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Routing Protocols for Underwater Acoustic Sensor Networks: A Survey from an Application Perspective

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Abstract

Underwater acoustic communications are different from terrestrial radio communications; acoustic channel is asymmetric and has large and variable end-to-end propagation delays, distance-dependent limited bandwidth, high bit error rates, and multi-path fading. Besides, nodes' mobility and limited battery power also cause problems for networking protocol design. Among them, routing in underwater acoustic networks is a challenging task, and many protocols have been proposed. In this chapter, we first classify the routing protocols according to application scenarios, which are classified according to the number of sinks that an underwater acoustic sensor network (UASN) may use, namely single-sink, multi-sink, and no-sink. We review some typical routing strategies proposed for these application scenarios, such as cross-layer and reinforcement learning as well as opportunistic routing. Finally, some remaining key issues are highlighted.

Keywords: underwater acoustic sensor networks (UASNs), application scenarios, routing protocol strategies

1. Introduction

Almost 71% of our plant is covered by oceans, and underwater networks become more and more important since they can be used for underwater information exchange, surveillance, ocean explorations and disaster prevention, etc., [1].

There are several challenges for underwater acoustic communication. First, because electromagnetic wave does not perform well in underwater environments due to the serious attenuation, acoustic communication is used as a major communication technology in underwater

networks [2, 3]. The acoustic channel is asymmetric with large end-to-end propagation delays and limited bandwidth as well as high bit error rates due to multi-path fading. Second, underwater sensor nodes' mobility caused by ocean currents brings intermittent connective links. Third, underwater sensor nodes are prone to failure because of corrosion, fouling, and limited battery power that is available. Furthermore, the speed of the sound can change with water temperature, which leads to changes in the transmission path and may be the cause of the data not being forwarded to the sea surface on time. Therefore, the routing protocols available for terrestrial wireless sensor networks are not suitable for underwater acoustic sensor networks (UASNs), and many new routing protocols have been studied.

There are several surveys on routing protocols for UASNs reported in the literature, which provide overviews about the basic ideas of the related protocols mainly following the taxonomy for terrestrial wireless sensor networks. In Ref. [4], the authors investigated the characteristics and algorithms of routing protocols and classified them into the non–cross-layer design, the traditional cross-layer design, and the intelligent algorithm design. The work in Ref. [5] discussed the current state of the art on the UASN protocol design and provided a detailed overview on the current solutions for medium access control, network, and transport layer protocols. A review and comparison of different algorithms was proposed in Ref. [6] to fulfill different application requirements with dynamic environmental conditions. All these investigations show that it is almost impossible to conclude that any particular routing strategy can cost-effectively support all underwater applications because each of them has certain strengths and weaknesses and is only applicable to specific situations.

In this chapter, we conduct a review mainly from an application perspective. An optimal protocol design must take into account different favorable features available in different scenarios to maximize routing performance, especially the characteristics of various network topologies. Therefore, it is interesting to investigate how each protocol exploits these features to maximize protocol performance and the feasibility of the proposed schemes.

The rest of the chapter is organized as follows. In Section 2, we briefly introduce the characteristics of application scenarios and routing strategies. In Sections 3–5, we discuss typical routing protocols of different strategies in single-sink–, multi-sink–, as well as zero-sink–based UASNs. In Sections 6–8, we discuss typical routing protocols based on cross-layer and reinforcement learning as well as opportunistic routing protocols. Finally, in Section 9, we draw the conclusions.

2. Major application scenarios and routing strategies

2.1. Application scenarios

Most applications of UASNs are related to underwater collection, where the surface units are used to collect data transmitted by underwater sensor nodes. Therefore, application scenarios can be classified into single-sink, multi-sink, and zero-sink according to the number of sinks that a UASN uses. As shown in **Figure 1**, in a single-sink–based UASN, there is only one sink node which can be static or mobile. A static sink node is fixed on the surface (in some cases on
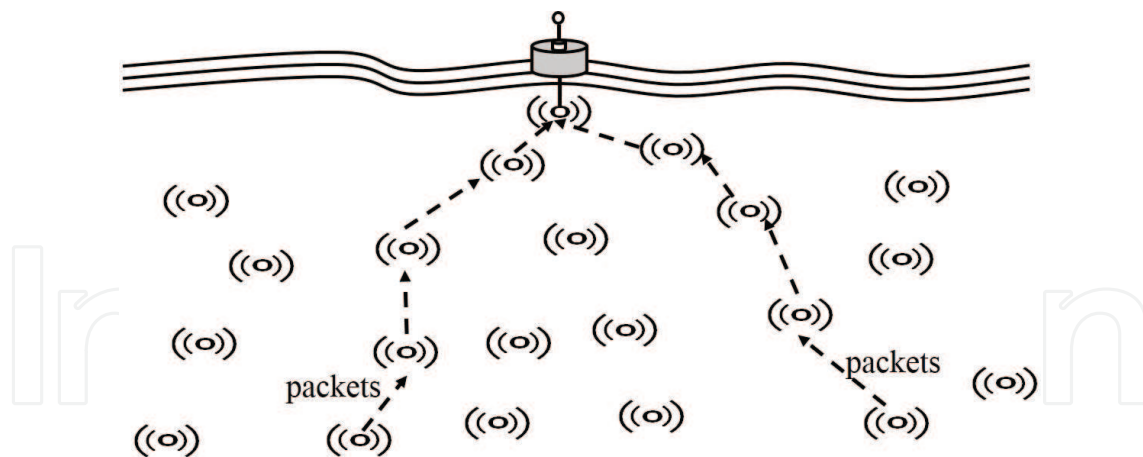
Figure 1. A static single-sink–based UASN.

the bottom) of the ocean as shown in **Figure 1** [1]. A mobile sink node moves to collect data from the sensor nodes deployed in the ocean as shown in **Figure 2**. The topology of a multi-sink–based UASN is shown in **Figure 3**, where two or more sink nodes are used to receive packets collected by sensor nodes [1]. A sensor node only needs to transmit the packets to one of the sink nodes close to the node. Sensor nodes in a multi-sink–based UASN can also be static or mobile. In a zero-sink–based UASN, several functionally identical autonomous underwater vehicles (AUVs) usually work as a team collaboratively, which requires communicating with each other, as illustrated in **Figure 4**.

