Reliable Data Collection Techniques in Underwater Wireless Sensor Networks: A Survey

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***Abstract*—Reliable data collection techniques, whose aim is to ensure that sensed data are received successfully by a sink, are essential for applications in Underwater Wireless Sensor Networks (UWSNs). However, traditional data collection with Radio Frequency (RF) functions poorly in UWSNs due to peculiar features of underwater. Moreover, acoustic communication creates challenges for the reliability of data collection such as high bit error rate, packet collision and voids in routing. Furthermore, the deployment of Autonomous Underwater Vehicles (AUVs) in some scenarios changed the paradigm of data collection and introduced new issues that affect reliability such as inaccurate navigation and lengthy travel time. Consequently, numerous studies focus on the relative reliability of various currently available data collection in UWSNs. In this paper, we first review the problems specific to UWSNs and their impact on reliable data collection. It is followed by a discussion about characteristics, challenges, and features associated with the design of reliable techniques in UWSNs. Afterward, to provide readers with an overview of reliable data collection techniques in UWSNs, this paper categorizes them according to their ability to enhance reliability at all the key stages of data collection. In this categorization framework, the advantages and disadvantages of each technique have been in-depth discussed. Finally, several possible areas for further research are identified and discussed.**

***Index Terms*—Data collection techniques, UWSNs, reliable, bit error rate, packet collision, void in routing, AUV.**

I. Introduction

THE OCEAN occupies more than seventy percent most of Earth's surface, yet we know very little about the natural and biological resources in the ocean. This represents a significant gap in scientific knowledge, as underwater exploration and monitoring are regarded as important aspects of the global economy and global security. Reliable data collection from underwater environments provides essential support for these studies, enabling data to be successfully received by sinks. For example, in underwater petroleum exploitation, reliable data collection is the basis for determining the location of petroleum. Furthermore, almost all underwater applications, including aquaculture, coastal surveillance and protection [1], monitoring of oil industry deployments [2], telecommunications, pollution and climate control [3], search missions and preservation of cultural heritage [4], rely on data collected underwater.

To improve the reliability of data collection in underwater environments, interest has been growing recently in using underwater wireless sensor networks (UWSNs), which consist of multiple sensors with the capability of sensing, storing and forwarding in data collection. However, several events can lead to data collection failure, including data corruption caused by interference and collision, and data loss caused by a wrong path. These events become much more challenging in the complex underwater environment than on land because the signal propagation medium widely used in terrestrial environments, such as radio frequency and optical communication, have limited application underwater [5]. Specifically, robust communication between sensor nodes can only be sustained for a few meters [6]. Furthermore, sensors may move with the water current and have limited energy, increasing the probability of such events.

In view of these immutable limitations, many schemes have introduced Autonomous Underwater Vehicles (AUVs) that travel between sensors to assist data collection. By leveraging the mobility of AUVs, signal propagation distance can be significantly reduced, thereby making RF, optical, and so on available in underwater environments. In addition, the presence of an AUV can alleviate the effects caused by the limited energy of sensor nodes. While limited by the speed of the AUV (roughly $1-5$*knots* [7]), which is three orders of magnitude slower than the propagation speed of acoustic waves (approx. 1500*m/s*), the corresponding result is that the collection time by AUV is normally longer than hop-by-hop data delivery by sensor nodes. In some data collection tasks, AUV-aided collection cannot meet the demand for time-sensitive data, in effect causing the loss of this part of the data. Moreover, satellite-based location and navigation techniques cannot work well in underwater environments. Other positioning and navigation methods also have a degree of inaccuracy caused by noise and interference from the underwater environment. Therefore, AUV-aided data collection techniques also involve reliability issues that must be resolved.

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In considering the various challenges of reliable data collection with or without AUVs, this paper divides the relevant published literature into two models: (1) hop-by-hop data collection and (2) AUV-aided data collection. The first model typically uses acoustic communication between nodes to replace the signal used in terrestrial environments [8]. Even when acoustic communication is bandwidth limited (*kb/s*) [9], it performs better over long transmission distances. In the second model, AUVs visit sensors to collect data, which effectively reduces the transmission distance. Alternatively, AUVs can act as a mobile relay or scheduler to mitigate the energy consumption of nodes.

Both models have unique characteristics and are best suited for different scenarios. Consequently, each poses different problems in terms of improving the reliability of data collection. The hop-by-hop transmission model must ensure reliable end-to-end transfer paths from source nodes to sink and reliable links between neighboring nodes. In other words, it must propose reliable routing design against packet loss and reliable link control against bit error and packet collision. As for the AUV-aided model, the main considerations are the accuracy of AUV location or navigation and optimization of the AUV path. Navigational accuracy refers to the precision with which the AUV guides itself from one point to another, it ensures that the AUV can travel close enough to enable reliable various communication. However, the accuracy of navigation techniques is difficult to ensure due to the complex underwater environment. The AUV pathway determines the order in which nodes are visited, which can ensure some valuable data from being collected in time but lead to unbalanced energy consumption between sensors. Unbalanced energy consumption will lead to void regions and incomplete data collection and thus affect the reliability of the data collected.

Numerous studies focus on the relative reliability of data collection in UWSNs, however, most of them are scattered in some available surveys which only covered a part of stages in data collection. As an illustration, the survey [10] reviewed a large number of UWSN MAC protocols which only ensure the link reliable during data collection. Similarly, techniques reviewed in [11] and [12] are interested in UWSN routing and AUV navigation separately. Although some surveys (e.g., [13]) provides multiple data collection stages, there is no clear lineage and classification around the reliable techniques of data collection. Different from previous surveys, this paper reviews not only comprehensive coverage of reliable UWSN data collection techniques, but categorizes and analyses them according to their characteristics on reliability. Specifically, reliable data-collection techniques for UWSNs reported in the literature are mainly divided into hop-by-hop and AUV-aided data collection models. To facilitate understanding of the major techniques used to improve reliability in data collection, we identify the two components of both models that apply to all key stages of data collection. Following further discussion of specific techniques that address the above-mentioned issues at each stage, some remaining issues for reliable data collection and possible directions for future research are considered.

The remainder of this paper is organized as follows: Section II provides an overview of the reliable data collection techniques in UWSN, including their characteristics, challenges and categorization. Section III briefly discusses reliable routing in hop-by-hop UWSN data collection. Section IV reviews data collection schemes in relation to link reliability, with a focus on bit error tolerance and packets collision-free packet scheduling during transmission. Section V reviews AUV navigation techniques for improving the reliability of data collection. The reliability of AUV travel is comprehensively discussed in Section VI. Section VII highlights a number of issues that remain unaddressed and therefore require further study. Section VIII concludes the paper.

II. Overview of Reliable Data Collection Techniques in UWSNs

This section briefly discusses the characteristics and challenges of reliable UWSN data-collection scheme design. A classification system for the UWSN reliable data-collection techniques surveyed is then proposed.

A. Characteristics and Challenges for Reliable Data Collection in UWSN

The complex underwater environment dictates following characteristics of data collection schemes in UWSNs: 1). Acoustic communication has inherent properties such as high latency and limited channel capacity. The acoustic propagation speed is five orders of magnitude slower than light speed in RF wireless networks. In addition, sound velocity varies based on different parameters such as temperature, salinity, and depth of water. As a result of the limited bandwidth, the data rate for underwater sensors rarely exceeds 100 *kbps* [14]. Note that the testing environments are different in previous works and thereby have a significant difference exists in the measurement range. In a given experimental environment parameter in [15], the end-to-end latency of different protocols are about 1.10 Sec. 2). Energy consumption by sensor nodes is a significant problem. Due to the special features of that environment, sensors in UWSNs are generally powered by batteries whose relative inaccessibility makes it difficult to recharge or replace this limited power supply when exhausted [9]. 3). UWSNs are three-dimensional, objects residing in an underwater environment and commonly exhibit passive mobility with water currents or active mobility exhibited by autonomous platforms. For instance, [16] sets a sensor move for 3 meters every second in a random horizonal directions. 4). Satellite-based location and navigation cannot work well for sensors or AUVs, which must use other methods when they submerged [17]. For example, the precisions for common commercial off-the-shelf Global Positioning System (GPS) is about 10*m* and the accuracy of other GPS are also in the meter range [12]. and 5). AUVs take a long time to travel between multiple sensors. For a AUV with speed 5*knots*, it need to take about 10 minutes per round to collect data [7]. Given the above-mentioned characteristics, reliable data collection in UWSNs faces the following challenges:

1) High Bit Error Rate: Compared to the wireless channels in terrestrial wireless sensor networks (TWSNs), underwater acoustic channels operate in more challenging conditions due to ambient noise, external interference and strong attenuation with increasing frequency [18]. The average signal-noise ratio of a channel with a $3000m$-long link in a $100m$-deep water is about $9 - 5.7dB$ within less than 1.5 minutes. The Doppler effect has a larger frequency shift and bandwidth spread at receivers in UWSNs because its magnitude is proportional to the ratio of the sender-receiver relative speed and the signal propagation speed [10]. As the relationship between Doppler scale and relative velocity between any pair of nodes is $v = ac$, where v is the relative velocity, a is the Doppler scale, and c is the sound speed. And relative velocity estimation based on Doppler can achieve a promised performance from the obtained data, e.g., Mason *et al.* [19] reach 0.1m/s deviation for node speed with maximal velocity $5m/s$ (9.7 *knot*). These phase and amplitude fluctuations lead to a high bit error rate (BER). Moreover, most available underwater acoustic channel modems can only support the half-duplex mode [20], which makes bit error tolerance design in UWSNs more costly.

2) Packet Collision: The limited bandwidth of acoustic channels results in long transmission and reception times, which increases the probability of collision between packets. The neighborhood of a node will constantly change due to characteristic 3) above, making it difficult for a node to obtain geographic information about its neighbors. The problem of hidden terminals [21] in 3D UWSNs is more intense due to the presence of neighbouring nodes in additional directions. Because of the uncertainty of neighborhood information, senders cannot know exactly whether a new packet transmission will achieve a collision-free reception.

3) Void in Routing: Void in routing refers that in a certain routing strategy, there is no available forwarding nodes for a packets even though there exist a valid path to sink. As depicted in Fig. 1, the routing strategy is that only the forwarder with the lowest depth in the transmission range can forward. Node e is regarded as a void node since it has no available neighboring node closer to sink as its forwarder. When node c has a packet from node A to be forwarded, it will select e instead of d as the next-hop under such a routing strategy, the packet thus falls into the void region and may be dropped. In UWSNs, void regions are more likely to occur, but predicting when and where is more difficult due to characteristics 2) and 3) above. In other words, the movement or exhausted energy of nodes may create additional voids and even make voids mobile. Critically, it is unrealistic to find a fixed routing path with a dynamic network topology. Without resolving such situation, the packet may be dropped even though there is a valid path from the sender to the destination [22]. As a result, data packets entering the region cannot find a route towards the destination.

4) Inaccuracy Location and Navigation: In TWSNs, the location and navigation system is satellite based and uses radio signals. However, such signals can only propagate in shallow waters and thus there is no access to a satellite in deep water [23]. As a result, accurate sensors and AUV location are hard to obtain and specialized navigation methods must be designed for AUVs that not only rely on satellite signals. Although acoustic communication performs better in UWSNs, it cannot achieve the same level of accuracy as RF performs in TWSNs. Equipped sensors usually generate measurement errors, the cumulative effects of which increase unbounded over time [24]. Node movement in three-dimensional UWSNs also poses greater challenges for navigational accuracy and path planning. Inaccurate navigation will cause an uncertain communication distance and quality between sensors and the AUV, thereby decreasing the reliability of data collection.

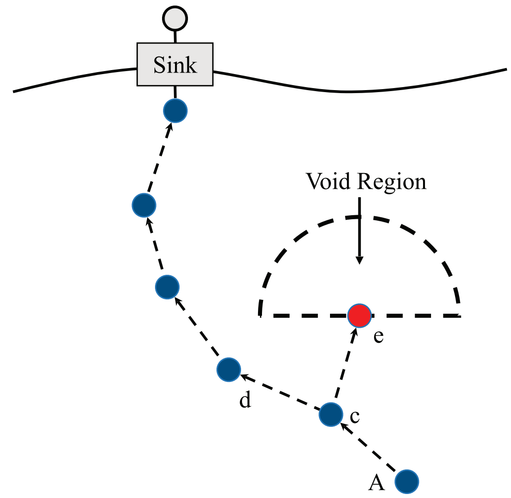

Fig. 1. An example of Void Region.

5) Long Travel Time of AUV: The driving speed of an AUV is relatively slow and there may be a long sequence of nodes to visit, resulting in a long travel time. This means that data in some nodes with a lower access priority may lose their information value while waiting for the arrival of the AUV. On the other hand, to satisfy the latency requirements of some data, other data may not be collected, which means that the data collection in that area is incomplete. Both scenarios will result in unreliable data collection.

B. Category of Surveyed Reliable Data Collection Techniques in UWSNs

The reliable data collection techniques surveyed in this paper can be roughly divided into two categories: hop-by-hop collection and AUV-aided collection, as illustrated in Fig. 2. The first category can be further divided into reliable link techniques and reliable routing techniques, which will be discussed in Sections III and IV, respectively. The second category includes reliable navigation (Section V) and reliable traveling (Section VI) of AUVs, which relate to the reliability of data collection in various ways.

