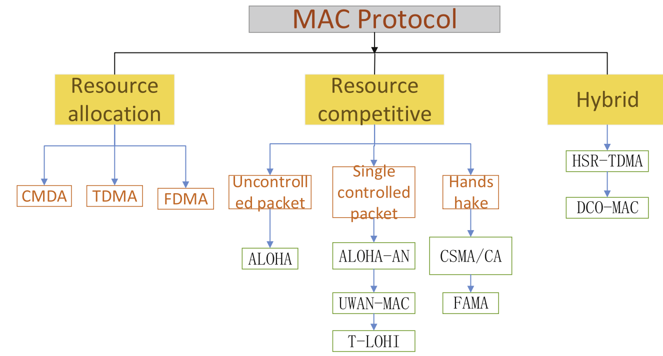

Fig. 4. Medium-access control protocols for underwater wireless sensor networks.

The core idea of resource-competitive MAC protocols is to obtain a wireless channel in a competitive manner for a node that needs to transmit data. They can be further divided into uncontrolled packet protocols, single controlled packet protocols, and handshake protocols. The main idea of the uncontrolled packet MAC protocol is that "send is up to you," but packet conflicts are easily generated. ALOHA (Abramson, 1970) is a typical uncontrolled packet protocol. Its extended protocol reduces collisions by combining channel listening (Chirdchoo et al., 2007), inferring the neighbor node working state (Chirdchoo et al., 2007), dividing time slices (Luiz et al., 2006), and a handshake protocol (Hongning et al., 2009). The core idea of the single control packet MAC protocol is to "use a single control packet to notify that adjacent channels are already occupied." These protocols include ALOHA with advance notification (ALOHA-AN) (Chen and Wang, 2007), under water acoustic network MAC (UWAN-MAC)) (Kyoung and Volkan, 2007), and the T-Lohi protocol (Syed et al., 2008). Based on the T-Lohi protocol, packet time division is further reduced by dividing time slices into units of contention cycles, utilizing asynchronous channel competition, and directly retreating (Di et al., 2011). The handshake protocol exchanges two-way information through channel interception and reduces the packet collision rate by reducing the number of occupied channels. The carrier sense multiple access/collision avoid (CSMA/CA) protocol (Youssef et al., 2002) is the most typical handshake MAC protocol. In the underwater acoustic sensor network, the problem of the exposed or hidden terminal is serious. Therefore, considerable research has been conducted on the handshake type MAC protocol in the underwater acoustic sensor network. When the hidden terminal problem exists, if a channel is detected as idle it does not necessarily mean that the channel is available; likewise, when the exposed terminal problem exists, if a channel is detected as busy, it does not necessarily mean that the channel is unavailable. To reduce the energy consumption caused by carrier sensing, some protocols no longer use carrier sense technology. Multiple access with collision avoidance (MACA) (Karn, 1990) is the first handshake protocol that does not use carrier sense; the channel negotiation is completed directly through the three-way handshake. On this basis, in studies in the literature (Bharghavan et al., 1994) the persistence strategy has been utilized to improve further the performance of the protocol. In the handshake protocol, packet collisions usually occur at the receiver because of the hidden terminal problem. Therefore, to solve the hidden terminal problem some protocols extend the control packet transmission time and ensure that all relevant neighbor nodes can receive relevant control information before the data packet is sent. The floor acquisition multiple access (FAMA) protocol (Fullmer and Garcia-Luna-Aceves, 1995) was the first protocol that could reduce packet collisions by adopting a delay control packet. On this basis, strategies, such as time slot partitioning (Molins and Stojanovic, 2006), sending alert packets (Peleato and Stojanovic, 2007), and scheduling data sending start and stop times (Guo et al., 2006), are utilized to solve further the hidden terminal problem. A node does not understand the data transmission requirements of other nodes and blindly transmits data according to its own needs, which is the root cause of packet conflicts. In relevant studies, space-time inconsistency was used to improve channel utilization and achieve parallel data transmission between multiple node pairs by the following or similar means: transmission of data packets and control packets together (Vanphuong et al., 2014), establishing and publishing node work schedules (Volkan and Kyoung, 2005), bidirectional data relative transmission (Liu et al., 2014), one (multiple) versus multigroup transmission (Chirdchoo et al., 2008), delayed response RTS control packet (Tracy and Roy, 2008), and advance reservation of next data transmission (Hu and FeiDSH-MAC, 2013).