Major factors that can affect the design of a routing protocol include the number of sink nodes and the topology of the corresponding UASN. Arranging multiple sink nodes in the network can improve the routing performance by shortening transmission path. A sensor node only needs to transmit the packets to the sink closer to it [1]. Deploying a UASN with static topology or a single-sink can simplify the design of a routing protocol. A zero-sink–based UASN may have several AUVs to work as a team, and it is more difficult to design routing protocols for this kind of UASN to achieve good performance.
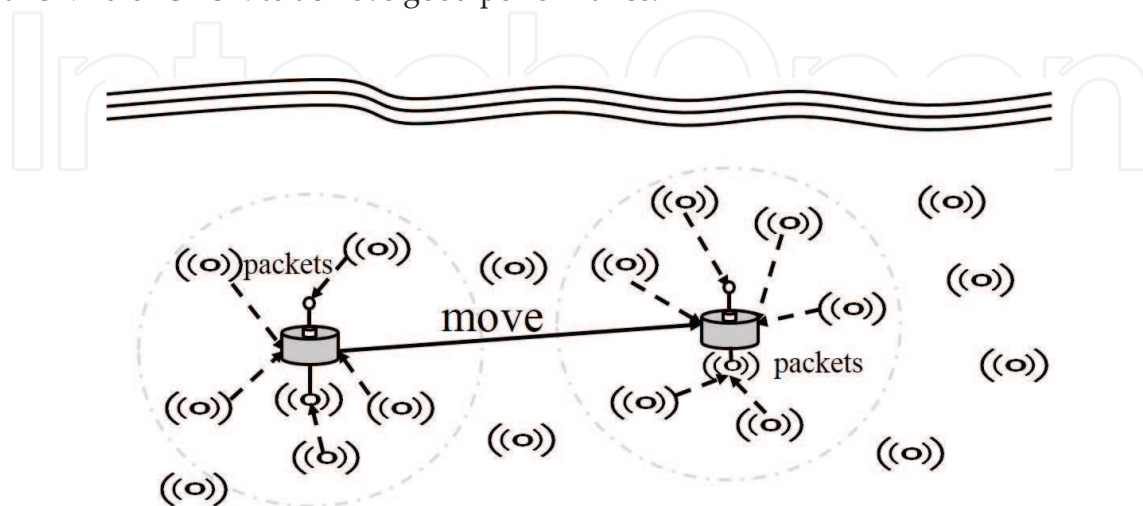

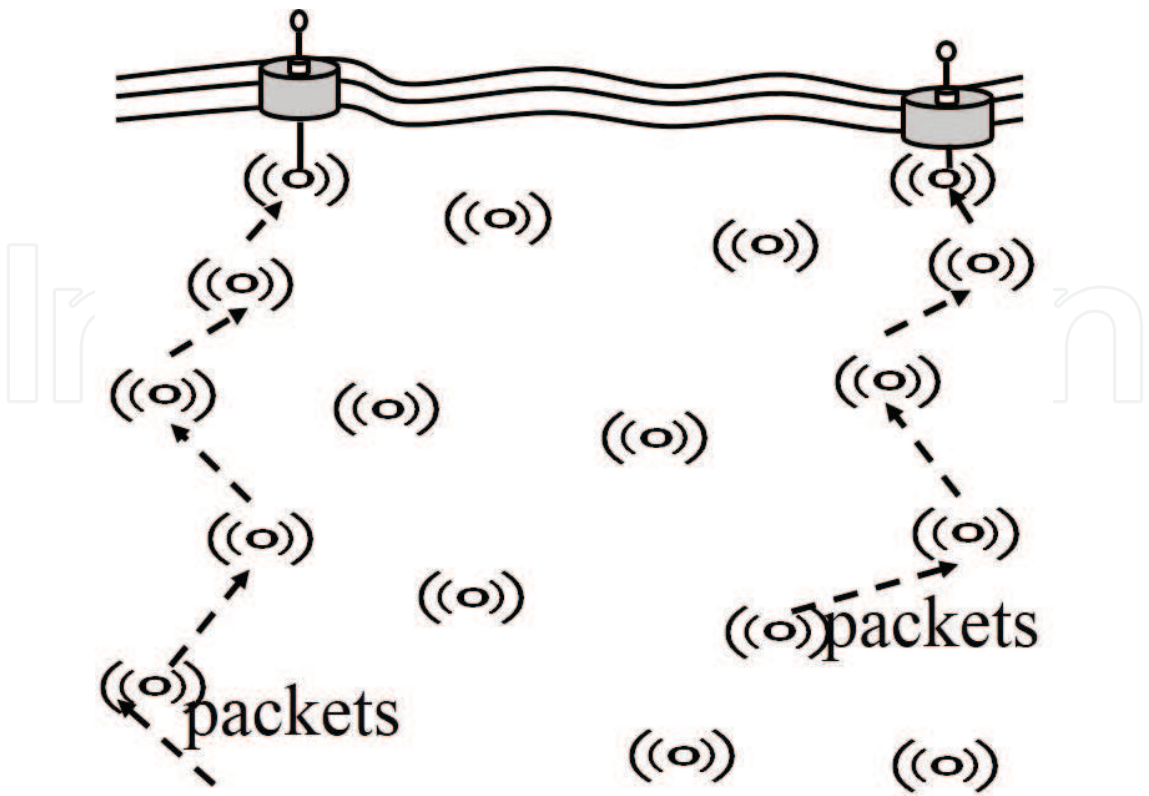**Figure 2.** A mobile single-sink–based UASN.
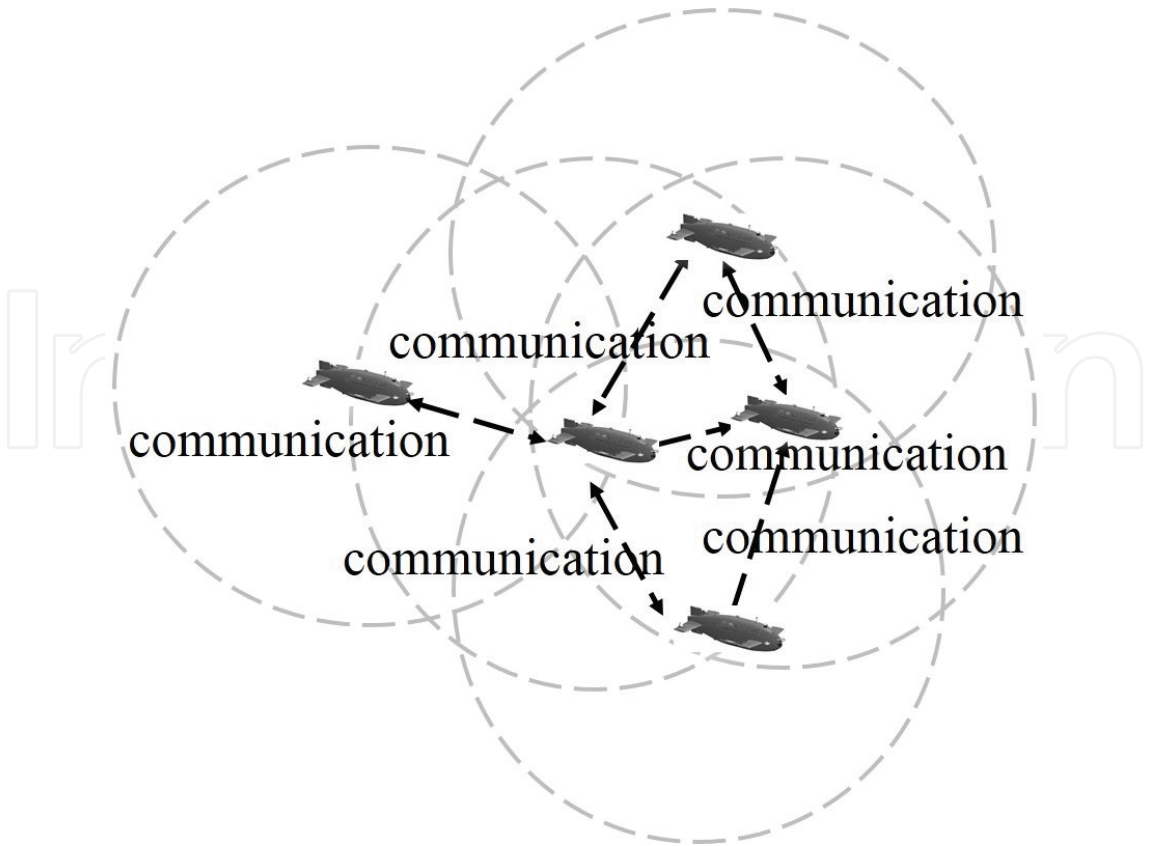
Figure 3. A multi-sink–based UASN.