The reliable link technique refers to the successful data transmission between neighboring nodes. It is primarily designed to solve the bit errors and collision caused by interference and multiple sensors which cannot share a common medium fairly respectively. The main techniques for preventing bit errors include redundancy and retransmission mechanisms. The redundancy mechanism (e.g., Forward Error Correction (FEC)) puts redundant data into packets to provide the receiver with error detection and correction capabilities, while in retransmission (e.g., Automatic Repeat Request

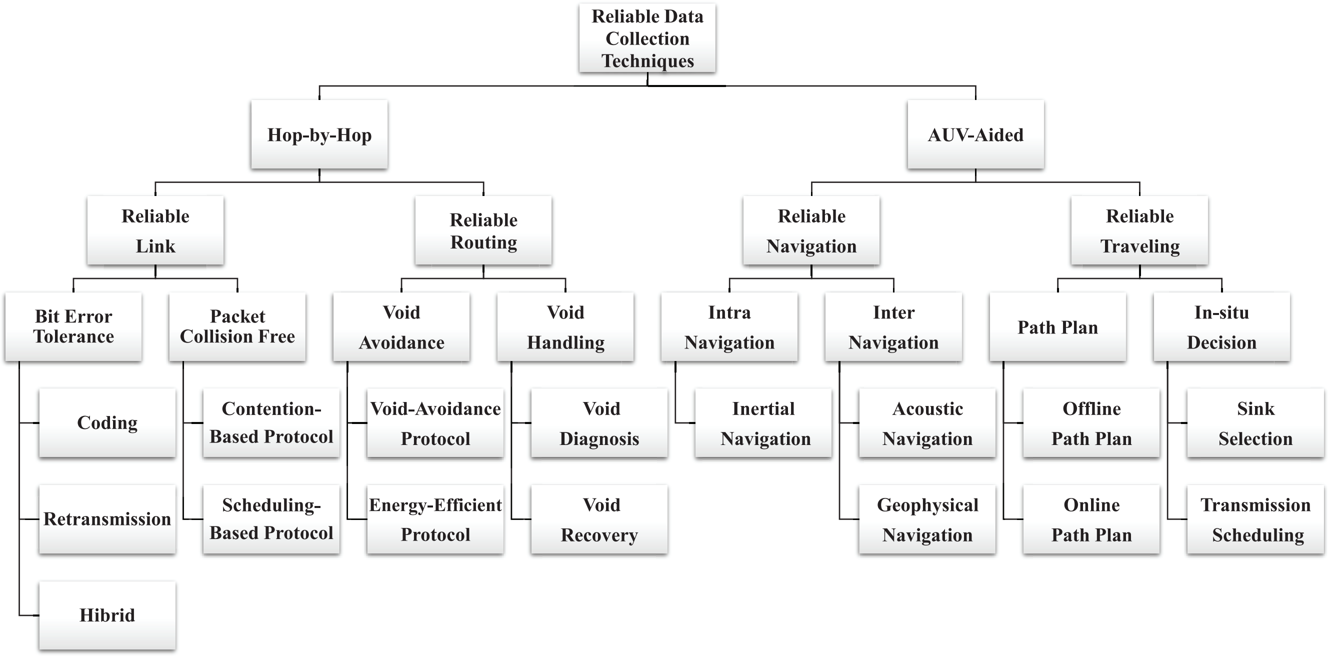

Fig. 2. Category of Surveyed Reliable Data Collection Techniques in UWSNs.

(ARQ)), the sender retransmits unsuccessfully received packets to assure transmission reliability. Collision avoidance is one of the main task of each Medium Access Control (MAC) protocol. In addition, underwater MAC protocols face many new challenges such as mobility support, longer propagation and transmission delay, spatio-temporal uncertainty [10]. They are classified as scheduling based, reservation based and cross-layer based in this paper.

Reliable routing techniques involve a reliable end-to-end transfer path from the source nodes to the sink, whose primary focus is on packet loss during routing. In UWSNs, packet loss occurs when the forwarding node cannot find a qualified node with a positive progress towards the destination, which is known as the void problem [11]. The surveyed techniques for solving this problem can be divided into the following two categories: void avoidance and void handling. Void avoidance techniques refer to those protocols designed to prevent packets from falling into the void area. However, when the void region is inevitable or a void has already occurred, void handling techniques are applied to locate and fix the void.

Navigational accuracy refers to the precision with which the AUV guides itself from one point to another [12]. The inability of AUVs to reach a predetermined location precisely will cause uncertainty in the quality of communications, thereby has an impact on the reliability of data collection. Techniques to improve navigational accuracy fall into one of three main categories: Dead Reckoning (DR), acoustic navigation and geophysical navigation. Specific methods to improve navigational accuracy will be discussed in accordance with these three techniques respectively.

Different approaches to path planning mainly affect the reliability of data collection in two aspects: incomplete data collection and sampling. To address the issue of incomplete data collection, current research has mainly focused on optimizing online and offline trajectory design algorithms by considering the timeliness and efficiency of the data. The incomplete sampling refers to the absence of data in some region due to the death of nodes. Unlike the problem of node lifetime in reliable routing techniques, the leverage of AUVs has relieved the energy consumption of nodes. However, because not all scenarios enable AUVs to visit each node per round, the trajectory design of AUVs may lead to unbalanced energy consumption between nodes. To further increase the lifetime of nodes, another type of research regards another type of research regards AUVs as a moving cluster head that schedules nodal transmission and wakeup-sleep time.

III. Reliable Link in Hop-by-Hop UWSN Data Collection

Link reliability is defined as reliable transmission between any two adjacent nodes in one hop. One factor that affects link reliability in UWSNs is the instability of channel quality caused by noise, interference, Doppler distortion, etc., which lead to a high BER [3]. Among them, Doppler effect becomes more severe especially in UWSNs because the magnitude between signal propagation speed and transmitter-receiver relative speed is much lower than they are in TWSNs. The other factor is the long propagation and transmission delays by acoustic communication. The long signal propagation delay leading to asymmetric information of transmission over the link, resulting in undesirable receiver-sender cooperation [10]. The long transmission delay caused by limited bandwidth increases the potential conflicts between packages. Therefore, MAC design strategies widely adopted in TWSNs are not suitable for porting to UWSNs directly.

In this section, we will review some techniques designed for UWSNs to counteract high BER and packet collision.

The bit error tolerance methods can mainly be categorized in terms of who (the sender or the receiver) is responsible for error correction. The sender-initiated approach adds redundant bits to packets while the receiver-initiated approach requests the retransmission of unsuccessfully received packets. These approaches are known as coding and retransmission, respectively. To solve the problem of packet collision at the receiver, MAC design in UWSNs is either reservation-based or scheduling-based. Table I summarizes them with a comparison in terms of collision-free mechanism, decision maker, operation conditions, performance, and major pros and cons. Operation conditions includes the dependence on time synchronization and location information. Whereas the performance mainly includes overhead of protocols and the collision probability after adopting them.

A. Bit Error Tolerance

1) Coding: The coding mechanism for link reliability mainly refers to Forward Error Correction (FEC). Senders embed redundant bits into data packets which receivers use to detect and correct bit errors in the communication process [18]. Channel coding for FEC at link-level often involves erasure codes [25] which transforms a message of k bits into a longer message with n bits such that the original message can be recovered from a subset of the n bits [26]. It is a FEC code under the assumption of bit erasures rather than bit errors. UWSNs use the same type of FEC code as TWSNs, including several linear coding schemes for which any linear combination of codewords is still a codeword. Traditionally, these linear coding schemes are partitioned into block code and convolutional code [27]. Block codes work on fixed-size blocks of bits at predetermined size such as Hamming code, repetition code, Bose-Ray-Chaudhuri-Hocquenghem (BCH), Reed-Solomon (RS), low-density parity-check code (LDPC) etc. For example, a Reed-Solomon code operates on a block of data treated as a set of finite-field elements called symbols, specified as $RS(n, k)$ with s-bit symbols. This means that the encoder takes k data symbols of s bits each and adds parity symbols to make an n symbol codeword. There are $n - k$ parity symbols of s bits each. A Reed-Solomon decoder can correct up to t symbols that contain errors in a codeword, where $2t = n - k$.

Another type of bit-level FEC method are convolutional code, which are error correction codes with memory. In brief, the coding rule is to encode k bits of input information to form n bits; the encoded n code elements not only relate to the current input k information, but remain related to the previous information. They are most often decoded with the Viterbi algorithm which allows asymptotically optimal decoding efficiency with increasing constraint length of the convolutional code, but at the expense of exponentially increasing complexity. However, this method has a high computational complexity which is not applicable to battery-operated underwater nodes.

The bit-level FEC method in UWSNs for link reliability are still the same as those adopted in TWSNs. Generally, the more redundant bits are transmitted, the higher the probability of successful correction. However, due to the limited bandwidth of underwater acoustic channels and the battery-powered energy source, too many redundancy bits in transmission are not suitable for UWSNs. To explore the efficiency of several common bit-level FEC for different data types (e.g., text, images and speech signal) in UWSNs, [28] tested convolutional codes, RS and Reed-Solomon Block Turbo Codes (RS-BTC) in real underwater conditions. Convolutional codes and RS seem more suitable for speech signal transmission with a short frame length, whereas RS-BTC works better for image transmission on longer frames and with a higher computational load.

2) Retransmission: To assure transmission reliability, a retransmission mechanism is triggered when bit errors are detected in received packets [29]. An automatic repeat request (ARQ) protocol is typically used in retransmission mechanisms, and include acknowledgement and timing schemes. The receiver sends an Acknowledgment (ACK) frame to indicate that it has successfully received the packet transmitted by the sender. If a received packet detects bit errors, the receiver sends a Negative Acknowledgement (NACK) frame to inform the failure reception to the corresponding sender. ARQ in TWSNs consists of Stop-and-Wait (SW-ARQ), Go-back-N (GBN-ARQ) and Selective Repeat (SR-ARQ). In SW-ARQ protocol, the sender cannot continue to transmit any other packets without ACK. Conversely, in GBN-ARQ, the sender can continue to transmit packets without ACK and deals with NACK and timeout later. It will returns to this failed data packet and retransmit it, including the packet after it. SR-ARQ only retransmits those packets without a positive ACK from the receiver [30]. The limited bandwidth and long propagation delay of underwater acoustic channels make the existing TWSN ARQ protocols underperform in UWSNs. Therefore, many ARQ schemes have been proposed to enhance their performance in UWSNs.

a) SW-ARQ in UWSNs: Traditional SW-ARQ can be directly applied but with low throughput because of the half-duplex links such as those described in [31]. To against the peculiar features of UWSNs, packet train schemes [32] have been proposed to enhance SW-ARQ by reducing the transmission of ACK. The packet train means that several different packets are sending at the same time. However in TWSNs, the transmission cost of ACK is relatively lower and the reduction of ACK may even create timeliness problems. Specifically, a group of nodes transmit without waiting for ACK one after another like a packet-train. After one packet-train arrives, the receiver responds with an ACK for this group of nodes to convey the result of error correction. The sender then retransmits the uncorrectable packets along with the next group, as shown in Fig. 3, in which data packet 5 is unable to be corrected and can be transmitted with data packets 7–11. Furthermore, in J-ARQ [33], it leveraged the long propagation delay in UWSNs. The sender first continuously transmits packet trains and waits for the earlier ACK but not the most recent one.

b) SR-ARQ in UWSNs: As noted previously, GBN-ARQ and SR-ARQ need full-duplex links for packet transmission and ACK reception without stop and waiting. Obviously,

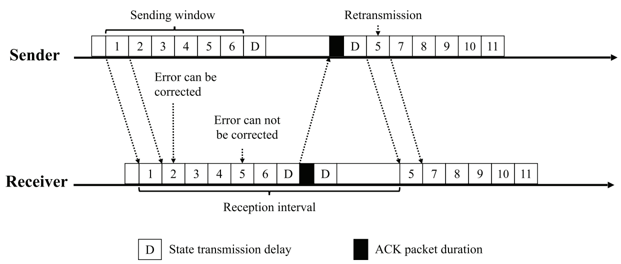

Fig. 3. An example of SW-ARQ in UWSNs.

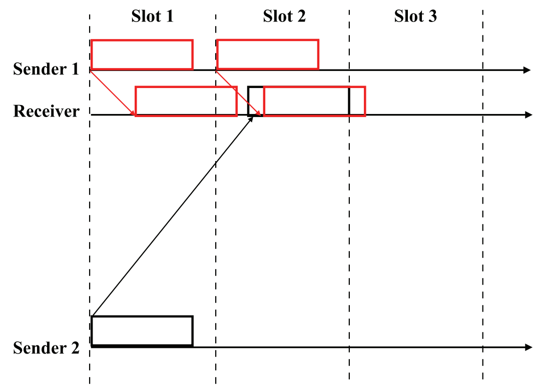

Fig. 4. An example of spatio-temporal uncertainty collision in UWSNs.

SR-ARQ can outperform GBN-ARQ under full-duplex links due to the lower number of retransmitted packets. Thus in UWSNs, some proposals trying to create full-duplex links. To support full-duplex links in UWSNs, the underwater acoustic channel can be split into two sub-channels by frequency division (FD) or time division (TD) technology. However, bandwidth limited underwater acoustic channels will be further reduced by both of FD and TD technology. FD requires a guard band between two sub-channels to against interference. And due to the difficulty of time synchronization in UWSNs [34], TD requires guard times to against inaccurate time synchronization. Furthermore, the time for a node to switch transmission or reception states also affects channel utilization. Thus, it can create full-duplex links by FD or TD to enable SR-ARQ in UWSNs. As an example using FD, the acoustic channel in [35] consists of a common control channel (CCC) and multiple in-band channels. CCC is dedicated to control packets (e.g., ACK). These can be used flexibly for either the transmission of data packets or remaining control packets. In such cases, a node can continuously transmit packets without waiting for ACK and retransmit uncorrectable packets depending on the channel condition. In Underwater Selective Repeat (USR) [36], senders leverage the long propagation delay feature in UWANs to allow the ACK receptions at the interval of multiple sending packets. Initially, a sender follows the SW-ARQ protocol by sending one data packet and waiting for the corresponding ACK to estimate the whole round-trip time (RTT). The sender then calculates the maximum number of continuously transmitted packets that can be interlaced in one RTT with ACK receptions. In other words, multiple transmission of data packets and ACK receptions can use the same channel at different times in one RTT.

3) Hybrid: Note that redundancy and retransmission mechanisms are not in conflict and would have a positive effect on each other. FEC can reduce the number of retransmissions, while ARQ eventually ensures transfer reliability following FEC failure. As shown in [37], FEC and ARQ are jointly used to correct bit error. Two types of hybrid mechanism, referred to as Type-I and Type-II HARQ, are illustrated in this paper. In Type-I HARQ, redundant bits are transmitted with data packets and the bit error can be corrected by the receiver itself. Retransmission will be triggered when an uncorrectable packet occurs following FEC. In Type-II HARQ, by contrast, the sender calculates a parity packet for each transmitted packet but does not forward them at the same time. If a packet is received with error bits, the receiver will ask the sender for the parity packet in order to correct the error. In other words, redundancy packets replace the original data packets in retransmission and redundancy bits are no longer required in each packet. For different scenarios in UWSNs, a variety of redundancy and retransmission mechanisms can be combined into a hybird mechanism, which may perform better in terms of network throughput and average packet transmission delay.

