Fundamentals and Advancements of Topology Discovery in Underwater Acoustic Sensor Networks: A Review

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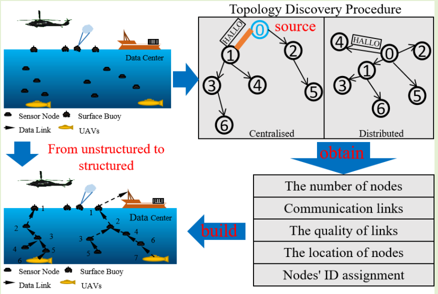
***Abstract*—With the extensive application of underwater acoustic sensor networks (UANs) in various fields such as commerce, marine environmental research, and national defense, the need for an autonomous and well-organized underwater acoustic network has been increasing. Topology discovery is a crucial step in constructing an underwater acoustic network, and node discovery and topology establishment are the essential components of the topology discovery process in UANs. This paper introduces the characteristics of underwater acoustic channels and networks and highlights their influences on topology discovery. We discuss the topology discovery protocol development in terrestrial networks (i.e., duty-cycle ad hoc network, Internet of things). The main focus of this paper is to study the topology discovery protocols of UANs. This paper also classifies and introduces the existing topology discovery protocols and compared their advantages and disadvantages to understand the current topology discovery methods. Furthermore, we also discuss the topology discovery protocol's influence on different layers' functions in the UAN protocol stack. Analyze the current research challenges in this field, followed by important open issues in UAN protocol development, which provide new opportunities for further research.**



***Index Terms*—Underwater acoustic sensor networks, topology discovery protocol, acoustic communication.**

I. INTRODUCTION

GIVEN 70% of the earth's surface is covered by water, countries worldwide are accelerating marine environmental monitoring, marine resources exploration and development, underwater exploration, and other research related to marine science and technology projects [1]–[3]. UANs usually consist of underwater sensors and vehicles that communicate with each other by acoustic links to accomplish specific tasks [4]. Due to its flexible deployment and great potential in Marine engineering, industry and national defense, the research on UANs becomes the center of marine information technology.

Researchers have been interested in UANs for decades. The primary review papers are about Underwater Acoustic Communication Modems [5], Support Technology [6], Routing Protocol [7], Media Access Control (MAC) Protocol [8], topology dataset [9], Localization [10], [11], wormhole detection [12] and so on. [5] has provided a comparative analysis of commercial and research modems based on their characteristics and design constraints. The article has discussed common parameters and exclusive parameters of both kinds of modems. Acoustic and magneto-inductive communications have been discussed in [6]. It has also reviewed several solutions to improve communication capacity and communication range. In addition, routing and MAC protocols [7], [8] have been studied. The authors in [9] have built a freely shared date set of underwater topology. It has provided a benchmark database of time-varying network topologies recorded across multiple sea experiments. [10] and [11] have given background

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information on the basics of localization and surveyed the localization schemes. Furthermore, [12] detects the wormholes by visualizing the distortions in edge lengths and angles among neighboring sensors. The efficient operation of these protocols and methods is relay on the topology information of the network.

Unlike a fixed network, a crucial yet challenging process for UANs is network topology discovery. Precisely, in the initial stage of network deployment of UANs, sensor nodes are randomly placed in a given sea area. The nodes have no communication infrastructure at the time of deployment. They know nothing about neighboring nodes' information. In this case, the network cannot carry out regular information interaction and processing. Therefore, to initiate network operation and establish the preliminary network structure timely, dynamically, and autonomously under the current network environment, the network topology discovery process is necessary [13]. Afterward, the upper-level protocols such as network channel access protocol and routing protocol can operate, and the network can run smoothly. A fast and effective method for topology discovery of UANs helps form the initial network structure and prolong its service cycle. It plays a vital role in the correct execution of various tasks of the network [14].

Compared with the terrestrial sensor network, the development of topology discovery in UANs is faced with many technical challenges. The speed of sound is slow (approximately 1500 m/s) yielding a large propagation delay. Moreover, the data rate is low than that of terrestrial networks. Furthermore, the acoustic channel has low link quality which is mostly due to the multi-path propagation and the time-variability of the medium. Meanwhile, the mobility of nodes increases the instability of the links.

Neighbor discovery protocols for terrestrial self-organizing wireless networks have been heavily investigated [15]–[22]. However, in UANs, the harsh environment and the unpredictable behaviors of acoustic links bring new challenges to topology discovery. A discovery process for initializing UANs was proposed in [23] based on polling by a master node in a centralized configuration. A node discovery protocol [24] was proposed to establish multi-hop, minimum-power acoustic communication links over a given coverage area. To solve the topology discovery and ID self-assignment problem, a fully distributed protocol was proposed in [25]. Diamant *et al.* [26] discussed a more efficient discovery algorithm to decrease the long delay brought by the traditional TDMA mechanism. Yun and Choi [27] proposed an application-based partial initialization protocol. This protocol initializes as many nodes as required to execute a given application. A join protocol was proposed in [28] to enable the integration of new nodes into an existing network. The proposed solution is based on the capability of a joining node to join local topology and schedule information into a probabilistic model that allows it to choose when to join the network to minimize the expected number of collisions. In [29], they proposed a kind of UAN named SOUNET where nodes build and maintain a tree topology by packet flooding.

To the best of our knowledge, no review paper classifies and thoroughly discusses the problem of topology discovery yet. Due to the lack of comprehensive research on topology discovery in UANs, it becomes a major bottleneck for the research and development of UANs. Moreover, it is difficult to find open research problems about topology discovery in UANs. Given the importance and research status of topology discovery, it is necessary to conduct a comprehensive investigation and analysis at this stage. The purpose of this study is to review, analyze, and compare the existing methods for topology discovery, which can provide a vital guideline to configure and optimize the current protocols and inspire new mechanisms based on the main characteristics of UANs.

The rest of this article is organized as follows. In Section 2, we analyze the main channel and network characteristics of UANs and identify the importance of understanding the factors of UANs for the design of effective network protocols. Meanwhile, we provide the fundamental design problems in the development of network topology discovery protocol. In Section 3, we elaborate and compare the existing topology discovery methods in detail. In Section 4, we study the open issue of supporting efficient network topology discovery algorithms and introduce several opportunities for further research, followed by the concluding remarks in Section 5.

II. BACKGROUND OF NETWORK TOPOLOGY DISCOVERY

A. Overview of Underwater Acoustic Sensor Networks

Underwater communication can use wired or wireless technologies. Wired transmission is via underwater cables or fiber optic cables, which has the advantages of signal stability and strong anti-interference ability. Still, the cost is prohibitively high for large-scale networks, and construction difficulties in laying cables underwater have limited its application. The wireless transmission method is less expensive, more convenient and flexible, and essential for underwater networks.

1) Underwater Acoustic Channel: As shown in Table I, radio waves are severely attenuated in seawater, reaching only 10 m underwater [31], [32]. The attenuation of optical in seawater is related to turbidity, penetrating 300 m underwater [34]. It has a low bit error rate and high transmission capacity. However, it has a short horizontal propagation distance. It is costly when we need long-distance communication. It has been proven in practice that acoustic waves are the most effective carrier that can carry information over long and medium distances underwater.