Figure 4. A zero-sink–based UASN.

2.2. Routing strategies

Table 1 lists routing strategies under reviewing.

Routing strategy	Characteristics	Application scenarios	Advantages	Disadvantages
Geo-based routing	It is based on GPS	All scenarios	Network architecture is simple	Positioning may be not accurate
Source routing	The transmission path is determined by the source node	Single-sink–based UASN with a static sink	It reduces the cost of route maintenance	It increases the packet overhead and routing cost
Hop-by-hop routing	The next-hop is determined by relay nodes	Except zero-sink–based UASN	Network is more scalable and flexible	The final path may be not optimal
Clustered routing	The nodes are usually divided into groups	Single-sink–based UASN	It has a good adaptability and can reduce data redundancy	It needs to select the cluster head
Cross-layer routing	It considers the characteristics of other layers	Single-sink–based UASN with a static sink and zero-sink–based UASN	It can minimize energy costs while maximizing the performance of the entire network	Routing protocol is more complex
Reinforcement learning scheme	Each node selects next hop via an iterative calculation of the reinforcement function	Single-sink–based UASN	It extends the lifetime of the network	More powerful nodes are required
Opportunistic routing	Each node selects several suitable neighbor nodes as a set of candidate-forwarding nodes	Multi-sink–based UASN with mobile topology	It improves the end-to-end success delivery rate of packet forwarding.	More powerful nodes are required

Table 1. Comparisons of major routing strategies.

2.2.1. Geo-based routing

Geo-based routing uses the position information of sensor nodes to find the best route from a source node to a destination node. Each node has to be aware of the target area, its own position, and all neighbors' positions. A node forwards packets to the target area in accordance with a certain policy based on the location information. At present, two common ways to obtain position information are using signal strength to estimate the relative coordinates and GPS. However, GPS cannot work well in underwater environments, and the relative coordinate of a node estimated by signal strength suffers from signal attenuation and noise interference.

2.2.2. Source routing

Source routing allows the sender of a packet to specify the route that the packet takes in the network partially or completely. The transmission path in is determined by the source node,

and the identification of all relay nodes in the path is embedded in the packets. Relay nodes can forward packets according to the planned path instead of selecting next hop by themselves [1]. During the route construction phase, a source node establishes a route by flooding route request packets (RREQs) in the network. Upon receiving an RREQ, the destination node responds by sending a route reply packet (RREP), which carries the route attached in the RREQ back to the source node. It supports asymmetric channel and reduces the cost of route maintenance. However, it increases the packet overhead and the routing cost. In addition, the performance degrades rapidly with the increase of mobility.

2.2.3. Hop-by-hop routing

Hop-by-hop routing allows each relay node to select its next hop by itself. The selection of next hop is usually based on its local view of the network. It can make the network more scalable and flexible, but the final path may not be optimal.

2.2.4. Clustered routing

Clustered routing divides the sensor nodes into geographical or logical groups, and the selection of cluster head considers the position distribution of nodes and residual energy. In each group, a cluster head is used as a gateway to communicate with other groups, and sensor nodes in each group only need to transmit packets to the cluster head. This strategy has a good adaptability and reduces data redundancy.

2.2.5. Cross-layer routing

Although the hierarchical protocol stack structure is clear, scalable, robust, and easy to implement, the inter-layer information is difficult to be shared and not conducive to the global optimization of network performance. Cross-layer routing strategies take into account the functions and information available on other layers. Through the power control and frame collision control, it can achieve the relevant hierarchical interaction and minimize energy costs while maximizing the performance of the entire network [7].

2.2.6. Reinforcement learning-based routing

Reinforcement learning-based routing aims to find the most suitable route by using Q-learning algorithm to learn the network states and adapts to topology changes at runtime intelligently without any off-line training. During the routing process, a node analyzes its residual energy and energy distribution of a group of nodes, establishes a reinforcement function, and selects the appropriate node to forward packets [8]. This strategy can extend the lifetime of the network as much as possible.

2.2.7. Opportunistic routing

Opportunistic routing takes advantages of the packet transmission opportunities due to mobility and broadcast of nodes, not only determining the next hop but also selecting suitable

neighbor nodes as a set of candidate forwarding nodes based on certain routing metrics. All nodes in the set receive packets and then the node with the highest priority completes the following transmission. It makes full use of channel broadcast characteristics to improve throughput and transmission reliability [9].

3. Single-sink–based UASNs

3.1. Static sink

A multi-path grid-based geographic routing protocol (MGGR) is proposed in Ref. [10]. It assumes that there is a sink fixed at the top in the middle of the grid, and the other sensor nodes are mobile and equipped with locator. Routing is performed in a grid-by-grid manner through gateways that use disjoint paths to relay data packets [10]. The disjoint paths and gateway election algorithm adopted in the protocol are helpful for balancing energy while achieving high delivery ratio and small end-to-end delay.

In Ref. [11], a location-based adaptive routing protocol (CARP) selects different paths for different levels of data packets, relying on the dynamic characteristics of underwater environments. CARP can adapt dynamic underwater environments, improve the quality of the network communication, and have better performance in transmission delay, energy consumption, and packet acceptance rate.

The hop-by-hop vector-based forwarding routing protocol (HH-VBF) is homogeneous to VBF which uses the notion of a "routing vector" to act as the axis of the "virtual pipe" [12]. However, it constructs different virtual pipes for the per-hop vector from each individual forwarder to the sink, instead of a single virtual pipe from the source to the sink as VBF. HH-VBF is less sensitive to the routing pipe radius threshold and has much better performance such as energy consumption and successful delivery rate than VBF in sparse networks.

A solution for routing joint control and node replacement decisions is proposed in Ref. [13] to minimize the node replacement costs and develop effective methods for practical implementation. Sensor nodes in the network are laid on the ocean floor to collectively gather and transmit seismic information. As the results indicate, it provides a lower average node replacement cost and meets higher service-level requirements, while it has a higher degree of simplicity.

A fault tolerant routing protocol (FTR) [14] assumes that the topology of the network is static and only a small fraction of the nodes is involved in routing. It detects substitutive links to revise the main path and build backup path. Simulations show that FTR achieves higher packet delivery ratio, small end-to-end delay, higher network throughput, and lower energy consumption than VBF and epidemic routing (ER) protocols.

3.2. Mobile sink

In Ref. [15], the authors proposed a mobicast routing protocol. All sensor nodes are randomly distributed in a 3-D environment, and an AUV travels along a user-defined route as a mobile

sink to collect data from sensor nodes within a 3-D zone of relevance (ZOR) and wakes up sensors in the next 3-D ZOR [15]. In addition, only sensor nodes in the 3-D ZOR can be notified to enter the active mode to transmit collected data. For this reason, it has better performance such as a successful delivery rate, power consumption, and message overhead.