B. Packet Collision Free

Collision occurs when multiple data packets arrive at a receiver at the same time, leading to reception failure. Preventing reception failure is one of the main objective of a MAC protocol [38]. Theoretically, if the receiver decides the transmission timing, it will achieve collision-free reception by scheduling upcoming packets. However, all transmissions are triggered by senders, not receivers. Therefore, to reduce the occurrence of collision and further improve the reliability of transmission, coordination between senders and receivers is necessary. In TWSNs, the signal propagation delay can be negligible, meaning that different senders can obtain transmission information from each other without delay [39]. In this case, collision can be avoided by staggering the sending time. However in UWSNs, even staggered sending times among different senders may result in a collision. For instance in Fig. 4, the packet at slot 2 sended by sender 1 and the packet at slot 1 sended by sender 2 arrived the receiver at the same time. This is referred to as spatio-temporal uncertainty in [39]. Furthermore, carrier sensing, which is widely used in TWSNs, may lead to hidden terminal [40] problems that are more serious in UWSNs due to the long propagation delay.

Viewed from a different perspective, the collision in UWSNs described above could also present new opportunities. For example in Fig. 4, if sender 1 and 2 begin their transmission at the same time slot 1, the two packets will arrive at the receiver without collision. With appropriate MAC design, transmission in UWSNs enables more collision-free concurrency by leveraging the long propagation delay. Mindful of the challenges and opportunities in underwater environments, numerous MAC protocols have been published to resolve the issue of collision in UWSNs. Below, we divide the MAC protocols specific to UWSNs into contention-based and scheduling-based protocols according to methods of coordination between senders and receivers.

1) Contention-Based Protocol: In this method, each node competes for shared channels to prevent other nodes using an identical channel. Depending on who is the decision-maker of the channel access, contention-based UWSN MAC protocols are divided into random access protocols and reservation protocols in this paper. When a sender begins the transmission without requesting consent from its expected receiver, it is called a random access approach. By contrast, a reservation approach involves a receiver feeding competition results back to the senders after receiving requests from multiple senders. When adapted these approachs in UWSNs, neither the carrier sensing nor the reservation is as efficient as in TWSNs. The real-time channel state sensed by senders is not available to guide transmission well due to the information asymmetry caused by long propagation delays. Similarly, the reservation may not feed back to senders timely like TWSNs and thereby sparking more potential competition for channel. Therefore, UWSN contention-based protocols have been proposed to overcome or leverage these features.

a) Random access: Generally, random access approaches mainly consist of ALOHA, Carrier Sense Multiple Access (CSMA), and their derivatives. Senders in ALOHA begin their transmission whenever their data is ready for delivery. Obviously, this kind of MAC protocol requires additional mechanisms to avoid collision in UWSNs. CSMA exploits carrier sensing, in which each node senses the channel for a while before accessing the channel in order to stagger their transmissions with those of others. As noted previously, carrier sensing does not work well in UWSNs.

One of the variance added to ALOHA protocols is the transmission start time. The analysis of ALOHA and slotted UWSN ALOHA protocols is proposed in [41]. Slotted ALOHA requires nodes to start transmitting at the beginning of a time slot rather than randomly. The analysis also shows that the best utilization for slotted ALOHA in underwater environments is the same as for ALOHA. This paper proved that TWSNs ALOHA protocols are not suitable to migrate to UWSNs directly. Reference [42] proposed two ALOHA-based protocols with collision avoidance and advance notification known as Aloha-CA and ALOHA-AN. While both pick up sender-receiver information from overhearing the packet headers. The difference between them is that ALOHA-AN transmits a small advance notification packet (NTF) first and then waits for a lag time before sending the data packets, which introduced extra signaling overhead. As the common techniques of collision avoidance, guard time and back-off mechanism are also been tried to join UWSN ALOHA protocols. In PDT-ALOHA [43], the guard time is calculated before each transmission according to the distance between nodes. And this paper shows that its throughput can reach $17 - 100\%$ higher than slotted ALOHA. A random back-off mechanism is added to ALOHA in [44] called ALOHA-RB, in which nodes set a random back-off time before transmission when a packet arrives or a collision occurs. However, both of them introduced extra time costs and thus result in long delays.

Another scheme added in UWSNs to enhance ALOHA performance is to assign an access probability to each sender. Such a scheme mainly considers the impact of long propagation delay on collision probability. Based on the local network topology, a stochastic transmission strategy LiSS [45] assigns each node a probability for transmission during each time slot without handshake. The transmission probabilities of each node are calculated by heuristic objective functions. Similarly, when a node needs to send a data packet in DTMAC [46], it decides to send with a fixed probability p or to receive with $1 - p$ in any m slots. In such cases, the same data packet may send repeatedly to increase the probability of successful transmission. The throughput-optimal value of p and m is given with the successful transmission probability as the tuning parameter. Further, some probability access strategies leverage long propagation delay to enable more concurrent transmissions. DAP-MAC [47] identifies neighbors by periodically broadcasting HELLO messages and using the time stamp in received packets to calculate the propagation delay of neighbors. DAP-MAC then creates the group compatibility relation and adopts a utility-optimization framework to determine the optimal channel access probabilities. Based on DAP-MAC, a traffic-adaptive receiver-synchronized (TARS) [48] further adjusts the packet transmission phase in a slot according to the distance between senders and receivers.

In UWSNs, carrier sensing may not directly available to avoid collision due to the long propagation delay as discussed above. Therefore, the variations of UWSN CSMA mainly involve the timing of transmission after carrier sensing, which may mitigate the impact of hidden terminals without handshaking. CSMA-ALOHA [49] adjusts the duration of carrier sensing to a random time period. Specifically, a node continues to sense if the channel is busy until the carrier has passed. The node then begins transmission if the channel is sensed idle after briefly sensing for a random amount of time. ALOHA-CS [50] adds a random back-off time before the next attempt at successful transmission once the channel is sensed idle. The back-off window size ranges according to the maximum propagation delay. The performance of above protocols is deeply related to the propagation delays between nodes. In addition to carrier sensing, senders in T-Lohi [51] proactively send a tone before data transmission, and then listen to the channel for a contention round (CR). During CR, if the sender does not overhear any other tones, it will start the transmission. Otherwise, it will backoff and repeat the above process in the next CR. Synchronized and unsynchronized T-Lohi are also analyzed by setting different types of CR. Synchronized T-Lohi can be exploited to estimate contender behavior whereas unsynchronized T-Lohi has lower run-time overhead and protocol complexity.

b) Reservation: Prior to data transmission, each sender sends a short Request-to-Send (RTS) message to win the idle channel from the expected receiver. The receiver then replies to the winner with a Clear-to-Send (CTS) message about the idle channel assigned to it. The above reservation process is decided by receivers, which could reduce the effect of hidden terminals effectively. Even when reservation increases the message exchange overhead and the probability of data packet

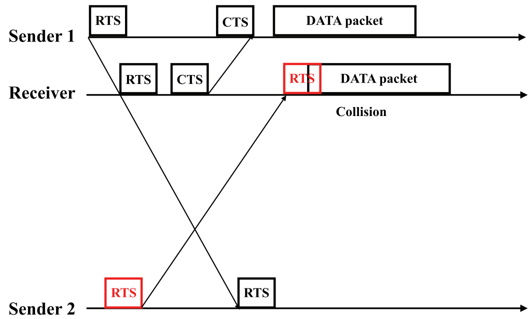

Fig. 5. RTS/CTS frames collide with an ongoing data.

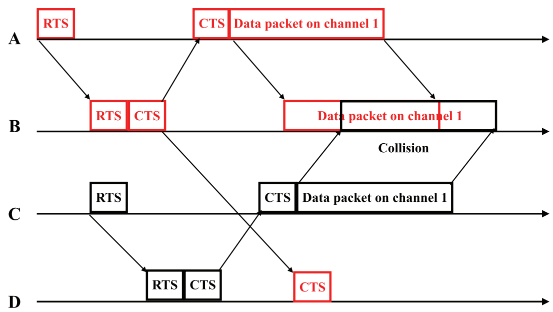

Fig. 6. RTS/CTS delayed arrival.

interference by messages, the overall efficiency and reliability of MAC protocols can be improved. However in UWSNs, the transmission of RTS/CTS frame takes long propagation delays, which prevents nodes from obtaining the reservation information in time to judge the status of a channel. As a result, the efficiency and success of such handshake process will be significantly reduced. For example in Fig. 5, if a node fails to overhear RTS/CTS from others in time and starts its own RTS, the RTS of that node may collide with an ongoing data packet. More seriously, as shown in Fig. 6, two pairs of nodes can complete a reservation almost simultaneously without hearing RTS/CTS from each other, resulting in the collision of data packets, which is called triple hidden-terminal problems in UWANs [52]. In the meantime, the long propagation delay may also present potential parallel opportunities for handshake process. We review some exist reservation approaches to deal with the above challenges and opportunities unique to UWSNs.

The problem shown in Fig. 5 can be solved by a slotted-based design or a dedicated sub-channel for RTS/CTS. However, the simply usage of these methods in UWSNs brings more serious implications on channel utilization than that in TWSNs. Thus, these methods needs to be optimized by special designs to adapt underwater environment. Any transmission (RTS/CTS, DATA or ACK) in slotted FAMA [53] is allowed only at the beginning of a slot and terminals are constantly listening to the channel. The slot is sufficiently long to guarantee that the RTS/CTS is received by all nodes within transmission range over the duration of one slot. In other words, before a node starts a transmission, it will overhear all foreign RTS/CTS and thus prevent data collision. However, such slot length setting caused long delay and bandwidth waste. Another available optimization is to adjust the allocation of sub-channel to RTS/CTS and data packets. RCAMAC [54] divides the available bandwidth into a control channel with less bandwidth and a data channel with much more bandwidth. Similarly, DCC-MAC [35] divides the channel into a common control channel (CCC) and multiple data channels. Nodes in DCC-MAC can adjust the bandwidth of their control channel adaptively by flexibly selecting the most suitable data channels to extend their control channel.

To handle the triple hidden-terminal problems revealed in Fig. 6, the transmission of RTS/CTS requires enough time to notify the nodes in the same collision domain. Whereas such requirement is unnecessary due to the negligible propagation delay in TWSNs. CUMAC [55] uses a cooperative collision detection scheme in which a beacon is added when asking neighboring nodes for channel status information. RTS/Beacon/CTS are exchanged on the control channel. After receiving an RTS, the node broadcasts a beacon and starts a timer to wait for collision detection responses from its neighbors. If no collisions are detected during this time, a CTS will be transmitted. Data collisions will only occur when none of the neighboring nodes perceive the channel condition correctly. However, the beacon and the timer introduced extra overhead into protocol. By contrast, PCAP [56] and APCAP [57] postpone the transmission of CTS so that a node can overhear foreign RTS/CTS during this time. Similarly, FI-MACA [58] sets a fixed period for listening to the channel before sending the CTS and abandons the transmission if it overhears any other RTS/CTS. This arrangement ensures that both RTS and CTS have enough time to reach their destination and can bring enough information to their neighbors, thereby reducing the occurrence of triple hidden-terminal problems. Moreover, these two approaches allow neighbors of the CTS receiver to take other actions during this period, such as data transmission or next round handshaking. However, as a consequence, long access delays are inevitable, plus, neither approach works well with high transmission loads.

2) Scheduling Based Protocol: In TWSNs, scheduling is mainly adopted to improve the throughput of protocols, whereas scheduling in UWSNs is typically treated as an efficient way to arrange collision-free transmission. Specifically, the process of scheduling in UWSNs calculates the transmission times or access channels of each node depending on the real-time communication status to assure collision-free reception. However, such a collision-free way needs to be supported by available and accurate information (e.g., channel status, traffic load, time synchronization, localization), which is more difficult and costly to be obtain in complex underwater environment. Moreover, the long propagation delays may cause information obsolete and thus need frequent specific information exchange.

To make scheduling efficient and available in UWSNs, what and how the information to be used and obtained for scheduling decision have been considered in protocol designs. The scheduling decision can be made by the sender itself, in which case it is known as sender-based scheduling, or the decision can be made by a scheduler such as receiver or cluster head, in which case it is known as scheduler-based scheduling.

Sender-based scheduling aims to apply the same scheduling rule to all senders. However, senders may not receive real-time and accurate information from the receiver because of the long propagation delay. By contrast, by transferring the decision to a scheduler, the transmission will be more orderly due to the integrity of global or partial information. Correspondingly, the scheduling overheads will also increase. Both types of scheduling are discussed in further detail below.

a) Sender-based scheduling: In first type of sender-based scheduling, senders schedule their transmission by neighbor information such as UD-TDMA [59]. Each node has an information record, which contains itself and its 2-hop neighbors from network initialization. With this information, each node forms a maximal independent set [60] to determine the maximum number of nodes which can transmit without collision during the same time slot. The node with largest degree among its 2-hop neighbors first decides its initial time slot and then informs its neighbors. Finally, each of the remaining nodes assigns itself a slot according to the other's decision. However, the 2-hop neighbor information needs frequent maintenance in dynamic underwater environment which will introduce high overhead.

Nodes in DOTS [61] also maintain neighbors' information, which is used to build a delay map which then informs subsequent intelligent transmission scheduling decisions. Whenever data is ready, the sender decides whether it can begin current transmission without interfering with its neighbors' reception. Whereas, DOTS passively obtain and update information about the sender's neighbors such as their propagation delay map and expected transmission schedules by receiving or overhearing any packets. While this passive way may collect obsolete information, which is susceptive to propagation delays. UW-FLASHR [62] divides the transmission cycle into a small experimental portion and a much larger established portion. In the experimental portion, senders transmit their requests for new transmission time slots. Once the nodes have exchanged these requests, a transmission schedule can be built for each sender and collision-free packet transmission during the established portion can gradually be achieved. During the experimental portion, too many senders will lead to inefficient access.

To reduce the large scheduling overhead in UWSNs, another type of sender schedules its transmission according to its own local information. MC-UWMAC [63] proposes a grid-based slot assignment procedure on the common slotted control channel and a quorum-based data channel allocation procedure, which requires only the location information of the nodes themselves. The network is virtually partitioned into a grid of cells as in Fig. 7. These cells are built so that the nodes in two adjacent cells are guaranteed not to be neighbors. By locating every sensor inside a unique cell, a unique slot number and channel can be assigned to each one. In this type of scheduling, each sender uses its own dedicated slot and transmission takes place in a unique data channel to achieve collision-free transmission. Due to the deeply depend on location information, such type of scheduling are not suitable for some highly dynamic underwater environment.