Compared to wireless networks on land, underwater acoustic networks face many challenges as underwater acoustic media drastically different from the radio. The underwater acoustic channel is characterized by high complexity, variability, strong multi-path, and limited frequency bandwidth [35], as shown in Fig. 1. Because of the acoustic communication channel's dynamic environment, the physical layer's reliability is a significant issue [36]. Many factors (such as passing ships, sea life, wind and waves, showers, and seasonal cycles [37]) can impact bit error rate, frame success rate, transmission power requirements. The dynamics of underwater acoustic channels are in both the time, space, and frequency domains. The typical signal propagation time between nodes in UANs is several orders higher than that using radio links. The long latency due to slow sound speed is one

TABLE I

Comparison of Various Underwater Communication Media [30]–[32]

Communication Methods	Propagation Speed	Security	Attenuation	Distance	Attenuation
Optical	$\sim 3e^8$ m/s	Good	$\propto$ turbidity	$\sim$300 m	0.39 dB/m-11 dB/m(turbid)
Radio Waves	$\sim 3e^8$ m/s	Poor	28 dB/km/100MHz	$\sim$ 10 m	Frequency and conductivity dependent (3.5-5 dB/m)
Acoustic Waves	$\sim$ 1.5 km/s	Relatively Better (using high frequency dolphin clicks [33])	$>$ 0.1 dB/m/Hz	$>$1000 m	Distance and frequency dependent (0.1-4 dB/km)

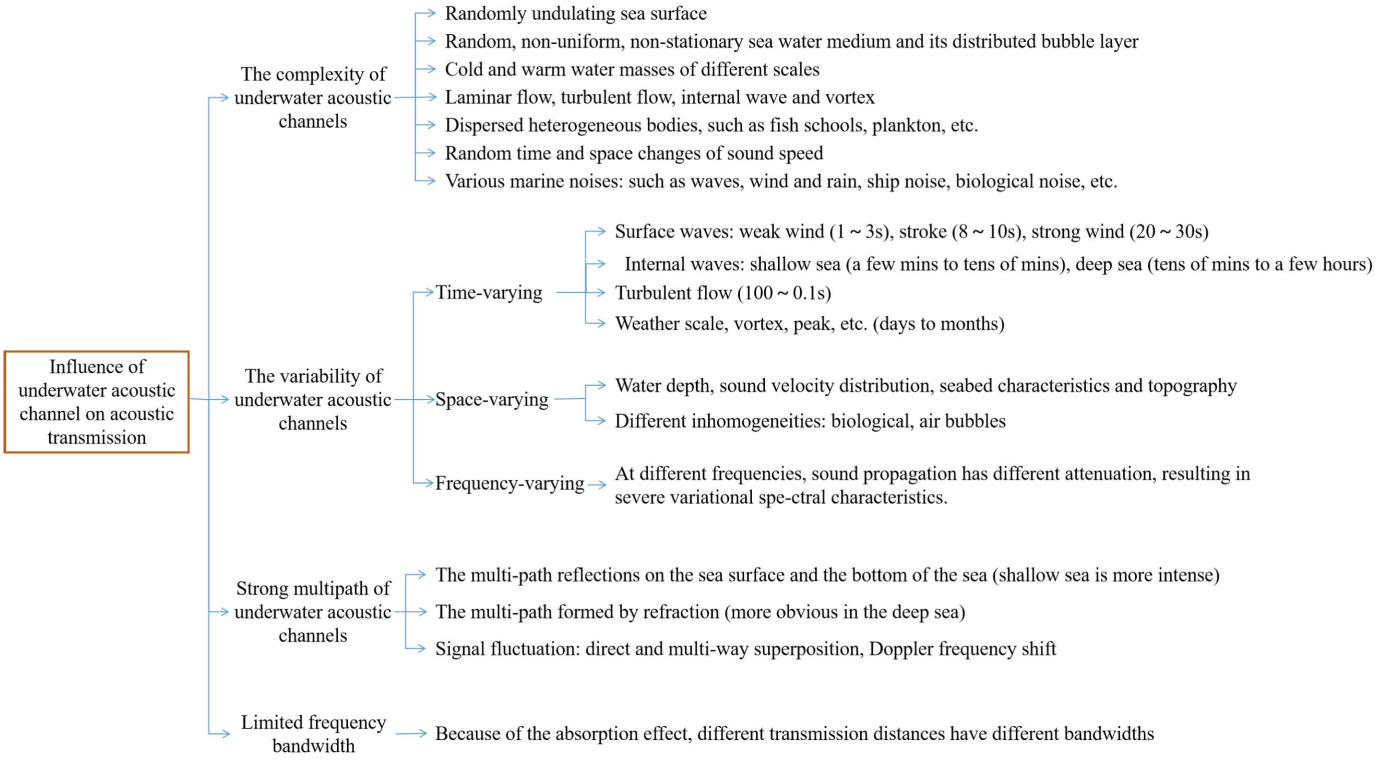

Fig. 1. Influence of underwater acoustic channel on acoustic transmission.

of the critical factors affecting acoustic networks. Even with fixed nodes given the non-constant sound speed in the water, the propagation delay can vary by several percentage points over the whole season. In addition, the multi-path effect of underwater acoustic channels is one of the critical factors [38]. The channel simulation was carried out for a shallow sea environment at a depth of 100 m, with a fixed position of the transmitting and receiving nodes (80 m and 50 m underwater, respectively, which drift with the sea), a frequency of 10 kHz and a communication distance of 1 000 m. As shown in Fig. 2, there is some variation in multi-path delay and amplitude. Furthermore, the bandwidth available is severely limited by propagation losses. The sound absorption coefficient increases with the increase of frequency, and the attenuation of high-frequency sound waves in water is high. For the long-distance underwater acoustic communication within the range of 10-100 km, the working bandwidth of the system is only a few kHz or less.

2) Underwater Acoustic Energy Efficiency: Also, energy efficiency is an important design criterion [39], since tone de-modulators typically consume between 1-100 watts of energy during transmission, as shown in Fig. 3. During normal operations, 39.4% modems use 1–8 W, 36.4% use 10–20 W, and 24.2% consume 30–40 W. Fig. 3 also shows power consumption during the reception modes. During reception, commercial modems consume power from 0.168 to 1.2 W, shown as blue circles.

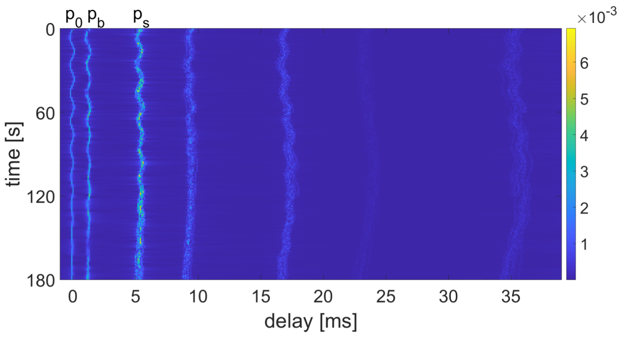

Fig. 2. Influence of underwater acoustic channel on acoustic transmission.

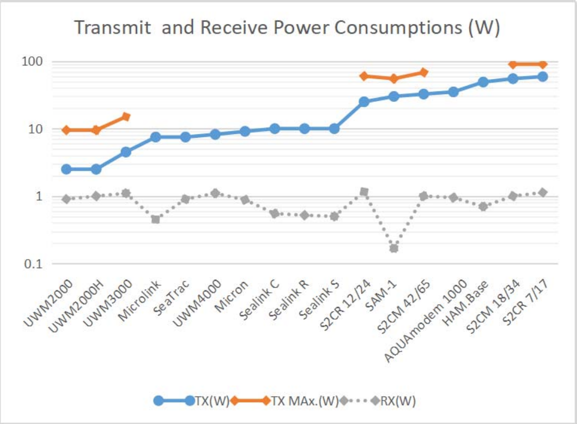

Fig. 3. Transmission and receive power of commercial modems.