Table 3
MAC protocol.

CAT	Description
Resource allocation	AD: Reducing packet conflict, No hidden terminal issues, Easy to sleep, Suitable for low power network DA: It cannot adapt to network topology flexibly.
Resource competitive	AD:Adapt to the changes of network topology.No complex time synchronization or control scheduling algorithms are required. DA:Conflict retransmission
Hybrid	Can effectively balance the advantages and disadvantages of the above two types of protocols

The hybrid MAC protocols that integrate multiple competing mechanisms and multiple access technologies, such as FDMA, TDMA, and CDMA, show a better performance. The hybrid MAC protocol has rapidly become a hot research topic in recent years. The existing research studies addressed mainly protocols that combine TDMA and CDMA protocols (Diamant and Lampe, 2011), TDMA and competition protocols (II and Mohapatra, 2007) (Namgung et al., 2010), and CDMA and competition protocols (Pompili et al., 2009) (Pompili et al., 2009). We show the MAC protocols in Fig. 4 and Table 3.

3.3. Underwater multimodal network

According to research on underwater networks, it is not feasible to build a high-speed and reliable underwater network using only one communication method. Multimodal underwater networks (MDUNs) based on different communication means are the most likely network form for the future.

It can be seen in Fig. 1 that three modes of communication coexist in the entire network. The sink node is located on the water surface, the subgrade base station is the data convergence center, and the RF used to communicate between the sink and the base station is also used between the sink and the sink. The sink node communicates with the underwater node and the underwater auxiliary autonomous underwater vehicle (AUV) through different frequency bands. The auxiliary AUV and the underwater node transmit data through short-range UOC.

The current definition of underwater polymorphic networks is not clear. When a system contains any set of technologies that do not interfere with each other, it is defined as multimodal (Diamant et al., 2018). Roee proposed a routing protocol based on MDUNs (Diamant et al., 2018). The MDUN discussed in this paper is an underwater network that uses three different frequency bands. The three frequencies of UAC are assumed to be mutually non-interfering. Roee used a combination of high-, medium-, and low-frequency UAC to form a six-node network. High- and medium-frequency hydrophones can transmit high and medium speed short-range data. Low-frequency underwater sound can travel over long distances. All nodes can be equipped with various UAC modulators of different frequency bands, and multiple links may exist between two adjacent nodes in the network. An additional MDUN model was proposed in (Han et al., 2019). The three communication methods, UOC, UAC, and electromagnetic waves, were adopted in the model. The overall network framework consists of a sink node, an underwater data source node, and a data offloading auxiliary AUV. The sink node is located on the surface of the water and collects underwater data. The underwater node is fixed in the underwater detection area by the anchor chain to generate video information. The data packet is generated at a speed of 5 M/min, and the AUV is used for underwater data unloading. The AUV and underwater nodes simultaneously have UAC and UOC capabilities, and the AUV also has wireless electromagnetic wave communication capabilities. The underwater node sends control information to the AUV through UAC to determine its node access path. The AUV unloads the node data packet through UOC when accessing the node, and then, the AUV surfaces and sends the data packet to the sink node through electromagnetic wave communication.