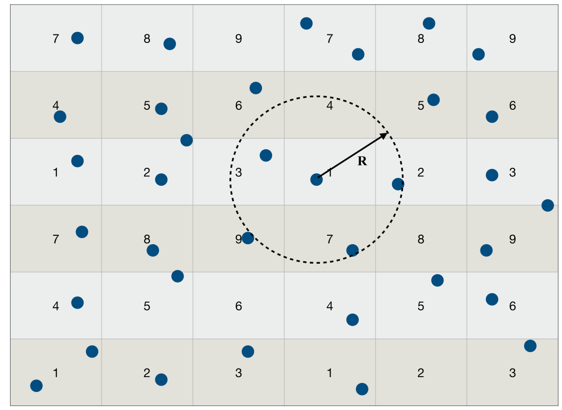

Fig. 7. Grid based virtual partition.

b) Scheduler-based scheduling: In this approach, decisions about scheduling are left to a scheduler which gathers information such as transmission requirements, propagation delay and so on, to achieve collision-free transmission. In UWSNs, The special challenges of this approach mainly include the high overhead of information gathering and limited medium to be allocated. This approach can be categorized as static or dynamic according to the method of medium allocation. Static scheduling allocates a fixed multiplexing unit (Time/Code/Frequency) to each node which remains unchanged over time, whereas dynamic scheduling adjusts the allocation of the multiplexing unit depending on the current transmission requirement.

The static scheduling approach NOGO-MAC [64] groups nodes and chooses a center among them. A different frequency band is assigned to each group according to its distance from the sink and then divided into orthogonal sub-channels for group nodes. Groups closer to the sink use the higher frequency bands and those further away use lower frequency bands. The sink allocates orthogonal sub-channels to each node in the group depending on the information collected during the transmission of other nodes. After allocation, each node uses its specified sub-channel for transmission. Obviously, such a process requires high information exchange overhead. C-MAC [65] divides the network into many cells arranged in a hexagonal configuration, like the internal structure of a beehive. Each cell and its six adjacent cells constitutes a group. All cells are assigned a fixed time slot by the sink and can only send packets during their own slot. The sink organizes seven time slots into a frame to cover a group and eventually ensures that neighboring cells use different time slots for transmission. However, such fixed slot setting reduces throughput when transmission load are unbalanced in different cells.

Similarly, GC-MAC [66] assigns a unique time slot to every node in a two-hop neighborhood graph with a cluster head by solving a Graph Coloring Problem (GCP). Each node is assigned a different color in any two-hop neighboring graph and nodes of the same color can thus transmit during the same time slot without collision. While the process of information collection and slot assignment require high overhead. ST-MAC [67] constructs a spatial-temporal conflict

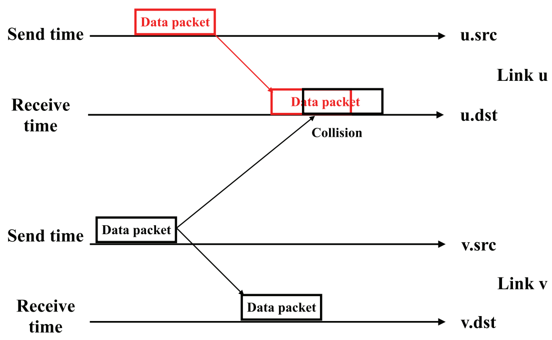

Fig. 8. Spatio-Temporal Conflict Graph.

graph (ST-CG) to describe the conflict delays among transmission links explicitly, in which a vertex indicates a transmission link and the edge represents the conflict relation between the two vertices. For example in Fig. 8, the conflicting relationship between link is *u* and *v*, where *u.src* and *u.dst* are respectively the sender and receiver of link *u*. The base station constructs the final ST-CG by checking all pairs of transmission links and then schedules the transmission time of each link by solving the vertex-coloring problem of the conflict graph using a traffic-based one-step trial approach (TOTA). However, the process of information gathering and calculation complicates the implementation.

By contrast, dynamic scheduling alters scheduling decisions based on delivery transmission requirements such as STUMP [68], which requires nodes to share propagation delay estimates and time slot requirements among their two-hop neighbors. The schedule must ensure that nodes which cause each other interference are assigned non-overlapping time slots, known as schedule constraints: the packet arrival time from different nodes to the receiver plus their slot durations should not overlap at the receiver. To satisfy these constraints, each scheduler should have all the sender-receiver information of its neighbor, resulting in large overhead. Four possible conflicts and their corresponding schedule constraints are discussed in [68]; distributed and centralized algorithms are then proposed to solve the scheduling problems. Ordered CSMA [69] combines round-robin scheduling and CSMA to achieve a dynamic schedule of transmission. In this protocol, the transmission of nodes is ordered by schedulers according to their position. When a node senses the termination of a transmitted carrier from the previous order node, it immediately starts transmitting itself. However, such a process relies on the stability of the network topology and thus needs frequent network reconfiguration, which will lead to large overhead.

C. Summary

The BER problem can be solved by FEC and ARQ in different perspectives to improve link reliability. Taking advantage of FEC can reduce the number of transmission failures while ARQ provides a safeguard if FEC fails. As for solving the problem of collision, contention-based UWSN MAC protocols are more suitable for a distributed and sparse network topology. Random access approaches can achieve lower overhead but will increase collision probability while the reservation-based approach has the opposite effect. By contrast, scheduling-based UWSN MAC protocols perform better in a centralized and intensive network topology than contention-based protocols. The reason is that nodes in a contention process cannot obtain complete transmission information and will become chaotic as the number of nodes increases, whereas the scheduling process can avoid these problems. However, the scheduling process requires more time and more complex calculations as the number of nodes increases. Sender-based scheduling leverages limited information and unified rules among senders to improve the efficiency of protocol. On the other hand, scheduling on a scheduler could achieve the most orderly transmission but with long delay and unbalanced energy consumption. In summary, FEC and ARQ complement each other, while both types of UWSN MAC design have their own characteristics and are suitable for different scenarios.

IV. Reliable Routing in Hop-by-Hop UWSN Data Collection

Reliable routing refers to finding a reliable path from source node to the sink. In TWSNs, routing protocols are typically designed based on the end-to-end method [70], in which a path is found from the source node to the sink in the discovery mode. However, UWSNs are characterized by a highly dynamic topology with high propagation delay, for which an end-to-end route discovery or maintenance design is not appropriate. Thus, to make the different routing methods available, greedy hop-by-hop routing, through which the next hop nodes are found only at each hop, is the most promising method in underwater environments [71], [72]. Greedy hop-by-hop routing in UWSNs mainly relies on geographic or depth information to forward data packets closer to the sink at each hop [73]. However, the appearance of void regions may cause greedy hop-by-hop routing to fail [4], [74]. Next, we will divide the solutions into two categories, which are void avoidance and void handling.

A. Void Avoidance

Void avoidance here means preventing packets from encountering a void region or preventing void regions from appearing. The former can be achieved by a void-avoidance protocol which aims to minimize the likelihood of forwarding a packet to nodes in a void region. However in UWSNs, it is costly to obtain globe network topology information and is difficult to maintain and update neighborhood information with mobile nodes. Thus, void-avoidance techniques proposed for TWSNs are not suitable in TWSNs and it is necessary to design void-avoidance protocols specific to UWSNs. The latter takes advantage of energy-efficient protocols to prolong the lifetime of nodes thereby further reducing void occurrence. The battery of underwater sensor nodes is hard to be replaced regularly in UWSNs, which requires minimal energy consumption of the nodes in the path.

TABLE I
UWSN MAC PROTOCOLS

Protocol name/ Reference	Collision-Free Mechanism	DM	Operation Conditions		Performance		Major Characteristics (Pros and Cons)
			SYN	LOC	Protocol Overhead	Collision Probability	
Aloha-CA [42]	Random Access	Se			Low	High	Pros: without any signaling before sending a packet Cons: less information to avoid collision
Aloha-AN [42]	Random Access	Se			Medium	Medium	Pros: more information from NTF to avoid collision Cons: introduced extra signaling overhead
PDT-Aloha[43]	Random Access	Se	✓	✓	Low	Medium	Pros: introduced adaptive guard-bands to reduce collision Cons: guard-bands caused bandwidth waste
ALOHA-RB[44]	Random Access	Se			Low	High	Pros: introduced random back-off without extra signaling and info Cons: may cause unnecessary waiting
LiSS[45]	Random Access	Se	✓	✓	Low	Medium	Pros: Lightweight stochastic to reduce collision without handshake Cons: needs extra network topology info and unnecessary waiting
DTMAC[46]	Random Access	Se	✓		Low	High	Pros: without any signaling exchange Cons: the repeat transmission of a packet caused bandwidth waste
DAP-MAC[47]	Random Access	Se	✓		Medium	Medium	Pros: leverage of LPD to enable more concurrent transmissions
TARS[48]	Random Access	Se	✓		Medium	Low	Cons: needs extra network topology info and unnecessary waiting
CSMA-ALOHA[49]	Random Access	Se			Low	High	Pros: a random carrier sensing duration with more access opportunities Cons: cause more collisions at the receiver
ALOHA-CS[50]	Random Access	Se			Low	Medium	Pros: add a random back-off if sensed an idle channel to avoid collision Cons: may cause long waiting time and affects by propagation delays
T-Lohi[51]	Random Access	Se			Low	Medium	Pros: the sending of tone has less signaling overhead Cons: the limited info of tone may cause unnecessary waiting
Slotted-FAMA[53]	Reservation	R	✓		High	Low	Pros: avoided the collision among RTS, CTS and ongoing packets Cons: the long slots cause long delay and bandwidth waste
RCAMAC[54]	Reservation	R	✓		Medium	Low	Pros: avoid collision by dedicated sub-channel for reservation
DCC-MAC[35]	Reservation	R			High	Low	Cons division of limited bandwidth brings performance bottleneck
CUMAC[55]	Reservation	R		✓	Medium	Low	Pros: handle hidden terminal by adding a beacon and a timer between RTS/CTS Cons introduced extra overhead and caused long access delays
PCAP[56] APCAP[57]	Reservation	R			Low	Medium	Pros: postponed CTS transmission so that avoid collision Cons: have a long access delay even with low transmission loads
FI-MACA[58]	Reservation	R			Low	Medium	Pros: avoid RTS/CTS collision by setting a fixed carrier sensing time Cons: low access probability with high transmission loads
UD-TDMA[59]	Scheduling	R	✓	✓	High	Low	Pros: achieve high concurrent collision-free by the usage of 2-hop neighbor info Cons: high overhead for obtaining and maintain 2-hop neighbor info
DOTS[61]	Scheduling	R	✓	✓	Medium	Medium	Pros: the delay map enable concurrent collision-free with low overheads Cons: the passive update of delay map is susceptive to propagation delays
UW-FLASHR[62]	Scheduling	R	✓		High	Medium	Pros: improve access success rate by dedicated slot for info exchange Cons: the performance largely depends on the number of nodes
MC-UWMAC[63]	Scheduling	R	✓	✓	Medium	Low	Pros: lower scheduling overhead with only the local information of nodes Cons: not suitable for some highly dynamic environment
NOGO-MAC[64]	Scheduling	Sc	✓	✓	High	Low	Pros: avoid collision by assigning orthogonal sub-channels to each node Cons: band allocation process requires high information exchange overhead
C-MAC[65]	Scheduling	Sc	✓	✓	Medium	Low	Pros: allocate collision-free time slot by dividing network into many "beehive" Cons: unbalanced transmission load in different cells will cause wasted bandwidth
GC-MAC[66]	Scheduling	Sc	✓	✓	High	Low	Pros: assign collision-free time slot between 2-hop neighbors by solving GCP Cons: large overhead of info collection and slot assignment for 2-hop neighbor
ST-MAC[67]	Scheduling	Sc	✓	✓	High	Low	Pros: the construction of the conflict graph effective avoids collision Cons: complex information gathering and calculation in implementation process
STUMP[68]	Scheduling	Sc	✓	✓	High	Low	Pros: leverage LDP to achieve concurrent collision-free transmission Cons: large overhead for information collection
Ordered CSMA[69]	Scheduling	Sc		✓	High	Low	Pros: combines round-robin and CSMA to achieve collision-free dynamically Cons: frequent network initialization caused large overhead

DM=decision maker. Se=sender, R=receiver, Sc=scheduling. LOC =Location information. SYN=time synchronization

1) Void-Avoidance Protocol:

a) Passive participation: In this method, nodes in the void region take themselves out of data forwarding voluntarily, as if they are not part of the network, in order to create opportunities for other available nodes. Passive participation methods are generally used in the receiver-based [75] routing protocols. Some receiver-based routing protocols such as DBR [76] have no specific solution for the void problem. Senders in DBR send packets with its depth information. When a receiver receives a packet, it compares the depth information and only forwards packets with higher depth after holding the packets for a while. Due to such a greedy mechanism of receiver-based routing in UWSNs, the removed void nodes actually increases delivery rates.

Building on DBR, WDFAD-DBR [77] uses a passive participation method involving two-hop depth information to prevent packets from entering a void region, by considering not only the current depth but also the depth of the expected next-hop. If a node is unable to find any neighbor in the upper hemisphere of its transmission range, it will directly drop the packet to create an opportunity for other receivers. However, WDFAD-DBR cannot identify trapped nodes in advance. In addition, using a fixed primary forwarding area may restrict

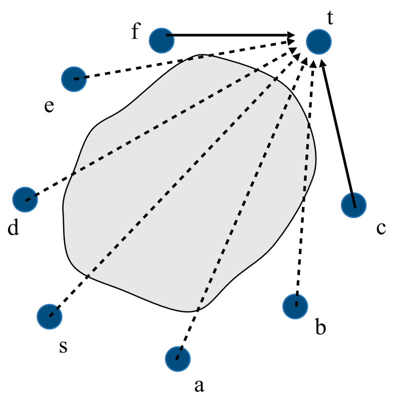

Fig. 9. Vector-shift Mechanism in VBVA.

the flexibility of path and forwarder selection in different situations.

Likewise, DBR-based EVA-DBR [78] excludes trapped nodes from the routing paths using a passive participation approach. Each node sets a self-detection timer to wait for packets from neighbors at lower depths. If a node cannot receive a packet from a lower depth neighbor during this time, the node announces itself as a trapped node by broadcasting a control packet and will then be excluded from the routing path. However, the passive reaction is inappropriate in a sparse network, which cannot solve the case if the only valid path to the destination is via the void node.

b) Proactive bypassing: Forwarders set the cost of trapped nodes to an infinite value and then find another node as their next hop in order to proactively bypass the void region. VBVA [79] is equipped with a proactive bypassing void avoidance method called a vector-shift mechanism. As shown in Fig. 9, node s cannot find available forwarding nodes on the current forwarding vector within the current pipeline. Node s then broadcasts a vector-shift packet to all its neighbors (e.g., a, b). After receiving the vector-shift packet, neighbors of node s will try to forward the corresponding data packet to the sink using their own vector (e.g., f, c). Processes like this will be repeated until the packet is delivered to the sink. However, vector-shift mechanism may create duplicated paths for packets to sink, called multi-copy problem, resulting in more energy consumption.