3.3. Geo-based routing

In Ref. [16], the authors proposed an integration method between localization and routing by using an AUV as an anchor node and "iterative localization". Each sensor node establishes multiple routes to the sink by extending control packets exchanged for localization and creates routing table to the sink in parallel with the localization process [16]. This method provides robustness to communication failure and decreases energy consumption between each localization.

A reliable and energy efficient vector-based forwarding protocol (REE-VBF) was proposed in Ref. [17]. The transmission way of data packets is local flooding, and an optimal node with the smallest desire coefficient is selected by establishing a set of adaptive selection mechanisms [17]. The optimal node forwards the packet at first to prohibit others transmitting repeatedly. Therefore, REE-VBF has a better performance on energy efficiency and reliability than others. In addition, it is suitable for the communication in shallow water areas.

In the directional flooding-based routing protocol (DFR) [18], a node knows its own location, its one-hop neighbors' location, and the location of a sink. It relies on a packet flooding scheme, with which the flooding zone is determined dynamically by the link quality among neighbors to increase the successful delivery ratio instead of relying on a path establishment between the source and sink node. The results show that DFR has a higher packet delivery ratio, less communication overhead, and shorter end-to-end delay than VBF.

A geographical optimized reflection-enabled routing protocol immune to link ambiguity (GORRILA) is proposed in Ref. [19], aiming to establish the best stable route from a source to a destination. It utilizes directional antennas to incorporate surface-reflected non-line-of-sight (NLOS) links in the routing process, instead of relying on the LOS link between one-hop neighbors, which adds delay to the data delivery time in establishing routes. In addition, a physical and medium access cross-layer scheme was also designed to optimize the route selection for maximum network throughput.

A sector-based routing with destination location prediction (SBR-DLP) protocol [20] was designed for a fully mobile topology network, in which each node is mobile and the destination node moves along a pre-planned route. In the routing process, the area around the current forwarder is divided into a plurality of sectors, wherein the first sector is halved by the vector from the transponder to the destination vector and the other sectors are tagged according to their angular differences from that vector. The SBR-DLP is highly adaptive to network dynamics and can improve the packet delivery ratio.

3.4. Source routing

A reliable and energy-efficient routing protocol (RER) was proposed in Ref. [21]. In the route discovery phase, a simple next-hop selection is introduced to select a node with the minimum

packet transmission delay to the current node as its next-hop node. After a route is set up, multiple nodes in the network can also send data packets to the sink through the same established route instead of building a new route. As a result, it allows the real-time data to arrive at the destination earlier and extends the network lifetime. The simulations show that RER performs better than the traditional routing protocols in terms of packet delivery ratio, average end-to-end delay, and average energy consumption.

Another source routing protocol called local area source routing (LASR) [22] is proposed for a small area of UASN. In this case, a source node does not need to care about the outside area of its transmission range. For this reason, each node just needs to share information of its neighboring nodes and finds a minimum cost path up to a determined sub-destination within its transmission range. Simulation results show that the proposed solution can reduce energy consumption, in comparison with other 3-D on-demand routing protocols.

3.5. Hop-by-hop routing

In channel-aware depth-adaptive routing protocol (CDRP) [23], the source node constructs a virtual ideal path to the sink node when it has data to send. Besides, the noise and the speed of sound under different water depths are taken into account in the selection of forwarders to reduce end-to-end delay and improve packet delivery ratio.

In view of the impact of the beam width and 3-D direction of underwater sensors in UASNs, beam width and direction concerned routing (BDCR) proposed in Ref. [24] can achieve relatively high packet delivery rate and ensure reasonable energy consumption. On the selection of forwarder, the sensor node makes its preliminary decision not only on its own distance to the sink node but also on the distance of the previous sender to the sink node. Then, a correction mechanism based on beam width and direction is designed to make the final decision.

Chen et al. proposed a per-hop-based routing protocol called depth adaptive routing protocol (DARP) in Ref. [25], which takes not only the sound speed in different water depths but also the depth and the distance to the sink into consideration. In the routing process, a source node broadcasts the packets and then the neighbors wait for some time to decide whether they are eligible to forward the packets or not. The simulation results verify that DARP outperforms other routing protocols in terms of end-to-end delay.

UASNs-MIMO (UMIMO)-routing [26] utilizes multiple-input multiple-output-orthogonal frequency division multiplexing (MIMO-OFDM) links to adaptively leverage the trade-off between multiplexing and diversity gain. With cross-layer design, it adapts its behavior to the noise and interference in underwater channels to choose a suitable transmission mode and allocate transmit power on subcarriers [26]. Moreover, the energy consumption is minimized according to the cooperation of transmitter and receiver to achieve the desired QoS (quality of service) according to application needs and channel condition.

SEANAR [27] is an energy-efficient and topology-aware routing protocol. It assigns larger weights to nodes with higher connectivity to the sink and adopts a simple yet effective greedy approach for making routing decisions. Although this is a simple greedy approach that uses

the degree information (i.e., the number of neighbors) as the criteria to choose the successor, simulation results show that SEANAR achieves higher packet delivery ratio and a lower energy consumption in comparison with greedy forwarding and VBF-based routing protocol.

Redundancy-based adaptive routing (RBAR) [28] is a routing protocol designed for underwater delay tolerant networks (DTNs). It adopts a binary tree-based forwarding procedure for the packet replication process, which allows a node to hold a packet as long as possible until it has to make another copy to satisfy its delay requirements [28]. Simulations show that RBAR can meet different delay requirements and achieve a good balance between delivery ratio, delay, and energy consumption.

3.6. Clustered network

A location-based clustering algorithm for data gathering (LCAD) [29] is a cluster-based routing protocol. The whole network is divided into 3-D grids and the sensor nodes are fixed at different depths. The sensor nodes at each tier are organized in clusters with multiple cluster heads. Data gathered from the sensor nodes are sent to their respective cluster heads and then cluster heads deliver the data to the sink via AUVs. Its performance depends on the positioning of the cluster heads. The simulation shows that it improves the network lifetime by at least five times as against a scenario, which does involve clustering.

A distributed underwater clustering scheme (DUCS) without GPS support was proposed in Ref. [30]. The nodes organize themselves into local clusters. A non-cluster head node forwards the packets to cluster heads in a single hop and then the cluster head transmits the packets to a sink via the relay of other cluster heads in a multi-hop mode. In order to solve a battery draining problem for the cluster head, the routing protocol performs random rotation of the cluster head. The simulation shows that DUCS can achieve a very high packet delivery ratio and minimize the proactive routing message exchange.

An energy optimized path unaware layered routing protocol (E-PULRP) [31] puts the sensor nodes into different layers in the form of concentric shells around a sink node. In each layer, an intermediate relay node is selected to deliver packets from the source node to the sink node. A mathematical framework is developed for energy consumption optimization. In comparison with other routing protocols for UASNs, E-PULRP is simpler and more topology independent.

The location unaware multi-hop routing protocol based on a hybrid, energy-efficient, distributed clustering approach (LUM-HEED) [32] is a new, homogeneous, multi-hop routing protocol. It can be adaptive to a hierarchal structure network model in which each node is initialized with a certain degree according to its distance to the sink. The difference between LUM-HEED and HEED protocols is that the nodes in HEED protocol must be location aware for communicating with the sink node. Note that the sensor nodes nearer to the sink have a higher degree. Simulation results show that LUM-HEED has better performance than HEED in terms of network lifetime and network traffic.