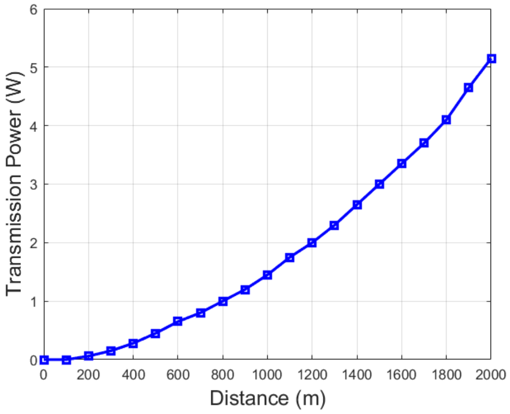

Fig. 4. Transmission power as a function of distance.

As shown in Fig. 4, the transmission power is a non-linearly increasing function of distance using the acoustic simulator proposed by Qarabaqi and Stojanovic [40]. Recharging the underwater bottom nodes is an expensive operation, and the modems constitute a significant burden for underwater vehicles with limited battery capacity. Moreover, the high transmission power is needed in UANs and noisy underwater channel causes packet losses and re-transmissions, wasting valuable energy [41].

3) Underwater Acoustic Sensor Network: Underwater information transmission is an indispensable way of interacting with information that enables humans to understand, explore and utilize the oceans. Most of the current underwater information networks are in the form of underwater acoustic sensor networks. The underwater acoustic sensor network is built based on underwater acoustic communication and is a self-organizing network [42]. The underwater acoustic sensor network is generally composed of surface buoys, Autonomous Underwater Vehicles (AUV), and various underwater acoustic nodes in the seabed or different underwater acoustic nodes in the ocean [43]. Researchers deploy nodes in specific water areas, and they collect and integrate data through underwater acoustic communication.

When performing specific tasks, the surface buoys will fuse the data collected through the interaction and cooperation of nodes and then transmit it to the control center on land through satellite communication or other means. No single underwater acoustic communication network can meet all the requirements; therefore, different applications need to adopt various methods in each layer of the network protocol stack [32].

TABLE II
COMPARISON BETWEEN WSNs AND UANs [30]

WSNs	UANs
more reliable, more matured understanding of the wireless link conditions	Poor channel quality [42]
Larger batteries,easy to recharge and replace	Limited battery capacity [44], [45]
Most applications require dense deployment	Sparse networks
nodes are placed manually, data is routed through predetermined paths	Self-organizing networks [7]
Most of the network architectures assume that sensor nodes are stationary	Dynamic topology [46]
Relatively stable deployment environment	Harsh marine environments [47]

UANs and terrestrial wireless sensor networks (WSNs) have some commonalities. However, due to the marine environment's unique characteristics, underwater acoustic networks have the following significant features, as shown in Table II: 1. Poor channel quality: The underwater channel is severely affected by propagation loss and ocean noise, making multi-path and Doppler effects apparent, resulting in unreliable transmission and link interruptions, which is one of the essential differences between UANs and WSNs. 2. Limited battery capacity: Compared with terrestrial wireless communication, underwater acoustic communication requires higher transmitting and receiving power and more complex signal processing technology, all of which require more battery energy consumption. Therefore, the efficient use of energy to maximize the network's operational life is a critical content in the design of the underwater acoustic network. 3. Sparse networks: the deployment of nodes in UAN is generally sparse given the high cost of construction and maintenance of underwater nodes and the large extent and area of the ocean. 4. Self-organizing networks: UANs usually deploy in sea areas without infrastructure, where the location of sensor nodes cannot be predetermined, and the adjacency between nodes cannot be predetermined. The network is, therefore, self-organizing, with nodes coordinating their behavior through hierarchical protocols and distributed topology control algorithms, allowing them to form an independent network quickly and automatically [48]. 5. Dynamic topology: such as battery energy depletion leading to network node failure and node movements, and new nodes joining the network lead to the change of topology. Therefore, the UAN needs to adapt to such changes [49] automatically. 6. High-reliability requirements: UANs usually deploy in harsh marine environments where sensor nodes are susceptible to dirt and seawater erosion, so node hardware is required to be highly waterproof, pressure-resistant, and corrosion-resistant. Also, as underwater nodes are not easy to manage and maintain, information transmission's reliability is ensured.

B. The Definition of Topology Discovery

The early UANs relied on the operator to manually initialize the network, and further manually to configure the routing from all nodes in the network to the sea surface gateway node. It requires the node information in the network (such as node locations, connectivity between nodes) in advance, which defeats the purpose of establishing a randomly deployed network with autonomous configuration.

With the increasing deployment of UANs, network topology discovery becomes an urgent issue. A node that sends a message thoroughly knows nothing about the message's recipient in the initial network deployment phase. When a reply is not received, it is not clear whether it cannot receive a response because of the interference from other nodes, or there are no active neighbor nodes around at all. Even a reply is received, it is not clear if or not any other neighbor nodes cannot accept the message. The main topology structures of the underwater acoustic network are star, tree, cluster, distributed. Network topology can be modeled through a graph $G(V, E, L, S)$, where V is the set of network nodes, and E is the set of links between them, L is the set of nodes' location, and S is the state of links and nodes. When nodes are deployed, $G(V, E, L, S) = Null$. Topology discovery is a process that nodes exchange control packets containing $G(V, E, L, S)$. A cycle is the time for a node completing control packet exchanges with its neighbors. A node gains the full knowledge of $G(V, E, L, S)$ after multiple cycles, which concludes the topology discovery process. Then, each node obtains network topology information including the number of nodes, the set of links, link quality, node location, routing table, etc. We define the process from no structure to establish a primary point-to-point links structure as the topological discovery in UANs. Different topology discovery algorithms can establish different topology structures for various network protocols and application processes. The network topology information is critical for MAC protocol, network management, and routing decisions.

C. Topology Discovery for Terrestrial Wireless Networks

1) Topology Discovery in Duty-Cycled Ad Hoc Networks: Ad hoc network is a kind of multi-hop self-organizing network composed of a large number of nodes with limited capabilities. The duty-cycled ad hoc network has emerged to reduce the energy consumption of nodes and extend the network's life cycle. In duty-cycle ad hoc networks, a node's entire life cycle can be divided into several work cycles of equal length, with each work cycle consisting of several time slots. The node wakes up in only a few specific time slots during an operating cycle while remaining asleep in the other time slots.

The neighbor discovery protocols for duty-cycled ad hoc networks are divided into probabilistic-based, deterministic-based, and collision-considered protocols. Probabilistic protocols [50] adopt probabilistic strategies at each node. Specifically, each node remains active or asleep with different probabilities. A representative one is the birthday protocol [51] where nodes transmit/receive or sleep with different possibilities. Probabilistic protocols have the advantages of being memoryless and stationary, incredibly robust. It is more suitable for decentralized environments where no prior knowledge or coordination is available. Moreover, they usually perform well in the average case by limiting the expected discovery delay. Its main drawback is the lack of a performance guarantee in terms of discovery delay. This problem is referred to as the long-tail discovery latency problem in which two neighbor nodes may experience an extremely long delay before discovering each other. In order to solve the problem of collision, Vazquez-Gallego proposed a feedback mechanism [52]. Its basic idea is that when a collision occurs, the discovered neighbors do not participate in the subsequent random transmission, and thus effectively reducing the conflict's probability. The PSBA protocol proposed by Chen *et al.* [53] again utilizes the prime number approach to minimize the evaluation discovery latency.

On the other hand, deterministic protocols are proposed to provide a strict upper bound on the worst-case discovery delay. In deterministic protocols, each node wakes up according to its neighbor discovery schedule carefully tuned to ensure that each pair of two wake-up schedules overlap in at least one active slot. The critical element in the deterministic protocol design is how to devise the neighbor discovery schedule to ensure discovery and minimize the worst-case discovery delay, regardless of the duty cycle asymmetry and the relative clock drift. Compared to probabilistic approaches, deterministic protocols have good worst-case performance. In contrast, they usually have a longer expected discovery delay. In deterministic protocols, both nodes' duty-cycle x and y is more than half in 51% protocol [54]. The U-CONNECT protocol [55] can have a lower duty cycle with the same delay as the quorum protocol. Chen proposed C-torus Quorum is similar to the Search Light protocol [56]. The Hello [57] protocol summarizes the above protocol, assuming that the time slot matrix's size is $m * n$, where m represents the length and n represents the number. By adjusting the relationship between m and n and appropriately shifting the wake time slot on the first line, four different protocols, Quorum, u-connect, Search Light, and c-torus quorum, can be obtained. Among such algorithms, the Blind Date algorithm [18] with the best performance was proposed by Wang. It is an improved algorithm based on the Search Light protocol.