An alternative approach to bypass the void region proactively is for each node to leverage the current state of its neighbors to make a routing decision. As shown in VAPR [80], multiple sonobuoys are deployed on the surface so that a packet can be delivered to any sonobuoy. Initially, every sonobuoy initializes the network by sending beacons, and each node updates its minimal hop to the surface, sequence number, data forwarding direction, and next-hop data forwarding direction to build a directional trail to the closest sonobuoy. However, such a network initialization process needs extensive signalling exchange. Following initialization, a node is identified whose depth level is the shallowest among its neighbors but deeper than that of the sonobuoys; this is known as a trapped node, and is usually found beneath the concave area of a void. Thus, forwarders can set the cost of trapped nodes to an infinite value to prevent sending packets to them.

Similarly, beacons are generated by the sink at the network initialization phase in LLSR [81] and nodes generate beacon messages when the network topology changes. Following initialization, each node selects a one-hop neighbor with the lowest hop count toward a sink. If there is a tie, then the one-hop neighbor with the best quality path toward a sink is selected. If the tie persists, then the neighbor with the lowest pressure is selected. Taking advantage of distributed beaconing, nodes in OVAR [82] periodically broadcast beacons, which include the hop count information and neighbor information with which to update neighbor tables, then select a path with a lower hop count. In this case, nodes automatically exclude all routes leading to void regions. The proactive bypassing method successfully prevents packets from entering a void, whereas beacons exchange leads to high communication overhead which is certainly a problem in UWSNs.

c) Flooding techniques: Another solution is to give a copy of one packet to more nodes in the network to increase the probability of bypassing the void region. The full flooding technique or original flooding is acceptable in TWSNs [83], however, the high cost of such flooding makes it unsuitable in UWSNs. Thus, to accommodate underwater conditions, flooding range and rate should be restricted to prevent too many copies of one packet.

The advanced flooding-based routing protocol [84] uses the attributes of flooding itself to avoid the void problem; additionally, it utilizes node position and a proposed network coding-based protocol to reduce the cost of flooding. By taking advantage of position information, only those nodes that are closest to the destination take part in the flooding process. Network coding means that nodes encode the incoming packets into one or more output packets instead of using the classic store-and-forward approach. In other words, the original information is shared among the encoded packets, finally, the sink is more likely to receive a piece of information rather than multiple same packets. However, the fusion protocol does not take the handling of void regions in extreme cases, such as no flooding candidate nodes, into account.

Directional Flooding-Based Routing (DFR) [85] controls the flooding direction and number of involved nodes which belong to a specific zone called flooding zone, adjusting on the basis of link quality. Nodes in the flooding zone are allowed to participate in forwarding the packet. The link quality is quantified according to the current angle and the reference angle. For example in Fig. 10, the current angle of node F is the angle value between FS and FD (CA_F). The reference angle of F is received from the previous forwarder P (RA_P), and is calculated by P by adjusting, in an additive-increase and additive-decrease manner, according to the quality of its link to its neighbors. If $CA_F \geq RA_P$, node F belongs to the flooding zone and rebroadcasts the packet, including its updating RA_F. Although the above method controls the flooding, the void problem may persist. DFR defined two kinds of void problem during controlled flooding: (a) when a new flooding

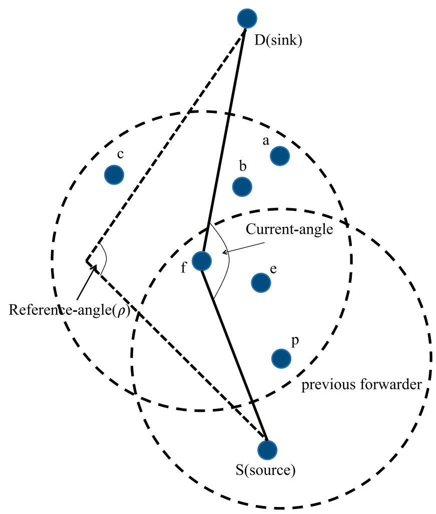

Fig. 10. Current Angle and Reference Angle in DFR.

zone has no forwarding node and (b) when none of its neighbors is closer to a sink. DFR further introduced corresponding solutions: requiring the flooding zone to include at least one node for (a) and exploring a detour path for (b). Although all these methods control flooding cost in different ways, creating duplicate packets and wasting network resources cannot be avoided.

d) Transmission power adjustment: The transmission power of each node can be adjusted in a cross-layer fashion to adapt special features of the acoustic signal in UWSNs [86]. A node can increase its forwarding range to pass through the void region and even on directly to its destination by adjusting transmission power. However, with the increasing of transmission power, the energy consumption of sensors and possible interference with other transmissions will become more serious especially in UWSNs. Thus, to exploit such a technique in UWSNs, requires a certain limitation and some adaptive strategies.

APCR [87] is composed of two phases: a layer assignment phase and a communication phase. The layer assignment phase starts when the sink sends an interest packet at its lowest power level. The interest packet carries a layer ID number based on the power level. Repeatedly, the sink sends with the next power level, each time incrementing the layer ID in the interest packet. Finally, each node can be assigned a layer ID according to the distance from the sink. The layering phase is repeated periodically depending on mobility among the nodes and the packet delivery ratio. Subsequently, in the communication phase, a node that wants to send data will first send a forwarder discovery packet with the highest level of power, then reduce its transmission power to the range that covers the closest of the neighbors that replied. Once a node is trapped due to a new void region on the current power level, power is increased to pass through the void. To prevent excessive power, if forwarders are found at multiple layers, then the power is decreased to retain only the closest layer.

The power-adjustment method also is adopted in PCR [88]. The proposed PCR protocol selects the most suitable transmission power level at each underwater sensor node, aiming at providing possible trapped nodes the option of passing through the void region. A node will exchange beacon messages using each permissible transmission power level for neighbor discovery; upon receiving a beacon, the node extracts the neighbor's information and stores it in its neighbor table. If there are not enough optional nodes in opportunistic routing at the current power level, the forwarder node will increase the power level to improve the packet delivery probability. PCR also considers the energy waste when using high power levels between sensor nodes.

Similarly, in focused beam routing (FBR) [89], the transmission power of the forwarding nodes can be controlled. A forwarder selects eligible candidates which lie within a cone emanating from the forwarding node towards the final destination. If the forwarder cannot reach any eligible candidates at maximum transmission power, it will shift its cone and find new candidates to the left and right of the main cone. After searching, the forwarder tends to choose paths with a minimal amount of zigzagging, that is, those paths with minimum deviation from the straight line between source and destination. The transmission power level in AHH-VBF [90] can also be increased to cover a larger range in sparse networks or decreased to save more energy in dense networks. These two protocols designed rely on the location of neighbors and destination, which is costly in some high dynamic underwater environments. Moreover, such shift mechanisms are not flexible enough when nodes follow an irregular distribution.

The drawbacks of power-adjustment technology are the additional energy consumption required when increasing power and the interference due to the extension of the transmission range. The former will reduce the network lifetime, while the latter will make the design of other protocols such as MAC more difficult.

2) Energy-Efficient Protocol: Sensor nodes in UWSNs are battery powered and difficult to recharge. Therefore, it is essential to design energy-efficient protocols to balance and reduce energy consumption between nodes. Otherwise, nodes will discharge more quickly, which may create a void region, reducing reliability. The following factors will affect the energy efficiency of a UWSN's routing protocol:

a) Energy balancing: This is one of the main requirements for extending the lifetime of nodes. In UWSNs, the destination of sensed data is normally to the sink, therefore nodes near the sink die earlier. This feature can be mitigated by deploying multiple sinks [14]. During routing, some nodes locate in a congested path and will result in low residual energy. With a focus on the problem of achieving energy balance, the following method has been proposed for underwater routing protocols.

Based on DBR [76], EEDBR [91] further considers the residual energy in the forwarding process. In DBR, a node at a shallow depth relative to its neighbors will always forward data while deeper nodes may idle. Finally, some nodes repeat the path of others and eventually die out earlier. Nodes in EEDBR share their residual energy and depth with neighboring nodes. In such cases, when a relay node receives a data packet, depending on the residual energy and depth, it stores the data for a specific period. As a result, the node with lower depth and higher residual energy will forward data first, yet the end-to-end path of packets may become longer. Based on WDFAD-DBR [77], EBER^2 [92] considered depth difference, residual energy and the number of potential forwarding nodes (PFNs) of the receiver node when calculating the holding time. The PFNs can be obtained by the two-hop routing mechanism. However, two-hop information acquisition will lead to additional energy consumption and communication overhead.

b) Forwarding participants: Forwarding participants of a source node refers to the nodes which are in its path to the destination. More forwarding participants means more average energy consumption per end-to-end transmission. The main factors affecting the number of forwarding participants are the length and number of paths. Due to the lack of globe network topology and broadcast nature of acoustic modems in UWSNs, the above factors are hard to control. Without a global network topology, guaranteeing the shortest path is costly. To facilitate acquisition of the network topology by nodes, researchers have designed various network initialization processes in which the network topology maintains a mechanism for layer-based and cluster-based topology. Since the changing channel with long propagation delay in UWSNs, the multi-copy problem becomes more serious that creates multiple paths for a packet to reach its destination, with the result that redundant copies of data packets are inevitably generated. The multi-copy problem occurs for two main reasons: a) the qualified receivers may not communicate with each other in a timely fashion, and b) the qualified receivers may be out of communication range with each other. A unicast protocol such as [89], [93] can eliminate this problem straightforwardly by selecting one next-hop forwarder one time. However, in the anycast protocol, forwarding eligibility must be determined and holding time must be calculated at the receiver to prevent this from happening. Another way to reduce forwarding participants is the flooding routing protocol [87], [88], [89], [90], which controls the flooding region to prevent the involvement of additional relay nodes as shown above.

Layer-based topology allows nodes to find the shortest number of hops to sink. PULRP [94], E-PULRP [95] and [96] use the hop count between the sink and nodes to layer the network into a set of concentric circles around a sink node. A probe is initiated at the sink node with a certain power level and then the probe is flooded to the network. A node receiving the probe will assign itself as the layer number of the probe plus one and eventually each node will occupy its own layer. As a result, all nodes in a particular layer can forward data to the sink node over an equal number of hops, meaning that the average path will be shorter. While the layered structure reduces forwarding participants effectively, it introduces network initialization and maintenance costs.

Cluster-based topology splits up the network to reduce the cost of nodes finding paths with a smaller network. To construct a cluster-based topology, the cluster size and cluster head (CH) selection scheme should be considered. Each sensor node in cDBR [97] is a CH candidate with the same initial probability. Each normal node chooses the CH with the least depth in their transmission range and automatically form clusters. However, such a random CH selection scheme is more prone to form void regions. VTP [98] forms the cluster according to location of nodes and selects two border nodes by rotation in each cluster as relay nodes, which balanced the energy consumption in cluster. Border nodes and nodes which have transmitted the latest data packet are given the highest priority for being relay nodes. In ACUN [99], further consideration is given to the fact that the CH closer to the sink node performs more data forwarding tasks, which may lead to its premature demise. To solve this problem, ACUN adjusts the size of the competition radius based on the distance between CHs and the sink node and the residual energy of a CH. ACUN first selects a candidate CH by the threshold method, then through competition among the candidates, finally selects the CH. While the clustered structure reduces the path of non-CH nodes, the lifetime of CH nodes will be shortened. Achieving energy balance in this structure is a serious challenge.

Opportunistic routing (OR), which is considered a viable solution in UWSNs, exploits the broadcast nature of acoustic channels and anypath routing to realize spatial diversity at the receivers, thereby mitigating packet loss [100]. OR chooses a group of forwarding candidates from neighboring nodes, however, the multi-copy problem need to be suppressed when the forwarder is determined by the receivers due to the long propagation delay in UWSNs. DBR allowed all candidate receivers to compute a holding time based on their depths and the sender node depth. Each candidate waits until its holding time expires, then it forwards the data packet. During the holding time, if a candidate receives the same packet from a lower depth node, it simply drops the packet. Taking advantage of the holding time mechanism reduces the number of redundant copies of the data packet but the problem cannot be completely avoided because of reason b) mentioned before.

Furthermore, HydroCast [101] takes the expected packet advance (EPA) metric into account when selecting neighboring nodes with higher quality links and embeds the ID of candidate nodes into data packets. On the basis of reducing candidate forwarders, HydroCast calculates the holding time like DBR. Yet the nodes at these higher quality links will take on more forwarding tasks and die early. As in EEDOR [102], candidate forwarders are first selected by the sender according to neighbor topology and then sorted in descending order based on depth. The holding time is calculated using the above sorted list. DVOR [103] exploits distance vectors by marking the number of hops from node to sink in advance and then calculating the holding time based on the distance vector to prevent low priority nodes from forwarding. However, nodes in EEDOR and DVOR have unbalanced energy consumption due to their pursuit of short paths to sink. As a result, there are always nodes on the critical path and die earlier. Reference [96] focuses on problem b and guarantees that eligible receivers are neighbors of each other by maintaining the neighbor table. To further reduce the impact

TABLE II
UWSN ENERGY-EFFICIENT PROTOCOLS

Protocol name/ Reference	Energy-Efficient		CM	Operation Conditions		Performance		Major Characteristics (Pros and Cons)
	Factor	Mechanism		SYN	LOC	Average EC	Occurrence Rate of Void	
EEDBR[91]	EB,NP	HT	A	✓		Medium	Medium	Pros: achieved energy balance by considering the residual energy of next hop
EBER²[92]	EB,NP	HT	A	✓		Medium	Low	Cons: may create long end-to-end path of packets
PULRP[94]	LP	LT	U	✓		Medium	High	Pros: reduced length of path effectively by layered structure
E-PULRP[95]	LP	LT	U	✓		Low	Medium	Cons: introduced network initialization and maintenance costs.
cDBR[97]	LP	CT	U	✓		Low	High	Pros: low clustering cost based on depth information Cons: the random CH selection scheme is prone to form void regions
VTP[98]	LP,EB	CT	U		✓	Low	Medium	Pros: the rotation of relay nodes balanced the energy consumption in clusters Cons: clustering rely on location of nodes and with higher cost
ACUN[99]	LP	CT	U		✓	Medium	Low	Pros: avoid early death of CHs by adaptive clustering process Cons: the competition process in CH election needs more message exchange
HydroCast [101]	NP	HT	A	✓		Low	High	Pros: reduced forwarders by considering expected packet advance (EPA) metric Cons: nodes with higher quality links will die earlier
EEDOR[102]	LP,NP	HT	A	✓		Low	High	Pros: descended holding time by depth reduces length and number of path Cons: unbalanced energy consumption between nodes
DVOR[103]	LP,NP	HT	A		✓	Medium	Medium	Pros: reduced path length by calculating the holding time based on distance vector Cons: the nodes closer to the sink died earlier
RE-PBR[104]	SO	PU	U	✓		Medium	Low	Pros: reduced SO by lightweight periodically update to replace route discovery Cons: cannot work well in dense network
RECRP[93]	SO	PU, CD	U	✓		Medium	Low	Pros: reduced signal exchange by using cross-layer information
[96]	SO	PU,CD	A	✓		Medium	Medium	Cons: the neighbor table estimated by cross-layer information are subject to bias
LARP[105]	SO	CD	U		✓	Low	Medium	Pros: utilizes RSSI method to update neighbor table with low SO Cons: rely on location information from anchor nodes which lack of scalability

EB=Energy Balancing, SO=Signaling Overhead, LP=Length of Path, NP=Number of Path; HT=Holding Time, PU=Periodic Updates, LT=Layered Topology, CT=Clustered Topology CD=Cross-layer Design; CM=Communication Model, A=Anycast, U=unicast; EC= Energy Consumption; CH=Cluster Head; RSSI= Signal Strength Indicator

of holding time to delay, the node which can forward a packet to its next hop most quickly has a shorter holding time.

c) Signaling overhead: In UWSNs, hop-by-hop routing discovery can be divided into two main methods: sender-proactive search and receiver-reactive forwarding [75]. In receiver-reactive protocols, senders greedy broadcast the data packet with local information such as depth without communicating with neighbors. Obviously, this approach generates less signaling overhead. However, such a scheme creates more serious multi-copy problem in UWSNs. Sender-proactive routing protocols select the next hop by searching the neighbor table maintained in each node or via one-time information exchange between the sender and receiver before data forwarding (such as the RTS packet in FBR [89]). Due to the node movement specific to UWSNs, dynamic neighborhood information also requires frequent signaling exchange to maintain and update. Upon comparison, the latter has higher signaling overhead and may mix signaling with data packets leading to interference.