The above two network models represent two typical multimodal underwater networks: non-AUV-assisted and AUV-assisted polymorphic networks. In our opinion, the underwater acoustic network proposed by Roee et al. is not a true MDUN. An underwater network using multiple medium communication technologies is more polymorphic. Its network form is representative, high-speed, and short-range, and the multimode network combining long-distance and low-speed communication technologies can improve the network delay, throughput, robustness, etc. as compared with the single mode network, and can ensure the reliable transmission of data. The superiority of the network architecture can sometimes greatly improve the performance of the network. For an ocean network, a pure underwater acoustic network can ensure sufficient coverage but cannot achieve big data transmission. A pure UOC network can achieve big data transmission but does not guarantee sufficient ocean coverage. Currently ocean data are growing exponentially, and multimodal underwater networks or heterogeneous underwater networks are more advantageous network models.

4. Autonomous underwater vehicle-assisted underwater wireless sensor networks

In the previous section, we mentioned a multistate network model that uses an AUV to assist data unloading. The AUV accesses the data source node unloading information in a network according to a certain algorithm and realizes the data transmission of video information (Yan et al., 2018). The algorithm of the AUV visiting path under this type of network becomes a key factor in network performance.

The addition of AUVs in an underwater sensor network undoubtedly improves the reliability of its data transmission. When a network includes AUVs, their number, access path, and energy consumption affects the network data transmission. At present, few research studies on AUV-assisted underwater networks exist. In (Gjanci et al., 2018), AUV path planning in a polymorphic network environment was examined, and the authors proposed a heuristic decision algorithm, greedy and adaptive AUV pathfinding (GAAP). GAAP enables AUVs to maximize the information value of the network and can adapt to emergencies that occur in the network. The algorithm in this paper enables an AUV to transmit network data to more than 80% of the theoretical maximum. GAAP has achieved good results in the path planning of a single AUV, but when the number of AUVs in the network increases, the problem of node access duplication affects the algorithm, which greatly influences the network performance. Petrika et al. research on underwater AUV path planning shows that the path decision method for underwater AUVs is an important part of the future underwater network. AUV-assisted communication methods have advantages over large-scale data transmission that are unmatched by traditional communication methods.

In AUV-based underwater multistate networks or heterogeneous networks, multiple AUV path decision algorithms, the optimization of AUV energy consumption, and intelligent path algorithms still need to be addressed. The AUV path planning problem is essentially a routing problem; however, it differs from routing. The routing algorithm has not been applied to the path decision of AUV, which renders this problem a new research topic. In the future, underwater networks will inevitably include AUVs. The research on AUV path finding can improve the reliability of underwater network data transmission. In the future, the AUV path decision protocol in the underwater network protocol stack will become important.

5. Challenges

To achieve reliable data transmission is a very difficult challenge in the ocean environment. We discuss the theory and methods used in underwater data transmission in the following sections. Challenges and open-ended questions based on existing research phases are presented and summarized in Fig. 5.

5.1. Communication

5.1.1. Underwater acoustic communication issues and challenges

Whereas the advantage of UAC for underwater communication is that long-distance communication can be realized and the communication distance can reach several tens of kilometers, it has serious defects in terms of the transmission rate, delay, and BER. Factors such as channel fading and multipath effects are important issues affecting UAC. In the current UAC research studies, the channel fading problem could be effectively handled by applying an equalization technique, but a reliable channel model needs to be established. For handling multipath effects, OFDM technology shows a better performance but requires auxiliary equalization techniques to correct the Doppler shift. To handle the low communication rate, MIMO-OFDM technology is adopted to increase bandwidth utilization and multiantenna technology to achieve improvement in the communication rate. In recent years, significant progress has been achieved in UAC, but it still presents many challenges. First, the diversity and complexity of the underwater environment render the modeling of underwater acoustic channels difficult and non-universal, requiring a reliable underwater acoustic channel estimation algorithm. Second, the high delay characteristic of UAC is the most difficult problem to solve. At present, no effective means exists to reduce the delay of UAC and no research related to this problem has been conducted. Third, the safety of UAC is a key issue in the future use of underwater acoustic networks. A secure authentication mechanism, reliable coding technology, and precise positioning technology will affect the safety and reliability of UAC.