Collision-considered protocols are proposed to resolve conflicts when more than two nodes are in a wake-up state. [58] proposed a novel self-adapting quorum-based neighbor discovery algorithm that can dynamically adjust its cycle pattern to decrease the impact of packet collisions. It has performed a rigorous mathematical analysis based on the square Quorum protocol by model the expectation of the delay due to conflicts. Besides, to address the problem that the number of all neighboring nodes may not be immediately available in practical applications, the protocol cites the approach of the method [59].

2) Topology Discovery in Internet of Things: The topology discovery protocols for the Internet of things (IoT) [60] are divided into o active discovery and passive discovery. The active discovery method involves the network nodes actively sending detection messages for network testing and later collecting feedback for network topology analysis.

Passive discovery methods are to create a probe node in the observation network. It collects data on topological information flowing through it and submits it to the host node [61]. The active discovery methods are mainly based on SNMP protocol [62], LLDP protocol [63], and ICMP protocol [64]. SNMP protocol is an application-level communication protocol defined for network management service, which provides a basic mechanism for exchanging management information between managers and agents. ICMP protocol is a protocol used to transfer control information or error information between a host and a router.

On the other hand, the passive discovery methods are mainly based on the OSPF protocol [65], [66]. The OSPF protocol is a link-state routing protocol that uses hello messages to find neighboring routers and establish neighbor relationships. At present, the most popular topology discovery focuses on energy measurement and packet loss rate. [67] provided the necessary and sufficient conditions for the neighbor's discovery and proved it theoretically correct. According to the necessary and sufficient conditions, they proposed an energy-efficient neighbor discovery for the IoT.

D. Topology Discovery for UANs

Although the fundamentals of communication technology and wireless networks still exist, underwater acoustic communications introduce new and often more challenging parametric mechanisms than RF communications. As a result, UAN cannot directly apply the topology discovery protocol of terrestrial wireless networks.

Network topology discovery is an essential component of subsea networks, regardless of functional requirements and design priorities. At the initial stage of network node placement, it is uncertain whether there is a communication link between nodes. Even if researchers place the network node according to the planned topological structure in advance, we cannot simply determine the neighbor group according to the physical distance between nodes [40]. The experimental data show that the signal power experiences fading that changes with time in UANs. In this case, the traditional systems' design needs to add fading margins to ensure adequate reception power. In other words, the transmitted power is set to a value higher than that considered necessary in the ideal sound propagation model. Moreover, topology discovery is still needed to find out the network's real-time link connection. For example, due to the underwater signal's time-varying, there is no guaranteed connection between a pair of nodes, A and node B, in the network. If the system mistakenly assumes that A and B always communicate and carry out transmission tasks, it may eventually lead to failure.

In general, for a centralized topology discovery process in UANs, the source node initiates a topology query request. All nodes in the network measure relevant data and collect packets to achieve the network topology discovery. These relevant data, including the node state and connectivity state, need to be collected in a limited time by nodes. It is a process of collecting the packet data generated by the related activity state of the network.

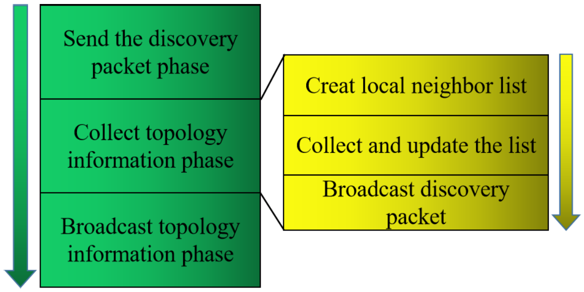

Fig. 5. Topology discovery process of underwater acoustic sensor network.

Network topology discovery is generally divided into three stages as shown in Fig. 5: sending discovery packet stage, collecting topology information stage, and broadcasting the whole network topology information stage. The sending discovery packet stage is initiated by the node (usually the source node or the first node of the group) that actively requests to acquire the network topology. The node broadcasts a topology request packet. When nodes receive a topology request packet from other nodes in the network, they create information about their local neighbors and broadcast the discovery packet. At the end of the first phase, the nodes know who their neighbors are. Each node forwards locally acquired partial topology information to the source node in the second phase, during which the topology information is collected. Through the first two stages, the source node can obtain the whole network topology. In the third stage, the complete network topology information is finally broadcast by the source node.

1) Impacts of Topology Discovery on the Different Layers of the Protocol Stack: Each layer of the protocol stack in UANs has its functionality [68], as shown in Fig. 6. The performance of higher layer protocols can be improved through performing an efficient topology discovery method. Accordingly, this part is to identify the impacts of topology discovery on higher layer protocols' performance.

Data-Link Layer: the MAC protocol of the data link layer is the basis for controlling and managing the shared communication media among all network nodes. All MAC protocols developed for UANs utilize the available neighborhood information on a single node to reduce or avoid transmission collisions and perform different channel access functions. Non-competitive MAC protocols, such as Time Division Multiple Address (TDMA) [69], Code Division Multiple Access (CDMA) [70], and Frequency Division Multiple Access (FDMA) [71], need to utilize the neighborhood information available on a single node to provide fair bandwidth utilization and avoid resource scarcity. Moreover, time synchronization is essential for TDMA protocol to realize collision-free transmission. TSHL [72] uses one-way and bidirectional MAC layer messaging to estimate clock skew and calculate clock offset, respectively. The TDMA-based LT-MAC protocol [73], LTM-MAC protocol [74] requires switching packets to obtain the latency between each pair of nodes. Each node in the network needs to repeat the RTM-ACK process until they know all neighbor nodes' relative latency. Handshake-based CS-MAC protocol [75] requires that each node is assumed to know their neighborhood information (such as the propagation

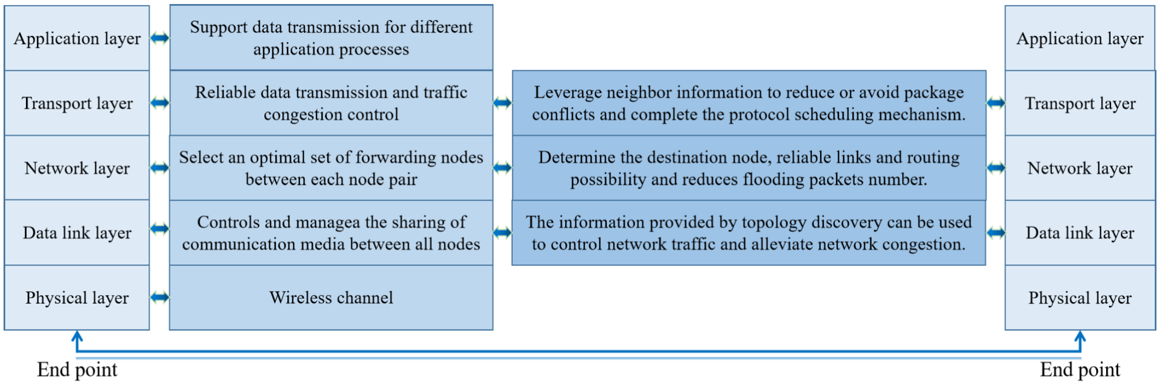

Fig. 6. Protocol stack.

delay to each of its single-hop neighbors) to complete the scheduling mechanism of the protocol. It is well known that hidden and exposed terminal issues severely affect network performance. The TED protocol [26] detects scheduling conflicts by finding pairs of nodes whose transmissions block each other (commonly known as near-far node pairs (NFNPs)).