Different update methods generate different numbers of signaling exchange, which include periodic proactive and reactive updates from data transmission. In the periodic proactive update method triggered by sensor nodes such as RE-PBR [104], each node periodically broadcasts an update message including its node ID, location, residual energy and so on. Meanwhile, each node continues to listen for the update message from its neighbors to update its route table. Another type of proactive update method is periodically triggered by the sink (RECRP [93]). To reduce the frequency of proactive updates, some papers describe reactively updating neighbor information without signaling exchange. LARP [105] adopts a received signal strength indicator (RSSI) method to obtain location information from data packet transmission. However in this paper, only the anchor nodes can estimate the location information, which lack of scalability. With the help of cross-layer information, [96] utilizes Doppler scale shift to estimate the relative speed between nodes and further estimate when their neighbors are out of range. However, the result estimated by Doppler scale shift is subject to bias, especially in highly dynamic environment. Table. II lists energy-efficient protocols studied for UWSNs, with a comparison in terms of the factor and mechanism for energy-efficient, communication model, operation conditions, performance, and major pros and cons. The performance mainly include the average energy consumption and occurrence rate of void region after adopting these protocols.

B. Void Handling

Unlike routing design in void avoidance, void handling focuses on the void itself, specifically how to diagnose and recover a void. Void diagnosis techniques assist nodes in discovering the region of voids, which provides critical information for void avoidance and void recovery. As for void recovery techniques, they try to recover the void region and the packets that fall into it. Different from TWSNs, the lack of globe network topology and passive mobility of nodes create higher demands on void diagnose and recover, thus unique techniques are required in UWSNs.

1) Void Diagnosis:

a) Network topology: Using the network topology to diagnosis a void region is the most accurate method. In this approach, information about the location of nodes gathers to a center and then all the void regions are identified. It is costly that additional message exchange and gathering time are required to achieve such a purpose in UWSNs. Furthermore, the computational complexity of void diagnosis by using network topology is higher than that of other techniques using in UWSNs. In DCR [106], nodes regard their nearest sonobuoy as a center around which to build the network topology in order to identify all connected and disconnected nodes. Taking advantage of the deployment of AUV that global network topology can be represented by a graph, sonobuoys in [107] can diagnose all the void regions from the graph. However, network topology is still difficult to maintain in UWSNs, even with the assistance of AUV.

b) Neighbor information: A node diagnoses nearby void regions by comparing gathered neighbor information such as depth, location, layer number and forwarding direction. Finally, each node identifies all trapped neighbors at a small cost, which may always include itself. However, nodes in such methods are unable to get a full view of the void region and thus provide limited information for void avoidance and recovery. Nodes in WDFAD-DBR [77] maintain the depth of neighbors upon receiving packets from them. In this protocol, neighbors with lower depth are the option for the next hop. Therefore, when a node can find no neighbors with lower depth, it will realize that it is trapped. Once all the nodes have performed a self-diagnosis, the process of void diagnosis is complete. A similar idea is applied in LLSR [81], in which each node initially stores the hop count value of their neighbor with the help of beacon messages generated by the sink. As the network topology changes, if a node cannot find a lower hop count value among one-hop neighbors, it will diagnose itself as the trapped node and inform its neighbors. Without using a neighbor table, nodes in EVA-DBR [78] overhear packets from lower depth neighbors to perform self-diagnosis. Each node sets a self-detection timer to wait for packets from lower depth neighbors. A node will consider itself to be in a void region if it cannot overhear any packets from lower depth neighbors.

c) Discovery packet: Each node broadcasts discovery packets to diagnose the void region before forwarding data packets. The flying discovery packet acts as a pathfinder to bring information back for corresponding protocols. The overhead and accuracy of this technique fall between those of the above two methods. For example, in APCR [87], when a node wants to send data to the sink, it will first send a forwarder discovery packet with the highest level of power. Subsequently, nodes receiving this packet will reply if they are in a lower layer. Thus, the void region can be diagnosed once the sender can no longer receive a reply from its neighbors. The discovery packet in VAPR [80] initially is the beacon message from the sonobuoy. Having received the beacon message, a node can tell whether it has received the message from deeper or shallower depth; it then sets its data forwarding direction to up or down separately. When multiple forwarding directions are received, the direction with minimal hop count is chosen for the node. In this way, the void area can be diagnosed if there have been any changes in direction.

2) Void Recovery:

a) Backward forwarding: Some void handling techniques allow a packet to fall into the void region and then start a recovery method to guide the packet back to a non-void node. As proposed in [108], if a forwarder cannot find any positive advancement to the destination, the packet will be routed back to the node with the least negative advancement. Unfortunately, this method may create a loop between the trapped node and normal nodes.

Backward forwarding technologies are generally used in conjunction with void avoidance, such as the back-pressure mechanism in VBVA [79]. When a trapped node cannot find an alternative route to the sink using a vector-shift mechanism, it will broadcast a back pressure packet to make the other nodes with negative progress perform the vector-shift. Unless new routes to the destination are found by a vector-shift triggered by other nodes, the back-pressure process continues.

b) Node depth adjustment: In some cases, nodes will be equipped with a depth adjustment device, which gives nodes the ability of autonomous mobility to control network topology. Specifically, each node trapped in the void region can move out of there to build a new connection with at least one non-void node.

DCR is the first geographic routing protocol which consider the nodes' vertical movement capability to deal with the void region [106]. Each node in DCR forwards packets to the nearest sonobuoy via a greedy approach, however a void region will be created because of the underwater environment. By using a centralized algorithm, all nodes trapped in the void region are identified by the DCR protocol. The updated adjusted depth available to them can also be calculated by sonobuoy. For a trapped node, DCR first gathers a list of its candidates' neighbors which are non-void nodes in the cylinder with a certain radius centered by this trapped node. DCR then calculates the updated depth of the trapped node corresponding to its candidates' neighbors for moving out of void region. Finally, DCR chooses the smallest displacement as the depth adjustment for the trapped node. The result of the above calculation is conveyed to the trapped nodes using the AUVs and then the movement to its new depth begins.

Unlike a centralized algorithm to calculate the depth adjustment, trapped nodes in GEDAR [109] send an announcement message to their neighbors and calculate their new depth. The neighbors which receive that message will remove the trapped node out of its routing table and reply with a message containing the information about their own neighbors. The trapped node will receive a set of two-hop neighbor information and then calculate a possible minimum displacement to directly connect them as a means of funding an available route to the sink. If the node cannot determine a new depth, the recovery mode function is called again. Based on the above depth adjustment method, GEDPAR [110] further introduced a layered network topology and power adjustment technology, which increase the efficiency of depth adjustment. However, such distributed depth adjustment method may create a lot of message exchange between neighbors.

Coutinho *et al.* [107] propose mechanisms for Centralized Topology Control (CTC) and Distributed Topology Control

(DTC) through depth adjustment. The CTC mechanism uses a predefined trajectory AUV to collect position information about all sensor nodes and then disseminates that information to the sink. Taking advantage of global network topology, trapped nodes can be identified and given a new depth calculated by the sink. In DTC, each trapped node independently decides whether it should move to a new depth and then sends a message to inform its neighbors. Only nodes that have an available route to the sink can reply with that message. The trapped node then aggregates all received responses and chooses the minimum updated distance to move. DA-VAPR [111] is proposed based on the greedy forwarding strategy in VAPR and leverages depth adjustment by using the Particle Swarm Optimization (PSO) algorithm. Specifically, a trapped node will stop beaconing, send an announcement message and schedule its new depth with minimum displacement by PSO. By using depth adjustment, routing protocols can effectively recover from the void problem. However, depth adjustment consumes a high amount of energy, for which the lifetime of trapped nodes must be sacrificed.

c) Backup facilities: In response to the problem of void regions, some studies introduce backup facilities such as AUV to collect information about the void boundary and trapped nodes. Backup facilities can also recover the void area by deploying new nodes. An AUV-assisted routing void prediction and repairing (PVPR) is proposed in [112], which utilizes AUVs to deploy new nodes to recover the void region once its occurrence has been foreseen. The routing void prediction based on a Markov chain model is proposed to ensure that AUVs come to the repair task before voids have already formed. RVPR enables nodes to predict routing voids nearby by recording the communication history of their neighbors based on a Markov chain model. The deployment position of the new node carried by the AUV is then calculated based on the PSO algorithm by maximizing the connectivity of the void area and minimizing the AUV moving distance. Nevertheless, this void region recovery method is limited by the speed of the AUV. It also introduced an additional deployment cost. The void related protocols in UWSNs are listed in Table III, mainly addressing void-related mechanism, decision maker, operation conditions, performance, and major pros and cons.

C. Summary

Reliable routing design in UWSNs mainly focuses on the existence of void regions caused by unpredictable movement and non-rechargeable sensors. In void avoidance techniques, nodes in void-avoidance protocols try to select a reliable route through passive participation, proactive bypassing, flooding or transmission power adjustment. Passive participation achieves minimal communication overhead. Other techniques obtain more information to enable selection of non-void neighbors as the next hop. Specially, transmission power adjustment uses cross-layer information to conveniently bypass the trapped nodes, however, it may cause energy to dissipate and interfere with other layers (MAC). On the other hand, energy-efficient protocols facilitate void avoidance by reducing the number of void regions created. To achieve energy balance, nodes give additional attention to residual energy when selecting their next hop. However, this may sacrifice some of the shorter path options. Forwarding participants can be reduced by shortening the path to the sink and lowering the number of data copies, which can be achieved by a network topology maintain mechanism and a holding time mechanism in opportunistic routing, respectively. Signaling overhead is shorter in receiver-based protocols and can be reduced in sender-based protocols by updating neighbor information periodically or through cross-layered information assistance.

Another technique known as void handing consists of void diagnosis and void recovery. The diagnosis of void areas can be achieved by using network topology, neighbor information or discovery packet. Upon comparison, the use of network topology has the highest accuracy but with higher overhead, whereas neighbor information is the opposite of it. Thus, all the above void diagnosis techniques are suitable for different scenarios and protocols. As the final guarantee of routing reliability, void recovery techniques can be divided into backward forwarding, node depth adjustment and backup facilities. Backward forwarding does not introduce any new equipment and thus create a loop between trapped nodes and others. Node depth adjustment increases energy consumption of trapped nodes and backup facilities increases network deployment costs.

V. Reliable Navigation in AUV-Aided UWSN Data Collection

AUVs are deployed in UWSNs currently to complete a variety of data collection tasks such as monitoring and exploration. Navigation is a key functionality of AUV which is used to calculate the current position and the position of AUV at a certain time in the future. Navigational accuracy is critical to the reliability of data collection. If AUVs are unable to reach a predetermined location precisely, the collection efficiency and the transmission energy consumption of the nodes will be affected. As GPS cannot work well in UWSNs, there are mainly two types of specialized navigation technologies for AUV: inter-navigation and intra-navigation [23]. The primary distinction between them is whether they utilize other information in addition to the state of AUV movement. However, each type of navigation has some degree of inaccuracy due to measurement error. More seriously, these inaccuracies will become significant through variations in AUV motion over time.