5.1.2. Optical communication problems and challenges

The two major advantages of UOC over UAC are the extremely high transmission rate and the millisecond delay; however, the short communication distance allowed by UOC is a major obstacle to its development. At present, the longest transmission distance that can be achieved

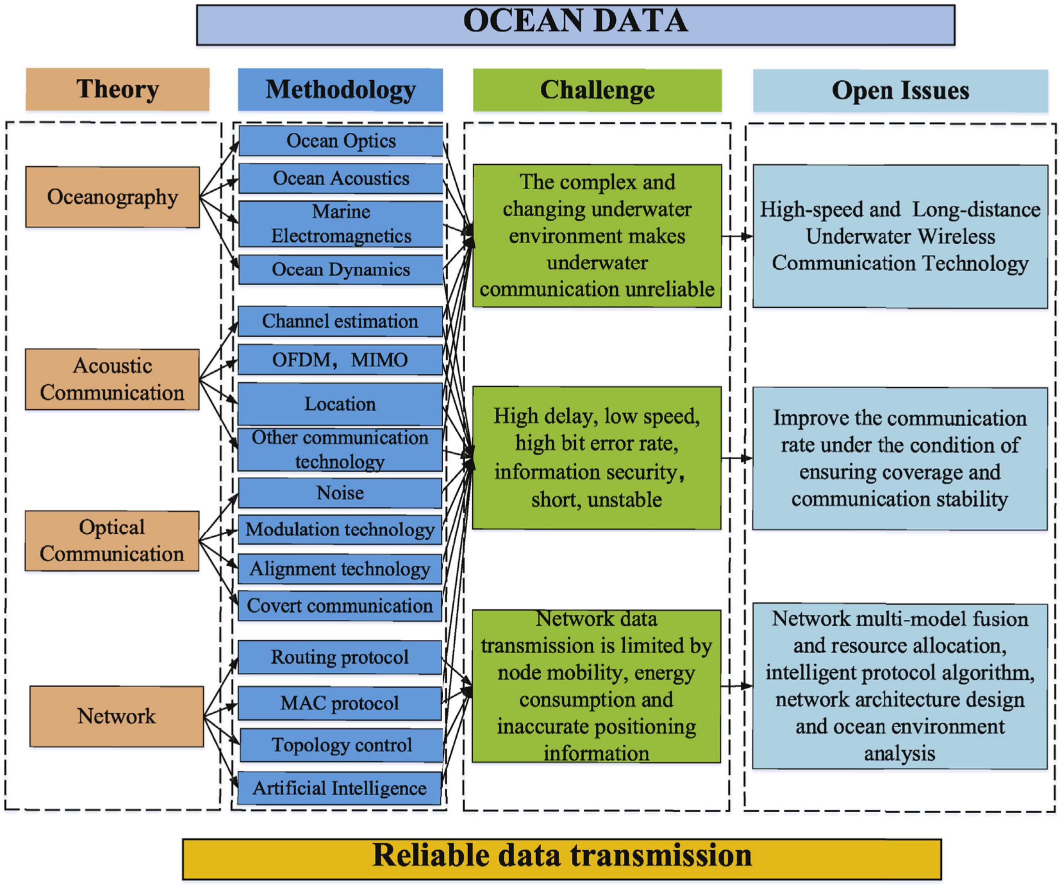

Fig. 5. Ocean reliable data communication challenges.

in a calm underwater environment is only 500 m, which is far from meeting the requirements of the smart ocean network. Because of the use of light as a communication medium, UOC nodes are prone to expose the location of the transceiver, which, in the aspect of military security, makes it difficult to implement secret communication. In addition, point-to-point UOC systems require highly accurate calibration techniques, but communication nodes frequently cannot easily maintain a stable position in an underwater environment. If a power system is used to maintain stability, the energy consumption of the nodes is increased, which reduces their lifetime, seriously affecting the data transmission efficiency and stability. The point-to-point communication method relies on the laser emitting unit, which consumes a large amount of energy and is heavily dependent on the water quality of the environment. To solve this problem, an underwater communication system using a scattered light source will be substituted. However, the light intensity scattering of the scattered light source causes the data transmission distance, channel noise, rate, and BER to be degraded, and thus, it is impossible to replace the application of the point-to-point communication system in specific scenarios. Therefore, the UOC system should also be diversified. The comprehensive utilization and networking of multiple UOC systems may be an important future topic.