Network Layer: The network layer's main task is to select an optimal set of forwarding nodes between each source-destination pair. For active or table-driven routing protocols, the source node can determine the routing possibility of its packets and arrange transmission accordingly by understanding the network topology. For reactive or on-demand routes [76], sources-initiated control packet flooding is required to conduct the route discovery process. The previous topology information can significantly reduce the amount of flooding. Therefore, it makes sense to use a topology discovery plan in the early stages of network operations. The layered acoustic routing protocol [77], [78] regularly needs to structure concentric spherical shells around the gathering node. Other sensor nodes are distributed on different layers of concentric spherical shells. This scheduling requires an effectively layered topology discovery [79] and ensures a specific convergence time. When the topology discovery complete, the network switches to a static scheduling agreement.

Furthermore, a significant cause of packet loss is the poor quality of the path link. Most hop-based routing protocols assume that sender/forwarder neighbors have highly reliable links with equal and symmetrical link quality. However, this assumption does not apply well to underwater networks. In the topology discovery stage, link quality measurements can find more reliable links. The protocol [80] considers the optimal link quality between forwarding nodes and neighbors by allocating appropriate weights and finally selects the best next-hop forwarding nodes. [81] proposed a scheme for delay-sensitive spatiotemporal routing (DSR) in software-defined networking (SDN-enabled UANs). The DSR-SDN includes three phases: First, topology awareness; second, spatiotemporal characteristics estimation; and third, routing computation.

Transport Layer: Transport layer protocols support reliable data transfer, and text traffic congestion control [82]. There are multiple relay nodes between the two end nodes, which cooperate to ensure end-to-end reliability in traditional transport layer protocols. Transport layer protocols can utilize the information provided by neighbor discovery and link quality estimation mechanisms to control network traffic rates and alleviate network congestion, which can support reliable end-to-end data transmission. [83] proposed a transport layer protocol, called optimal retransmission timeout (RTO) interval stop-and-wait transmission (ORIT), used in underwater delay or disruption tolerant networks (DTNs).

Application Layer: The purposes [82], [84] of an application layer are three-fold: (i) to provide a network management protocol that makes hardware and software details of the lower layers transparent to management applications; (ii) to provide a language for querying the sensor network as a whole; (iii) to assign tasks and to advertise events and data. [85] presented the design, test, and experimentation at sea of four JANUS-based services for operationally relevant underwater applications: 1) first contact and language switching; 2) transmission of automatic identification system data to submerged assets; 3) transmission of meteorological and oceanographic data to underwater vessels; and 4) support in distressed submarine operations. The collected results show that JANUS is a feasible solution to increase maritime situational awareness in the underwater domain.

2) The Performance Parameter of Topology Discovery: Considering the resource limitation of UANs and the high dynamic characteristics of wireless acoustic links, different parameters must be considered in the design of network topology discovery protocol to provide effective network establishment. Accordingly, the critical performance parameters are described as follows:

Topology Construction Convergence Delay: It is defined as the total time from the beginning of the topology discovery process to the end of the topology discovery process. Ideally, topology discovery latency is as low as possible, as the highly dynamic of underwater links means that topology discovery and maintenance are more frequent. Simultaneously, energy constraints and the need to complete network tasks do not allow the topology discovery phase to take up too much network time.

Energy Consumption of Topology Construction: It is defined as the total energy consumption required in the topology discovery process. The energy consumption of general topology

TABLE III
TABLE SUMMARIZING OF THE DISCOVERY PROTOCOLS DISCUSSED

Protocols	The goal	Control mode	Search technique	The method	Performance index
Disc [23]	Generate the shortest route from the master node to each node in the network.	Centralized	Breadth-first	Master node polls and aggregates the neighbor discovery data	Shortest paths
N-Disc [24]	Establish multi-hop, minimum-power acoustic communication links.	Distributed	Depth-first	Distributed power control and random access to provide connectivity within a finite power budget	Energy consumption, average time consumption and number of nodes discovered
TED [26]	Reduce the time overhead of the discovery phase while accurately discovering acoustic links.	Distributed	Breadth-first	Allows simultaneous transmissions from different nodes while controlling the number of possible collisions in an optimized fashion.	Number of collisions, link reliability, convergence time, number of received packets and number of link tests
CFVE [88]	Reduce the collision probability of the discovery phase	Centralized	Breadth-first	Use the TDMA to access channel	Energy consumption and average time consumption
DIVE [25]	Assign the node IDs and share additional information to discover the other nodes	Distributed	Breadth-first	An optimized discovery cycle and discovery packet scheduling	Average time consumption, transmitted packets and energy
ETDP [81]	Achieve adaptive node ID assignment and topology discovery simultaneously	Centralized	Breadth-first	An optimized discovery cycle and discovery packet scheduling	Average time consumption, transmitted packets and energy

discovery is calculated by transmitted, received, and idle energy. The time of received (transmitted) packets in the discovery process multiply by the power required by each accepted (transmitted) packet is received (transmitted) energy consumption. Idle energy consumption is equal to idle time multiplied by idle power. These three values calculated by all nodes in the network are added together to obtain the total energy consumption.

Accuracy of Network Discovery: An essential goal of the network topology discovery protocol's design is to find the adjacent nodes and network topology correctly in the network establishment stage. Therefore, discovery protocols need to maximize the probability that nodes be discovered by other nodes and improve other nodes' chances to identify the maximum number of possible neighbor nodes.

The Integrity of Network Discovery: It is defined as the completeness of discovered topology information. The discovered topology information should include all connectable nodes in the network and their connection relations. If there is a lack of existing nodes and links can affect the operation of other protocols. So, the topology information should be consistent with the actual network layout.

III. THE PROTOCOLS OF TOPOLOGY DISCOVERY

Given the problem description of underwater acoustic network topology discovery and several key factors that affect the performance of underwater acoustic network topology discovery, scholars have studied from many aspects. According to the way of work, topology discovery algorithms in UANs can be divided into two categories: centralized and distributed. In the centralized underwater acoustic network topology discovery protocol, the leader node and the ordinary node are set before the beginning. The node discovery process is divided into multiple discovery cycles. A leader node triggers each discovery cycle. After completing the discovery cycle, the next cycle leader is selected to continue to operate the next discovery cycle. For the distributed topology discovery protocol, all network nodes have the same function, and no need to set control nodes in advance. All nodes operate equally and obtain the network topology in a distributed way. During the discovery process, each node in the network broadcasts a Hello packet according to the local timer and completes the topology discovery by receiving, updating, and sending the Hello packet.

A summary of typical underwater topology discovery protocols is shown in Table III. Next, we describe in detail the topology discovery methods in UANs.

A. Disc

Joseph A. Rice, Ong, and Chee Wei [23] proposed a Discovery Process for initializing (Disc). The master node carries out the topology discovery of the whole network through polling. When the master node in the network receives a network discovery command from the server, the master node sends a certain number of broadcast *pings* with preset transmission power. As a collision will occur when two or more neighbor node packets arrive at the master node simultaneously, the protocol repeats the broadcast *ping* many times to avoid other nodes not receiving the ping. Eventually, these broadcast *pings* are aggregated at the master node to form a global list of neighbors, including the node IDs and the number of hops. After that, the master node selects the nearest node from the single-hop neighbor nodes and commands it to find its neighbor. The node finds its single-hop neighbor by sending a *ping* and then packages its neighbor information to the master node. Thus, that goes on. Finally, the entire network topology will be obtained.