A. Intra-Navigation

Intra-navigation is an autonomous system that does not depend on external information but only information from equipped sensors on AUVs such as the Doppler velocimeter, accelerometer and so on. The results of these measurement are then calculated by a DR algorithm to estimate the location and direction of an AUV. For example, the pose of a AUV can be estimated by available heading from a compass and available velocity from a Doppler velocimeter. However, measurements by such equipment are subject to greater interference and noise in underwater environments. The nominal standard deviation of Doppler velocimeter is on the order of

TABLE III
UWSN VOID RELATED PROTOCOLS

Protocol Name/ Reference	Void-Related Mechanism			DM	Operation Conditions		Performance		Major Characteristics(Pros and Cons)
	VD	VA	VR		SYN	LOC	Protocol Overhead	PDR	
WDFAD-DBR [77]	NI	PP	\	R	✓		Medium	Medium	Pros: prevent packets from entering a void by two-hop depth information Cons: cannot identify trapped nodes in advance
EVA-DBR[78]	NI	PP	\	R	✓		Low	Low	Pros: self-detection by overhear packets from lower depth with low overhead Cons: inappropriate in a sparse network
VBVA[79]	NI	PB	BF	Se		✓	Medium	High	Pros: have comprehensive void-handling mechanisms based on vector-shift Cons: exacerbate the multi-copy problem, resulting in more energy consumption
VAPR[80]	DP	PB	\	Se	✓		High	High	Pros: build a directional trail to the closest sonobuoy to avoid void problem Cons: network initialization process needs extensive signaling exchange
LLSR[81]	NI	PB	\	Se	✓		Medium	High	Pros: utilized one-hop neighbor information to avoid packets entering a void
OVAR[82]	NI	PB	\	Se	✓		Medium	High	Cons: extra communication overhead to maintain one-hop neighbor table
[84]	DP	F	\			✓	High	High	Pros: the coding based mechanism reduce the cost of flooding Cons: have not considered the extreme cases such as no flooding candidate nodes
DFR[85]	DP	F	\			✓	High	High	Pros: the control of the flooding direction reduces number of involved nodes Cons: creating duplicate packets, resulting in more energy consumption
APCR[87]	DP	PA	\	Se		✓	High	High	Pros: pass through the void increase with different transmission power level
PCR[88]	DP	PA	\	R			High	High	Cons: beacon exchange and increased power cause more energy consumption
FBR[89]	DP	F,PA	\	Se		✓	Medium	Medium	Pros: the cone shift mechanism with power control reduces protocol overhead Cons: demands the positioning between forwarding nodes and the final destination
AHH-VBF[90]	DP	PA	\	R		✓	High	Medium	Pros: adapted transmission power in sparse and dense networks Cons: not flexible enough when nodes follow an irregular distribution.
DCR[106]	NP	\	DA	Se		✓	High	High	Pros: diagnosed and recovered void precisely based on globe network topology Cons: rely on the deployment of AUV to get location information
GEDAR[109]	NI	\	DA	R		✓	High	High	Pros: calculated new depth from two-hop neighbor information to recover void
GEDPAR[110]	NI	PA	DA	R		✓	High	High	Cons: created a lot of message exchange by distributed depth adjustment method
[107]	NP	\	DA			✓	High	High	Pros: proposed centralized and distributed depth adjustment method Cons: design only for long-term and non-time-critical applications
DA-VAPR [111]	DP	\	DA	Se	✓		High	High	Pros: added void recovery to VARP by depth adjustment Cons: sacrificed the lifetime of trapped nodes
PVPR[112]	NI	\	BF			✓	Low	Medium	Pros: utilized AUVs to recover void with low overhead of nodes Cons: limited by the speed of the AUV.

VD=Void Diagnosis, NI=Neighbor Information, DP=Discovery Packet, NP=Network Topology; VA=Void Avoidance, PP=Passive Participation, PB=Proactive Bypassing F=Flooding, PA=Power Adjustment; VR=Void Recovery, BF=Backward Forwarding, DA=Depth Adjustment, BF=Backup Facilities. PDR=Packet Delivery Ratio

$0.3 - 0.8$*cm/s* and the bias range of accelerometer is from 0.01*mg* to 0.001*mg* [12]. As a result, the measurement error and noise-accumulated errors increase with time unboundedly during DR.

To improve the reliability of inertial navigation, Kalman filtering (KF) methods such as Extended KF (EKF) [113] and Unscented KF (UKF) [114] are mainly used to derive an estimate of position. KF is an algorithm that uses the state equation of a linear system to optimally estimate the system state from a sequence of uncertain observations. Generally, the prediction of the next state uses an existing physical model and a statistical model to describe uncertain factors. Depending on the difference between predictions and observations, the state of the system can be revised. However, Kalman-based methods need a constant and pre-known covariance matrix of noise. Recently, a few works introduced machine learning methods to predict the mobility of vehicles according to inertial data. Reference [115] classifies pitch angles when the vessel sails close to waves. Reference [24] employs a neural network to predict pitch angles accurately by exploring the complex relationship between pitch angles and accelerations.

B. Inter-Navigation

Inter-navigation mainly includes acoustic navigation [116] and Geophysical Navigation [117]. Acoustic navigation deploys acoustic beacons in the data collection area to assist AUVs. Specifically, AUVs measure the time of flight (TOF) of signals from acoustic beacons to perform navigation. The main system methods are long baseline (LBL), short baseline (SBL) and ultrashort baseline (USBL) [118]. LBL requires the installation of at least two beacons placed over a wide mission area, as shown in Fig. 11, and the location of the AUV is based on triangulation of acoustic signals. SBL and USBL systems use a single beacon with multiple baselines. The baselines of SBL are placed in different positions on the AUV, as shown in Fig. 12, while the baselines of USBL are placed closely on the order of less than 10*cm* on AUV, as shown in Fig. 13. The

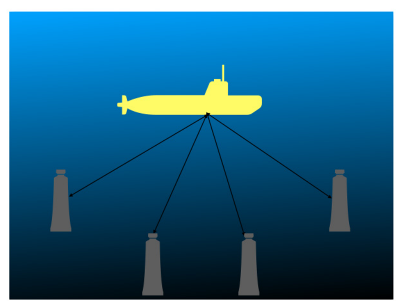

Fig. 11. An example of LBL: Beacons are placed over a wide area.

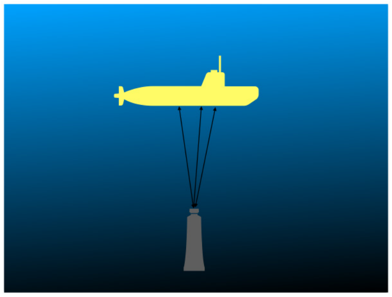

Fig. 12. An example of SBL: The baselines are placed in different positions on the AUV.

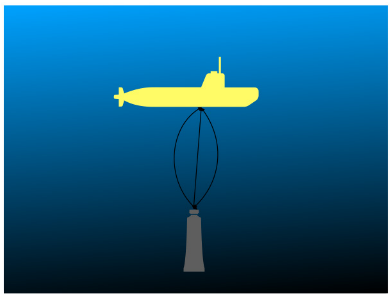

Fig. 13. An example of USBL: The baselines are closely spaced on the AUV.

precision of LBL systems yield generally better than $1m$ and the accuracy of USBL is about $0.1\%x$, where x is the target distance [119]. LBL has high localization accuracy and a large cover range but with a high deployment cost. USBL is different from LBL and easier to equip on an AUV, while SBL falls in between them. However, acoustic signals migrate, diffuse and attenuate when they propagate underwater, resulting in navigational inaccuracy.

Geophysical navigation refers to those methods that use external environmental information for navigation. This information can be obtained by preexisting or purposefully deployed equipments such as captured images, sonar and magnetic/gravitational maps. Simultaneous localization and mapping (SLAM) is the main technology used in these methods, which autonomously build a map of the environment and localize the AUV. SLAM improves navigational accuracy by extracting the augmented state vector from the information with suitable feature locations and covariances. SLAM algorithms can be classified as online and offline [120]. Online SLAM algorithms only estimate the current pose of the AUV and the map of its environment while offline SLAM algorithms accumulate information to calculate the posterior over the entire trajectory of the AUV.

EKF-SLAM [121], [122] is a typical category of online SLAM which linearizes the system model by Taylor expansion then takes a recursive approach to estimate the current pose and map, while SEIF–SLAM [123] maintains an information matrix building from environment information. Generally, in offline SLAM algorithms, an AUV's pose is represented as nodes on a graph, while motion and observation constraints are modeled as edges. For example, iSAM [124] updates a matrix factorization to solve the offline SLAM and HOGMAN [125] optimizes the calculation of the spatial distribution over a manifold. Particle filters [126] and artificial intelligence (AI) [127] can be used in both types of SLAM. In particle filter-based SLAM, the pose and all features are represented by particles in the state space [128]. In AI-based SLAM, a neural network such as a self-organizing map (SOMs) [127] or an unsupervised neural network [129] is trained to recognise features in the environment.

C. Summary

Intra/Inter-navigation technologies complement each other in different scenarios. For short-range missions (up to $10km$), intra-navigation can provide sufficient accuracy alone. If the mission requires a higher level of accuracy or a larger range (up to $100km$), SLAM techniques and the deployment of beacons can help correct inaccuracies generated over the course of the mission. For missions above $100km$, the inaccuracies from intra-navigation becomes serious and the development of beacons is not practical. A geophysical navigation system involving maps is one of the main way to improve accuracy.

VI. Reliable Traveling in AUV-Aided UWSN Data Collection

To improve the reliability of UWSNs, some AUV-aided traveling schemes have been proposed recently. In this scenario, AUVs travel among sensor nodes to collect sensed data and manage them. The leverage of the AUV mobility reduces the communication distances in UWSN and thus improve the channel quality of the data delivery. The presence of AUVs also provides facilities for a multi-modal Underwater Communication System (UMCS), which combines the characteristics of different underwater communication technologies [130]. Moreover, the introduction of an AUV can replace some of the original function of sensor nodes such as relay and cluster management which can effectively extend the lifetime of nodes.

Although an AUV does improve the reliability of data collection, its driving speed is relatively slow, creating long delays in data collection. An AUV may not visit some nodes in time because of the contradiction between data timeliness and its speed. Moreover, it is inefficient for AUVs to travel to all nodes when there are excessive number of nodes. Thus, it is worthwhile carefully planning the path of the AUV. In addition to path planning, AUVs make other efforts in relation to transmission between nodes. The decisions made by AUVs during traveling impact on the transmission load among nodes, which ultimately affects the lifetime of nodes. Corresponding to path planning, this process is called in-situ decision in this paper.

A. Path Planning

Path planning algorithms for AUV can be divided into online and offline. In offline path planning, the AUV already has the information about the node before it begins its journey, whereas online path planning processes randomly arriving nodal information in real time. In different scenarios, the optimization objectives of path planning vary according to the data requirement, such as Value of Information (VoI) and level of emergency. Ultimately, the reliability of data collection is improved by these optimized path plans.

1) Offline Path Planning: Khan *et al.* proposed four methods for fixed grid areas: shortest path with the genetic algorithm, Lowest Energy Cluster First (LECF), On-the-way-Lowest Energy Cluster First (OLECF) and On-the-way Lowest Mean Energy Cluster First (OLMECF) [131]. On-the-way means that if the AUV finds any other cluster on its journey to the destination cluster, it first visits and communicates with the intermediate cluster before moving to the destination. However, the scenario in this scheme has limitations that all sensor nodes are fixed at the seafloor and AUV maintains the exact location information of all nodes. The same assumption is applied to [132], it divided the network into clusters, each of which is divided into several sub-clusters. Such mechanism can reduce the impact of un-equal relay node multi-hop path distance, and thus avoid the void problem. The AUV plans to travel to all the Sub-cluster Head nodes (SHs) and Cluster Heads (CHs) to collect data. A local-search-based heuristic TSP solver is used to solve the optimization problem as mentioned in [133].

In AEEDCO [134], an offline strategy is proposed to access each cluster head using the shortest possible path, which is only suitable for static network topology. This is formulated as a Traveling Salesman Problem (TSP) and the Ant Colony Algorithm (ACA) is applied to solve the TSP problem. Similarly, in [135], AUVs travel to all cluster head nodes in a clustered network. However, the cluster head will not be replaced by other nodes and thus may die earlier. The path optimization has the objective of maximizing the VoI of the total network by formulating the problem as a combinatorial optimization problem and providing an Integer Linear Programming (ILP) model to solve it. An optimal algorithm based on Branch-and-Bound (BB) method and two near-optimal heuristic algorithms based on the ACA and the Genetic Algorithm (GA) are proposed to solve the problem.

2) Online Path Planning: Gjanci *et al.* propose a Greedy and Adaptive AUV Path finding (GAAP [136]) algorithm based on an integer linear programming mathematical model with maximized VoI as the optimization objective. The VoI of the data from an event is highest at the moment the event is detected and decay with time. In this scenario, the AUV moves continuously along a path to collect data, accessing only one node at a time and greedily selecting the node with the highest VoI as the target. However, the algorithm is suitable only for the sparse network. In another VoI-based work, data collectors are fixed with the underwater anchor to collect data from nodes around [137]. An AUV is deployed to dynamically visit data collectors to maximize the VoI within a given time. Once receiving the VoI information from data collectors, the AUV dynamically chooses the collector whose income function is maximum as the current visiting target if the AUV is within a visiting time period.

The AUV travel time is also taken into consideration in [138]. If the AUV successfully collects data from a sensor node in time, it will obtain a prize, whereas it incurs a penalty if it fails to visit a sensor. This is known as prize collecting TSP (PC-TSP). To obtain the real-time situation from nodes, AUV requires frequent communication with the sensors. Unlike in ACMC [139], it adopts the greedy algorithm to make a predetermined trajectory by selecting the next visited node with the smallest distance based on the location of CHs. The ordinary nodes close to the above AUV trajectory are then selected as secondary cluster heads to share the workload of cluster heads. Finally, the AUV corrects its trajectory to cover all the cluster heads and their secondary cluster heads in the same way.

B. In-situ Decision

During the journey of an AUV, some of the original functions of the sensor nodes are replaced by in-situ decisions by AUV. The first type of function is the selection of a sink between sensors. Without an AUV, the sink of a specific area is elected by sensors through massive communications. The introduction of an AUV can reduce such communications and even act as a sink. Another replaceable type of function is transmission scheduling between nodes. An AUV can be regarded as a mobile scheduler to balance and reduce energy consumption among nodes.

1) Sink Selection: This mainly refers to the selection of cluster heads and gateway nodes, which take out more transmission and forwarding tasks than ordinary nodes. With the help of an AUV, the clustering algorithm and gateway nodes selection can be further optimized as the following:

a) Clustering algorithm: Utilizing the location information, [131], [140] divide the overall sensing area into homogeneous square grids and sensor nodes are aware of their attribution. Each grid has a Cluster Centroid Point (CCP) as the destination for the AUV in which all nodes belonging to this area can communicate with the upcoming AUV. After traveling through a grid, the AUV will select a new cluster head with the largest residual energy for this grid to balance the energy.

A K-means clustering algorithm based on the globe network topology is used in [139] to divide N nodes into K clusters. First, K nodes which follow a distance threshold are randomly selected as the initial clustering centers. Then each remaining sensor node chooses its closest center to complete the division. Thereafter, the cluster center updates according to the average value of the coordinates of the nodes in the cluster. Except for the initialization process, this process is repeated until the nodes in each cluster are stable. Once cluster centers and their member nodes are determined, the node closest to the cluster center is selected as the cluster head. Although the selection of cluster head ignores the residual energy, there are secondary cluster heads near the trajectory of AUV to share the transmission loads.