A mobility aware routing protocol, called temporary cluster-based routing (TCBR) [33], divides the sensor nodes in different clusters according to their locations. Ordinary nodes collect and forward the packets to a nearer cluster head and then courier nodes can move vertically and

deliver them to the multiple sinks deployed on the water surface with a piston module. TCBR takes the advantage of multiple-sink architecture with requiring any location information of sensor nodes. This makes it suitable not only for stationary and mobile networks but also for the hybrid networks [33].

A staggered time division multiple access (TDMA) underwater medium access control (MAC) protocol with routing (STUMP-WR) [34] is a distributed and channel-scheduling routing protocol and designed for heavily loaded underwater networks. The sensor nodes select and schedule links to overlap communications by using a distributed algorithm for leveraging the long propagation delays [34]. The simulation shows that STUMP-WR outperforms several protocols proposed for underwater networks in terms of bits delivered per unit of energy and throughput.

4. Multi-sink–based UWSNs

4.1. Static UASNs

The depth-controlled routing protocol (DCR) in Ref. [35] uses the distance of the nodes to its nearest sink in a greedy forwarding strategy. In the network initialization phase, a sensor node moves to get a good and stable topology to improve the connectivity and routing performance. DCR shows better results than the current depth-based routing protocol (DBR) in terms of data delivery ratio, delay, and average number of redundant packets with the same energy per packet consumption.

Focused on energy balancing, the dual-sink efficient and balanced energy consumption technique (DSEBET) in Ref. [36] first establishes links between nodes based on their optimum distance value and then picked relay nodes based on their minimum distance value for the transmission of data. Long-distance nodes from one sink will share their data to another sink if they come in range of sink; otherwise, they will establish a multi-hop path for transmission of data to the respective sink [36]. In this way, energy is balanced to improve network lifetime and throughput.

A new routing protocol called MobiSink was proposed in Ref. [37] to tackle the problem of high energy consumption and reduce the instability period based on the deficiencies of depth-based routing and energy-efficient depth-based routing. Each of the four mobile sinks moves in its own region, following linear motion in the horizontal region to collect data from the nodes [37]. If the sink enters the transmission range of these nodes, the packet is forwarded directly from the high-level node to the sink. In this way, the data forwarding load is reduced on the middle node.

4.2. Mobile UASNs

In the dual-sink (DS) VBF protocol [38], all nodes are dynamic, and dual-sink architecture is deployed to increase the number of nodes that are participating in the data-forwarding procedure. In comparison with VBF, in DS-VBF, each node calculates its distance from the nearest sink and transmits the packets to it. It considers both residual energy and location

information instead of just location information to discover an optimized path to save energy [38]. Thus, it can improve the packet delivery ratio, reduce end-to-end delay, and balance total energy consumption to prolong network lifetime.

The hop–by-hop dynamic addressing-based (H2-DAB) routing protocol in Ref. [2] chooses the next hop node in a greedy strategy for broadcasting based on the hop count, called HopID, from source nodes to sink nodes on the surface water. H2-DAB can easily handle the node movements and support multiple sink architecture. However, the problem of multi-hop routing still exists with which nodes near the sink drain more energy because they are used frequently.

4.3. Geo-based routing

Similar to the geo-based routing in single-sink–based UASNs, the geo-based routing in multi-sink UASNs uses the position information too. The difference is that in multi-sink–based UASNs, packets are sent to one of the sink nodes [1].

In Ref. [35], the DCR is a centralized and distributed geographic routing protocol, with depth adjustment-based topology control for recovery of invalid communication area. A greedy forwarding strategy is proposed for geographic routing.

The DS-VBF in Ref. [38] is a dynamic and geographical routing protocol, considering both residual energy and location information as priority factors to discover an optimized routing path to save energy. Every sensor node is aware of its own location, and each data packet contains the location information of the source, forwarder, and destination nodes. In addition, a range of fields used for node mobility notion is also known by each sensor node. Based on the simulation results in comparison with VBF, average end-to-end delay is reduced but remaining energy and packet reception ratio are increased.

5. Zero-sink–based UWSNs

A trajectory-aware communication scheme based on statistical inference to model position uncertainty, combined with a practical cross-layer optimization for a WHOI acoustic micro-modem, is adopted in a paradigm-changing geographic routing protocol [39] to minimize energy consumption. Acoustic communications are used to transfer information between gliders and finally to a surface station. Implemented and tested in the proposed underwater communication test bed, it shows improvement over other routing protocols with only statistical approach or cross-layer approach in terms of end-to-end reliability, throughput, and energy consumption [39].

An AUV-aided routing method integrated path planning (AA-RP) protocol [40] uses AUVs to collect data from sensor nodes following a dynamic path, which is planned by AUVs. It utilizes the cooperation of multi-tasks to reduce energy consumption and avoid hot spot and zone problem with a dynamic gateway node scheme. The simulation shows that, although the AA-RP does not require location information in the routing process, it can balance energy consumption, avoid hot point and hot zone problem, and save energy by combining multi-tasks with a good delivery ratio.

6. Cross-layer routing

The energy-efficient interference-aware routing protocol in Ref. [41] is a centralized cross-layer heuristic solution for an efficient use of the scarce resources of UASNs. It provides a class of scheduling, power control, and routing policies and selects the next transmission node by considering different delays in packet delivery, maximal node buffer size, distance to the sink, and channel usage. Such routing can increase the overall network throughput and outperforms others in terms of energy consumption and throughput.

A new geographical and distributed routing algorithm was tailored for the characteristics of 3-D underwater environment in Ref. [42]. A model characterizing the acoustic channel utilization efficiency allows setting the optimal packet size for underwater communication. Moreover, the problem of data gathering was investigated at the network layer by considering the cross-layer interactions with MAC layers, forward error correction schemes between the routing functions, and the characteristics of underwater acoustic channels [42]. In the light of different application requirements, two distributed routing algorithms were introduced to minimize energy consumption.

The gossiping in underwater acoustic mobile ad-hoc networks (GUWMANET) scheme in Ref. [43] realizes medium access and routing functionalities in a cross-layer design. It is based on impulse communication as a physical layer method. GUWMANET needs only 10 bits of additional overhead in combination with the generic underwater application language (GUWAL), which has a 16-bit header with a multi-cast source and destination address.

A multi-path power-control transmission (MPT) scheme [44] smartly combines power control with multi-path routing and packets at the destination. MPT is divided into three parts: multi-path routing, source-initiated power-control transmission, and destination packet combining. With carefully designed power-control strategies, MPT consumes lesser energy than the conventional one-path transmission scheme without retransmission [44]. Besides, since no hop-by-hop retransmission is allowed, MPT introduces much shorter delays than the traditional one-path scheme with retransmission.

The CARP in Ref. [45] is a distributed cross-layer solution for multi-hop delivery of data to a sink in underwater networks. Next-hop selection takes explicitly into account the history of data packet delivery, the link quality, and how successful a neighbor has been in forwarding data toward the sink [45]. The results show that CARP can achieve throughput efficiency that is up to twice the throughput of focused beam routing (FBR) and almost three times that of DBR. It also obtains remarkable performance improvements over FBR and DBR in terms of end-to-end packet latency and energy consumption.