Through a master node controls network discovery process, the Disc protocol can discover all the nodes in the network and the shortest path from the master node to each node. Such a centralized process allows the host node to detect and control the progress of the discovery process. Moreover, the protocol only finds the path from the master node to other nodes, rather than whole the topology information in the network. When the protocol fulfills the network's preset requirements, the master node has the flexibility to end the entire protocol. Secondly, when dealing with more complex networks, only the performance of the master node needs to be improved, rather than the processing capacity of all nodes in the whole network. Finally, in running the protocol, the protocol only needs to apply to the master node. Thus, it is simple to change and upgrade the protocol. Although this protocol has many advantages, it also has some problems. The protocol defines a master node A that broadcasts ping to start the discovery process. During this process, each node finding a new node must inform node A. The master node A stores the received information and commands to find the next node. When the network is multi-hop networks, this way causes a lot of time delay.

B. N-Disc

Milica Stojanovic *et al.* proposed a node discovery protocol [24] (N-Disc). This algorithm adopts power la to divide the Discovery process into multiple cycles. When the protocol is completed, the links between nodes in the network and the power levels required for communication between different links are obtained. Each node has a pre-allocated finite energy level (p_0, $p_1, \ldots, p_l$), and each level corresponds to the corresponding transmission distance. The protocol stipulates that the nodes send the discovery packet at the lowest energy level first. The master node is preset as the initial leader to start the discovery process. After that, it starts the receiving mode and waits for the reply. If no response is received after T_l, the leader increases its power level and re-sends the discovery packet. The node receives discovery packets from the leader, reads the information in the discovery packet, and replies to the leader. The leader saves the information from all the reply packets, updates the list of its neighbors. If the number of neighbors of the leader is greater than 1, then the leader sends the ECP packet to the node closest to it and selects the closest node as the next leader. Of course, as long as the closest node has never been a leader. In the initial stage of the network, the nodes have not obtained the information about other nodes, so that the reply packets may collide at the leader. When the leader finds the collision, it cannot know the ID of the colliding node. At this time, the leader sends the collision reply packet. The node that receives it checks whether it is in the leader's contact list. If so, it will not do any processing. If not, the node will back off randomly and re-transmit the reply packet.

The N-disc protocol aims to build a multi-hop minimum power underwater acoustic communication link in a given region. The protocol starts from the lowest power level. Finally, all its neighbors' lowest transmitted power can be obtained at every node in the network. Thus, in the network operation process, the whole network can complete the information exchange and network function with the lowest transmitting power and then reduce the overall work energy consumption. However, energy level leads to an increase in node discovery cycles. For example, it assumes that node a with power level P_0 sends disc packet, but it did not find any node. Then node a will start the second cycle, which re-sends the $disc$ packet with power level P_1. If it still has not found any node, node a will start the third cycle that it re-sends disc packet with power level P_2 until neighbors reply packet. Furthermore, the protocol selects a leader that initiates the next cycle among the neighbor nodes. Each node in the network can be elected as a leader at most once. The following situations can occur when the leader selected the next leader: the leader x sends ECP packet to the next-hop node to select the next leader, but all the next-hop nodes have been a leader before. Therefore, ECP is returned to the leader x. The leader x needs to select the next leader among the node on the same hop with the leader x. This process causes an increase in time delay. Moreover, once the ECP packet is lost, the network topology discovery process will be terminated. Hence, the protocol is highly dependent on the ECP received correctly. It has not come up with an efficient loss avoidance mechanism of the ECP packet to reduce the loss probability of the ECP.

C. DIVE

Petroccia [25] from the NATO STO Center for Maritime Research and Experimentation in Italy proposed A Distributed ID Assignment and Topology Discovery Protocol (Dive). This protocol is a fully distributed and self-organizing protocol, which can realize the autonomous assignment ID of network nodes and the discovery of network topology. The fully distributed and self-organizing protocol includes two processes. The first process is assignment and discovery, responsible for the ID assignment of nodes and network topology acquisition. The second process is repairing the repeat. It is responsible for correcting assigned node IDs to avoid duplication of node IDs.

During the assignment and discovery process, when the DIVE protocol is turned on, each node generates a long random integer K_x, and a timer Tx_Timer (which is set in direct proportion to the value of K_x) is turned on. When the Tx_Timer overtimes, each node x broadcasts the HELLO packet. After sending the HELLO packet, node x starts a second timer $Waiting\_Timer$. After the timer overtimes, the decision on performing the ID assignment process or transmitting again the node information depends on several factors: (1) the node does not receive any HELLO packets; (2) The value saved in the node does not match the value received by the node from other nodes; (3) Link estimation.

The DIVE protocol is a fully distributed topology discovery protocol that uses a random access mechanism and incorporates autonomous node assignment. The random K value generated by the node serves as the network node's temporary ID. The advantage of distributed way lies in that all nodes in the network have equal rights. After node placement, all nodes start their neighbor discovery process simultaneously. Therefore, in a specific network topology environment, the topology discovery process can be completed quickly in this way. Finally, the protocol can cope with the addition of new nodes and the disappearance of old ones. However, in this protocol, the value K randomly generated by the node acts as the node's temporary ID, requiring setting an extensive range of random number values to avoid duplication, resulting in a comprehensive discovery control packet. If the random number's scope is set to be small, more repeated values will appear in the network, significantly affecting network discovery performance. Besides, the nodes in the distributed protocol once found a new K and then sent the HELLO packet, so would constantly send the packet. Although the authors set up a waiting time delay in the protocol and hope that in this period of waiting delay can receive multiple new nodes' HELLO, the collision of packets and the inefficiency of sending packets still exist.

D. TED

Roee Diamant *et al.* proposed the TED algorithm [26] (topology-efficient discovery) to find network link information with low delay and define a reliable link. Slot division has been completed before network node deployment. TED does only obtain the initial topology discovery, not the tracking work of topology changes. After time synchronization, the protocol is executed including two parts: 1) Discovery of communication links among nodes; 2) Discovery of near and far node pairs. The TED algorithm requires extensive link testing to demonstrate the accuracy of reliable link discovery. Hence, TED aims to send as many packets as possible in a limited number of time frames. Multiple nodes send I short packets of length T_p with minimal collisions. Each packet of nodes K $(K \in N)$ is delayed by Δ_ks to reduce collisions, so that slot lengths are equal to $IT_p + Imax(\Delta_k)$.

The TED protocol proposes a reliable link definition. The link between two communicating nodes is a reliable link within a specified time window if at least L short packets are correctly received. TED aims to discover reliable links in the network. As the discovery of reliable connections needs nodes to send more short packets, TED allows multiple nodes to send packets within the same time slot to reduce the time overhead. This multi-node simultaneous transmission will increase the probability of collision. The protocol builds the collision model of the node packet to solve the collision problem. Based on the model, the paper deduced the formula of collision probability of packets. Parameters (such as the number of nodes sending packets, the number of packets sending packets, and the length of the interval between each packet in each time slot) are derived under the condition of the lowest collision rate. However, the formula for derivation in TED contains four variables. The authors obtain an alternate subset of parameters by alternating maximization. For example, assume that three of these variables remain unchanged; the fourth variable is obtained by calculation when the convergence time is minimum. Still, an optimal global case is difficult to calculate. Also, the packet interval of each node that is a parameter obtained by optimization is a matrix. It is simply processed in the calculation process of the TED protocol to simplify the complexity. The matrix parameters generate additional degrees of freedom. With the increase in the number of parameters to be optimized, the algorithm's complexity increases significantly. This part of the work will be an important problem to be solved by the TED protocol in the future.