The cluster heads selection problem is formulated as a maximal clique problem (MCP) under the constraint of communication distance between cluster heads in [134]. The improved Bron–Kerbosch search algorithm in [141] is chosen to solve the MCP by finding all possible cluster head sets and then the remaining nodes choose the closest cluster head each time. Energy utility is used to measure these cluster head sets, creating a tradeoff between energy consumption and network

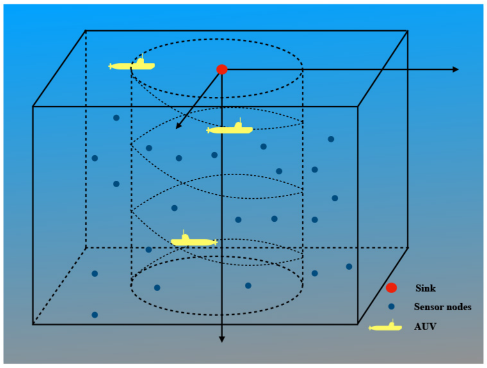

Fig. 14. Spiral Trajectory Design.

throughput with the help of the AUV. To prolong the lifetime of nodes depends on the ranking of their energy utility in each round, sensor nodes take turns to be the cluster head.

b) Gateway node: In some predefined paths, the sink is selected near the trajectory; this is called the gateway node. To balance the energy of these potential gateway nodes, the AUV lets different nodes near the designed trajectory act as the gateway in each round. For example, in AEDG [142], the trajectory of the AUV is predefined (elliptical). Nodes near the trajectory are selected as Gateway Nodes (GN) and the other nodes are associated with GN based on the Received Signal Strength Indication (RSSI) from their control packets. After gathering data, gateway nodes send these data to an AUV. GNs are rotated to balance energy consumption, which follows a residual energy-based threshold mechanism. However, the predefined elliptical trajectory is not suitable for large areas that it covered few nodes. The further the node is from the trajectory, the harder it is to deliver data to AUV.

In [143], a trajectory adjustment mechanism is applied. The AUV travels around the network on a predefined spiral trajectory as shown in Fig. 14. The initial position of the AUV on the surface is changed per up-down cycle to eliminate the relative fixability of nodes and trajectory of the AUV so that the nodes beside the trajectory of the AUV are no longer fixed. In this work, a reliable time mechanism is also proposed to guarantee that the nodes near the AUV trajectory have sufficient time to communicate with the AUV. However, such predefined trajectory is not flexibility to the timeliness of data. In the same scenario, Han *et al.* further consider the energy consumption and probability of failure of AUVs [144]. Malfunction discovery and repair mechanisms are applied to ensure that the network operates appropriately when an AUV fails to communicate with the nodes while collecting data. Once a gateway node realizes that an AUV may have failed, it marks the AUV as unreachable and starts a new timer with a length of projected maintenance time. Then the gateway node floods this information to all nodes. Nodes received the information cancel the unreachable label of the AUV when the timer has expired.

2) Transmission Scheduling: The introduction of an AUV provides more energy-saving scheduling options such as short-range transmission and a mobile scheduler. The former provides multiple transmission medium (e.g., radio, optical) for nodes known as transmission medium scheduling. The latter is referred to as transmission management, which can schedule transmission and wakeup-sleep time, centralized for sensor nodes.

a) Transmission medium scheduling: Yoon *et al.* utilize multi-medium communication between the AUV and sensor nodes to reduce the energy consumption AURP[145]. In this method, small size control packets use long distance and low-rate communication, the data transmission between the sensor nodes and AUVs involves mid-range communication, and short-range and high-speed communications are used between the AUVs and the sink. To achieve high packet delivery ratio in such a scheme, there are a large number of control packets in the network which result in high energy consumption. Cheng and Li propose a data gathering protocol that takes the importance of data into account DGS[146]. Data is categorised into important data and normal data. Important data uses long-range acoustic communication between sensors while normal data waits for the arrival of an AUV. However, nodes near the trajectory take on more forwarding and thereby consume more energy with a shorter lifetime. Similarly, in [136], nodes propagate short event packets acoustically with VoI information and wait for an AUV to collect data packets using a short distance optical data link.

b) Transmission time scheduling: To take on more transmission energy for sensor nodes, AUVs play a critical role in scheduling the sleep-wake and transmission time intra-cluster [140]. Initially, the AUV creates and broadcasts a hello packet including a reply time for each member node in a cluster. By comparing reply packets from each member node, the AUV assigns wakeup time and transfer time to nodes within the cluster based on the intra-cluster topology. Due to there is no additional packet among nodes, clustering outperforms traditional schemes and the wakeup-sleep schedule further saves energy and decreases the probability of data loss.

In [134], the AUV sends an ACTIVE packet to the cluster head once it enters a cluster. The ACTIVE packet contains the transmission schedule for each node. The longer the distance between an intracluster node and cluster head, the earlier the transmission time. The cluster head then broadcasts a WAKE packet and intracluster nodes calculate their waiting sending time. After collecting from all the intracluster nodes, ACK conveys the transmission time in the next round. The transmission continues until the cluster receives a PULSE packet from the AUV.

C. Summary

The AUV-aided data collection schemes in UWSNs are listed in Table IV, mainly comparing in terms of path plan, in-suit decision, operation conditions, performance, and major pros and cons. The main advantages of AUV-aided data collection schemes include i) making swift and large-scale underwater data communication possible and ii) further energy savings for underwater nodes. However, the speed of an AUV is much slower than the propagation speed of an acoustic signal. To build on the strengths and avoid the weaknesses, reasonable path optimization and management are important.

TABLE IV
UWSN AUV-AIDED DATA COLLECTION

Protocol name/ Reference	Path Plan		In-suit Decision		Topology	Operation Conditions		Performance		Major Characteristics(Pros and Cons)
	Model	DA	SS	TS		SYN	LOC	ECN	PDR	
[132],[141]	Offline	\	CH	Time	FG	✓	✓	Low	High	Pros: AUV reduced ECN effectively by scheduling transmission among nodes Cons: can only work with fixed network topology
[133]	Offline	\	CH	\	Cluster		✓	Medium	High	Pros: the sub-cluster mechanism avoid the void problem Cons: AUV travels all sub-cluster heads with a longer trajectory
AEEDCO[135]	Offline	\	CH	Time	Cluster		✓	Low	High	Pros: design EE clustering and MAC with the help of AUV Cons: cannot suitable for dynamic network topology
[136]	Offline	VoI	CH	\	Cluster		✓	Low	High	Pros: AUV jointly considering VoI and energy balancing among CHs Cons: CHs died earlier without replacement mechanism
GAAP[137]	Online	VoI	\	Medium	\			High	Medium	Pros: adapts to random events even with node movement Cons: suitable only for the sparse network
[138]	Online	VoI	CH	\	Cluster		✓	Medium	Medium	Pros: maximize the real-time VoI collected from data collectors Cons: needs to deploy data collectors which are anchored
[139]	Online	Ti	\	\	\			High	Medium	Pros: add prize and penalty mechanism for real-time path planning Cons: AUV requires frequent communication with the sensors
ACMC[140]	Online	\	CH	Time	Cluster		✓	Medium	High	Pros: nodes close to the AUV trajectory shared the work of cluster heads Cons: needs globe network topology of nodes when clustering
AEDG[143]	Offline	\	GN	\	\	✓		Medium	Low	Pros: balanced energy by the rotation of gateway nodes near the trajectory Cons: the predefined elliptical trajectory is not suitable for large areas
[144], [145]	Offline	\	GN	\	\	✓	✓	Low	High	Pros: achieve EE by spiral trajectory adjustment mechanism Cons: not flexibility to the timeliness of data
AURP[146]	Online	VoI	GN	Medium	\		✓	High	Medium	Pros: packets with different size use different transmission medium Cons: the large number of control packets in the network
DGS[147]	Online	Ti	\	Medium	Layer	✓	✓	Medium	Medium	Pros: data with different importance use different transmission medium Cons: the nodes near the trajectory consume more energy and die early

DA=Data Attributes, Ti=Timeliness; SS=Sink Selection, CH=Cluster Head, GN=Gateway Node; TS=Transmission Scheduling; FG=Fixed Grid; ECN=Energy Consumption of Nodes, EE=Energy-Efficient, PDR=Packet Delivery Ratio

In future, it would be worthwhile facilitating the capability of AUVs to improve the reliability of data collection in different scenarios by making full use of their features.

VII. Future Research Directions

In this section, some technical and practical issues remain for further investigation have been proposed. Based on the literature surveyed above, we have identified the following techniques which have potential for further research to improve the reliability of data collection.

1) Multi-Medium: This refers to the combination of multi communication mediums in UWSNs such as acoustic, optical, magnetic induction, and wired pipeline. This technique encompasses any set of non-mutually interfering underwater communication technologies, which may have various advantages from different communication medium. With the diversification of marine applications, increasing types of data have different time sensitivities, information value and volume. Theoretically, multi-medium communication is a valuable solution to the above-mentioned data requirements by reasonably assigning such communication resources of the nodes for the data links. Such technology makes it possible for each underwater device flexibility to select a appropriate communication medium in a variable environment. On the other hand, when a communication mediums is not available, it can be replaced with another medium to ensure reliable transmission.

However, it is costly to equip multiple modems on each node or to deploy AUVs for multiple communication mediums. Moreover, the usage of each communication medium in UWSNs has its special pros and cons in different scenarios, which may limit the efficiency of multi-medium communication. For instance, high-quality optical signals can only be maintained at short ranges and are easily influenced by environment conditions, which rely on the deployment of sensors. Mobile AUVs can break this limitation while their slow speed creates another performance bottleneck. Thus, how to optimally exploit the multi-medium communications capabilities in different scenarios is worth developing for solving practical problems, including the trade-off between hardware deployment and multi-medium switching. Specifically, the optimal design based on multi-medium communication for modem selection, AUV path planning, sensor deployment, transmission resources assignment, and multi-medium system deserved further research in the future.

2) Multiple-Input Multiple-Output (MIMO): This technique provides multiplex and diversity gains that deploy multiple antennas on the sender and receiver [147], through which the signal-to-noise ratio (SNR) or channel capacity can be enhanced to enable long-range and high-throughput communications. Bring the multiplex gain of MIMO to UWSNs has the potential for a substantial increase in channel capacity without increasing available bandwidth and transmit power, which can potentially be combined with any modulation or multiple access techniques [148] such as orthogonal frequency division multiplexing (OFDM). And the diversity of MIMO exploits the independent fading in the multiple antenna links to enhance signal diversity, which could effective against high signal attenuation and interference in UWSNs. In addition, the precoding technology in MIMO could improve the signal power at the receiver side with appropriate phase and gain weighting on the same signals, and results in considerable signal-to-interference ratio improvement.

However, MIMO in underwater acoustics communication is a relatively new field of study and faces a lot of hurdles when it comes to deployment. First of all, it is verified that increasing the array size is beneficial, yet antenna deployment at underwater sensors requires greater spacing. Generally, the half-wavelength linear uniform array is adopted to decide the antenna spacing, while the underwater wavelength is longer than that in terrestrial [149]. By forming a virtual antenna array using multiple underwater nodes could alleviate this problem [150], however, this requires a high level of time synchronization and signaling overhead. Secondly, underwater acoustics communication faces serious multipath effects due to the signal reflection from the wavy sea surface, sea-bed ,and numerous obstacles. This problem gets severe in the case of MIMO that much more delayed replicas will reach the receiver and thus creates more Inter-Signal Interference (ISI) [151]. Moreover, more serious implications of the Doppler effect in UWSNs causes severe Inter-Carrier Interference (ICI) [152]. With MIMO creating more signals, the calculation of Doppler shifts becomes more difficult. There is still a lot of room for further research to make MIMO available in UWSNs, which could also provide opportunities to improve the reliable of data collection in UWSNs.

3) Cross-Layer Design & Co-Design: The traditional data-collection technique is to distribute all collection process into sub-layers of network with no information share among them. In UWSNs, the main network bottlenecks are the communication cost and the variable environment, which almost be handled in each layer repeatedly. Each layer has the solution applicable to itself, such as void-handling techniques are being adopted at the network layer and MAC protocols at the data link layer. Combining the information from other layers for the cross-layer design can effectively break these bottlenecks in data collection. For example, using information about transmission power from the physical layer can help constitute the optimal route or link. Co-design, which is a systematical plan for cooperation at different layers to achieve a common objective, goes even further. From a macro perspective of data collection, all possible optimal options could be jointly considered to achieve a maximum performance gain through layer-to-layer interactions.

Both cross-layer design and co-design in UWSNs break down the abstraction layers model (e.g., Open Systems Interconnection (OSI), Internet protocol suite (TCP/IP)) to some extent, which means that such methods may suffer from low portability, scalability. Once the protocol in one layer has been changed, it may affect the performance of other layers, resulting in functional redundancy or even prevent other layers from working. Optimization of these protocols is also made more difficult by considering multiple layers of information simultaneously. Thus, the challenge of cross-layer design or co-design is mainly on how to find effective interfaces between different layers without affecting their original function, which still needs further study.

4) Real-Time Prediction: The accuracy and timeliness of information required for data collection are difficult to maintain due to the dynamic network topology and the long signals propagation delays. Whereas most of existing data collection techniques for UWSNs assume that nodes move slowly or are stationary. To adapt data collection techniques to realistic highly dynamic underwater environments, it is necessary to enable sensors or AUVs to abstract environmental characteristics using real-time prediction or from historical data, by learning approaches such as reinforcement learning [153], [154]. Specifically, real-time predictions such as the mobility of void areas and nodes, the data create rate and transmission load have not been investigated thoroughly. They can be used to optimize the real-time decision for route congestion control, link scheduling policies and AUV path selection.

However, the real-time prediction for UWSNs suffers from a lack of training samples that most of the existing work is performed in the simulator [10]. Besides, the limited power supply of underwater nodes restricts the deployment of large-scale learning models due to their high computational complexity and energy consumption. Whereas, real-time predictions mentioned above demand accurate prediction to ensure the reliability of data collection. To adapt to the UWSNs, there needs a trade-off between the complexity and energy efficiency of learning models. In future research, more accurate real-time prediction models with lower complexity or overheads need to be researched to the underwater environment so that the data collection can be more reliable.

VIII. Conclusion

In this paper, an overview of reliable data collection techniques in UWSNs has been presented. Different researchers have focused on different network layers and methods during data collection, which can be divided into reliable link and path in hop-by-hop data collection and reliable navigation and traveling in AUV-aided data collection. For each model and stage, reliable techniques for data collection have been explored in detail individually, and various challenges have been considered and addressed. In the reliable link techniques, various coding, retransmission mechanisms and MAC strategies for handling bit error and packet collision have been researched separately. As for existing reliable routing techniques, these mainly focus on the void problem by relying on a certain routing strategy. Unlike hop-by-hop transfer architecture, the utilization of AUVs brings new opportunities and challenges by taking into account the optimal design of AUV navigation and path planning. Finally, several topics of further research directions are discussed to improve the reliability of data collection in UWSNs.

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