7. Reinforcement learning-based routing

A novel Q-learning-based delay tolerant routing (QDTR) protocol [8] with predictions empowered by adaptive filters is adaptive and energy efficient. The adaptive filters are used to predict future neighbor contact. With the Q-learning agent, the routing protocol can adapt

to changes in the network. Since the routing problem is formulated as a Markov decision process (MDP), in which the state space is composed by all the nodes in the network, QDTR is fully distributed without any central control. The simulation results have shown that QDTR yields significantly better network performance in energy consumption, end-to-end delay, and delivery ratio in comparison with most of the existing DTN routing protocols.

A multi-level routing protocol for acoustic-optical hybrid underwater wireless sensor networks (MURAO) [46] is a multi-level Q-learning-based routing protocol for a novel acoustic-optical hybrid UASN. The network is physically partitioned into several groups and logically divided into two layers. Taking advantage of the long range but slow acoustic transmission and fast optical communications with multi-level Q-learning, MURAO performs better than the flat Q-learning-based routing.

In Ref. [47], a Q-learning-based tracking scheme based on the buffer size and residual energy of the individual node was used to find the next forwarder. It aims to reduce the dropping on the packets, the number of forwarders, and energy consumption of the sensor nodes. The lifetime of the network is expected to increase.

Another Q-learning-based energy-efficient and lifetime-aware routing protocol (QELAR) was proposed in Ref. [48] to prolong the lifetime of networks. The residual energy of each sensor node as well as the energy distribution among a group of nodes is factored in the throughput routing process to calculate the reward function, which aids in selecting the adequate forwarders for packets. Compared with VBF, QELAR has a longer lifetime.

8. Opportunistic routing

The geographic and opportunistic routing with depth adjustment-based topology control for communication recovery over void regions (GEDAR) in Ref. [49] adjusts the topology by moving void nodes to new depths and using greedy opportunistic forwarding mechanisms to transmit packets. The communication void region occurs whenever the data is transferred to a node that is not closer to the destination than the node; the node located in a communication void region is called void node. Compared with the baseline routing protocols, GEDAR outperforms in data packet delivery ratio.

The void-aware pressure routing protocol (VAPR) in Ref. [50] exploits periodic beaconing to build directional trails toward the closest sonobuoy and features greedy opportunistic directional forwarding mechanisms for packet delivery. It can be efficiently performed even in the presence of voids [50]. The simulations show that VAPR outperforms existing schemes by significantly lowering the frequency of recovery fallbacks and effectively handling node mobility.

With the opportunistic-based DARP in Ref. [51], forwarding node selection is dynamic and independent for each node. DARP takes different acoustic signal speed, depth, and distance to sink into account to find the minimum end-to-end delay path, which may not be the shortest path directly from the source to the sink. Furthermore, it does not need to continuously maintain neighbors' information or to exchange control packets.

The HydroCast in Ref. [52] is a hydraulic pressure-based anycast routing protocol, which exploits measured pressure levels to route a packet upward to lower depths. The opportunistic routing mechanism can limit co-channel interference by selecting the subset of forwarder. The dead-end recovery method can guarantee the delivery. Because HydroCast uses adaptive timer setting at each hop, it is mainly used for depth-based communication with sparse network and performs better than DBR in terms of delivery ratio and end-to-end delay.

9. Conclusion and open issues

We summarize the routing strategies mentioned above in **Table 2**. Most routing strategies are suitable for a static UASN, and just a small scale of them can be applied in a mobile UASN. However, one of the most important characteristics of UASNs is mobility. From the adaptability of the application scenarios, geo-based routing protocols cannot work well in mobile UASNs due to frequent localization. In addition, the characteristics of acoustic channels are also the limitation of the design of geo-based routing protocols. Clustered routing protocols also do not perform well in mobile UASNs because of the grouping cost.

Cross-layer routing protocols may have good performance in static UASNs. Source-routing protocols are based on the location of sensor nodes and usually adapted to single-sink–based UASNs. On the opposite, hop-by-hop routing protocols can be applied in both single-sink and multi-sink–based UASNs.

Routing strategy\	Scenarios				
	Single-sink–based UASNs		Multi-sink–based UASNs		Zero-sink–based UASNs
	Static sink	Mobile sink	Static topology	Mobile topology	
Geo-based routing	✓		✓		✓
Source routing	✓				
Hop-by-hop routing	✓	✓	✓	✓	
Clustered network	✓		✓		
Cross-layer routing	✓				✓
Reinforcement learning-based routing	✓				
Opportunistic routing				✓	

Table 2. Categories of routing strategies.

Reinforcement learning-based routing protocols have good adaptability. It may be applied to dynamic networks by the design of reward functions.

The above discussion shows that it is impossible to design just one or two routing protocols that can cost-effectively support all underwater application scenarios. Many routing proposals for UASNs are only in the simulation phase and have not been testified in the actual environments. Researchers still follow the design philosophy of routing protocols for terrestrial wireless networks, which is not enough for UASNs. An optimal design must take into account each different favorable feature available in different scenarios.

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References

[1] Qian L, Jiang SM. A review of routing protocols of underwater acoustic sensor networks from application perspective. In: 2016 IEEE International Conference on Communication Systems (ICCS); 14-16 December 2016; Shenzhen, China: IEEE; 2017. pp. 1-6. DOI: 10.1109/ICCS.2016. 7833633

[2] Ayaz M, Abdullah A. Hop-by-hop dynamic addressing based (H2-DAB) routing protocol for underwater wireless sensor networks. In: 2009 International Conference on Information and Multimedia Technology; 16-18 December 2009; Jeju Island, South Korea: IEEE; 2010. pp. 436-441. DOI: 10.1109/ICIMT.2009.70

[3] Tonghong L. Multi-sink opportunistic routing protocol for underwater mesh network. In: 2008 International Conference on Communications, Circuits and Systems; 25-27 May 2008; Fujian, China: IEEE; 2008. pp. 405-409. DOI: 10.1109/ICCCAS.2008.4657802

[4] Li N, Martínez J-F, Meneses Chaus J, Eckert M. A Survey on underwater acoustic sensor network routing protocols. Sensors. Mar. 2016;**16**(3):414. DOI: 10.3390/s16030414

[5]   Akyildiz IF, Pompili D, Melodia T. State-of-the-art in protocol research for underwater acoustic sensor networks. In: Proceedings of the 1st ACM International Workshop on Underwater Networks; Los Angeles, CA, USA. New York, NY, USA: ACM; 2006. pp. 7-16. DOI: 10.1145/1161039.1161043

[6]   Muhammad A, Imran B, Azween A, Ibrahima F. A survey on routing techniques in underwater wireless sensor networks. Journal of Network and Computer Applications. 2011;**34**(6):1908-1927. DOI: http://dx.doi.org/10.1016/j.jnca.2011.06.009

[7]   Wang G, Liu K. Routing protocol based on cross-layer design in wireless sensor networks. Journal of Beijing University of Aeronautics and Astronautics. 2010;**36**(6):732-735. DOI: 10.13700/j.bh.1001-5965.2010.06.027. [in Chinese]

[8]   Tiansi H, Yunsi F. An adaptive routing protocol based on connectivity prediction for underwater disruption tolerant networks. In: 2013 IEEE Global Communications Conference (GLOBECOM); 9-13 December 2013; Atlanta, GA, USA: IEEE; 2014. pp. 65-71. DOI: 10.1109/GLOCOM.2013.6831049