E. CFVE

Liu and Zhao [86] proposes an efficient conflict-avoiding underwater network topology discovery (CFVE) protocol that utilizes network node IDs' uniqueness to access the channel by TDMA. The time is divided into frames, each of which consists of a different time slot. Each node in each frame sends a packet in a different time slot according to the node ID distribution. Every node in the network takes up a time slot. According to the local preset time slot table, all nodes know their time slot, and each time slot is assigned to only one node. Thus, each node sends the respective packet data in a different time slot and carries on the discovery control packet exchange without conflict. Finally, CFVE realizes the discovery of all the links and nodes in the network.

Considering the energy and time-delay limitation in UANs, CFVE adopts a TDMA access mechanism to avoid packet discovery conflict. CFVE can complete topology discovery with minimum time delay and energy consumption. However, the protocol requires good time synchronization, which can be difficult in UANs. Also, when the number of nodes in the network is large, the delay overhead will increase significantly, resulting in low channel utilization.

F. ETDP

ETDP [79] proposes an efficient topology discovery protocol (ETDP) to implement adaptive node ID assignment and topology discovery. The ETDP protocol is divided into three phases: HELLO message transmission, DISC message transmission, and IDA message transmission. Firstly, the network is layered, and neighbor discovery is realized through the HELLO message transmission phase. This way, the partial network topology data can be obtained at the end of the DISC packet transfer phase. Finally, each node calculates its unique ID based on the topology information and sends IDA packets in the final stage. To avoid packet conflicts in the initial network state, ETDP controls the Topology Discovery (TD) packet transmission based on the local timer and divides the network into different layers so that nodes can transfer TD packets in an orderly manner. Each node can obtain the network topology and independently assign the node ID using the received TD packet. Based on the tree topology, the protocol does not need the prior information of known node ID. It realizes the hierarchical discovery of nodes and the assignment of node ID independently.

However, the protocol relies heavily on the central node. When the network center node fails, the protocol cannot be started and run.

IV. OPEN ISSUE AND OPPORTUNITY OF TOPOLOGY DISCOVERY IN UANS

In the underwater energy transmission carrier, sound waves are easily affected by various aspects of the sea surface, seabottom, and seawater medium in the process of propagation, and its characteristics will also change with time and space.

A. Open Issues

Compared with traditional land wireless networks, underwater acoustic network topology discovery protocol still has the following challenges and problems to be solved, as shown in Table IV.

TABLE IV
RESOLUTION OF OPEN ISSUES

Open issues	Disc	N-Disc	TED	CFVE	DIVE	ETDP
Collision avoidance mechanism	–	–	✓	✓	–	✓
Time saving	–	–	✓	✓	✓	✓
Time asynchronous	✓	✓	✓	–	✓	–
Energy saving	–	–	–	✓	✓	✓
Stability	✓	✓	✓	✓	✓	–
Scalability	–	–	–	–	✓	✓

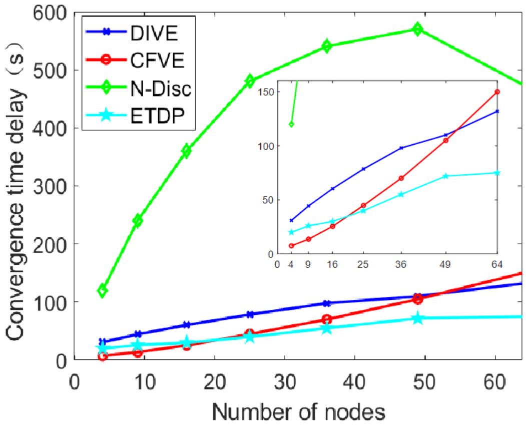

Fig. 7. Convergence delay.

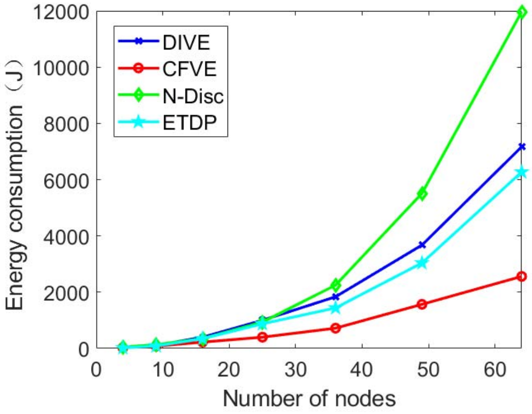

Fig. 8. Energy consumption.

(1) The underwater acoustic network is randomly distributed. At the initial stage of the network, nodes know nothing about their surrounding information, making it very difficult to deal with collision problems. A topology discovery process can form the initial network structure. Therefore, an effective network topology discovery protocol helps develop the initial network structure, improving the routing protocol and MAC layer protocols' efficiency and providing a network foundation for data fusion, time synchronization, and target positioning tasks. Meanwhile, the topology discovery protocol can prolong the network lifetime.

(2) In the marine environment, the sound propagation rate is prolonged and unstable. Ideally, a topology discovery algorithm needs to minimize the collision probability and convergence time delay [87]. The low propagation speed of acoustic waves dramatically reduces the throughput of the network. Simultaneously, the propagation delay is not unchanged. It will change with the different propagation speeds or the movement of nodes. The propagation speed varies significantly under different channel conditions, such as the influence of water temperature, salinity, and mineral content. We compared the convergence delays of the five protocols, as shown in Fig. 7. The performance of the topology discovery protocol is evaluated via OPNET simulation where the pipe stage of the underwater acoustic channel is adopted. In our simulation evaluation, nodes are randomly distributed in an area of 3000 m × 3000 m, where the node communication distance is 700 m and the data rate is 7500 bps. The size of the network is constant as the number of nodes increases. The number of nodes is varying between 4 and 64. When the maximum number of nodes is considered, the maximum number of layers is 5. The transmission, reception, and idle powers are set to 8 W, 1.3 W, and 0.285 W, respectively. It is shown that as the number of nodes increases, the convergence time increases rapidly. Therefore, the propagation time delay is an essential factor affecting the topology discovery. The topology discovery algorithm requires frequent control information exchange among network nodes to obtain correct and perfect topology information, which dramatically increases protocol design difficulty. To meet the topology discovery requirements, how to reduce its influence on the convergence delay of topology discovery is the basis of designing topology discovery protocols.

(3) To date, as far as we know, there is no low-cost, high-precision positioning and time synchronization system for underwater sensor nodes, such as GPS for surface sensor nodes. When nodes are not globally clock synchronized, they need asynchronous operations to discover their neighbors still efficiently. In asynchronous systems, nodes start node discovery at different times and therefore miss each other's transmissions.

(4) As the energy consumption of transmitting underwater acoustic signals is high, and the underwater node cannot achieve continuous power supply by battery power, the energy is limited. Moreover, because of the location of the node, battery replacement is more inconvenient than on land. We compared the energy consumption of the five protocols, as shown in Fig. 8. Reducing the number of discovery packets and optimizing the discovery cycle can minimize each node's energy consumption in the topology discovery stage. Besides, link quality measure is also one of the critical issues during the topology discovery process.

(5) Stability and scalability are required. The time-varying of the underwater acoustic channel makes its communication

quality easily affected. When the number of nodes is large, the amount of communication calculation and complexity also increase, which inevitably increases the protocol's energy consumption and implementation difficulty. Also, the dynamic Marine environment makes the network nodes flow randomly with the ocean current. The change of channel environment causes the time-on-time connection of the link. Such flow and change will bring the appearance and disappearance of the nodes in the network simultaneously. Therefore, the network topology discovery technology should guarantee the correctness of the acquired network topology. Simultaneously, it is another consideration to design a topology discovery protocol that can extend and realize the function of multi-network conjunction when the number of nodes increases.

B. Opportunities

1) The Trends of the Wireless Topology in Real-Life Applications: Currently, one important real-life application of UANs is for marine data collection. The marine data collected and delivered by UANs can be used to support many applications. We discuss some of these application trends and the importance of network topology information for them, including maritime applications, underwater localization, and marine life tracking [88].