5.2. Networking

The realization of underwater networks is the ultimate goal of applying underwater communication technology, and the importance of building a maritime network is self-evident. At the network level, underwater routing is an important problem in underwater networking and has been studied more than any other aspect in recent years. Underwater routing introduces more problems and challenges than traditional land routing. In general, the topological structure of a land network does not involve the problem of height. In such a network, the routing algorithm needs to be considered and designed only on a two-dimensional plane and the connection between nodes in the network is stable. However, in the underwater environment, the network topology constitutes a three-dimensional structure. First, this significantly increases the complexity of network routing algorithms, and second, the node location is affected by the ocean and changes significantly. The instability of the communication connection between nodes and the energy limit of nodes are important challenges in the design of routing algorithm; in addition, MAC protocol problems also have similar routing problems.

With the popularity of machine learning in recent years, many scholars have proposed underwater routing algorithms, underwater channel estimation methods, and equalization algorithms based on machine learning. Algorithms based on machine learning can handle underwater node mobility, information VHs, and node energy consumption effectively. The effect of these algorithms as compared with greedy algorithms will lead to a more reliable performance. Intelligent algorithms frequently require a large amount of data training and powerful computing power, which undoubtedly introduces more overhead to the network. UAC systems can achieve high coverage but a very low communication rate, whereas UOC systems achieve a high communication rate but low area coverage. The MUDN form that integrates UOC and UAC can ensure coverage and realize local high-speed data transmission, but bottlenecks in the network, which affect delay and throughput, still remain. The application of underwater AUVs for auxiliary data transmission in the underwater network can significantly ameliorate these bottlenecks. Although the change in network structure will lead to a performance improvement, it will also introduce problems, such as the path planning problem of AUVs and the resource allocation problem of underwater acoustic and optical systems.

6. Conclusion

According to underwater communication technology and network research, we can conclude that the future of ocean data transmission will involve the multimodal and heterogeneous characteristics of different communication technologies after employing a reasonable deployment topology technology. The resources of network nodes and different areas in the network vary. Moreover, the regional communication rate and quality will have a clear difference. In ocean communication, no communication technology, network structure, or protocol exists that can fully adapt to all the application environments, and thus, diversity will be the distinctive feature of future ocean communication networks. In addition, traditional non-intelligent algorithms have shown clear deficiencies in terms of the changeable ocean environment. Network protocol algorithms based on artificial intelligence will play an important role in the future ocean network.

In this survey, we first examined the existing survey papers and background. We discussed underwater communication technologies, including UAC and UOC, and networking cover routing protocols and MAC protocols. The factors affecting the reliability of underwater network, including communication technology and network technology, are investigated and analyzed. Then we analyzed the current research advances, underwater multimodal UWSNs, and AUV-assisted UWSNs. Finally, we highlighted issues and challenges that must be addressed in the future to improve underwater data transmission. We hope that this review will help researchers and developers understand the perspectives and current state of underwater data transmission development, and the challenges it presents.

Conflict of interest statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Acknowledgment

This research was supported in part by the National Natural Science Foundation of China Joint Fund under Grant No. U1701263, the National Natural Science Foundation of China (NSFC) under grant No. 61672131, No. 61871286, the Innovation Foundation of Tianjin University and Tianjin Key Laboratory of Advanced Networking (TANK).

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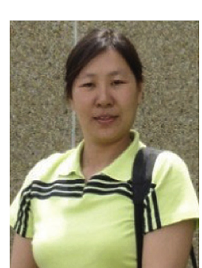

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