[9]   Tian K, Zhang B, Ma J, Yao Z. Opportunistic routing protocols for wireless multihop networks. Journal of Software. 2010;**21**(10):2542-2553. DOI: 10.3724/SP.J.1001.2010.03740. [in Chinese]

[10] Al-Salti F, Alzeidi N, Arafeh B. A new multipath grid-based geographic routing protocol for underwater wireless sensor networks. In: 2014 International Conference on Cyber- Enabled Distributed Computing and Knowledge Discovery; 13-15 October 2014; Shanghai, China: IEEE; 2014. pp. 331-336. DOI: 10.1109/CyberC.2014.64

[11] Li J, Du X, Xing J, Yang Q. Location based adaptive routing protocol for underwater acoustic sensor networks. In: International Conference on Automatic Control and Artificial Intelligence (ACAI 2012); 3-5 March 2012; Xiamen, China: IET; 2013. pp. 1315-1319. DOI: 10.1049/cp.2012.1221

[12] Nicolaou N, See A, Xie P, Cui JH, Maggiorini D. Improving the robustness of location based routing for underwater sensor networks. In: OCEANS 2007—Europe; 18-21 June 2007; Aberdeen, UK: IEEE; 2007. pp. 1-6. DOI: 10.1109/OCEANSE.2007.4302470

[13] Mohapatra AK, Gautam N, Gibson RL. Combined routing and node replacement in energy-efficient underwater sensor networks for seismic monitoring. IEEE Journal of Oceanic Engineering. 2013;**38**(1):80-90. DOI: 10.1109/JOE.2012.2208850

[14] Xu M, Liu G. Fault tolerant routing in three-dimensional underwater acoustic sensor networks. In: 2011 International Conference on Wireless Communications and Signal Processing (WCSP); 9-11 November 2011; 2011 International Conference on Wireless Communications and Signal Processing (WCSP). IEEE; 2011. pp. 1-5. DOI: 10.1109/WCSP.2011.6096859

[15] Chen YS, Lin YW. Mobicast routing protocol for underwater sensor networks. IEEE Sensors Journal. 2013;**13**(2):737-749. DOI: 10.1109/JSEN.2012.2226877

[16] Hirai S, Tanigawa Y, Tode H. Integration method between localization and routing in underwater sensor network. In: 2012 IEEE 15th International Conference on Computational Science and Engineering; 5-7 December 2012; Nicosia, Cyprus: IEEE; 2013. pp. 689-693. DOI: 10.1109/ICCSE.2012.99

[17] Wang P, Fu DH, Zhao CQ, Xing JC, Yang QL, Du XF. A reliable and efficient routing protocol for underwater acoustic sensor networks. In: 2013 IEEE International Conference on Cyber Technology in Automation, Control and Intelligent Systems; 26-29 May 2013; Nanjing, China: IEEE; 2014. pp. 185-190. DOI: 10.1109/CYBER.2013.6705443

[18] Daeyoup H, Dongkyun K. DFR: Directional flooding-based routing protocol for underwater sensor networks. In: OCEANS 2008; 15-18 September 2008; Quebec City, QC, Canada: IEEE; 2009. pp. 1-7. DOI: 10.1109/OCEANS.2008.5151939

[19] Emokpae L, Younis M. Signal reflection-enabled geographical routing for underwater sensor networks. In: 2012 IEEE International Conference on Communications (ICC); 10-15 June 2012; Ottawa, ON, Canada: IEEE; 2012. pp. 147-151. DOI: 10.1109/ICC.2012.63637

[20] Chirdchoo N, Soh WS, Chua KC. Sector-based routing with destination location prediction for underwater mobile networks. In: 2009 International Conference on Advanced Information Networking and Applications Workshops; 26-29 May 2009; Bradford, UK: IEEE; 2009. pp. 1148-1153. DOI: 10.1109/WAINA.2009.105

[21] Wei Y, Kim DS. Reliable and energy-efficient routing protocol for underwater acoustic sensor networks. In: 2014 International Conference on Information and Communication Technology Convergence (ICTC); 22-24 October 2014; Busan, South Korea: IEEE; 2014. pp. 738-743. DOI: 10.1109/ICTC.2014. 6983274

[22] Eunjo K, Jonggu K, Poh KC, Seongeun Y, Daeyoung K. Energy efficient local area source routing protocol of underwater sensor networks in the deep ocean. In: 2007 International Symposium on Communications and Information Technologies; 17-19 October 2007; Sydney, NSW, Australia: IEEE; 2007. pp. 948-953. DOI: 10.1109/ISCIT.2007.4392152

[23] Chen YD, Chen YW, Lien CY, Shih KP. A channel-aware depth-adaptive routing protocol for underwater acoustic sensor networks. In: OCEANS 2014—TAIPEI; 7-10 April 2014; Taipei, Taiwan: IEEE; 2014. pp. 1-6. DOI: 10.1109/OCEANS-TAIPEI.2014.6964460

[24] Zhang S, Li D. A beam width and direction concerned routing for underwater acoustic sensor networks. In: 2013 IEEE 9th International Conference on Mobile Ad-hoc and Sensor Networks; 11-13 December 2013; Dalian, China: IEEE; 2014. pp. 17-24. DOI: 10.1109/MSN.2013.21

[25] Chen YD, Lien CY, Wang CH, Shih KP. DARP: A depth adaptive routing protocol for large-scale underwater acoustic sensor networks. In: 2012 Oceans—Yeosu; 21-24 May 2012; Yeosu, South Korea: IEEE; 2012. pp. 1-6. DOI: 10.1109/OCEANS-Yeosu.2012.6263505

[26] Kuo LC, Melodia T. Cross-layer routing on MIMO-OFDM underwater acoustic links. In: 2012 9th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad

Hoc Communications and Networks (SECON); 18-21 June 2012; Seoul, South Korea: IEEE; 2012. pp. 227-235. DOI: 10.1109/SECON.2012.6275782

[27] Wu X, Chen G, Chen J. Energy-efficient and topology-aware routing for underwater sensor networks. In: 2010 Proceedings of 19th International Conference on Computer Communications and Networks; 2-5 August 2010; Zurich, Switzerland, Switzerland: IEEE; 2010. pp. 1-6. DOI: 10.1109/ICCCN.2010.5560016

[28] Zheng G, Zheng P, Bing W, Cui JH, Wu J. Adaptive routing in underwater delay tolerant sensor networks. In: 2011 6th International ICST Conference on Communications and Networking in China (CHINACOM); 17-19 August 2011; Harbin, China: IEEE; 2012. pp. 1044-1051. DOI: 10.1109/ChinaCom.2011.6158310

[29] Anupama KR, Sasidharan A, Vadlamani S. A location-based clustering algorithm for data gathering in 3D underwater wireless sensor networks. In: 2008 International Symposium on Telecommunications; 27-28 August 2008; Tehran, Iran: IEEE; 2008. pp. 343-348. DOI: 10.1109/ISTEL.2008.4651325

[30] Domingo MC, Prior R. Design and analysis of a GPS-free routing protocol for underwater wireless sensor networks in deep water. In: 2007 International Conference on Sensor Technologies and Applications (SENSORCOMM 2007); 14-20 October 2007; Valencia, Spain: IEEE; 2007. pp. 215-220. DOI: 10.1109/SENSORCOMM.2007.4394923