Intelligent Interconnection of Underwater Objects: Nowadays, with the increasing demands for marine detection and exploitation, researchers explore the possibility of applying the Internet of Things (IoT) technology underwater. As a result, the concept of the Internet of Underwater Things (IoUT) was first discussed in 2010s [89] and defined as an extension and novel category of the IoT, which is promising to establish intelligent connection of underwater objects and enable smart ocean.

Coastal Monitoring: Coastal monitoring includes accurate localization of marine vehicles, provision of weather and climate data for specific oceanic locations, accessing bio-geographic data such as the recognition, counting, and distribution of underwater species, etc.

Underwater Localization: A very useful data type included in underwater network topology is related to the positioning of undersea devices, systems, animal species, and data sources. They are critical to geo-tag underwater sensory and imagery data. For example, cooperative navigation can be supported by underwater network topology information.

Marine Life Tracking: Undersea animals may be quite small and they cannot carry heavy inertial sensors, transponders, sonars, or cameras. Therefore, sophisticated new tracking methods can be devised using wireless localization and positioning technologies supported by network topology information.

2) The Opportunities of the Topology Discovery: The existing underwater acoustic network topology discovery methods are almost for the fixed network with a constant number of nodes. Nevertheless, now the underwater acoustic network has been rapidly developed. Deployments of UANs have begun to evolve from using a small number of subsea communications equipment from the same manufacturer to dozens of heterogeneous nodes, including collaborative autonomous underwater and surface vehicles. This deployment of more extensive, more complex subsea collaborative networks, used in conjunction with other advanced technologies, is a future trend. As networks grow in size and complexity, the problem of ensuring reliable data exchange between collaborating devices and correctly configuring subsea nodes before deployment becomes difficult. Most of the proposed policies assume unique IDs assigned to network nodes to support correct message exchange but do not address allocating those IDs dynamic. One possible solution is to use long-bit IDs, but due to limited communication bandwidth and low data rates, this may affect the performance of UANS. Another option is to assign the network-wide global ID to the node before deployment. It will reduce the length of IDs assigned to each node, but it significantly combines deployment and operation complexity with network size. Also, this solution requires complete knowledge of all future network sizes during a given deployment. Therefore, the underwater acoustic network topology discovery protocol needs an effective node ID self-assignment process.

Also, UANs will frequently face the situation of multi-heterogeneous networks merging with the changing of network scale. It is urgent to study the topology discovery algorithm suitable for combining heterogeneous networks to replace the respective operations' traditional patterns. Roberto Petroccia studied the topology discovery algorithm suitable for the joint construction of the heterogeneous network and applied it to the CommsNet17 underwater sensor network. From 27 November to 6 December 2017, the NATO STO Marine Research Center organized the Maritime Experimental Activity (CMRE) in La Spezia Bay [90] to deploy a persistent underwater acoustic sensor network on CommsNet17. The network deploys a multi-hop network consisting of up to 11 nodes, including static (buoys, common underwater sensor nodes) and mobile (AUVs, surface vehicles). The network supports specific tasks, including autonomous and distributed network discovery and node configuration and the network topology's underwater docking. Two main scenarios are considered: first, all nodes are deployed simultaneously; second, deploy and configure the first subnet consisting of five nodes, then add other nodes (from two nodes to five nodes) to the first subnet. It is verified that the proposed DIVE protocol can enable different networks to interact and coordinate and can bring various networks to a standard configuration.

In many network applications with high real-time requirements, it is not desirable to spend too much time on network initialization. According to the specific application, how to realize the optimal trade-off scheme between energy consumption and convergence delay or to study the fast topology discovery algorithm within the acceptable energy consumption range is one of the problems that need to be studied in the future. The unstructured underwater acoustic network, coupled with the underwater acoustic channel's time-varying characteristics, will occur a more challenging collision, re-transmission, and loss of control packets. These increase the energy consumption and time delay of network discovery. Therefore, a suitable mechanism of packet collision avoidance and recovery is needed for topology discovery. The discovery cycle's optimization design can also reduce the number of discovery cycles and the number of control packets to complete the topology discovery process more efficiently.

Most of the current topology discovery protocols in underwater acoustic networks assume symmetric links, resulting in poor adaptability of topology discovery protocols and poor link quality awareness. The topology discovery protocol of underwater acoustic networks should discover complete information (including reliable link quality information) and ensure network nodes' continuous discovery and trustworthy links. This need adds link quality measurement phase, including software-based link quality measurement method and hardware-based link quality measurement method into the topology discovery cycle. Based on the discovery cycle design, software-based link quality measurement will determine the parameters of monitoring time window size, network traffic, detection packet size to determine the initial stable link in the topology discovery stage. It measures link quality based on successful and unsuccessful transmission packets within a predetermined time window. As a result, they can provide more detailed information about changes in link quality. However, it is not easy to choose the time window size, network traffic rate, and probe packet size. They have a significant influence on the quality of link estimation. The hardware-based link quality measurement methods, including analyzing the received signal strength, link quality index, signal-to-noise ratio, make a preliminary link quality assessment to provide rapid link quality identification and provide real-time channel quality information in the receiving packet. However, since the measurement is only based on the first symbol or the first few symbols of the received packet, without considering the packet loss distribution, the link's data transmission quality will be overestimated when there are too many packet losses. Hybrid link quality measurement techniques are usually defined as a weighted function of link quality estimation measures based on software and hardware. However, each metric's weight must be further set based on the environmental conditions and performance requirements of the underlying application.

Furthermore, the previous methods are mostly centralized or semi-distributed. The research of fully distributed topology discovery algorithms is now an issue. In a centralized mechanism, all nodes should report their identities to the central node. After that, the central node determines each node's neighboring nodes and notifies all nodes of their adjacent set. In this way, the central node's performance requirement is much higher than that of the ordinary node, so it is necessary to add the central node's anti-destruction mechanism. Otherwise, once the central node is damaged, the discovery process will not be able to proceed. The distributed neighbor discovery method allows nodes to cooperate to perform neighbor discovery, and all nodes have equal status, thus eliminates the reply delay to the central node. Still, it is challenging to design the algorithm.

V. CONCLUSION

The topology discovery process is necessary for the network protocol to perform its function. In recent decades, the research of underwater acoustic networks has received extensive attention. However, no paper classifies and thoroughly discusses the problem of topology discovery in underwater wireless sensor networks. Therefore, it is necessary to summarize the current research work on topology discovery of underwater acoustic networks. We have attempted to investigate the basic concepts of topology discovery in underwater acoustic networks in this context.

To comprehensively review the existing topology discovery protocols, we divided them into centralized and distributed protocols, analyzed each protocol's working process, and summarized each protocol's characteristics. The centralized topology discovery protocol needs to set the central network node. The central node has a more robust performance compared with the ordinary node. It triggers the topology discovery process and controls the scheduling of the discovery cycle. This protocol relies heavily on the central node. In contrast to centralized is distributed topology discovery algorithm, in which all nodes in the network have the same status and perform the same topology discovery process. It saves the process of forwarding to the central node and has a low convergence time delay, but the protocol design is complex. Currently, most of the topology discovery protocols in underwater acoustic networks are centralized. The distributed topology discovery protocols will play an essential role in future ocean networks.

Based on the analysis and discussion presented in this paper, we identify some open issues in designing effective network topology discovery protocols. Therefore, we highlight future research opportunities to encourage new research further to investigate the topology discovery protocols of underwater acoustic networks.

VI. CONFLICT OF INTEREST STATEMENT

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

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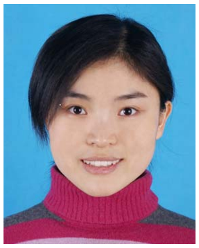

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