[31] Gopi S, Govindan K, Chander D, Desai UB, Merchant SN. E-PULRP: energy optimized path unaware layered routing protocol for underwater sensor networks. IEEE Transactions on Wireless Communications. 2010;**9**(11):3391-3401. DOI: 10.1109/TWC.2010.091510.090452

[32] Ce W, Gongliang L. LUM-HEED: A location unaware, multi-hop routing protocol for underwater acoustic sensor networks. In: Proceedings of 2011 International Conference on Computer Science and Network Technology; 24-26 December 2011; Harbin, China: IEEE; 2012. pp. 2336-2340. DOI: 10.1109/ICCSNT.2011.6182441

[33] Ayaz M, Abdullah A, Jung LT. Temporary cluster based routing for underwater wireless sensor networks. In: 2010 International Symposium on Information Technology; 15-17 June 2010; Kuala Lumpur, Malaysia: IEEE; 2010. pp. 1009-1014. DOI: 10.1109/ITSIM.2010.5561598

[34] Kredo II K, Mohapatra P. Distributed scheduling and routing in underwater wireless networks. In: 2010 IEEE Global Telecommunications Conference GLOBECOM 2010; 6-10 December 2010; Miami, FL, USA: IEEE; 2011. pp. 1-6. DOI: 10.1109/GLOCOM.2010.5685230

[35] Coutinho RWL, Vieira LFM, Loureiro AAF. DCR: Depth-controlled routing protocol for underwater sensor networks. In: 2013 IEEE Symposium on Computers and Communications (ISCC); 7-10 July 2013; Split, Croatia: IEEE; 2014. pp. 453-458. DOI: 10.1109/ISCC.2013.6754988

[36] Khan MA, Javaid N, Majid A, Imran M, Alnuem M. Dual sink efficient balanced energy technique for underwater acoustic sensor networks. In: 2016 30th International

Conference on Advanced Information Networking and Applications Workshops (WAINA); 23-25 March 2016; Crans-Montana, Switzerland: IEEE; 2016. pp. 551-556. DOI: 10.1109/WAINA.2016.156

[37] Shah PM, Ullah I, Khan T, Hussain MS, Khan ZA, Qasim U, Javaid N. MobiSink: Cooperative routing protocol for underwater sensor networks with sink mobility. In: 2016 IEEE 30th International Conference on Advanced Information Networking and Applications (AINA); 23-25 March 2016; Crans-Montana, Switzerland: IEEE; 2016. pp. 189-197. DOI: 10.1109/AINA.2016.167

[38] Pouryazdanpanah KM, Anjomshoa M, Salehi SA, Afroozeh A, Moshfegh GM. DS-VBF: Dual sink vector-based routing protocol for underwater wireless sensor network. In: 2014 IEEE 5th Control and System Graduate Research Colloquium; 11-12 August 2014; Shah Alam, Malaysia: IEEE; 2014. pp. 227-232. DOI: 10.1109/ICSGRC.2014.6908727

[39] Chen B, Hickey PC, Pompili D. Trajectory-aware communication solution for underwater gliders using WHOI micro-modems. In: 2010 7th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON); 21-25 June 2010; Boston, MA, USA, USA: IEEE; 2010. pp. 1-9. DOI: 10.1109/SECON.2010.5508262

[40] Zhuo W, Hongmei G, Longjie J, Xiaoning F. AUV-aided communication method for underwater mobile sensor network. In: OCEANS 2016—Shanghai; 10-13 April 2016; Shanghai, China: IEEE; 2016. pp. 1-7. DOI: 10.1109/OCEANSAP.2016.7485345

[41] Shashaj A, Petroccia R, Petrioli C. Energy efficient interference-aware routing and scheduling in underwater sensor networks. In: 2014 Oceans—St. John's; 14-19 September 2014; St. John's, NL, Canada: IEEE; 2015. pp. 1-8. DOI: 10.1109/OCEANS.2014.7003110

[42] Pompili D, Melodia T, Akyildiz IF, Ian F.. Routing algorithms for delay-insensitive and delay-sensitive applications in underwater sensor networks. In: Proceedings of the 12th Annual International Conference on Mobile Computing and Networking; Los Angeles, CA, USA. New York, NY, USA: ACM; 2006. pp. 298-309. DOI: 10.1145/1161089.1161123

[43] Goetz M, Nissen I. GUWMANET-multicast routing in underwater acoustic networks. In: 2012 Military Communications and Information Systems Conference (MCC); 8-9 October 2012; Gdansk, Poland: IEEE; 2012. p. 1-8.

[44] Zhou Z, Peng Z, Cui JH, Shi Z. Efficient multipath communication for time-critical applications in underwater acoustic sensor networks. IEEE/ACM Transactions on Networking. 2011;**19**(1):28-41. DOI: 10.1109/TNET.2010.2055886

[45] Basagni S, Petrioli C, Petroccia R, Spaccini D. Channel-aware routing for underwater wireless networks. In: 2012 Oceans—Yeosu; 21-24 May 2012; Yeosu, South Korea: IEEE; 2012. pp. 1-9. DOI: 10.1109/OCEANS-Yeosu.2012.6263538

[46] Hu T, Fei Y. MURAO: A multi-level routing protocol for acoustic-optical hybrid underwater wireless sensor networks. In: 2012 9th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks

(SECON); 18-21 June 2012; Seoul, South Korea: IEEE; 2012. pp. 218-226. DOI: 10.1109/SECON.2012.6275781

[47] Thangarajan R, Siva T, Boopalachakaravarthy R. Adaptive energy efficient routing protocol with extended lifetime in underwater sensor networks. In: 2013 International Conference on Communication Systems and Network Technologies; 6-8 April 2013; Gwalior, India: IEEE; 2013. pp. 322-326. DOI: 10.1109/CSNT.2013.74

[48] Hu T, Fei Y. QELAR: A machine-learning-based adaptive routing protocol for energy-efficient and lifetime-extended underwater sensor networks. IEEE Transactions on Mobile Computing. 2010;**9**(6):796-809. DOI: 10.1109/TMC.2010.28

[49] Coutinho RWL, Boukerche A, Vieira LFM, Loureiro AAF. Geographic and opportunistic routing for underwater sensor networks. IEEE Transactions on Computers. 2016;**65**(2):548-561. DOI: 10.1109/TC.2015.2423677

[50] Noh Y, Lee U, Wang P, Choi BSC, Gerla M. VAPR: Void-aware pressure routing for underwater sensor networks. IEEE Transactions on Mobile Computing. 2013;**12**(5):895-908. DOI: 10.1109/TMC.2012.53

[51] Yang CH, Ssu KF, Lin YY. A delay-awareness routing protocol in intermittently connected underwater acoustic sensor networks. In: 2013 IEEE 19th Pacific Rim International Symposium on Dependable Computing; 2-4 December 2013; Vancouver, BC, Canada: IEEE; 2014. pp. 138-39. DOI: 10.1109/PRDC.2013.31

[52] Lee U, Wang P, Noh Y, Vieira LFM, Gerla M, Cui JH. Pressure routing for underwater sensor networks. In: 2010 Proceedings IEEE INFOCOM; 14-19 March 2010; San Diego, CA, USA: IEEE; 2010. pp. 1-9. DOI: 10.1109/INFCOM.2010.5461986